Materials & Manufacturing






Business growth in a transformative journey to zero emissions

UK FIRES

Materials & Manufacturing

UK FIRES is a 5-year research programme funded by £5m of UKRI support and the subscriptions of an active and growing industrial consortium. With academics from six universities spanning from materials engineering through data science to economics, corporate strategy and policy and an industry consortium spanning from mining through construction and manufacturing to final goods.

UK FIRES stands for placing Resource Efficiency at the heart of the UK's Future Industrial Strategy. When we proposed UK FIRES, it was to focus on Resource Efficiency as the key means to reduce industrial emissions. However, in 2019, both houses of Parliament unanimously approved a change to the UK's climate change act to target zero emissions in 2050. This has been reinforced by recent Government targets for 2030 and 2035.

So, although we haven't changed our name to UK FIZES, our focus is now on placing Zero Emissions at the heart of the UK's Future Industrial Strategy.

UK FIRES takes a pragmatic approach: we focus only on technologies that are available to us today and exclude those that have yet to be proven at meaningful scale, since they simply may not be ready in time. In 2050 we aim to meet the energy demand of UK society by non-emitting electricity generation.

In December 2019, UK FIRES released the "Absolute Zero" report, a ground-breaking description of the operation of the UK with zero emissions by 2050, without relying on as as-yet un-scaled energy sector or negative emissions technologies. This pragmatic but striking view of the journey to zero emissions has attracted widespread interest including a full debate in the House of Lords in February 2020.

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Absolute Zero: Materials & Manufacturing

Facing the reality that new energy-sector technologies won't solve climate change fast enough reveals rich opportunities for innovation and growth in UK materials and manufacturing sectors.

UK law commits us to zero emissions by 2050 with most of the reduction occurring by 2035. But we're not on track to deliver. That's because corporate and political strategy today is counting on new technologies, like carbon capture and storage, biofuels, hydrogen and negative emissions technologies to meet the challenge, while business elsewhere continues largely as usual. It isn't going to happen in time. The new technologies are mainly still on drawing boards, and it takes time to deploy them at scale.

Instead, delivering zero emissions in reality by 2050 requires a different economy. It's one that can deliver high quality lifestyles, but it's an economy that will be powered only by emissions free electricity. We won't have as much electricity as we'd otherwise like, so we'll reduce our use of two-tonne cars and badly insulated houses, for example. For some time we'll have to restrain our use of goods, like ruminants and cement, that can't be electrified. But this new economy can deliver great lifestyles and great businesses.

In manufacturing, we won't be able to access the same volumes of material as in the emitting past, but we have the opportunity for huge growth in the UK. The closure of high-emitting international freight will open up new demand for domestic production. The need to close the high-emitting material suppliers of the past creates new opportunities for electric materials production. The business of matching material supply to consumer demand for goods will transform and grow.

This report, the outcome of wide industrial consultation and new analysis by UK FIRES, focuses on four substantial areas of growth potential:

- As blast furnaces, cement kilns and existing petrochemical plants are closed under UK law, demand for electric material production will grow in proportion. For some materials, such as steel or glass, electric production is already familiar and operates at high volume, but will grow to make better use of UK scrap and innovate to transform recycling into upcycling. For others, such as cement and most plastics, new electric production routes will be invented and find rapidly expanding demand.
- As the supply of primary materials made from oil and minerals diminishes, the demand for high value material recovery and recycling is certain to expand. Businesses will grow to service every aspect of material collection, separation, management, re-processing and re-integration into existing practices.
- With a reduced supply of electricity and material, businesses that deliver efficiency whether through consultancy, equipment supply, design or management services, will find new rapidly expanding markets, seeking motor efficiency, targeted electric heat, and material efficiency in both design and processing.
- In response to reduced material supply, customers will want longer use from goods, and seek businesses to maintain, upgrade, adapt and exploit capital assets for longer and with more value.

In all, this report reveals £270bn of innovation and growth potential for UK materials and manufacturing businesses. Seeing through the fictions of technology solutions and facing the reality of climate change leads not to hairshirts, but a wealth of opportunity. By anticipating a realistic delivery of our legal commitment to zero emissions, this report sets out a credible basis for optimism and growth in UK production.

Absolute Zero: Materials & Manufacturing

In December 2019, UK FIRES published "Absolute Zero" the first physically grounded description of reaching zero emissions by 2050 using today's technologies.

Absolute Zero had a huge impact, in government, the media, in a full debate in the House of Lords, and in businesses and innovation groups across the UK. After Stephen Hawking's PhD thesis, it is the most-downloaded document from the University of Cambridge archive.

Absolute Zero matters because it challenges assumptions of risk in addressing climate change. The conventional narrative of climate policy is that the peoples of developed economies will not accept any change in their behaviour in order to mitigate climate change, so solutions must be technological and invisible to the public. As a result, for twenty years, politicians and corporate leaders have talked about Carbon Capture and Storage, Hydrogen, Negative Emissions Technologies and Biofuels as the basis of a future zero emissions economy. The conventional story for manufacturing is that supplies of today's materials will be maintained at today's levels, or higher, so incumbent supply chains can continue to function with only marginal changes.

But this technologically transformed economy hasn't appeared and shows no sign of doing so. Less than 0.1% of the world's emissions are captured and stored, almost entirely for the purpose of extracting more oil and gas. There is no substantial supply of zero emissions hydrogen, biofuel production is a tiny fraction of total oil demand, and the new processes of materials production are still on the drawing board. Governments and the high-emitting sectors continue to announce plans to deliver "net zero" by 2050, but with no serious commitments to implementation.

This wouldn't matter if Climate Change was just a conversation topic, and mitigation an expensive but optional burden. But it isn't. If we don't mitigate climate change, in addition to damage from extreme weather and sea-level rise, around a billion people in countries near the equator will starve to death by the end of this century. Really delivering zero emissions by 2050 is a matter of life and death.

The leaders of governments and corporations today are not facing this reality: business as usual cannot continue, but they are acting as if it will. Absolute Zero therefore redressed the balance. Given the awful consequences of inaction, corporate and political strategy should guarantee that we deliver zero emissions above all other priorities and doing so involves requires caution about the scale and deployment rates of invisible technological solutions.

Climate policy to date has largely anticipated consumer demand by projecting past growth, and then "back-cast" the supplies of new technologies required to deliver it. This is so unlikely to happen, that we urgently need a different starting point. Absolute Zero provided it by forecasting future non-emitting energy supply from recent growth rates, and then anticipating the goods and services it can supply.

This report works out the consequences of the Absolute Zero story for the Materials and Manufacturing sectors in the UK. It tells a story of huge opportunity for new business growth. The emitting sectors of the past, whether in blast-furnace steel making, cement kilns, conventional petrochemical production, or the manufacture of combustion engines must all close. That creates a large and fertile space for innovation, in the production and servicing of new solutions that deliver high quality living with zero emissions.

Absolute Zero reveals a tremendous opportunity for innovation and growth in materials and manufacturing. This report aims to reveal and stimulate that growth.

Key Messages

Entrepreneurial Opportunity

Delivering zero emissions materials and manufacturing in the UK by 2050 is an opportunity for business growth:

Supply Of Industrial Equipment

ELECTRIC INDUSTRIAL HEAT

- £15 billion to supply high and moderate temperature electric industrial heat through specialised plasma-based or electrode-based heating.

INDUSTRIAL HEAT PUMPS

- £9 billion to supply industrial heat pumps and other forms of low temperature process heat up to 200 °C.

ELECTRICITY PRODUCTION

- £5 billion annual market in the supply chain for renewable electricity production.

New Production Capacity

HIGH QUALITY RECYCLING

- £8 billion annual revenues from high quality recycling of recovered material currently exported; further opportunities to increase material recovery.

CARBON EMBODIED IN TRADE

- £56 billion revenue increase for UK-based manufacturing to reach at least 90 % of consumption in all sectors; taking responsibility for more carbon embodied in trade.

ELECTRIC TRANSPORT EQUIPMENT AND DOMESTIC ELECTRIC HEATING

- £39 billion in supply of new electric transport equipment and domestic electric heating to enable the transition to zero emissions.

New Business Models & Consultancies

MATERIAL EFFICIENCY

- £1 billion opportunity for new consultancy businesses to provide software, tools, and training in enhancing the material efficiency of design and manufacturing.

THROUGH-LIFE ENGINEERING SERVICES

- £32 billion annually for business providing through-life engineering services, driven by uptake beyond aerospace into all types of durable goods.

SHARED USE OF GOODS

- £40 billion annual opportunity in offering shared use of goods in transport, industrial equipment and appliances.

Policy Support

Targeting Absolute Zero rather than Net Zero, as we propose here, requires a shift in thinking at all levels of policy discourse. This starts with public philosophies; climate change should be seen as an existential threat arising from business as usual, not an inconvenience to it. Solutions lie throughout the supply chain, including how final services are delivered, requiring implementation through entrepreneurship, not merely a fix in the energy sector. Our view is business model innovation is even more important than technology innovation; and in some sectors this is the only way to avoid closures.

Implementing Absolute Zero in Materials and Manufacturing will require several additional policy mechanisms over the current Net Zero strategy, as is highlighted here:

Form of policy mechanism	Current Net Zero Strategy actions	Additional actions to support Absolute Zero Materials and Manufacturing
Markets and taxation	New UK ETS	Re-balance waste export duties to match landfill tax Non-linear energy tariffs to promote energy efficiency; avoid discounts to large users Re-balance VAT to favour asset maintenance over replacement Feed-in-tariffs to support introduction of newly electrified heat
Messaging	Targets and 'leadership'	Clarity about true costs, complexity and availability of hydrogen compared to electrification Clarity about forms of recovery and recycling Demonstration of asset utilisation and life extension in public funded bodies Describe opportunities for high-value on-shoring
Crisis Management	BAU, bailouts	Anticipate future steel crises with plans to invest in electrification, not subsidise ongoing emissions. Anticipate reduction in international freight due to shortage of zero emissions alternatives
Monitoring, Reporting & Verification	International MRV	Mandate regular corporate reporting on non-electric heating usage National statistics on recovered material exports National standards for embodied emissions certification incorporating total material footprint
Government Regulation & Action (including gov funds)	ICE car ban Industrial funding i.e., CCS & Hydrogen funds Industrial clusters	Phased-bans of non-electric heating equipment Innovation support for material efficiency in design and processes Innovation support in productivity and processes for repair, maintenance and upgrade Innovation support for materials production without process emissions

Decarbonisation of UK Materials and Manufacturing: A Vision

Ambitious national targets have been set for decarbonisation, but at present the bulk of the UK's industrial emitters either have no stated plan, or are banking on expensive carbon capture and storage or alternative fuels:

- Only 20% of major materials and manufacturing companies we surveyed had a stated ambition to reach net zero emissions
- Only a 44% emissions reduction considered achievable by sector expert groups without carbon capture and storage

With this report we've set out a vision for decarbonisation of UK materials and manufacturing assuming these technologies play a very small role. We consulted widely on this topic – and established six major themes for change; from electrification of materials production through to eliminating process emissions, as set out in the table. As we see it, together, action in these areas can achieve full decarbonisation, through avoiding emissions at source and managing demand for zero carbon electricity.

Our central message with this report is that zero emissions is an opportunity for UK enterprise, and so within each theme we have provided a unique estimate for the scale of entrepreneurial opportunity, these cover the space of the three themes set out earlier: supply of new industrial equipment, new production capacity and consultancies and new profitable business models. These, and a vision for the changes required are set out in detail over the following sections.

**Total market to achieve decarbonisation goals, not annual. All other opportunity sizing annual.*

DECARBONISATION THEME	Entrepreneurial Opportunity		
	SUPPLY OF INDUSTRIAL EQUIPMENT	NEW PRODUCTION CAPACITY	NEW BUSINESS MODELS AND CONSULTANCIES
ELECTRIFICATION OF MATERIALS PRODUCTION	**£24 billion***		
HIGH QUALITY RECYCLING	**£ 6 billion***	**£9.4 billion**	**£0.3 billion**
IMPROVE RESOURCE EFFICIENCY	**£2 billion***		**£ 1 billion**
MORE SERVICE FROM GOODS		**£54 billion**	**£ 78 billion**
NEW DEMAND FOR UK MANUFACTURING	**£5 billion**	**£100 billion**	
ELIMINATE PROCESS EMISSIONS		**£0.1 billion**	
Total	**£37 billion**	**£165 billion**	**£80 billion**

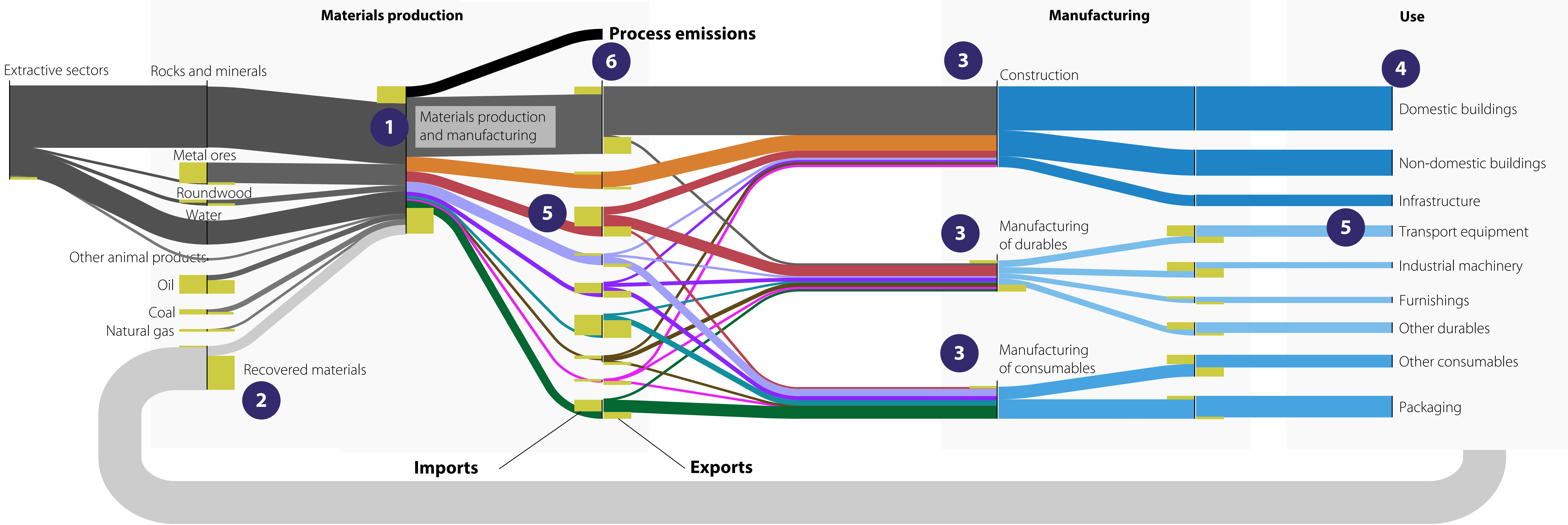
UK materials and manufacturing: mass flows and greenhouse gas emissions, 2018

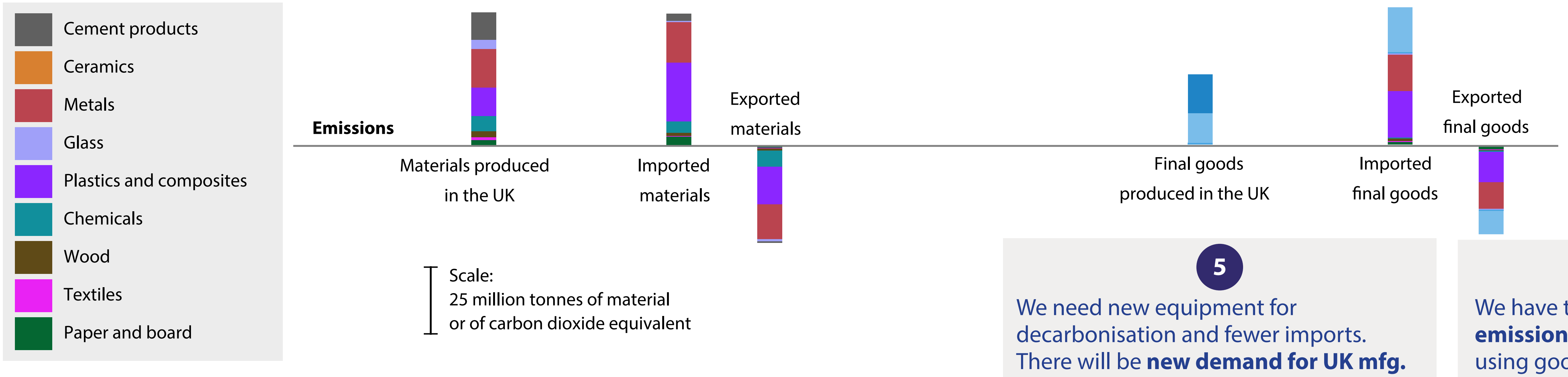
1 Process heating accounts for ~50% of industrial emissions. We should **electrify** this & use non-emitting electricity.

