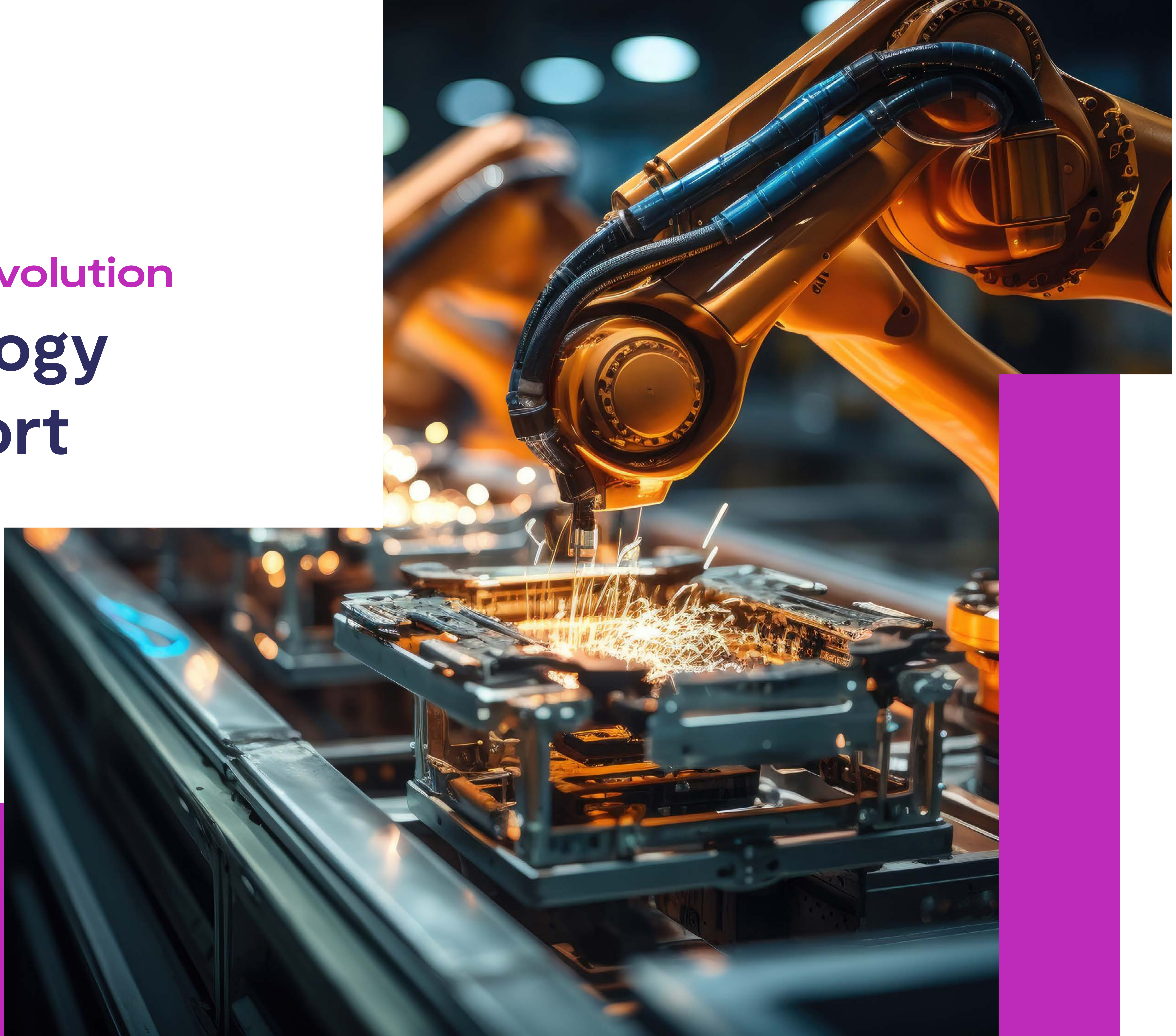
Delivered by
Innovate UK

Driving the Electric Revolution

Metals Technology Deep Dive Report



Dr Sven Knowles

Raluca Popovici

Contents

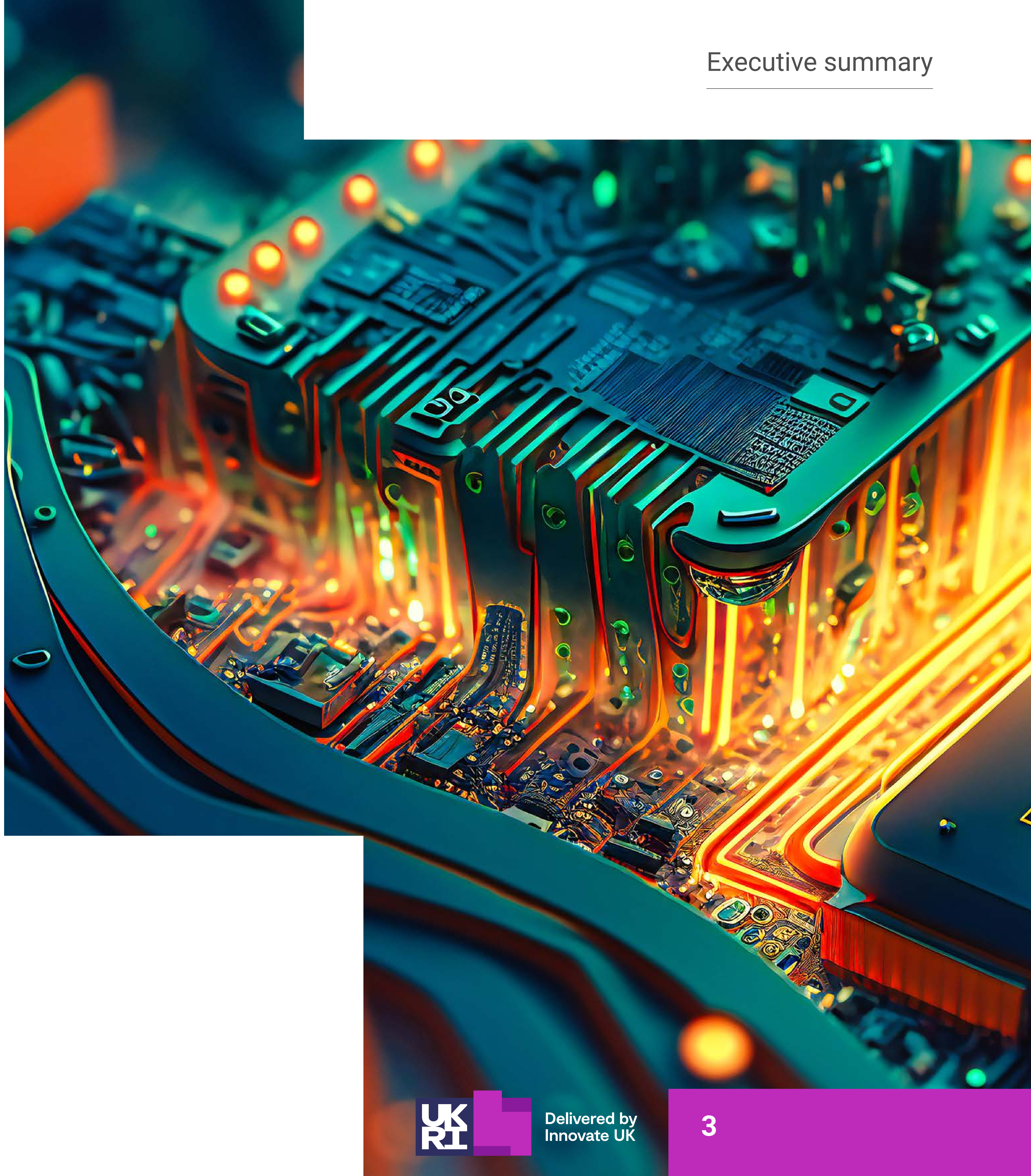
Executive summary

On 22 July 2022 the UK Secretary of State for Business, Energy and Industrial Strategy published a policy paper titled *'Resilience for the Future: The UK's Critical Minerals Strategy'* outlining a new critical minerals strategy for the UK, meaning the UK joins numerous other nations that have or are establishing strategies to secure the supply of critical minerals.

Most critical metals have constrained supply bases that are slow and costly to expand, vulnerable to political will, and lacking geographical diversity.

The UK now has a published list of the minerals it considers to be 'minerals with high economic vulnerability and high global supply risk'. Many of these critical metals are facing huge demand growth forecasts, often involving multiple end-use industries — both traditional and future-facing.

Following meetings and interviews with users and suppliers of these metals, this report explores where these metals are used in Power Electronics, Machines and Drives (PEMD) industries, how they are used, what metal and technical constraints companies are addressing, and future aspects need to be addressed for future critical metals.



Introduction

This report was commissioned by UKRI's Driving the Electric Revolution Challenge, delivered by Innovate UK, and sits as part of the Technical Deep Dive that Innovate UK KTN undertook across the UK landscape considering the metals currently used in PEMD technologies and within its related supply chains. Its goal is to achieve a better understanding of how these metals directly affect the PEMD supply chain and their roles in bringing about net zero.

Net zero is the future vision and strategy of the UK to reach maximum carbon footprint reductions by 2050. This strategy also sits at the centre of what the Driving the Electric Revolution Challenge is working to achieve by recognising that electrification will play a huge role in decarbonisation, and creating a more secure and resilient supply chain across all technology sectors.