2 Only 25% of recovered materials in the UK is recycled in the UK. We should do more **high quality recycling**.

3 Manufacturing sectors use 40% more material than needed. We should improve **resource efficiency**.

4 Fewer goods can be used to deliver the same service. We should **improve service efficiency.**





5 We need new equipment for decarbonisation and fewer imports. There will be **new demand for UK mfg.**

6 We have to **eliminate process emissions** from making materials and using goods.

Electrification of Materials Production

Process heating in industry relies on burning fossil fuels, and this must stop. We see no alternative to a widespread and rapid shift to electrifying industrial heat across the board, with virtually all heat required to produce and recycle materials sourced from renewable electricity.

Electrifying process heat – in combination with grid decarbonisation – can deliver large reductions in CO2 emissions: process heat is currently responsible for about 50% of all materials and manufacturing emissions. Whilst this is a nascent strategy, the more we engage with this issue, we've found evidence that:

- Electric alternatives exist for almost all uses of combustion in materials production, and these are often commercially available.
- High-grade electric heat can deliver multiple units of heat for every unit of electric input, especially at low to moderate temperatures
- Electric heating can deliver greater flexibility and economy at smaller scale, allowing greater competition and localised production.

Full implementation of electric process heat is an opportunity for UK production business to show international leadership whilst generating new markets in the development and supply of the equipment to enable the transition, with a total market size estimated at £24 billion. Overleaf we break this down into the major changes anticipated in each material production sector.

Image: Alexlukin / Shutterstock.com

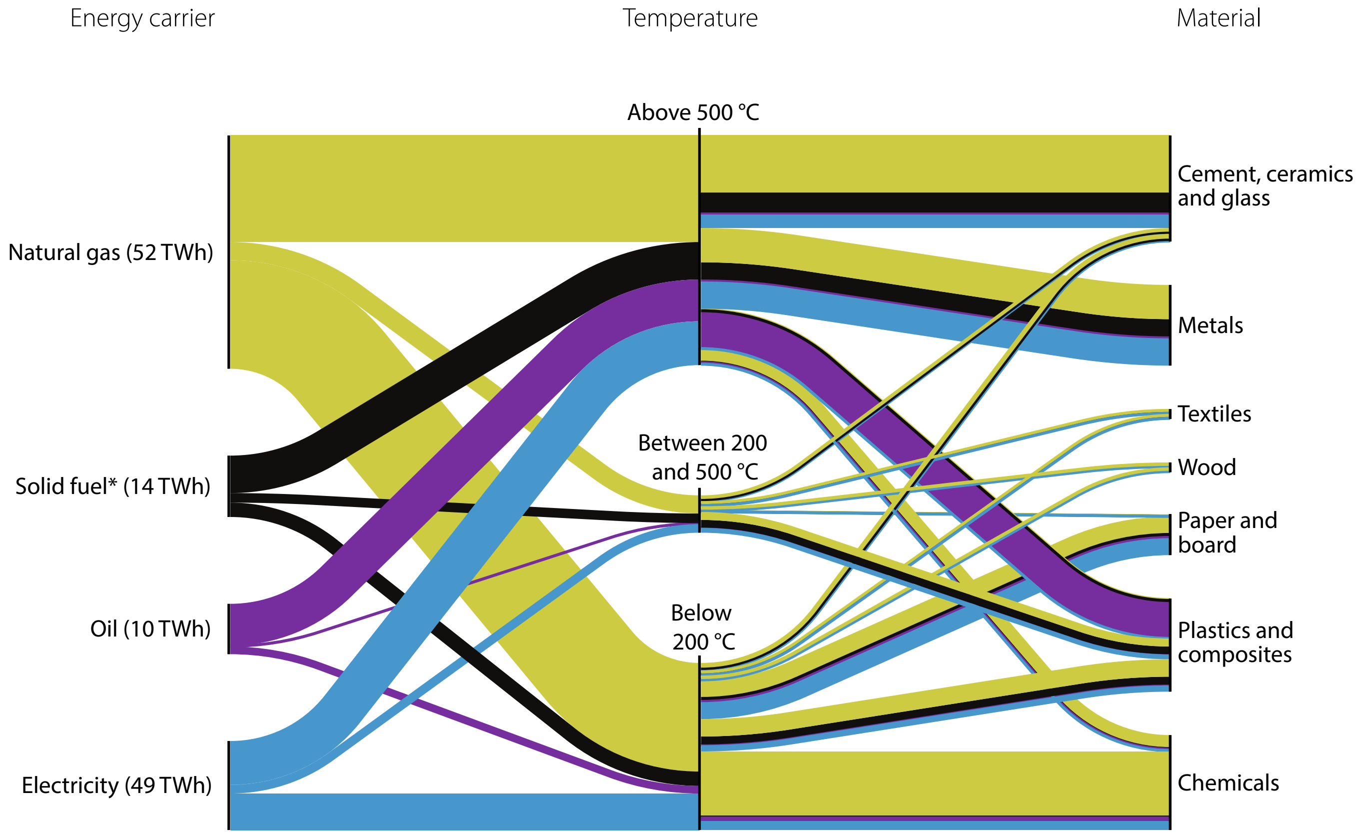
Growth Opportunities

Supply Of Industrial Equipment

New Production Capacity

Process heating in industry relies on burning fossil fuels, and this must stop. We see no alternative to a widespread and rapid shift to electrifying industrial heat across the board, with virtually all heat required to produce and recycle materials sourced from renewable electricity.

Heat for materials production in the UK, 2018



**Solid fuel is 85% coal and 15% coke and does not include waste or bioenergy.*

About half the heat used in UK materials production today is supplied at below 500°C. At this temperature there are several options to substitute the current means of delivering heat with electrical devices, including electrode boilers, resistance heating or heat pumps. Doing so would transform the emissions footprint of the chemicals and paper industries, where low temperature uses of heat dominate. The plastics, metals, cement, ceramics, and glass industries all also require substitute heating at higher temperature, replacing current use of coal, oil and natural gas.

Evidence and Methodology: Quantifying the decarbonisation themes: page 35

Metals

Combustion in the metals sector is dominated by the blast furnaces used in producing steel from iron ore, and gas furnaces for process heating throughout the metals supply chain, including hot deformation processing and heat treatment. Electrifying metals requires:

£3.9bn investment in electrification of steelmaking

9
Electric Arc Furnace facilities

9 Mt / yr
new production capacity

£4.9bn investment to supply electric heat in downstream metals sector

5 GW
replacement capacity using induction and resistance heating tech

Glass and Ceramics

Primary glass making requires 1700°C heat to melt feedstock prior to casting or shaping. Ceramics production, including clay-based bricks and tiles, uses air-heating to temperatures above 1000°C. Fossil-fuel use is widespread, and electrifying the sector requires:

£1.1bn investment to electrify ceramics kilns

110
sites for upgrade - all UK ceramics production

6 Mt /yr
new production capacity

£1.7bn investment to electrify glass furnaces

40
UK container glass, flat glass and fibre sites upgraded

4.1 Mt / yr
new production capacity

CASE STUDY

The US is among the leading adopters of Electric Arc Furnace (EAF) steelmaking, with over half of production in 2013 from more than 110 so-called 'mini mills'. Capacity is growing with major investments totaling over $8bn announced in recent years from Steel Dynamics, SDI, Big River Steel, JSW & Arcelor Mittal. These firms have recognized the profit potential from moving up the quality ladder by recycling higher quality steel. UK providers of plant for EAF steelmaking, such as Primetals Technologies are making headway in supporting this growth in the US market. Will the UK follow suit and realize the benefits of high value electric-steelmaking?

Chemicals and Plastics

Process heat is widely used throughout the chemicals and plastics supply chain; in steam-cracking, polymerisation and processing of plastics, fertiliser production and inorganic chemicals such as soda ash and titanium dioxide. Currently just 11% of process heating is electric but we think this can increase to almost 100%.

£1.1bn to electrify steam crackers

3

UK ethylene production sites

2.3 Mt / yr new production capacity

£1.4 Billion investment in renewable-powered hydrogen electrolysis plants

7 TWh

per year low temperature heat provided by industrial heat pumps or Electric resistance heaters

8

plants supplying hydrogen for ammonia and as a chemical 800MM3 per year capacity

£9 Billion investment to electrify other process heat in plastics and chemicals

3 TWh low temperature process heat from new heat pumps

4 TWh medium temperature heat from new electrode heating

3 TWh high temperature heat through electric furnaces or plasma heating

Paper and Printing

The UK's approximately 50 paper mills predominantly process recovered paper and imported wood pulp, therefore the major heat requirements are for drying in paper making (and not pulping). At present 50% of this heat is supplied by electricity.

£400m to electrify process heat in paper mills

50

paper mill sites in the UK

0.8 GW new electric heating capacity

CASE STUDY:

Most major glass furnaces are gas-fired, but all electric melting has been successfully applied in the glass industry for decades, using immersed electrodes. German-based manufacturer Horn Glass have developed an all-electric concept that produces higher quality glass, at higher efficiencies than fossil-fired furnaces – making small furnaces more cost efficient.

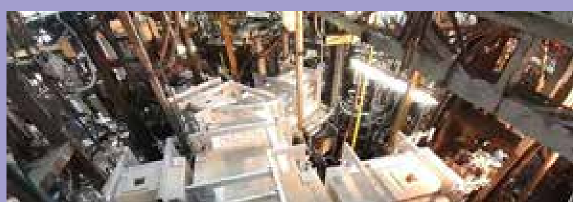


Image: Horn Glass

High Quality Recycling and Recovery

Despite huge efforts in collection and recovery, rates of recycling in the UK –producing new materials from recovered feedstock – are still low. To achieve zero emissions, we expect a huge increase in materials production by high quality recycling from recovered material feedstock, in metals, plastics and paper.

The current process of producing materials from virgin feedstocks like steel from iron ore is energy intensive and often causes unavoidable process emissions due to the chemical reactions required. Melting and reprocessing recovered feedstock (recycling) is a viable and usually less energy intensive alternative without process emissions. However, at present only a quarter of material collected from waste streams is recycled in the UK.

Our view is that achieving zero-emissions requires virtually all materials to be produced by recycling, to both avoid process emissions, and reduce energy intensity. This in turn requires a transformation in collection and sorting infrastructure, materials production facilities and product design.

Full implementation of this vision opens business opportunities not just in the supply of recycling and recovery equipment (£6 billion), but also in expanded UK production (£9 billion), and new business models around recovery and product design (£0.3 billion). These are set out overleaf.

Image: Oleksiy Mark / Shutterstock.com

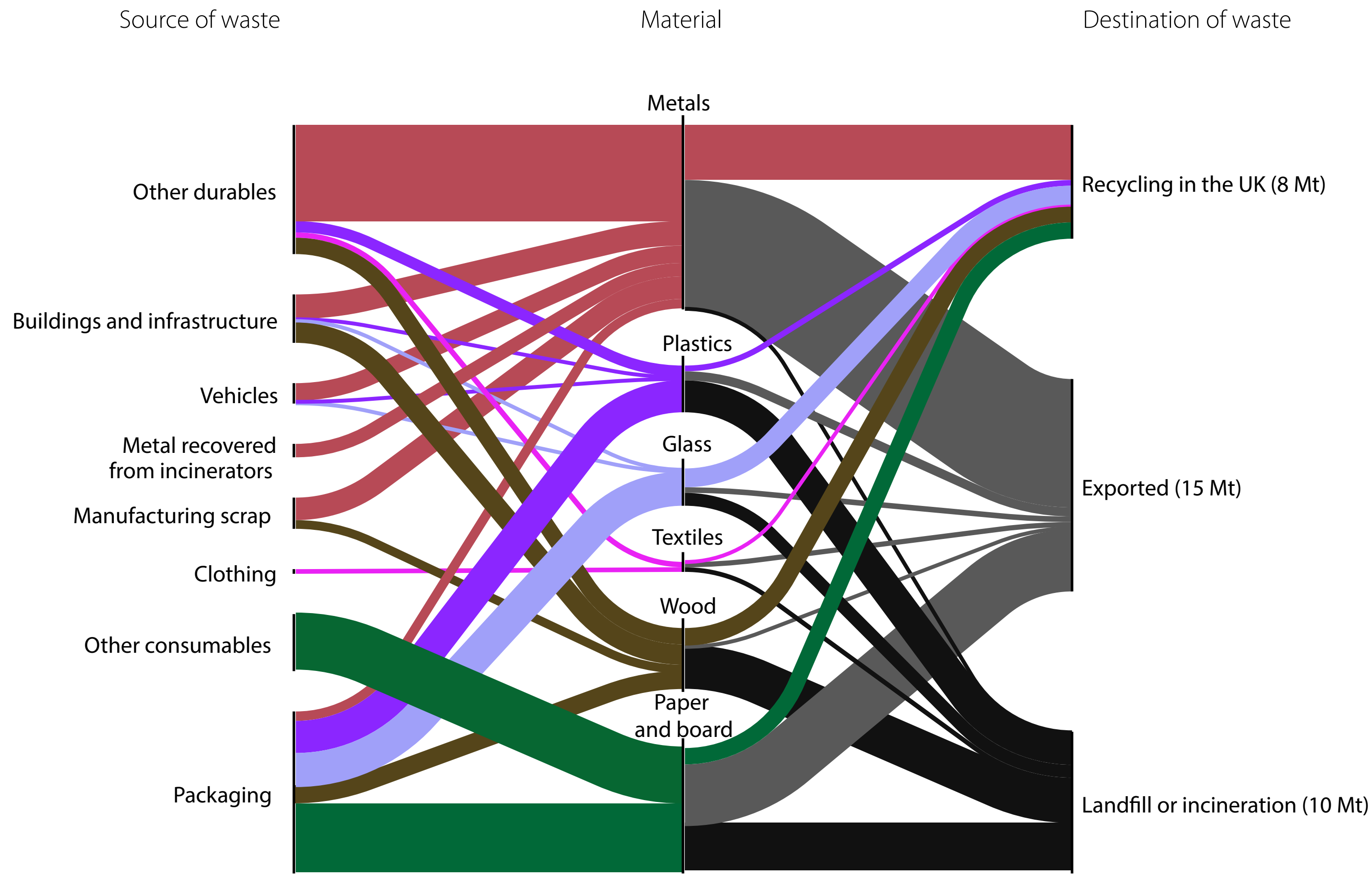
Growth Opportunities

New Production Capacity

New business models & consultancies

Despite huge efforts in collection and recovery, rates of recycling in the UK –producing new materials from recovered feedstock – are still low. To achieve zero emissions, we expect a huge increase in materials production by high quality recycling from recovered material feedstock, in metals, plastics and paper.

Material flows from goods at the end-of-life in the UK, 2018



**Solid fuel is 85% coal and 15% coke and does not include waste or bioenergy.*

Whilst almost 70% of recyclable materials avoid landfill, a very large quantity of these is currently exported. In fact, just a quarter of end-of life materials are recycled in the UK. This applies across the board: metals are the most recycled material group by volume, but still only a fraction of this is done in the UK. Only glass has a greater than 50% recycling rate. Plastics could be the biggest story: high emissions impact, very low recycling rate. Nearly half of recovered material in the UK originates from packaging and other consumables.

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Bulk Material Production from Recovered Materials

Producing high quality bulk materials from sorted and cleaned feedstock requires investment in facilities typically to remelt and cast the product. This is well established in most sectors, except for some plastics and cement.

£2.1 billion additional investment in secondary steelmaking

£1.8bn

annual value of new steel production

5

new Electric Arc Furnace facilities established

£0.3 billion investment in aluminium remelting facilities

6

new production plants of delivering an output of 0.4 Mt per year, with 100% recovered input

£0.9 bn

annual value of new aluminium production

£1.8 billion investment in recycled plastic production facilities, covering PP, HDPE, LDPE, PET, PVC, and PS

29

mechanical recycling plants of combined output 1.5 Mt per year

6

chemical recycling plants of total output 0.4 Mt per year

£1.7bn annual value of new plastics production

£0.3 billion investment in production of flat glass and container glass from recovered feedstock

5

new production sites with 1.0 Mt per year output

£0.3bn

annual value of new glass production

CASE STUDY

Advanced Electric Machines (AEM) – electric motors with no rare earth metals or copper

Rare earth magnetic materials are becoming widely recognised as a key issue in future motor designs. Utilising design, manufacturing and material innovations AEM removes both the rare earth magnets from their SSRD motor, while offering system (motor and converter) level power density of over 20kW/litre and 6.5kw/kilogramme and achieving peak efficiencies around 96%. As well as removing the magnets the team at AEM have developed a patented manufacturing process which allows SSRD to use aluminium windings in place of copper. The removal of both the magnets and the copper from the system means that SSRD has the potential to save over 60% on the Bill of Materials cost, will be lighter and the whole motor can be upcycled by melting down through an electric arc furnace into high grade steels without the need for any disassembly.

£3.0 billion investment in recycled paper and board production

£3bn

investment in recycled paper and board production

11

new production sites with 6 Mt / year output

£4.6 bn

value of new paper and board production

CASE STUDY

Recycling Technologies are developing processes to convert end-of-life plastic into useful feedstock for making new plastics or other chemicals. These technologies could displace some extraction of virgin fossil fuels and reduce the quantity of incinerated material. Recycling Technologies are building pilot plants that achieve this using thermal cracking, where the feedstock material is heated up until it breaks down into shorter molecules. They are exploring two avenues for this technology, either by converting a mix of end-of-life plastics into high-quality feedstock or by reverting styrene polymers back to monomers. Styrene plastics are difficult to recycle, and these recycled monomers can be made into products with the same quality as with using virgin feedstock. These examples illustrate the business potential of finding higher quality uses for recovered material. There is an opportunity for significant growth in the UK for businesses such as Recycling Technologies to provide the equipment for up to 5 chemical recycling plants, taking a share of the £800m investment required to deliver an output of 0.3 million tonnes of recycled plastic per year.

Improving Material Recovery & Feedstock Preparation

Improvements in disassembly and sorting would enable high quality recycling, increasing the quantity and value of recovered material. Automated disassembly of home appliances and vehicles, and recovery of Critical Raw Materials (CRMs) from consumer electronics are key opportunities whilst better sorting can avoid contaminants and increase feedstock value:

£1 billion investment in state-of-the-art steel recovery facilities

11.3 Mt UK steel scrap to be processed

£0.6 bn per yearvalue addition by avoiding downcycling

£400 million investment in end-of-life home appliance disassembly

24 facilities to process all TVs, refrigerators, freezers, washing machines, air conditioners and other electric goods.

£600 million investment in automotive disassembly plants

28 plants to provide automotive components for reuse and high quality feedstock for metal, plastic and glass recycling.

£90 million investment in 55 new facilities to recover CRMs from PCB waste

13.6 kt/yr new installed capacity to process all UK PCB waste

£650 m annual value of CRMs theoretically recoverable

Increased Use Of Secondary Material In Products

Secondary material is usually cheaper than primary material. There is an opportunity for product designers to use more secondary material in applications where primary is currently specified but not strictly needed. We think packaging is a big opportunity for this, with the following savings expected if recycled content could reach

£120m for plastic packaging, current recycled content 13%

£70m for steel packaging, current recycled content ~5%

£90m paper and cardboard packaging, current recycled content 69%

£60m for glass packaging, current recycled content 39%

Improve Resource Efficiency

Improvements in resource efficiency – making goods with fewer resources – will be essential for the UK industrial sector to thrive with zero emissions. Without this, by 2050, the supply of renewable electricity to power industrial processes, as well as transport and domestic uses, would be severely stretched.

We envision a rapid evolution in design practices for industrial goods, including buildings, aimed at cutting wasted material and other inputs used to make them. The savings that are possible suggest a large market in offering solutions, and these will only increase as the cost of material inputs increase further. A significant improvement in manufacturing yields will reduce the amount of material currently scrapped and reprocessed.

The business opportunities to deliver these changes, in the form of new business models, or specialised consultancy services are large (over £1 billion annually) and are set out in further detail over the following pages.

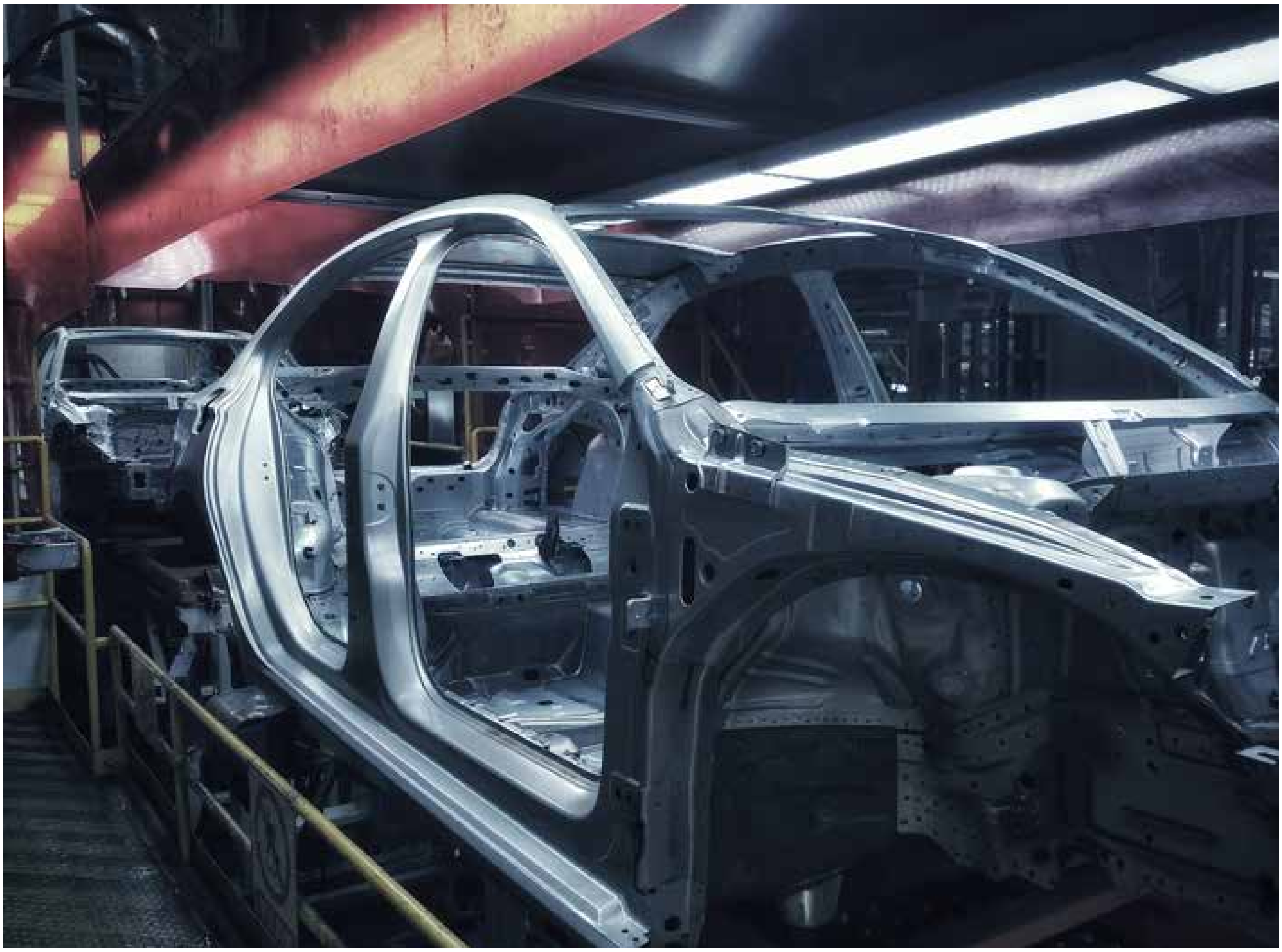


Image : Jenson / Shutterstock.com

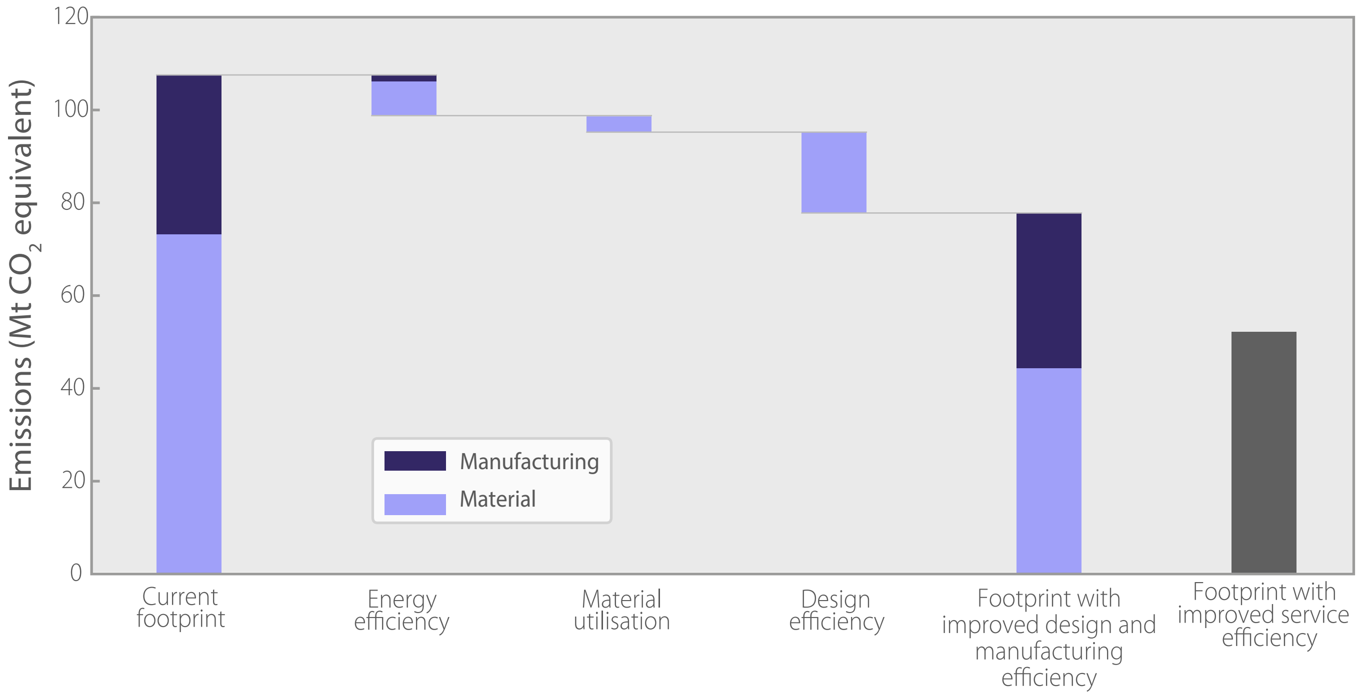
Growth Opportunities

Supply Of Industrial Equipment

New business models & consultancies

Improvements in resource efficiency – making goods with fewer resources – will be essential for the UK industrial sector to thrive with zero emissions. Without this, by 2050, the supply of renewable electricity to power industrial processes, as well as transport and domestic uses, would be severely stretched.

Emissions reduction from improving the efficiency of making goods



The UK's industrial emissions footprint is 117 Mt CO2eq, yet our analysis estimates that only 78 Mt CO2eq is needed if material production, manufacturing, and design, was optimised for resource efficiency; a 33% reduction. Most of the footprint, which includes both products produced and used in the UK, and those imported and used, is from the production of materials (71%). The remainder is from downstream manufacturing processes.

Our analysis suggests there are opportunities to enhance energy efficiency that can achieve a reduction of 8 Mt CO2e or 7%, affecting both the material and manufacturing footprints. A reduction of 7 Mt CO2eq, or 6%, could be achieved by improving material utilisation. The biggest opportunity is the 21 Mt CO2eq, or 18%, saving from designing goods to use less material.

These opportunities generate similar reductions in energy demand; a vital part of the transition to all-electric zero emissions future.