UK industry has a growing need to invest in innovative, efficient manufacturing, to find a way to reduce energy costs and overheads, and to improve productivity to help keep the UK PEMD supply chain competitive.

The current innovation landscape is very much industry focused with emphasis on enabling the design, development and market growth of PEMD supply chains, across all technological areas. This includes the manufacturing capabilities and upskilling of the workforce to meet these challenges.

This report explains what the current sector landscape looks like and what the challenges are. It reviews base metals, ferro-alloys, precious metals, and speciality metals, avoiding hard emphasis on rare Earth elements and magnetics.

It concludes by summarising industry feedback and recommendations for future actions that could be undertaken to further understand and promote these requirements.

Base metals

Al, Cu, Pb, Ni, Zn

(+silicon and ferro-alloys)

Precious metals

Pt, Au, Ag, Pd, Ru, Os, Ir, Rh

Speciality metals

Co, Ge, Ga, In, Se, Sb, Mg, Mo, Cd, Be, Bi, Cr, Nb, V, Hf, Li, Mn, Re, Ta, Te, Ti, W

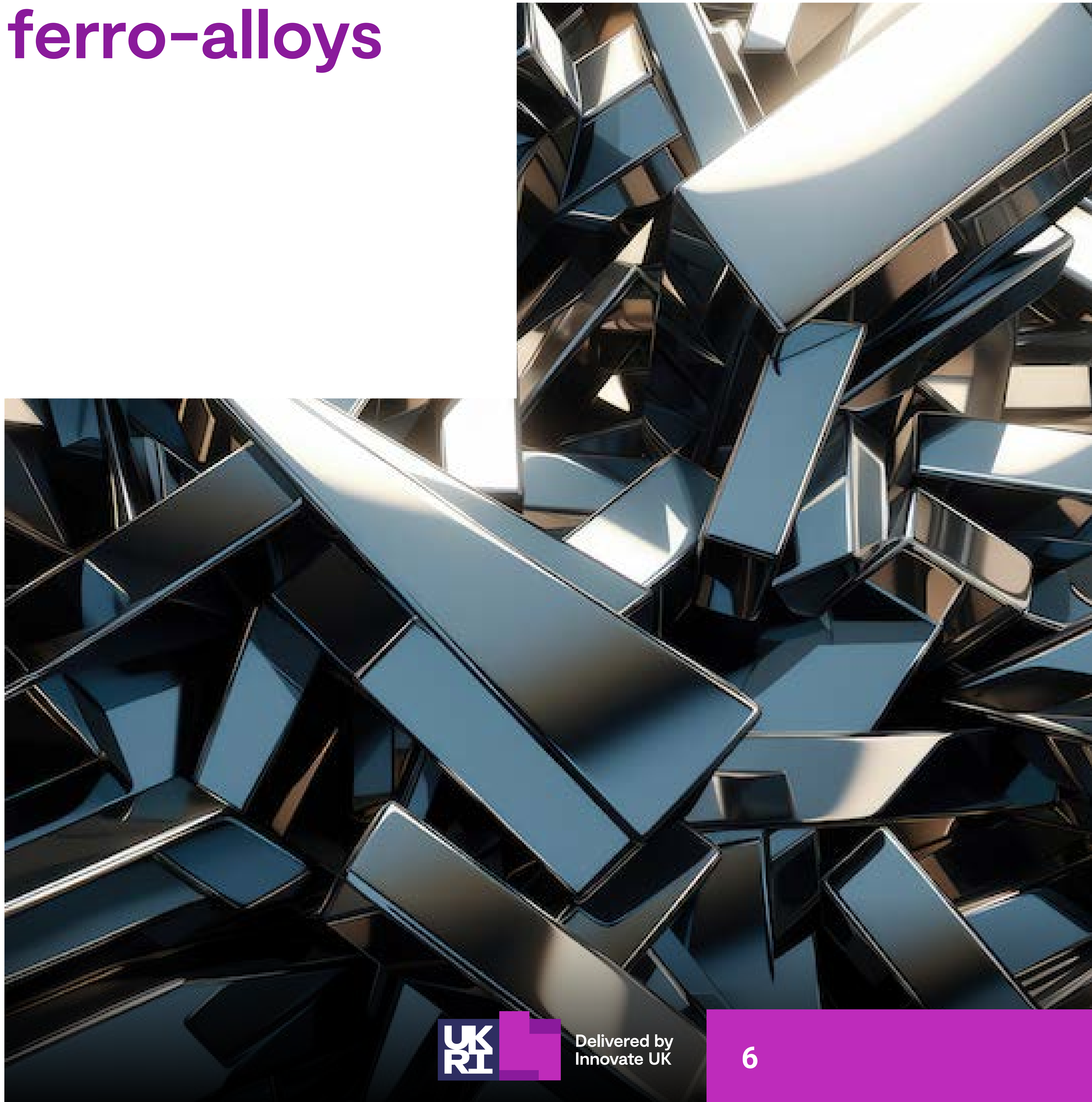
Non-ferrous metals, silicon and ferro-alloys