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Energy Efficiency

The efficiency of energy conversion devices continues to improve, and there are significant opportunities to replace low-performing devices with the best technology where the embodied carbon of the devices themselves is not a barrier.

£550 million to supply high efficiency IE5 class motors to all industrial applications.

13 GW
nameplate capacity to be changed

£300 m
annual electricity saving

£590 million opportunity to supply high efficiency boilers to replace current natural gas and oil boilers

13GW
heating capacity to be changed

£285 m
annual fuel savings

£330 million opportunity to upgrade high temperature industrial heating devices

4 GW
capacity for upgrade

£285 m
annual fuel savings

Improving Process Yields

Almost half the metal purchased to make car bodies is trimmed off as scrap during production, with similar – or worse – scrap rates in component making for aerospace and other industries. We anticipate opportunities for companies providing solutions, be they better design for manufacturing, novel processes or process routes.

CASE STUDY

Automotive scrap reduction

Almost 45% of sheet metal purchased by the car industry is scrapped during processing and remelted at low value. The University of Cambridge is developing a novel drawing process, DeepForm that promises further improvements. Globally £8 billion is wasted on scrap from automotive bodies annually, and £12 billion is spent on sheet metal tooling to produce an estimated 105 new model variants each year. DeepForm aims to exploit this market opportunity through providing an alternative toolset which provides better parts with a fraction of the scrap. The DeepForm process, developed in the UK, has the potential to be exported globally to become the standard production technology for car bodies fit for zero emissions.

2100 kt total metal currently scrapped during uk manufacturing which could be halved

£300 m
annual saving achievable

£150 m
annual market for introducing new metal forming and shaping techniques

4500 kt cement wasted due to over-ordering and inefficient mixing

£150 m saving opportunity if waste reduced by... **...50%**

150 kt plastic scrapped during manufacturing annually

£40 m annual saving if scrap reduced by **40%**

Reducing Material Use By Design

Current commercial buildings are designed with as much as 2.5 times the material than is required by design codes, mostly due to early design decisions on grid layout, spans and building typology that lock in high material use. Similarly, studies suggest manufacturers of transport equipment, industrial goods and durable goods could realize substantial material savings through light weighting and down-sizing. Large markets for design solutions will emerge as these industries move towards zero emissions.

£1.9 billion annual material saving opportunity in uk construction inputs

£400 m market for software design tools and training on design practices

80K design engineers across the UK reached

£750 million material saving opportunity for uk manufacturers of transport equipment

£340 m annual market for software tools and training for design efficiency

70K product design engineers reached

CASE STUDY

Emerson are experts in the monitoring and control of industrial processes. Most material producers only monitor the flows of energy, so Emerson have developed a tool to analyse the flows of material in conjunction with energy. In this tool, energy and material flows are combined into a single metric of resource efficiency based on exergy, which represents the available energy from bringing a system into equilibrium with its environment. The new tool identified the potential to increase the resource efficiency of a steel blown oxygen plant by 7 %. 40 % of that improvement was related to material efficiency and would have been missed if the analysis was only based on energy.

Image: Emerson

More Service From Goods, For Longer

It won't be enough to just make goods and buildings more efficiently, we'll also need to make more use of fewer goods. In a resource-constrained future it will be essential to extend the lifetimes of many products, through refurbishment, reconditioning and repair, with producers responsible for ensuring equipment operates at high efficiency throughout its lifespan. Most packaging and many single-use consumables will be re-used. When products do reach the end of their first serviceable life, remanufacturing will play an ever-bigger role in bringing as much of the material as possible back to life as-new.

As for our previous theme, these changes will be driven by a scarcity of zero-emissions resources, with an expected shortfall of 40% of non-emitting electricity in the absence of efficiency measures. This offers rich opportunities for entrepreneurship, extending the reach of through-life engineering services, where UK businesses are already leaders, and transforming the productivity of repair businesses.

Image: Jacques Tarnero / Shutterstock.com

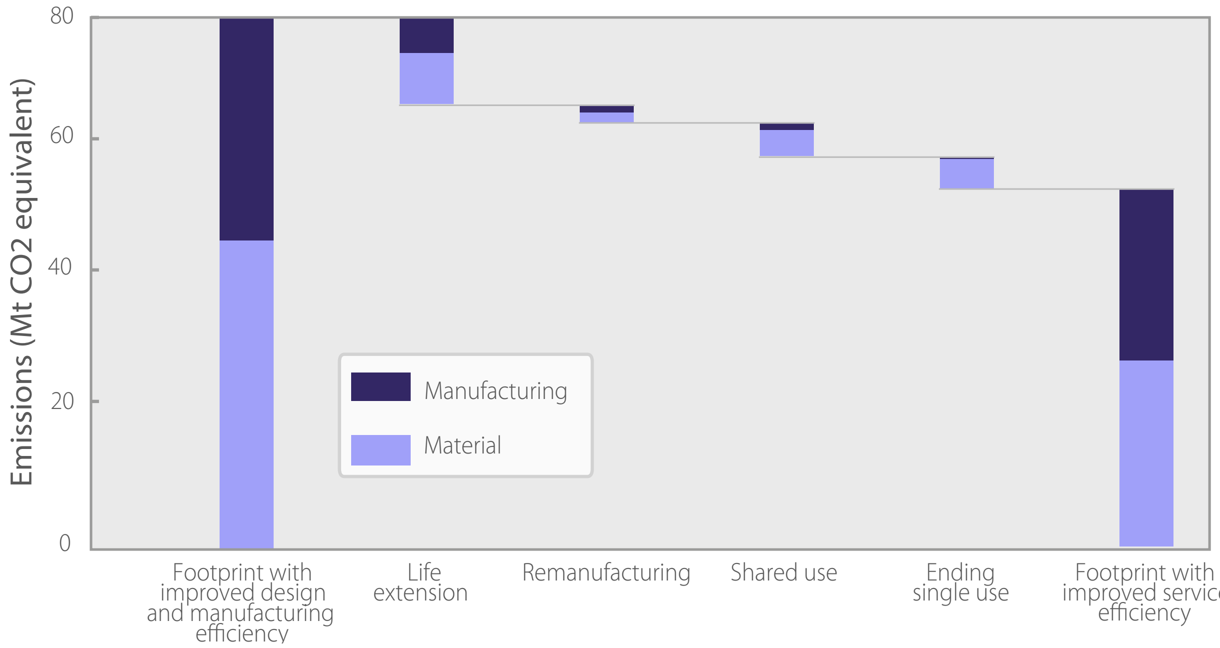
Growth Opportunities

New Production Capacity

New business models & consultancies

It won't be enough to just make goods and buildings more efficiently, we'll also need to make more use of fewer goods. In a resource-constrained future it will be essential to extend the lifetimes of many products, through refurbishment, reconditioning and repair, with producers responsible for ensuring equipment operates at high efficiency throughout its lifespan.

Emissions reductions from increasing the service delivered by goods



Making more use of fewer goods can reduce the UK's industrial emissions footprint by almost a third; and when combined with improved manufacturing efficiency a total 53% cut in emissions is possible.

Our analysis suggests the biggest impact is achieved through life extension of goods such as transport or industrial equipment (12 Mt CO2eq, or 15%), whilst remanufacturing, increasing shared use and ending single use each have a modest but important benefit (3%, 7% and 6% respectively). Business opportunities associated with each of these are highlighted next.

Given that these measures would generate a similar reduction in demand for energy – it suggests there is a viable pathway to zero emissions manufacturing and materials, powered by renewable electricity, maximising high quality recycling, and operating with greater efficiency.

Evidence and Methodology: Quantifying the decarbonisation themes: page 47

Life Extension: Repair, Recondition And Re-Use

If durable goods were used for longer and replaced less frequently, demand for virgin materials would reduce; saving energy and emissions. A large expansion in through-life service and reconditioning activity, and greatly expanded and more productive repair is needed:

£36 billion annual opportunity to provide long-lasting appliances through recondition and service contracts

£11 bn
on industrial equipment; life extends to 62 years

£7.6 bn
on appliances; life extends to 19 years

£17 bn
on transport equipment; life extends to 37 years

£22 billion annual market for direct sale of long-lasting products

£4 bn
Appliances and other durables

£6.5 bn
Industrial equipment

£11 bn
Transport equipment

£11 billion annual market for off-contract repair services

Opportunity to improve productivity from current **£23/hr** to above economy-wide average **£35/hr**

Ending Single-Use

Single-use consumables account for almost a quarter of material use, and a significant fraction of industrial emissions. Many options exist for replacing consumables, especially packaging, with durable alternatives:

£0.5 billion market for the provision of re-usable packaging

80
number of cycles of reuse before packaging is discarded

3x
increase in material weight per item

70%
of packaging is re-used

£0.6 billion market for the provision of re-usable household consumables

20
number of cycles of reuse before consumables are discarded

3x
increase in material weight per item

25%
of household consumables are re-used

CASE STUDY

770 wind turbines in the UK are expected to be decommissioned over the next four years within the UK. Currently, this involves complete removal of the turbine and foundations, and the cost can reach 3-4% of the entire capital expenditure. Alternatively, offshore wind farms could be repowered using new turbines and utilising the original foundations as these are typically designed for 100-year life spans. Furthermore, innovative companies such as Renewable Parts Ltd. in Scotland, and programmes such as the ORE Catapult's Circular Economy for Wind Sector Joint Industrial Programme work to realise economic and carbon savings through the remanufacture of certain wind turbine components, avoiding the need to make the entire component from scratch.

Remanufacturing: making as-new

Components for our engineered goods do not have to be made from scratch every time; remanufacturing - producing warranted as-new subsystems and components from end-of-life 'core' – is already big business and looks set to expand as material scarcity increases.

£0.4 billion expansion in remanufacturing for automotive, rail and marine sectors

0.8 Mt CO_{2e}

additional saving

£0.9 billion increase in remanufacturing of industrial and medical equipment

0.3 Mt CO_{2e}

additional saving

£1 billion increase in remanufacturing of electrical appliances and furniture

0.1 Mt CO_{2e}

additional saving

Shared use of goods

Sharing use of emissions intensive assets could allow the UK to get closer to meeting its emissions targets without compromising consumer access to the services provided by goods. Successful business models can be applied to more under-utilised assets, resulting in fewer assets needed overall:.

£20 billion annual market for short-term rental of cars, LCVs and HGVs by 2050

7%

per year growth to 2050

2.3m

total membership of car clubs by 2050

£18 billion annual market for rental of industrial and construction equipment 2050

5%

per year growth to 2050

£2 billion annual market for rental of appliances and other household durables by 2050

5%

per year growth to 2050

£21 billion market for the construction of additional low to mid-rise flats

300%

increase in flat building

50%

reduction in construction of other dwellings

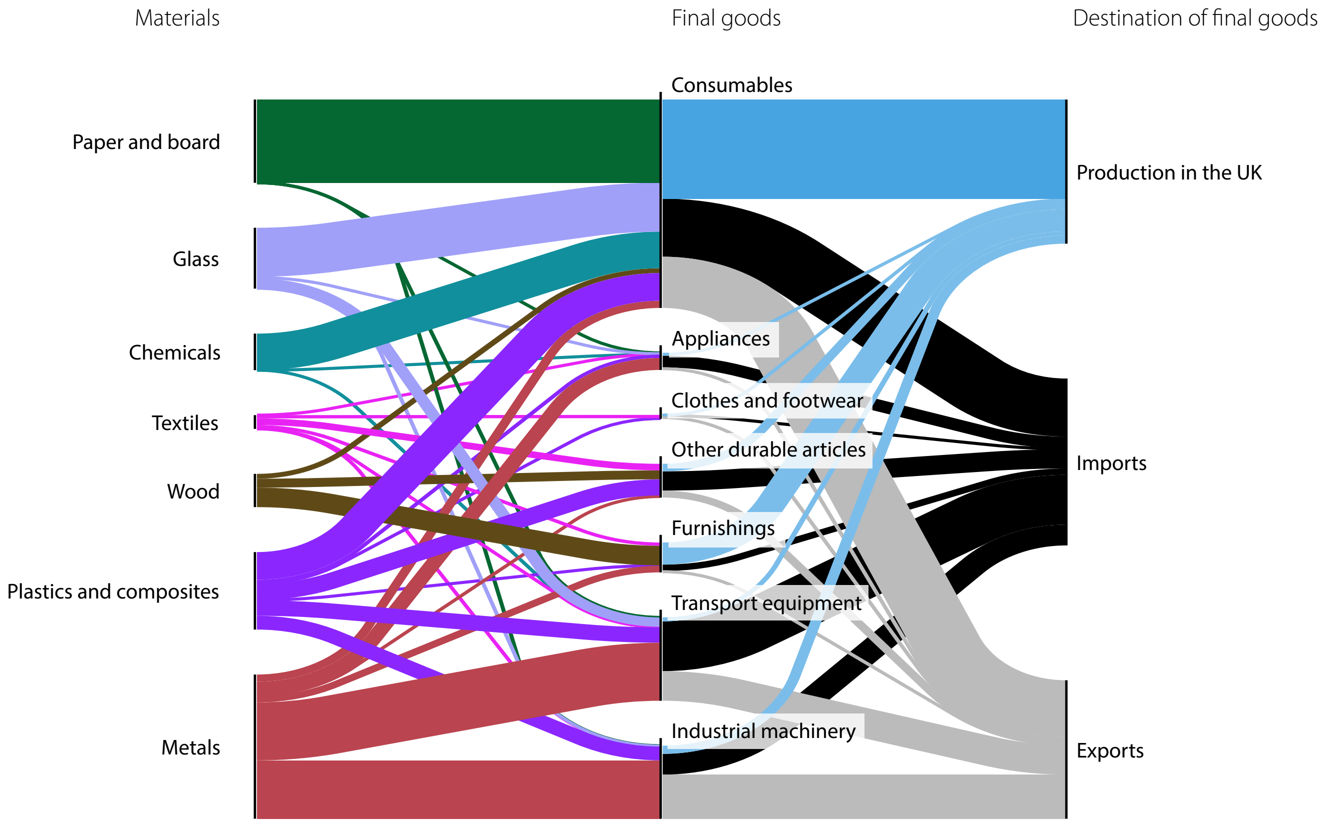
New Demand for UK Manufacturing

Reaching a full zero emissions economy will mean new patterns of demand and new opportunities for UK materials and manufacturing. This is most apparent in the supply of new decarbonisation equipment – products such as electric vehicles, renewables and grid infrastructure, heat pumps and thermal insulation – where there are huge opportunities for new or expanded UK supply chains.

We also anticipate growth in sectors such as materials production and durable goods where the UK currently relies heavily on imports. This growth could be driven by two factors: limited availability of carbon-free global transportation options and rising public appetite for eliminating consumption as well as territorial emissions.

Image: Avigator Fortuner / Shutterstock.com

Imports, exports and domestic production of final goods in the UK



Just 46% by weight of goods purchased in the UK are sourced from domestic production. The majority of these (69%) are consumables including packaging and household items.

The remaining 54% by weight is supplied by imports; most notably transport equipment (5 Mt), appliances (1 Mt), industrial machinery (2 Mt) and other durables (2 Mt). Except for a limited volume of goods that reaches the UK by electric rail, produced without emissions abroad, much of these goods would not be compatible with zero emissions.

Conversely UK businesses currently exporting might be threatened by limited availability of zero-emissions transport – including industrial machinery (4 Mt), transport equipment (3 Mt), and consumables (5 Mt).

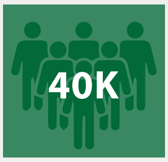
Equipment to enable the transition to zero emissions

New equipment and products will be required to enable decarbonisation in our homes and transport. We've outlined just three key areas to illustrate the scale of opportunities for UK manufacturers in the supply chain for such products:

£3 billion opportunity in supply of heat pump devices

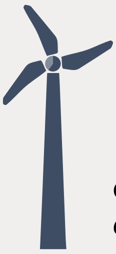
£3 bn

opportunity in supply of heat pump devices



installers with specialist training required

£5.3 billion per year capex for offshore wind generation



2.2 GW capacity to be installed yearly from 2023-2050

Opportunities in the supply chain, assuming 60% UK content:

Project management (£180 million)

Turbine assembly (£90 million)

Blade manufacture (£620 million)

Castings and forgings (£180 million)

Drive train (£700 million)

Tower and other components (£700 million)

Cables (£260 million)

Substations (£600 million)

Foundations (£700 million)

Installation and commissioning (£1.2 billion)

£41 billion market for electric vehicles (EVs) by 2035-2050, increasing from £5 billion in 2021

2.3 million EV registrations annually by 2035, increasing from 0.5 million in 2025

Opportunities in the supply chain by 2035:

Vehicle assembly (£20 billion)

Research and development (£5 billion)

Battery pack (£10 billion)

Motors (£2 billion)

Inverter or converter (£1 billion)

Power distribution and control (£3 billion)

CASE STUDY

Sky Group, a media and telecommunications company, are pioneering circular electronics. In 2016, Sky changed their business model to a service-based contract for their main customer hardware. At the end of a customer's contract, the hardware is sent back to Sky, allowing Sky to have responsibility over the full lifecycle of the product. Since 2016, 3.5 million devices have been reworked. Overall, the move to a service model has reduced the requirement for new products to be manufactured and has reduced the carbon footprint of the device from 15 to 1.1 kg CO_2e for a new versus refurbished. The same approach could apply to other consumer electronics, reducing demand for imported electronics and offering opportunities for new UK-based businesses involved in collection and reconditioning or remanufacturing.

CASE STUDY

Emerson – innovations in heat pump design

Emerson make components for industrial, commercial and residential heat pumps. These range from compressors to systems that integrate the various elements of heat pumps and enable efficient operation and control, leveraging their expertise to meet the stringent requirements of the EU Ecodesign Directive. Emerson and Hydro Quebec, a large power utility in eastern Canada, developed a commercial-grade CO_2 heat pump to deliver cooling and hot water to commercial buildings. The first application of this technology will be in a federal government building in Gatineau. The same strategy could be applied to meet the predicted increase in demand for residential or industrial heating equipment.

UK manufacturing onshoring

Transportation constraints and carbon border adjustments could mean that UK production of materials, components and manufactured goods increases significantly. UK production might increase to at least 90% of current consumption, requiring the following annual increases in domestic production:

£3.4 bn Plastics, where UK production is 57% of consumption

£2.3 bn Paper and board where UK production is 46% of consumption

£1.1 bn Metals, where UK production is 87% of consumption

£0.4 bn Textiles where UK production is 84% of consumption

£20 bn Appliances, where UK production is 36% of consumption

£14 bn Transport equipment, where UK production is 60% of consumption

£13 bn Durable articles, where UK production is 53% of consumption

£2.2 bn Furnishings, where UK production is 82% of consumption

Eliminate Process Emissions

Process emissions are greenhouse gases emitted due to chemical reactions – other than combustion - in the manufacturing or use of goods. Our commitment to net-zero means that all significant process emissions arising from chemical reactions in the production and use of manufactured goods will have to be eliminated; and where there are no mitigation options substitute materials or devices will be required.

Process emissions are almost 37% of manufacturing emissions; significant enough to warrant attention, especially in primary cement, chemicals, and metals production, and due to use of refrigerants and aerosols. In the short section that follows we look at what can be done, and we pick out some key business opportunities.

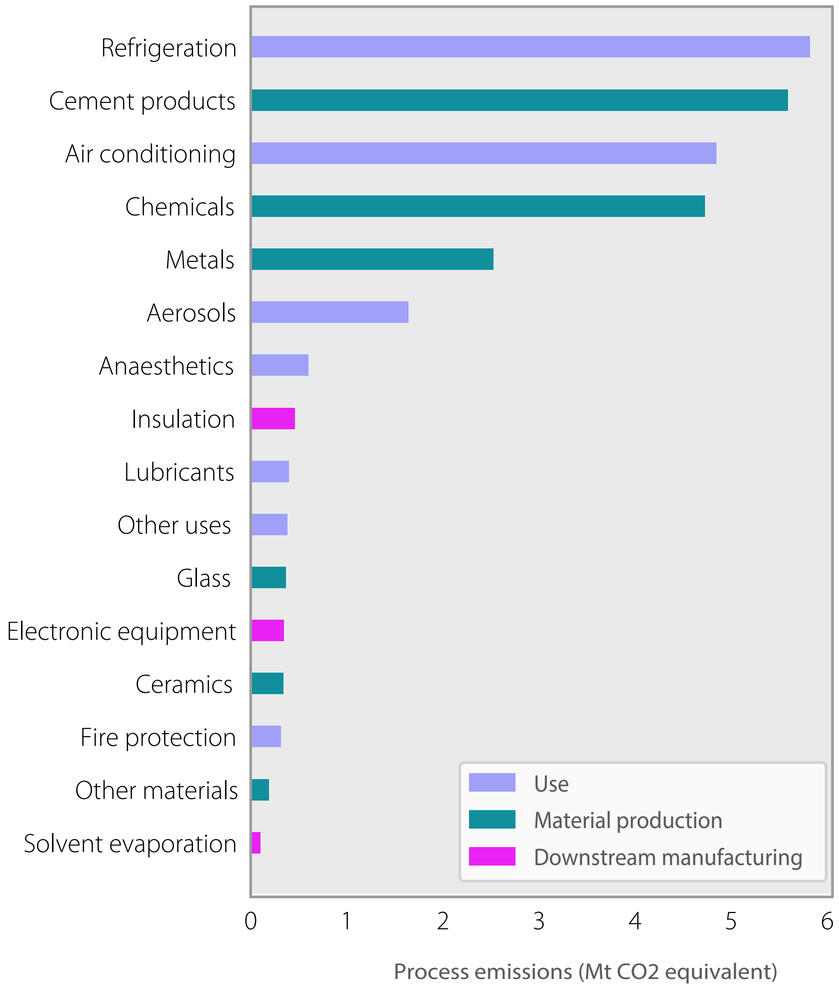
Image: Nordroden / Shutterstock.com

Growth Opportunities

New Production Capacity

Process emissions are greenhouse gases emitted due to chemical reactions – other than combustion - in the manufacturing or use of goods. Our commitment to net-zero means that all significant process emissions arising from chemical reactions in the production and use of manufactured goods will have to be eliminated.

Process emissions in the United Kingdom in 2018



The graph above shows process emissions generated in the United Kingdom from using goods, producing materials and other manufacturing operations. Two of the largest sources of emissions are due to using heat pumps to either control the temperature of liveable spaces or to refrigerate goods. The remaining significant emissions arise from producing cement, chemicals and metals. The other sources are individually responsible for less than 0.5% of the territorial emissions in the UK.

Evidence and Methodology: Quantifying the decarbonisation themes: page 54

Materials and chemicals production

Process emissions in major materials production processes can be avoided through measures including:

STEEL

avoid blast furnace iron making by using recovered steel as a feedstock for EAF steel making

CHEMICALS

ammonia production from green hydrogen; electrification of oil cracking, alternative routes to producing soda ash and titanium dioxide

CEMENT / BRICK

wholescale changes in cementitious materials production and construction practices to be outlined in upcoming UK FIRES report on focusing on building materials and construction

GLASS

avoid primary production through increased use of recovered feedstock in float glass as well as container glass production

Opportunities to mitigate residual process emissions from the much-expanded EAF steelmaking:

£59 m

annual market for inert electrodes, replacing current graphite electrodes

£30 m

market for a replacement to quicklime as a slag

£10 m

additional saving market to replace coal used for slag foaming and carburisation

Products in use and disposal

The key process emissions to mitigate are the use of refrigerant gases, and aerosol propellants. Opportunities include:

£37 MN

annual market for the production of alternative refrigerant gases with low or zero global warming potential, driven by Regulation (EU) No 517/2014.

Opportunities for dry-powder inhalors to replace propellants where clinically appropriate and alternative propellants in household aerosols.

CASE STUDY

Race to Zero - pathway to net zero cooling

The UN led Cool Coalition has brought together 29 private sector cooling suppliers as part of the Race to Zero initiative. These suppliers are developing cooling solutions aligned with their customers' net-zero commitments. Cooling solutions are often highly polluting due to the energy requirements, refrigerants and insulation foam gas used. Regional frameworks such as the EU F-Gas Regulation, demonstrate how refrigerant emissions can be reduced, however further refrigerant phase downs and out are needed. The Climate Action Pathway Net Zero Cooling report estimates that meeting future cooling needs sustainably can reduce the costs of renewable energy build out by up to $3.5 trillion by 2030. They have identified three impact areas (passive cooling, super-efficient equipment and appliances, and ultra-low GWP refrigerants) which are required to achieve zero emission cooling, and estimate that the implementation of new tooling technologies can reduce up to 260 GtCO2e emissions worldwide

How We Created This Report

New Demand For UK Manufacturing

This report brings together several pieces of research from the UK FIRES team. The ideas for the decarbonisation themes arose from an industry workshop that took place in December 2020, whilst much of the analysis draws on work carried out to map materials flows in the UK production system. Specific business opportunities were approximately quantified in desk studies carried out throughout 2021. Each of these activities is described in more detail here, so that others can comment and build on what we have found out.

Workshop: establishing the themes

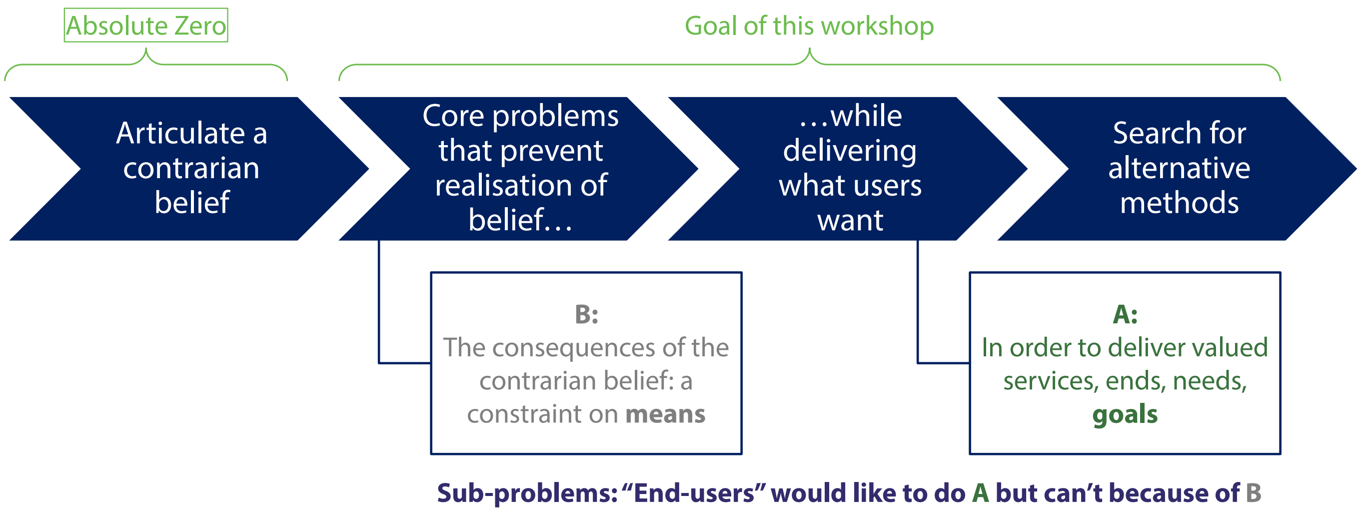
The six decarbonisation themes presented in this report (Electrification of materials production; High quality recycling and recovery; Improved industrial resource efficiency; Enabling long-lasting goods; New demand for UK manufacturing; and Eliminating process emissions) were generated from a longer list of opportunities raised in a workshop hosted by UK FIRES on 1 December 2020.

The workshop involved 28 external participants from companies spanning raw material extraction, material production and processing through to manufacturing of transport and industrial equipment. It was based on a development of the 'Value-lab' framework of Felin et al. (2021), in which business opportunities are structured around realising a contrarian belief, see figure.

Participants were presented with the contrarian belief that zero emissions manufacturing will need to be achieved without reliance on major new energy infrastructure, as set out in the UK FIRES Absolute Zero report (Allwood et al., 2019). They were provided with a list of essential services 'A' that still need to be delivered by manufactured goods, and a list of constraints 'B' that arise from the contrarian belief, for example: "We want to provide high temperature process heat (A7) but combustion of fossil fuels will end (B5)"

Participants discussed specific sets of service-constraint pairings in groups and possible solutions were recorded by the UK FIRES team. For example, discussing the A7-B5 pairing, participants raised examples of where and how process heating in materials production could be provided by electric means, such as ladle pre-heating in electic-arc furnace steelmaking. These solutions were reviewed by the UK FIRES team, resulting in a long-list of opportunities that were subsequently grouped into the six decarbonisation themes presented in this report.

UK FIRES Materials and Manufacturing workshop summary



Mapping the UK production system

UK FIRES developed a detailed map of mass flows within the UK production system. The Sankey diagram of pages 6 and 7 is an aggregated view of the material production and manufacturing sections of this model. The UK FIRES production system map tracks approximately 1000 objects that can be produced in the UK, imported and exported and flow between more than 1000 processes that transform raw and recovered materials into final goods. This map is based on software that enforces mass balance and conciliates data sources using a linear constrained optimisation solver and the semantic technology methods proposed by Germano et al. (2021).

The biggest source of data that underpins the UK FIRES production system map are the Prodcom statistics provided by Eurostat (2021a).

This source contains data on the production, imports and exports in physical and monetary units of around 4000 goods. The flows of recovered materials are constrained using data from other databases from Eurostat (2021b): ENV_WASTRT, ENV_WASTRD and ENV_WASGEN.

The vertical bars shown on pages 6 and 7 represent greenhouse gas emissions related to manufacturing and trade. These were estimated using statistics on UK greenhouse gas emissions reported by ONS (2020). Since ONS (2020) only report emissions generated in the UK territory, the emissions of traded goods were estimated by assuming that traded goods have the same greenhouse gas emissions intensity as goods produced in the UK.