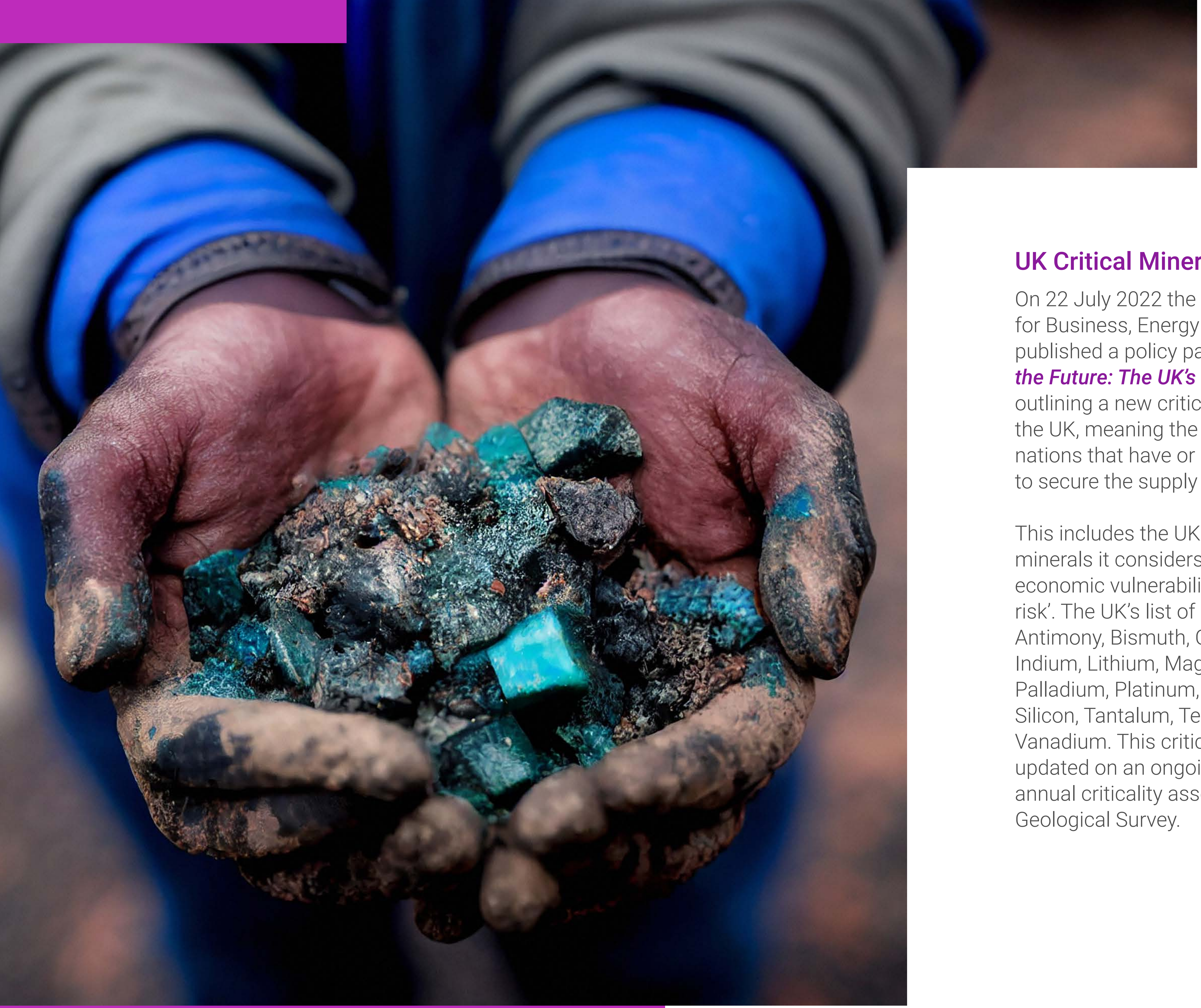
What does the ecosystem landscape look like?

The Institute for European Studies (IES) 2050 blueprint report outlines that the European Union's ecosystem for metals stands as a frontrunner for industries to transition to a climate neutral system showing an increase in electrification, circular economy, recycling and reuse of base metals production.

The report further goes on to illustrate how these changes have created a positive impact by demonstrating a reduction in greenhouse gases and increased electricity in energy mix across multiple key technology sectors. The global strategy to reach net zero has set a precedence, with the UK's decarbonisation mechanisms facing international competition. With a dedicated industrial strategy, the future of carbon neutral, net zero electrification can be secured if proper investment is placed in innovation, to enhance value chains, change policies and push further towards circularity and reuse.