Services provided by manufactured goods, and anticipated constraints on future manufacturing

Services	Constraints
A1: A comfortable living space	B1: Steel: blast furnace steel production will end, scrap arisings ~ 66% of current UK demand
A2: Prepare, store and cook nutritious food	B2: Aluminium: electrolysis of aluminium will end
A3: Travel with comfort and convenience	B3: Glass: there is no glass made from virgin raw materials
A4: Light to allow safe work and play	B4: Plastics: potentially we will only use plastics derived from plants, e.g. PHA, PLA, bio-PET
A5: Stay clean and healthy	B5: Combustion of fossil fuels (for heat and propulsion) will end
A6: Communicate and sociaise	B6: Supply of non-emitting electrical power is only 60% of current total energy demand
A7: High temperature process heat > 250°C	B7: No trans-ocean freight: constrains supply of critical metals, minerals, biomass and ores
A8: Low temperature process heat	B8: No intercontinental flight: constrains high value/ perishable goods & in-person meetings
A9: Separate materials	B9: Limited biomass supply – e.g. of softwood, bio-derived oils etc.
A10: Join / mix materials	
A11: Shape materials	
A12: Move materials and goods	

Quantifying The Decarbonisation Themes

Our methods for evaluating the scope of change under each of our 'decarbonisation themes' and estimating the size of the business opportunities are set out over the following pages. Please get in touch if you have any feedback on how we did this.

Electrification of materials production

Heat flow analysis figure (page 9)

The Sankey diagram of the flows of heat in UK materials production was produced with energy consumption data provided by the Department for Business, Energy & Industrial Strategy (BEIS, 2020). This dataset includes energy consumption data disaggregated by fuel type, energy conversion device and industrial activity by Standard Industrial Classification (SIC) code, which we allocated to the materials on the right-hand side of the figure. We have disaggregated the flows of energy related to "Low temperature Process" further than the data provided by BEIS (2020), using data from Heat Roadmap Europe (2017), which contains splits of energy use across shorter temperature ranges for metals, chemicals, ceramics and glass, and paper and board.

Opportunity evaluation

Opportunity to electrify blast furnace steelmaking		
	Value	**Notes**
Current output of blast furnace steelmaking in UK	6.6 Mt / year	UK FIRES Materials map, based on PRODCOM data (Eurostat, 2021a)
Number of EAF plants this could be replaced by	9	Assuming a nominal output of 1 Mt / year, and capacity factor of 0.75
Investment cost for these plants	£ 3.9 billion	Assuming investment cost of £ 430 million / Mt/year based on 8 publicly announced investments in the US
Annual market	£0.43 billion	Assumes 1 plant per year
Opportunity to supply electric heat in downstream metals sector		
	Value	**Notes**
Total heat use in sector	6.4 TWh	From Energy Consumption in the UK dataset (BEIS, 2020): use of natural gas and oil in metals sector. Assumes solid fuel is used for primary steelmaking
Installed capacity required	4.9 GW	Assumes capacity factor of 0.15 – average proportion of time that plant is operating at full power.
Total cost	£ 4.9 billion	Assumes average cost of furnace is £1,000 / kW
Annual market	£0.49 billion	Assumes replacement carried out over 10 years

Opportunity to electrify ceramics kilns		
	Value	**Notes**
Total production in sector	4.2 M tonnes / year	DECC Industrial Decarbonisation Report: Ceramics (DECC, 2015c)
Number of major ceramics kiln sites	150	(DECC, 2015c)
Cost of electric kiln per unit production	£ 130k / (t /day)	DECC report quotes £20 million per site in heavy clay construction (3.75 M tonnes / year production, 68 sites) (DECC, 2015c)
Total market to replace kilns at all 150 ceramics sites	£1.4 billion	
Annual market	£0.14 billion	Assumes replacement carried out over 10 years
Opportunity to electrify glass furnaces		
	Value	**Notes**
Number of furnaces	29 – Container glass 5 – Flat glass 5 – Glass fibre	British glass (British Glass, 2021)
Average furnace size	400 t / day – Container glass 700 t / day – Flat glass 300 t / day – Fibre glass	DECC Industrial Decarbonisation Report: (DECC, 2015b)
Cost of electric glass furnace per unit production	£ 100k / (t / day)	DECC report quotes £40 million per site – assume 400 tonne / day capacity (DECC, 2015b)
Total market to replace all glass furnaces	£1.7 billion	
Annual market	£0.17 billion	Assumes replacement carried out over 10 years
Opportunity to electrify steam crackers		
	Value	**Notes**
Existing cracker capacity, and number of sites	3 sites 2.2 M tonnes capacity	Data from Petrochemicals Europe (2021)
Investment cost for steam cracker with 1 Mt / year capacity	£0.3 billion	Cost data from Spallina et. al (2017) Steam cracker is 30% of cost of ethylene plant
Estimated market for electrifying steam crackers	£ 1.1 billion	Assumes electric cracker requires 33% more investment than conventional plant
Annual market	£0.11 billion	Assumes replacement over 10 years

Opportunity to electrify process heat in plastics manufacturing		
	Value	**Notes**
Use of combustion for process heat in plastics manufacturing	6.9 TWh	Source: ECUK End use data tables table U4, 2019 Use of natural gas, solid fuel for low temperature process heat, drawing, separation and 'other'
Installed capacity required	3.1 GW	Assumes capacity factor of 0.25 – average proportion of time that plant is operating at full power.
Total market for electrifying process heat in plastics industry	£ 3.2 billion	Assumes average cost of electric heating is £1,000 / kW
Annual market	£0.32 billion	Assumes replacement carried out over 10 years
Opportunity to provide green hydrogen for ammonia and current industrial uses		
	Value	**Notes**
Current demand for hydrogen in the UK	620 Mm3 / year (in Ammonia) 160 Mm3 / year (as H2)	As modelled in UK FIRES Materials map, based on PRODCOM data for 2018 (Eurostat, 2021a)
Capacity for green hydrogen plant	100 Mm3 / year	Estimate. Typical capacity for currently installed plant is 37 Mm3 / year
Investment cost for green hydrogen plant	£1.75 million / Mm3 / year	Estimate based on publicly announced plans to build green hydrogen plant in Saudi Arabia
Total market for green hydrogen plant installation	£1.4 billion	8 plants
Annual market	£0.14 billion	Assumes replacement carried out over 10 years
Opportunity to electrify process heat in chemicals and pharmaceuticals manufacturing		
	Value	**Notes**
Use of combustion in chemicals manufacturing (low temperature)	14.4 TWh	From ECUK End use data tables table U4, 2019 (BEIS 2020) Use of natural gas, solid fuel for low temperature process heat, drawing, separation and 'other'
Use of combustion for in chemicals manufacturing (high temperature)	3.0 TWh	From ECUK End use data tables table U4, 2019 (BEIS 2020) Use of natural gas, solid fuel and oil for high temperature process heat in SIC 20 & 21. Excludes steam cracking
Proportion of all heat < 200°C	0.37	White paper on industrial heat pumps
Installed capacity required	2.2 GW < 200°C 2.7 GW >200°C & <500°C 1.0 GW > 500°C	Assumes capacity factor of 0.33
Total market for electrifying process heat in chemicals and pharmaceuticals	£6.0 billion	Assumes average cost of electric heating is £1,000 / kW

Annual market	£0.6 billion	Assumes replacement carried out over 10 years
Opportunity to electrify process heat in paper mills		
	Value	**Notes**
Use of combustion in paper and printing (low temperature heat)	3.9 TWh – paper mills 0.6 TWh – printing 4.4 TWh - total	From ECUK End use data tables table U4, 2019 (BEIS 2020) Use of natural gas, solid fuel and oil for low temperature process heat, and drying/separation SIC 17 & 18
Installed capacity required	0.8 GW	Assumes capacity factor of 0.75 in paper mills, 0.33 in printing
Total market for electrifying process heat in paper and printing	£0.2 billion – paper mills £0.2 billion – printing £0.4 billion - total	50 paper mills at average cost £4.5 million from DECC industrial decarbonisation report (DECC, 2015d) Cost of electric heating £1000 / kW for printing
Annual market	£40 million	Assumes replacement carried out over 10 years

High quality recycling and recovery

Waste and recovery mass flow figure (page 13)

The Sankey diagram of flows of waste in the UK was produced using datasets on material flows from goods at the end of life from the European Union, trade statists and WRAP. There were small discrepancies when conciliating the various datapoints, so we enforced mass balance for each material by minimizing the error between the input data and the calculated mass flows.

- The flows of metal were calculated using data from UK STEEL (2019), COMTRADE which is a database of trade flows and ENV-WASPAC, ENV-WASELV which are datasets of waste flow collected by Eurostat.
- The flows of plastic are based on data from the P-Word report. These data were not disaggregated by "Source of waste", so other sources of data were used provide more detail: the amount of plastic waste from packaging was taken from ENV-WASPAC; the plastic waste arising from vehicles was estimated using the flows of metals and the material composition of vehicles provided by PlasticsEurope (2013); the plastic waste arising from Buildings and infrastructure was provided by ENV-WASGEN.
- Most of the glass waste is due to packaging and the flows in the figure were calculated using data from ENV-WASPAC. The glass waste arising from Buildings and infrastructure was estimated by Hestin et al. (2016) and the glass flowing from vehicles was estimated using the flows of metals and the material composition of vehicles provided by PlasticsEurope (2013).
- The flows related to textiles were produced using data from WRAP (2019).
- Wood waste arising from packaging was estimated from ENV-WASPAC. Wood Recyclers Association (2020) provide mass flow data on how wood waste is processed in the UK, these data were used to estimate the wood flowing to each waste destination.
- The flows of paper and board arising from other consumables were estimated using data from WRAP (2020). ENV-WASPAC was used to calculate the flows arising from packaging and COMTRADE was used for the mass of paper and board being exported.

Opportunity evaluation

Opportunity to increase steel recycling by utilising scrap exports, excluding scrap used to displace blast furnace production		
	Value	**Notes**
Total steel recovered in the UK [1]	11.3 Mt / year	UK FIRES materials map, based on PROD-COM data for 2018 (Eurostat 2021a) . Assumes 80% of 'mixed metal' is steel.
Current output steelmaking in UK [2]	8.2 Mt / year	Blast furnace steel making and EAF steel making; UK FIRES Materials map, based on PRODCOM data (Eurostat 2021a)
Number of additional EAF plants possible	5	Calculated as: ([1] – [2]) / (0.75 * 1) Assumes average plant size 1 Mt / year, and capacity factor of 75%.
Investment cost for these plants	£ 2.1 billion	Assuming investment cost of £ 430 million / Mt/year based on 8 publicly announced investments in the US
Annual value of production	£1.8 billion	Assuming steel price $800 / tonne
Annual market for equipment	£0.22 billion	Assumes capacity increase over 10 years
Opportunity to increase aluminium remelting by utilising scrap exports		
Total aluminium exported in UK	0.4 Mt / year	COMTRADE database (COMTRADE, 2021)
Number of additional remelting facilities	6	Assuming average plant size 100 kt / year, and capacity factor of 75%.
Investment cost for these plants	£ 0.23 billion	Assuming investment cost of £ 380 million / Mt/year based on 5 publicly announced sites in US/Canada
Annual value of production	£0.9 billion	Assuming aluminium price £2.05 / kg
Annual market for equipment	£0.02 billion	Assumes capacity increase over 10 years
Opportunity to increase plastics recycling by increasing use of scrap exports and recovery and recycling of currently disposed plastic		
Plastics currently recycled in UK [1]	0.4 Mt / year	P-Word report (Cullen et al., 2020)
Plastics currently exported [2]	1.0 Mt / year	ENV-WASTRD database (Eurostat, 2021b)
Plastics currently disposed in UK [3]	2.3 Mt / year	P-Word report (Cullen et al., 2020)
New mechanical recycling facilities	29 1.5 Mt / year additional output	Mechanical recycling is applied to 50% of UK plastic waste [1]+[2]+{3]. This is the estimated volume of PP, HDPE, LDPE, and PET in waste stream, based on their share of consumption (Cullen et al., 2020). Average facility output 50 k tonnes / year.
New chemical recycling facilities	6 0.4 Mt / year output	Chemical recycling is applied to 11% of UK plastic waste [1]+[2]+{3]. This is the estimated volume of PVC and PS in the waste stream, based on their share of consumption (Cullen et al., 2020 and Eurostat 2021a). Average facility output 75 k tonnes / year.
Investment cost	£1.8 billion	Assumes an investment of £35 million per plant (mechanical) and £135 million per plant (chemical), based on 4 publicly announced investment plans

Annual value of production	£1.7 billion	Assuming plastic price £0.94 / kg – the average value of HDPE as reported in PRODCOM database across the EU-27 in 2019. (Eurostat 2021a)
Annual market for equipment	£0.18 billion	Assumes plant capacity increases over 10 years
Opportunity to increase glass recycling by increasing overall recycling rate to 90%		
Glass currently recycled in UK [1]	1.4 Mt / year	ENV-WASPAC database (Eurostat 2021a) – container glass - and information from Saint Gobain on flat glass production
Glass currently exported [2]	0.4 Mt / year	ENV- WASPAC database (Eurostat 2021a)
Glass currently disposed in UK [3]	0.9 Mt / year	ENV- WASPAC database (Eurostat 2021a)
New glass recycling facilities	5 1.0 Mt / year additional output	Recycling is applied to 90% of UK glass waste [1]+[2]+{3]. Average facility output 700 tonnes per day – typical for a flat glass production site
Investment cost	£0.3 billion	Assumes an investment of £0.1 million for each tonne per day capacity (DECC, 2015b)
Annual value of production	£0.3 billion	Assuming glass price £0.3 / kg – the average value for flat glass (23111290) in PRODCOM database across the EU-28 in 2019, assuming 4mm thickness (Eurostat 2021a)
Annual market for equipment	£0.03 billion	Assumes plant capacity increases over 10 years
Opportunity to increase paper recycling by increasing overall recycling rate to 75%		
Paper currently recycled in UK [1]	1.2 Mt / year	
Paper currently exported [2]	4.5 Mt / year	
Paper currently disposed in UK [3]	3.5 Mt / year	
New paper recycling facilities	8 4 Mt / year additional output	Recycling is applied to 75% of UK paper waste with 80% yield accounting for limit on number of times paper can be recycled [1]+[2]+{3]. Average facility output 1500 tonnes per day.
Investment cost	£2.2 billion	Assumes an investment of £0.19 million for each tonne per day capacity, based on recent investment announcement by Pratt paper
Annual value of production	£3.5 billion	Assumes paper price £0.81 / kg – the average value of uncoated paper and paperboard (17124240) in PRODCOM database across the EU-28 in 2019 (Eurostat 2021a)
Annual market for equipment	£0.2 billion	Assumes plant capacity increases over 10 years
Opportunity to improve metal scrap sorting		
Total steel scrap	11.3 M tonnes	UK materials map based on PRODCOM 2018 data (Eurostat, 2021a)

Total investment in scrap sorting	12 plants £1.0 billion	Assumes an investment cost of £90 million per Mt per year capacity. Average facility output of 1 Mt per year. From pg 31, Hall et al. (2021)
Value of product if remelted as rebar	£4.8 billion	Assuming rebar value as per table below, from MEPS European Steel prices (MEPS international, 2021)
Value of product if remelted with the same steel class as its input	£5.5 billion	Assuming scrap composition is as per table below, using product type split derived from Daehn et al. 2017 and UK FIRES Material map. Steel price data from MEPS International (2021).