Base metals sit at the baseline of our economic infrastructure, whilst precious metals are more commonly used within various high technology applications which include solar panels, electronics and fuel cells. There is a growing need for various minerals and metals to achieve a low carbon future, in sectors such as: batteries, solar power, wind power, clean mobility, electric vehicles, power electronics and grid infrastructure. Europe has shown a constant decreasing capability of non-ferrous metals such as aluminium, copper, lead, nickel, zinc and cobalt compared to countries like China, for example, whose market share dominates with these metals.





UK Critical Minerals Strategy

On 22 July 2022 the UK Secretary of State for Business, Energy and Industrial Strategy published a policy paper titled ***'Resilience for the Future: The UK's Critical Minerals Strategy'*** outlining a new critical minerals strategy for the UK, meaning the UK joins numerous other nations that have or are establishing strategies to secure the supply of critical minerals.

This includes the UK's first published list of the minerals it considers to be 'minerals with high economic vulnerability and high global supply risk'. The UK's list of 18 critical minerals is: Antimony, Bismuth, Cobalt, Gallium, Graphite, Indium, Lithium, Magnesium, Niobium, Palladium, Platinum, Rare Earth Elements, Silicon, Tantalum, Tellurium, Tin, Tungsten, Vanadium. This critical minerals list is being updated on an ongoing basis following annual criticality assessments by the British Geological Survey.

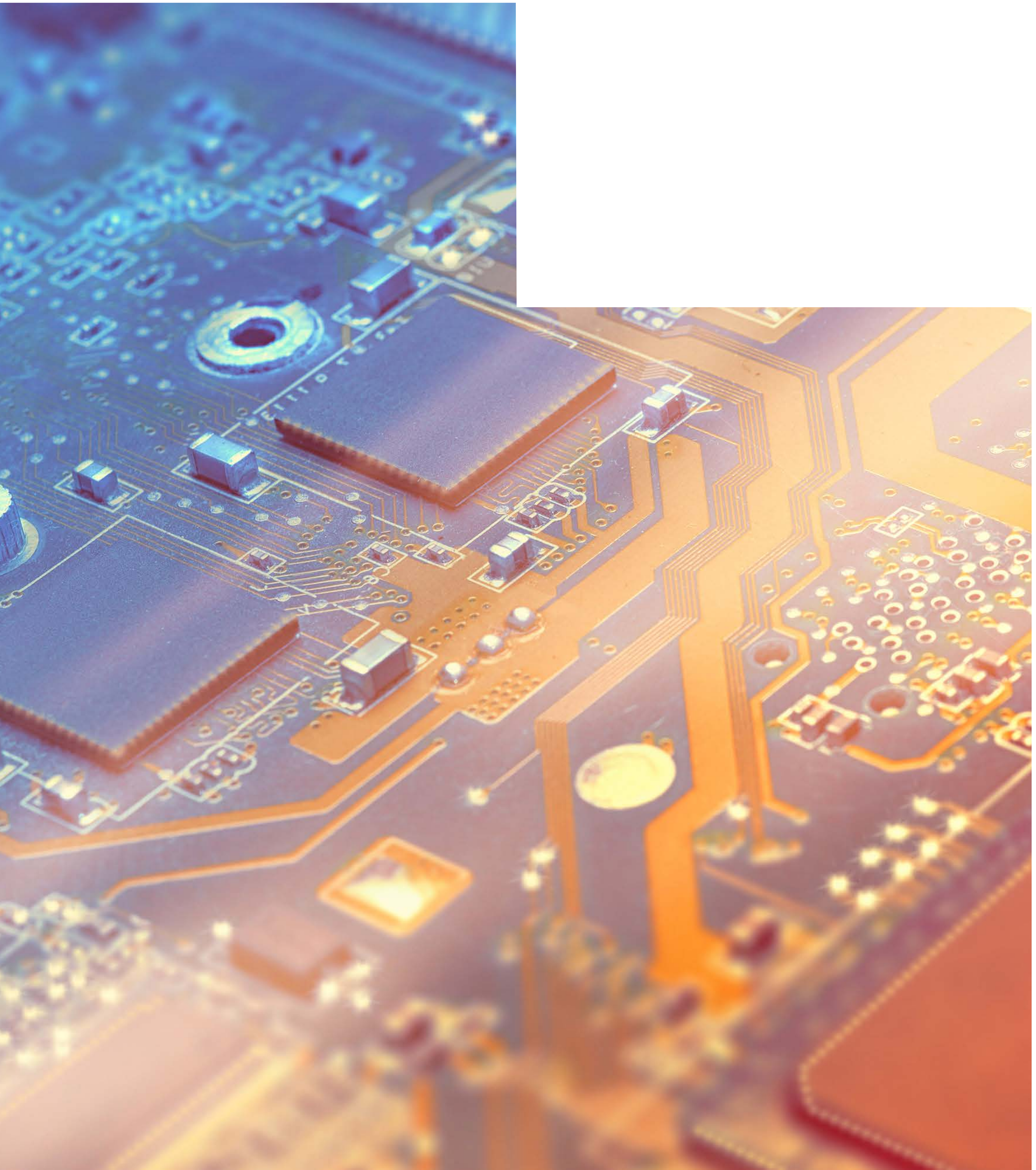
Technologies that provide a route to net zero such as power electronics, machines (motors/generators), drives, batteries and photovoltaics rely heavily on these minerals.