Proposed classification system and estimated availability of steel scrap				
Class	Copper max limit wt%	Type	Estimated scrap availability	Value £ / tonne
1	0.06	Sheet	4.2	£520
2	0.15	Tubes, rods, bar & plate	4.7	£480
3	0.25	Formed and rolled sections	0.5	£530
4	0.4	Reinforcing bars & castings	1.9	£430

Opportunity for home appliance and automotive disassembly plants		
Mass of end-of-life appliances	1.3 M tonnes	Current annual consumption from UK FIRES materials map based on PRODCOM data (Eurostat 2021a); assume that demand is static so this is matched to end-of-life scrap
Mass of end-of-life vehicles	4.6 M tonnes	Current annual consumption from UK FIRES materials map based on PRODCOM data (Eurostat 2021a); assume that demand is static so this is matched to end-of-life scrap
Total investment in appliance disassembly	24 plants, £430 million	£18 million investment per plant, capable of processing 900,000 units per year. Based on Fuji Ecocycle plant. (Fuji General, 2009).
Total investment in vehicle disassembly	28 plants, £600 million	£21 million investment per plant, capable of processing 170 k tonnes per year. Based on Group GPA recycling centre (Group GPA, 2021)

Waste flow, number of items				
TV	Smartphones	Desktops	Laptops	Monitors
8,600,00	20,400,000	480,000	3,900,000	2,900,000

Mass and value of critical metals contained in electronic waste					
	Gold	Silver	Palladium	Platinum	Total
Mass	11,600 kg	23,600 kg	1,400 kg	100 kg	
Value £	£550m	£14m	£81m	£2m	£649m

Opportunity to recover critical raw materials from PCB waste		
Mass of PCB waste in end-of-life consumer electronics	13.6 k tonnes	Annual scrap in 2021; Calculated from material composition (Cuccihelia et al, 2015) data on the five common consumer electronics (TVs, Smartphones, Desktop Computers, Laptops and Monitors) along with waste flow estimates determined from a dynamic stock model for 2020
Total investment in recovery plant	55 plants, £ 88 million	£1.6 million investment per plant, capable of processing 0.25 k tonnes PCB per year Source: Emak Makina, 2021
Value of CRMs within PCB waste	£649 million	Theoretical maximum based on 100% collection and recovery. Critical material prices based on report from Material Focus (2021)
Opportunity to increase the recycled content of packaging		
Cost of primary production, £ per tonne [1]	£550 – Steel, £780 – PET/HDPE, £540 – Virgin pulp, £50 – Glass inputs	Steel prices from MEPS International (2021)– non-weighted average of all products except rebar. Plastics from PRODCOM database, (Eurostat 2021a) (PRC 20164062, PRC 20161050). Virgin pulp price from COMTRADE (COMTRADE, 2021)– average of codes (HS 4701, HS 4702, HS 4703). Inputs to glass making – silica sand (PRC 08121150), disodium carbonate (PRC 20134319) and quicklime (PRC 23521033)
Cost of secondary production, £ per tonne [2]	£420 – Steel, £380 – PET/HDPE, £410 – Recycled pulp, £15 – Recovered glass	Steel rebar prices from MEPS International (2021). Plastics prices from WRAP (2021a), with allowance for remelt and 50% processing cost. Recycled pulp price from COMTRADE (HS 470620). Cost of recovered glass from WRAP (2021c).
Price differential	£130 – Steel, £400 – PET/HDPE, £130 – Paper, board £35 – Glass	[2] – [1]
Current use of material for packaging, and recycled content	3. 1 Mt - Plastic (13%), Mt – Steel (5%), 3.1 Mt - Paper/board (69%), 3.2 Mt – Glass (39%)	Use of material for packaging from UK FIRES materials map, based on PRODCOM data (Eurostat 2021a). Recycled content data from WRAP UK Plastics Pact Annual Report 2019/20 (WRAP 2021b), Confederation of Paper Industries annual review 2020/21 (Confederation of Paper Industries, 2021). , BritGlass - Recycled content of UK Manufactured Glass Packaging (British Glass, 2017)

Improve the efficiency of making goods

Bar graph of emissions reduction from improving resource efficiency (page 17)

The current UK footprint was estimated using UK greenhouse gas emissions data provided by ONS (2020). This dataset contains emission values aggregated by UK Standard industrial classification codes. These data were used in conjunction with the mass flows estimated in the UK FIRES production system map to estimate the total footprint due to the production of final goods that are used or consumed in the UK. The resource efficiency savings were estimated as follows:

Energy efficiency: the potential to improve energy efficiency in the UK was based on the efficiency of energy conversion devices in the UK estimated by Paoli et al. (2018) and the practical efficiency limits of energy conversion devices modelled by Paoli et al. (2020). Energy savings were estimated from the potential efficiency improvements and UK energy consumption data reported by BEIS (2020). These savings were converted to emissions using the factors reported by BEIS (2019). The resulting emissions savings are only representative of UK production, so they were scaled to match UK consumption using the mass flows of the UK FIRES production system map. We assumed that the same savings would apply to the global supply chain. Paoli et al. (2018) and Paoli et al. (2020) did not analyse devices that process materials at high temperatures (for example furnaces or rolling mills) so these potential improvements were estimated as follows:

- Metals: DECC (2015) mention that the energy intensity of steelmaking from virgin raw materials using best available technology is 14.8 GJ/t whereas the average energy intensity in the UK is 17.1 GJ/t. This potential reduction was applied to all metals. According to DECC (2015), the UK already produces steel from scrap with an energy intensity similar to best available technology, hence no energy savings related to this production route were included in the figure.
- Glass: Conradt (2019) mentions that the average energy intensity of glass furnaces is 25 % less than the best available technology. We used this value as a potential efficiency improvement in glass making.
- We applied the average of the potential improvements related to glass and steel to the remaining materials.

Material utilisation: the potential emissions savings were estimated as follows:

- Metals: 2.1 Mt/yr of metal manufacturing scrap were produced in 2018 according to the UK FIRES production system map. Horton et al. (2019) estimate that this scrap could be reduced by 32 % whereas ongoing UK FIRES research on sheet metal forming could achieve savings of 55 %. We used the average of these values and the average greenhouse gas intensity of steelmaking reported by Material Economics (2018) to estimate the emissions savings from producing less metal scrap.
- Cement products: Shanks et al. (2019) reported that up to 27 % more cement is added to concrete above the amount required. Our estimates assume that half of this cement could be saved. In addition, 5 % extra cement is ordered above what is needed when casting concrete on site (which represents 47 % of the cement used in the UK, according to Shanks et al. (2019)). We assumed that the over-ordered cement could be eliminated.
- Plastics and composites: Keoleian et al. (2012) reported material utilisation of plastic forming processes. We used the average of the reported values (4 %) to estimate the quantity of plastic scrap produced in UK manufacturing and assumed that plastics scrap production could be reduce in the same amount as metal scrap production (43 %).

No data was found on possible material utilisation improvements for the other materials considered in this report.

Design efficiency: design efficiency improvements consist of designing goods with less material or specifying goods with smaller sizes to meet specific needs. We estimated the potential weight reduction of the following durables and used the UK FIRES production system map to quantify the resulting material consumption savings:

- Buildings and infrastructure: these could be delivered with 62 % less material by: optimising the grid design and decking choice of buildings; increasing the utilisation ratio of structural elements and design buildings with less complexity. These savings are explained in the UK FIRES construction innovation report.
- Transport equipment: we assumed that the weight of cars can be reduced by 28 % (cars in 2001 in the UK weighed 14 % less than today according to ICCT (2020) but there are other possible savings by using higher strength materials in car design or intentionally specifying smaller cars).
- Appliances, Industrial machinery and Other durable articles: we assumed that the weight saving applied to Transport equipment would also apply to these goods.

Opportunity evaluation

Oppportunity to supply high efficience IE5 class motors to all industrial applications		
	Value	**Notes**
Total annual energy used by motors in industry	29.4 TWh	ECUK end use energy tables, 2018
Assumed motor efficiencies	0.87 - current average 0.968 - best available	Paoli and Cullen, 2020, Paoli et al. 2018
Saving opportunity from converting to highest efficiency class	3.0 TWh / year £298 million	Assumes electricity cost of £0.1 / kWh
Installed capacity to be changed	12 GW	Assumes a capacity factor of 0.25, and that 10% of motors are already high efficiency
Cost of changing all motors to IE5	£550 million	Assumes IE5 motors cost £45 / kW on average
Annual business opportunity	£55 million	Assumes lifespan of 10 years
Opportunity to supply high efficiency boilers to replace current natural gas and oil boilers		
Total annual energy used by industrial boilers	41 TWh / year - Natural gas 2 TWh / year - Oil	ECUK end use energy tables, 2018
Assumed efficiencies - natural gas	0.75 - current average 0.9 - best available	Paoli and Cullen, 2020, Paoli et al. 2018
Assumed efficiencies - oil	0.8 - current average 0.9 - best available	Paoli and Cullen, 2020, Paoli et al. 2018
Saving opportunity from converting to highest efficiency class	7.1 TWh / year £285 million	Assumes electricity cost of £0.1 / kWh
Installed capacity to be changed	18 GW	Assumes a capacity factor of 0.25, and that 10% of boilers are already high efficiency
Cost of changing all boilers to highest efficiency	£590 million	Assumes high efficiency gas boilers cost £33 / kW on average, and high efficiency oil boilers cost £37 / kWh
Annual business opportunity	£59 million	Assumes lifespan of 10 years
Opportunity to upgrade high temperature industrial heating devices		
Total annual energy used for high temper-ature heating	21.5 TWh / year	ECUK end use energy tables, 2018
Normalised efficiency improvement	0.81 - current average 1 - best available	Based on efficiencies of glass making from Conradt, 2019, and EAF steel making from Parsons Brinckerhoff and DNV GL, 2015
Saving opportunity from converting to highest efficiency class	4.1 TWh / year £160 million"	Assumes electricity cost of £0.1 / kWh
Installed capacity to be changed	3 GW	Assumes a capacity factor of 0.75, and that 10% of these devices are already high efficiency
Cost of changing all boilers to highest efficiency	£330 million	Assumes cost of £113 / kW. Calculated from Semel, 2012
Annual business opportunity	£33 million	Assumes replacement carried out over 10 years

Opportunity to introduce new metal forming and shaping techniques		
Total metal manufacturing process scrap, UK	2100 k tonnes	UK FIRES materials map for 2018
Realistic potential to reduce scrap	45%	Average of 32% from Horton and Allwood, 2017, and 55% from ongoing UK FIRES research on sheet metal forming
Metal costs	£560 / tonne - purchase price £257 / tonne - scrap value	Purchase price - MEPS International European steel prices, July 2020 - June 2021, average of all types Scrap value - LME steel scrap price Jan 2021 - June 2021"
Saving opportunity	905 k tonnes £296 million	Saving assumes the cost of handling scrap is 10% of its value
Market size for introducing new technologies	£148 million	Assumes 50% of saving is obtainable by an enabling business
Opportunity to improve efficiency of plastic shaping		
Total plastic manufacturing process scrap, UK	140 k tonnes	XX
Plastic costs	£811 / tonne - purchase price £240 / tonne - scrap value	Purchase price - Prodcom database, average of primary LDPE, HDPE, PET, PVC, PP, PA and PS, produced in EU 27 - 2020 Scrap value - WRAP - average of reported PET, HDPE and LDPE scrap values - accessed Oct 2021"
Saving opportunity	62 k tonnes £37 million	Assumes a 43% scrap reduction achievable, and cost of handling scrap is 10% of its value
Market size for introducing new technologies	£18 million	Assumes 50% of saving is obtainable by an enabling business
Opportunity to enable cement waste reduction		
Cement wasted in the UK	710 k tonnes - over-ordering 3800 ktonnes - over-specification in mixing	Cement use from UK FIRES materials map; Over-specification in mixing from Shanks et al., 2019
Cement purchase price	£67.5 / tonne	PRODCOM database, 2020 - Sales of Portland cement in EU-27
Saving opportunity	2300 kt £150 million	Assumes a 50% waste reduction is realistically achievable
Market size for introducing new practices	£75 million	Assumes 50% of saving is obtainable by an enabling business
Opportunity to save material in construction design		
Use of materials in construction in the UK	Steel - 3.5 Mt Ceramics - 6.6 Mt Cement - 9.9 Mt Plastics - 0.9 Mt Wood 0.8 Mt Glass - 0.3 Mt	Source: UK FIRES materials map for 2018

Maximum potential to reduce inputs by design	30% - Flexible grid choice 15% - Optimal decking choice 4% - Structural member utilisation 4% - Frequency calculation revision 9% - Optimal complexity 62% - Total saving"	Max possible savings for steel and cement in commercial construction, UK FIRES construction innovation report.
Material saving opportunity	Steel - £600 million Ceramics - £60 million Cement - £210 million Plastics - £230 million Wood - £90 million Glass - £30 million Total - £1,210 million	Assumes 50% of maximum potential is achievable on average for all buildings and infrastructure construction. Steel price data from MEPs International, other material price data from PRODCOM database for EU-27, 2020
Number of employees in construction sector	2.1 million	ONS Annual Business Survey
Number of designers reached by new software tools	80,800	Assumes 15% are working in design, and 25% of these are reached
Market size	£400 million	Assumes license fee of £5000 per user
Opportunity to save material in design of manufactured products		
Use of materials in manufactured products produced in the UK	Steel - 5.0 Mt Plastics - 1.9 Mt Wood 1.8 Mt Glass - 0.5 Mt	Source: UK FIRES materials map for 2018
Material saving opportunity	Steel - £400 million Plastics - £220 million Wood - £90 million Glass - £30 million Total - £745 million	Assumes a 14% reduction in material input; a reversal of the average weight increase in passenger vehicles between 2001 to 2019. Source - ICCT, 2020. Steel price data from MEPs International, other material price data from PRODCOM database for EU-27, 2020
Number of employees in manufacturing sector	2.1 million	ONS
Number of designers reached by new software tools	68,700	Assumes 10% are working in design, and 25% of these are reached
Market size	£340 million	Assumes license fee of £5000 per user

Enable goods to deliver more service, for longer

Bar graph of emissions reduction from improving service efficiency (page 21)

The starting point for this figure is the UK materials and manufacturing footprint with improved design and manufacturing efficiency of page 17. The emissions savings were estimated as follows:

Life extension: Allwood et al. (2019) estimated the electricity savings of doubling the life of certain durable goods. The same approach was applied to estimate the potential savings from life extension in this report, the life of the following goods was doubled: Industrial machinery, Transport equipment, Clothes and footwear, Appliances, Other durable articles.

The extended life footprint was increased by 20 % to account of emissions due to additional maintenance of goods (as assumed by Allwood et al. (2019)). The reduction in demand was converted to emissions savings using the mass flows calculated in the UK FIRES production system map.