Consequently, the demand for critical minerals in terms of price, regional dependence and political discussion is expected to dramatically increase. According to the International Energy Agency, the world in 2040 is expected to need four times as many critical minerals for clean energy technologies as it does today.

Critical metals will be fundamental to the UK economy as the world continues to electrify in order to meet the challenge of net zero. Therefore, the importance of securing a stable, responsible supply chain and the route to recycling these materials is essential.

Emerging critical metal examples:

- **Rare Earth elements (REEs):** A group of 17 elements that are essential for many high-tech applications, including electronics, wind turbines, and electric vehicles. China is currently the dominant supplier of REEs which has raised concerns about supply security.
- **Lithium:** A key component of batteries used in electric vehicles and other portable electronics. While lithium is relatively abundant, there are concerns about environmental impacts associated with lithium mining and processing.
- **Cobalt:** An important component of batteries, particularly those used in electric vehicles. Most of the world's cobalt supply comes from the Democratic Republic of Congo, where there are concerns about human rights abuses in the mining industry.
- **Tungsten:** Used in a variety of high-strength and high-temperature applications, including cutting tools, aerospace components and electrical contacts. The supply of tungsten is concentrated in a few countries and concerns have been raised about its environmental and social impacts.
- **Indium:** Used in the production of flat panel displays and other electronic devices. While indium is relatively abundant, it is often a by-product of other mining operations, and its supply may be subject to fluctuations.
- **Vanadium:** Used in the production of steel and other alloys, as well as in energy storage applications. Most of the world's vanadium supply comes from China and Russia, which raises concerns about supply security.



Metals critical to PEMD

Non-ferrous metals have shown great importance within Europe’s current value chain and are essential to the strategic push towards low carbon solutions and technologies. These types of metals, alongside silicon and ferro-alloys, constitute the baseline for most of today’s infrastructure such as buildings within the construction sector; vehicles within the transportation sector; electronics and energy generation, and also within specific sectors such as defence with UAVs, robotic and military ground and aerial vehicle technologies.

Each base metal feeds into each technological area. This explains why metals are of key importance to improve the sustainability of vehicles, electronics, equipment, machines, etc., to reduce the carbon footprint and bring about net zero. Metals such as ferro-alloys are used to improve the tensile strength, life cycle wear, maintenance against corrosion and resistance to external elements in order to increase the lifetime of steel-based infrastructures and vehicles. Some are used to bring about direct improvement in the operation of core products such as electronics, motors, generators and transformers. All these metals show the complexity of today’s value chains and how the ecosystem of a set of metals can influence a broad range of end-user sectors.

The focus for this report is on the so-called electrical metals (Figure 1), and their use in PEMD applications.

A simple example of metals used in electrical wiring or cables are:

- **Copper (Cu):** is highly conductive, inexpensive, economical and ductile (being able to bend, flex and fold to a certain degree without causing damage to the wires, cables, and insulation). It is also thermal resistant (being able to withstand a large amount of heat without causing damage) and recyclable.
- **Gold (Au):** is usually used as a coating metal around other material strands. Similarly it is inexpensive and often used to coat connection points where thin wires are present. It is also categorised as a noble metal and is highly resistant to chemical attacks even at high temperatures.
- **Silver (Ag):** is known to be the most conductive metal. It has great durability and flexibility, but can easily react to oxidation and is not resistant to environmental effects, affecting its longevity.
- **Aluminium (Al):** is very cost efficient. It is durable and ductile (easily bent and flexed allowing for easy moulding of the material) and it is also lightweight, making it perfect for use in aerospace cabling for example.

Copper (Cu)	Silver (Ag)	Aluminium (Al)
Gold (Au)	Zinc (Zn)	Nickel (Ni)
Lead (Pb)	Tin (Sn)	Lithium (Li)
Beryllium (Be)	Tungsten (W)	Mercury (Hg)
Palladium (Pd)	Rhodium (Rh)	Niobium (Nb)
Tantalum (Ta)	Cadmium (Cd)	

Figure 1. Electrical metals

Benefits to ESG of improved metal supply to PEMD industries

The Environmental, Social, and Governance (ESG) benefits brought about from the PEMD industries are substantial as they provide a route to net zero by creating new clean technologies through innovation and bringing about electrification. The benefits include:

- **Environmental:** PEMD can displace the requirement for the burning of fossil fuels through electrification of sectors dominated by combustion, such as power generation and transport. In addition to this PEMD can reduce energy consumption and therefore greenhouse gas emissions. For example, by using energy-efficient power converters, power electronics can improve the energy efficiency of devices and systems, resulting in reduced energy consumption and lower emissions. Additionally, power electronics can enable the integration of renewable energy sources into the grid, which can help reduce dependence on fossil fuels and further reduce emissions.
- **Social:** PEMD can improve the safety, reliability and accessibility of energy systems. For example, power electronics can improve the stability of the grid, enabling better management of power fluctuations and reducing the risk of blackouts. Additionally, power electronics can enable the development of microgrids and off-grid energy systems, which can increase access to energy in underserved communities.
- **Governance:** PEMD can support sustainable business practices and reduce operational risks. For example, by using energy-efficient power electronics, companies can reduce their energy costs and improve their bottom line. Additionally, by investing in sustainable and socially responsible practices, companies can improve their reputation and reduce the risk of negative social and environmental impacts associated with their operations.

There can also be a cost to ESG associated with metal supply. Within a PEMD context, these costs are often similar to, or lower than the cost of the alternatives they displace but should still be considered. They include extraction (e.g. ground water contamination), modern slavery, and reliance on unfriendly states for key materials.

In the case of the metals used in PEMD, their sourcing, transport, application, remanufacturing and recycling should all be considered.

Metals such as iron and steel alloys have been reported to have the longest use cycle, an average of 150 years, because they are highly efficiently processed in an industrial setting, which in turn can also affect their recyclability. The lifespan of non-ferrous metals like aluminium and copper, and metals such as gold and silver, are found to have a significantly lower use cycle life of just over 50 years.

Electrical steels in the PEMD industry sector are used in magnetic cores which affect the environment directly and indirectly. Direct effects can include things like acoustic noise, and indirect effects such as the emission of greenhouse gases due to the electrical energy conversion into iron loss that has produced fossil fuels into the atmosphere. This can and does contribute to climate change.

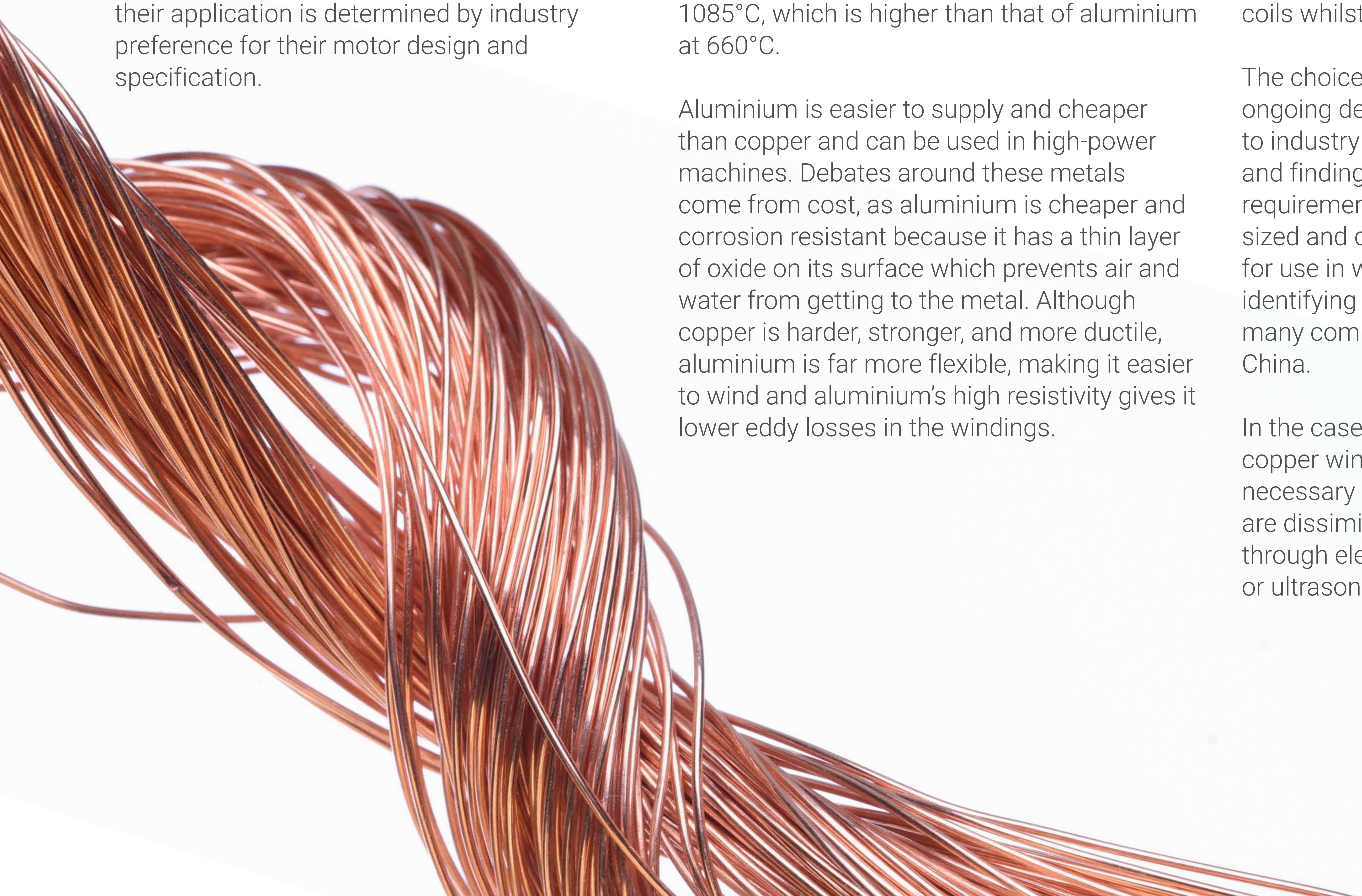
Overall, the development of PEMD can contribute to a more sustainable and equitable energy system, with benefits for the environment, society, and corporate governance. By prioritising ESG considerations in their PEMD investments and operations, companies can not only achieve better financial performance, but can also contribute to a more sustainable and resilient energy future.