Remanufacturing: the emissions savings were estimated by Parker et al. (2015). Since Parker et al. (2015) reported the emissions savings for the whole European Union, the emissions data was scaled to the UK using the turnover from remanufacturing which was reported by Parker et al. (2015) for the whole European Union and for the UK.

Durable goods: we used the reduction in equipment sales described in the opportunity evaluation table for this theme to calculate the reduction in material consumption for each of the following durable goods:

- Transport equipment: 19 %
- Industrial machinery: 13 %
- Appliances: 1 %

Buildings and infrastructure: we assumed that construction of all domestic buildings apart from flats would be 25 % of the current floor area. The construction of flats would increase so that the total constructed floor area remains constant (the construction of flats by floor area would increase by a factor of 5). Data on floor area by building type is reported in the opportunity evaluation tables of this theme.

The reduction in material demand from lower sales of durables and a larger share of flats in construction was estimated using the mass flows of the UK FIRES production system map.

Ending single use: 7 studies comparing reusable and single use business to business packaging were reviewed to estimate the potential emissions reduction from ending single use of goods (these studies are referenced in the opportunity evaluation table of this theme). From these, only 5 studies achieved lower emissions with reusable packaging and their average emissions reduction was 48 %. Since replacing single use of goods was only successful in 5 out 7 studies, we assumed that the potential material savings from ending single use goods was 34 %.

Opportunity evaluation

To provide long-lasting appliances through recondition and service contracts		
	Value	**Notes**
Value of current UK production of appliances and other durables [1]	£13 billion	UK FIRES production system map, based on PRODCOM data. Other durables includes plastic, wood and metal articles
Current spend on repair [2]	£ 6 billion	ONS Annual Business Survey
% of products to be sold through service contracts [3]	50%	Assumption of this report
Overall customer saving from servitisation, % [4]	28%	Middle of range 25-30% reported by Servitisation study - Aston Business School, 2013
Market for products as a service	£6.9 billion	([1]+[2])*[3]*(1-[4])
To provide long-lasting industrial equipment through recondition and service contracts		
Value of current UK production of industrial equipment [1]	£21 billion	UK FIRES production system map, based on PRODCOM data.
Current spend on repair [2]	£ 6 billion	ONS Annual Business Survey
% of products to be sold through service contracts [3]	50%	Assumption of this report
Overall customer saving from servitisation, % [4]	28%	Middle of range 25-30% reported by Servitisation study - Aston Business School, 2013
Market for products as a service	£9.6 billion	([1]+[2])*[3]*(1-[4])
To provide long-lasting transport equipment through recondition and service contracts		
Value of current UK production of transport equipment [1]	£35 billion	UK FIRES production system map, based on PRODCOM data.
Current spend on repair [2]	£ 7 billion	ONS Annual Business Survey
% of products to be sold through service contracts [3]	50%	Assumption of this report
Overall customer saving from servitisation, % [4]	28%	Middle of range 25-30% reported by Servitisation study - Aston Business School, 2013
Market for products as a service	£15.3 billion	([1]+[2])*[3]*(1-[4])
To provide long-lasting durable goods		
Life increase, % of original life [5]	100%	Assumption of this report
Price premium for long-lasting goods [6]	25%	Assumption of this report
Market for sale of long-lasting goods (outside of recondition and service contracts)	"£4.0 billion - Appliances and other durables £6.5 billion - Industrial equipment £11 billlion - Transport equipment £21.5 - Total"	([1]+[2])*(1-[3])/(1+[5])*(1+[6])
To provide off-contract repair services		
Increase in annual repair costs for long-life products, % of current [7]	33%	Based on Oponeo, 2017

Market for high productivity repair outside of recondition and service contracts	"£4.0 billion - Appliances and other durables £2.9 billion - Industrial equipment £3.7 billlion - Transport equipment £10.5 - Total"	([1]+[2])*(1-[3])*(1+[7])
To provide reusable packaging		
Current UK packaging production [1]	"£0.9 billion - Glass packaging £3.3 billion - Plastic packaging £3.7 billion - Paper and board packaging £1.3 billion - Metal packaging £9.3 billion - Total"	Source: PRODCOM database, 2018
Number of times durable packaging would be used [2]	85	Average of 7 studies comparing durable and single-use B2B packaging - Singh et al, 2006; Ross and Evans, 2003; Palsson et al., 2012; Goellner and Sparrow, 2014; Albrecht et. al, 2013; Accorsi et. al, 2014; Koskela et. al, 2014
Applicability of reusable packaging [3]	70%	Assumption, based on 5 out of 7 studies reported a benefit
Unit cost of reusable packaging, % of single-use packaging [4]	600%	Assumption - 2 x the difference in mass between reusable and single-use packaging (300% of single-use pacakaging)
Annual market for reusable packaging	£480 million	[1]*[3]/[2]*[4]
To provide reusable household consumables		
Current UK production [1]	"£5.9 billion - household consumables £1.3 billion - printed products"	Source: PRODCOM database, 2018
Applicability of reusable alternatives [3]	25%	Assumption of this report
Number of times reusable alternative used [2]	20	Assumption of this report
Unit cost of reusable alternative, % of single-use [4]	600%	Assumption of this report
Annual market for reusable alternatives		[1]*[3]/[2]*[4]
To provide remanufacturing services across various manufacturing sub-sectors		
Numbers obtained directly from the Remanufacturing Market Study by European Remanufacturing Network, 2015 - Table 12, Transformation case		
To provide short-term rental services for transport equipment		
Current UK market	"£44 billion - Sales of equipment [3] £2.5 billion - Short-term rental [1]"	Sales of equipment from PRODCOM, 2018. Short term rental market estimated by scaling size of rental and leasing market - £18.7 billion for SIC 77.1 from Annual Business Survey - by proportion of rental and lease equipment that is for short-term rental. Data from BRVLA, 2021

% of all assets currently in shared use [4]	3%	Total registrations from Department for Transport, 2021; Size of short-term rental fleet from BRVLA, 2021
Growth in rental market (past 10 years) [2]	7%	Annual Business Survey data 2009-2019
Number of sales avoided by each asset rented [5]	5	Assumption of this report. COMO UK, 2021 suggest that 18 purchases are avoided for each car club
Market for products as a service	£15.3 billion	([1]+[2])*[3]*(1-[4])
Annual market for short-term rental, 2050	£20.4 billion	[1]*(1+[2])^20
Reduction in equipment sales due to increase in short-term rental	19%	"Sales demand if no assets were shared, [6], is given by: [3]/(1-[4]+[4]/[5]). % of assets that will be shared, by 2050 [7] given by: [4]*(1+[2])^20 Future sales demand = [6]*(1-[7]+[7]/[5])"
To provide short-term rental services for Industrial machinery		
Current UK market	"£19 billion - Sales of equipment [3] £4.3 billion - Short-term rental [1]"	Sales of equipment from PRODCOM, 2018. Short term rental market estimated to be 25% of rental and leasing market - £17 billion, SIC 77.3 from Annual Business Survey
% of all assets currently in shared use [4]	4.5%	Estimated by ([1]/[5])/[3]
Growth in rental market (past 10 years) [2]	3%	Annual Business Survey data 2009-2019
Number of sales avoided by each asset rented [5]	5	Assumption of this report
Annual market for short-term rental, 2050	£18 billion	[1]*(1+[2]*1.5)^20
Reduction in equipment sales due to increase in short-term rental	13%	"Sales demand if no assets were shared, [6], is given by: [3]/(1-[4]+[4]/[5]). % of assets that will be shared, by 2050 [7] given by: [4]*(1+[2]*1.5)^20 Future sales demand = [6]*(1-[7]+[7]/[5])"
To provide short-term rental services for appliances		
Current UK market	"£26 billion - Sales of equipment [3] £0.5 billion - Short-term rental [1]"	Sales of equipment from PRODCOM, 2018. Short term rental market estimated to be 25% of rental and leasing market - £1.8 billion, SIC 77.2 from Annual Business Survey
% of all assets currently in shared use [4]	0.3%	Estimated by ([1]/[5])/[3]
Growth in rental market (past 10 years) [2]	3%	Annual Business Survey data 2009-2019
Number of sales avoided by each asset rented [5]	5	Assumption of this report
Annual market for short-term rental, 2050	£1.9 billion	[1]*(1+[2]*1.5)^20
Reduction in equipment sales due to increase in short-term rental	1%	"Sales demand if no assets were shared, [6], is given by: [3]/(1-[4]+[4]/[5]). % of assets that will be shared, by 2050 [7] given by: [4]*(1+[2]*1.5)^20 Future sales demand = [6]*(1-[7]+[7]/[5])"
To build more flats		

Current additions to stock - domestic buildings (m2)	"4.1 million - Detached houses 9.1 million - Terraced houses 8.6 million - Semi-detached houses 0.5 million - Bungalows 4.0 million - Flats"	
Change in annual additions - increased shared use scenario	"Reduction by 50% - Detached houses, terraced houses, semi-detached houses, bungalows Increase by 280% - Flats"	No change in the total additions to stock
Increase in market for flats	£21.8 billion	Assumes average cost of £1,950/m2 - Cost-modeling, 2021

New demand for UK manufacturing

Sankey diagram of material flows of final goods in the UK (page 25)

Most of the flows shown in the figure were estimated in the UK FIRES production system map. The UK FIREs production system map does not track whether UK consumption is met by production or imports. This knowledge is required to draw this figure because some imports might be exported without any processing in the UK. The percentage of re-exports was estimated using data from Lankhuizen et al. (2019) who estimated the average re-exports in the UK between 2000 and 2010 and data on exports of goods in the UK is provided by World Bank (2021). The estimated percentage of re-exported goods was 4 % between 2000 and 2010. We assumed that this value also applies to 2018 and used it to estimate the mass of imported goods that are exported. The remaining balance is met by UK production.

Equipment to enable the transition to zero emissions		
Supply of heat pump devices		
	Value	**Notes**
Current size of heat pump market	£94 million - 2019 [1]	PRODCOM database - 28.25.13.80
Number of installations	"35,000 - 2019 [2] 1,100,000 - 2035 (Projection) [3]"	Heat pump association, 2019
Projected size of market	£2,950 million - 2035	[1]*[3]/[2] - Assuming cost per heatpump is constant
Offshore wind generation		
Capacity due to be installed annually 2030-2050 [1]	2.3 GW	UK offshore wind sector deal, from Noon-am, 2019
Capex cost for offshore wind per unit capacity [2]	£4 million / MW	From Renewable Energy Foundation, 2020

Capex cost breakdown for offshore wind [3]	"3.3% - Project management 1.7% - Turbine assembly 11.7% - Blade manufacture 3.3% - Castings and forgings 13.3% - Drive train 13.4% - Tower and other components 5.0% - Cables 11.7% - Substations 13.3% - Foundations 23.3% - Installation and commissioning"	Department for Business, Innovation and Skills, 2014
Annual opportunities in the supply chain for offshore wind	"3.3% - Project management 1.7% - Turbine assembly 11.7% - Blade manufacture 3.3% - Castings and forgings 13.3% - Drive train 13.4% - Tower and other components 5.0% - Cables 11.7% - Substations 13.3% - Foundations 23.3% - Installation and commissioning"	"[1]*[2]*1000*60%*[3] Assumes 60% UK content, UK government target - Noonam, 2019"

increase in UK Materials Production								
Material	**Production [Mt]**	**Imports [Mt]**	**Value of Imports [£ billion]"**	**Exports [Mt]**	**Apparent consumption [Mt]"**	**Production as % of apparent consumption**	**Increase in production to reach 90% of apparent consumption [Mt]**	**Estimated value of this increase [£ billion]"**
Metals	9.7	8.8	£36.0	5.8	12.68	76%	1.7	£7.0
Chemicals	4.1	8.5	£6.6	4.7	7.87	52%	3.0	£4.3
Plastics and composites	2.0	4.5	£12.2	3.1	3.43	59%	1.0	£2.8
Paper and board	3.1	5.2	£3.7	1.2	7.11	44%	3.3	£2.3
Textiles	1.7	0.6	£1.8	0.1	2.18	80%	0.2	£0.7
Glass	6.8	0.5	£0.4	2.1	5.13	132%	0.0	£-
Wood	6.0	5.1	£4.1	5.9	5.21	115%	0.0	£-
Ceramics	6.3	1.2	£1.2	0.6	6.91	91%	0.0	£-
Cement products	14.9	6.4	£0.5	4.9	16.40	91%	0.0	£-

Notes	Production + Imports - Exports				Production + Imports - Exports			Based on value per tonne of imports
Increase in UK production of durable goods								
Type of goods	**Production [Mt]**	**Imports [Mt]**	**Value of Imports [£ billion]"**	**Exports [Mt]**	**Apparent consump-tion [Mt]"**	**Production as % of apparent consump-tion**	**Increase in production to reach 90% of apparent consump-tion [Mt]**	**Estimat-ed value of this increase [£ billion]"**
Appliances	0.4	1.0	£29.8	0.2	1.26	35%	0.7	£20.0
Transport equipment	2.8	4.8	£43.3	2.8	4.89	58%	1.6	£14.1
Other dura-ble articles	2.8	2.5	£25.2	0.8	4.46	63%	1.2	£12.1
Clothes and footwear	0.1	0.3	£20.4	0.3	0.12	75%	0.0	£1.2
Industrial machinery	2.8	4.0	£24.4	4.1	2.68	105%	0.0	£-
Furnishings	5.5	0.6	£6.5	0.1	5.96	92%	0.0	£-
	Production, Import and Export data from UK FIRES mate-rials map, drawing on PRODCOM data for 2018				Production + Imports - Exports			Based on value per tonne of imports

Eliminate process emissions

Bar graph of process emissions in the UK (page 29)

The data shown in this figure were reported by NAEI (2021).

Materials and chemicals production					
Mitigate residual process emissions from much-expanded EAF steelmaking					
Product	Expected steel production volume [2] [M tonnes]	**Current usage [1] [kg / tonne steel]**	**Expected use [3] [k tonnes]**	**Value [4] [£ per kg]**	**Market size [£m]**
Graphite electrodes	11	1.5	17	£3.60	£59
Coal charge	11	12	132	£0.04	£6
Lime for slag	11	25	275	£0.10	£28
Notes	Assumption of this report, see Theme 2	From Echterhof, 2021	[1] * [2]	Graphite data from Industrial Heating, 2019; Coal data from ONS 2021b; Lime data from Agrigem, 2021	[3]*[4]

Opportunity for production of alternative refrigerant gases		
	Value	**Notes**
Current value of refrigerant production	£13 million	From PRODCOM database, 2019: PRC 20595971 - Mixtures containing halogenated derivatives of methane, ethane or propane
Current size of market for devices(£ million)	£1,400 - all other refrigeration £90 - heat pumps	From PRODCOM database, 2019: selected codes under 2751 and 2825. Heat pumps is 28251380
Future size of market for devices(£ million)	£1,400 - all other refrigeration £,2900 - heat pumps	Future heat pump market - see Theme 5
Future market for refrigerants	£37 million	[1]*[3]/[2]

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