> **“Steel transported within the UK produces 50% less CO_2 than steel sections sourced from the EU. Supply routes can offer total emissions of less than 10 kg CO_2 per tonne of steel in some cases – four times less than steel sourced from mainland Europe. The average distance UK manufactured steel sections are transported to our customers is less than 150 km.”**
>
> *British Steel*

Metals currently in use in the PEMD industry

Electrical conductors

A key outcome from the interviews was that there is an ongoing transition from copper to aluminium for motor windings. Both metals are thermal and electrical conductors, and their application is determined by industry preference for their motor design and specification.



Copper is soft, malleable and ductile with a reddish-orange colour. Aluminium is soft, non-magnetic and ductile and appears silver-white in colour. Copper has a melting point of 1085°C, which is higher than that of aluminium at 660°C.

Aluminium is easier to supply and cheaper than copper and can be used in high-power machines. Debates around these metals come from cost, as aluminium is cheaper and corrosion resistant because it has a thin layer of oxide on its surface which prevents air and water from getting to the metal. Although copper is harder, stronger, and more ductile, aluminium is far more flexible, making it easier to wind and aluminium's high resistivity gives it lower eddy losses in the windings.

Aluminium can be more susceptible to oxidation in the cast resin. The wound coils tend to be larger, requiring more cross-section to carry current, with copper having smaller coils whilst carrying twice the current.

The choice between the two metals is an ongoing debate, and it typically comes down to industry needs, material specifications, price and finding suppliers. For copper there is a requirement for suppliers to provide correctly sized and dimensioned insulated copper wire for use in windings, but many had challenges identifying UK suppliers, and subsequently many companies were looking to Europe and China.

In the case of using both metals (for example copper windings and an aluminium busbar) it is necessary to join copper to aluminium. These are dissimilar metals, and this is typically done through electron beam welding, laser welding, or ultrasonic welding.

In terms of recycling and remanufacturing, between the two metals, aluminium is the material that can be recycled with steel, whereas copper has been considered a contaminant to steel during its recycling process. This makes aluminium the more environmentally friendly material for use within motor structures as it is easier to recycle at end-of-life.

Based on the discussions, it is clear that both copper and aluminium have a role to play in motor manufacturing for the foreseeable future, and as the know-how and techniques in working with aluminium continue to be developed, we expect to see a growth in this area.

Electrical steels

It was found that companies are typically sourcing their electrical steel from outside the UK where it was said to be cheaper and easier to source from countries such as China, India, and Germany.

To give an approximate quantifiable measurement comparison, interviewees said that it was cheaper and easier to find a supplier of dimensioned electrical steels in India (with tooling costs as low as £18K) compared to the UK where similar tooling could cost anything up to £90k.

Products sourced externally (from China, India, etc.) can be significantly cheaper, reportedly sometimes costing less than the transportation cost of similar products manufactured within the UK.

However, utilising offshore suppliers reportedly comes with disadvantages. For electrical steels used in rotors, suppliers often need special tooling that is challenging to design to meet tight tolerances. For overseas sourcing the current freight shipping time can be long resulting in significant delays if produced test parts are not within tolerance and need to be reworked. In selecting suppliers, companies are considering the ESG credentials as well as the current economic situation.

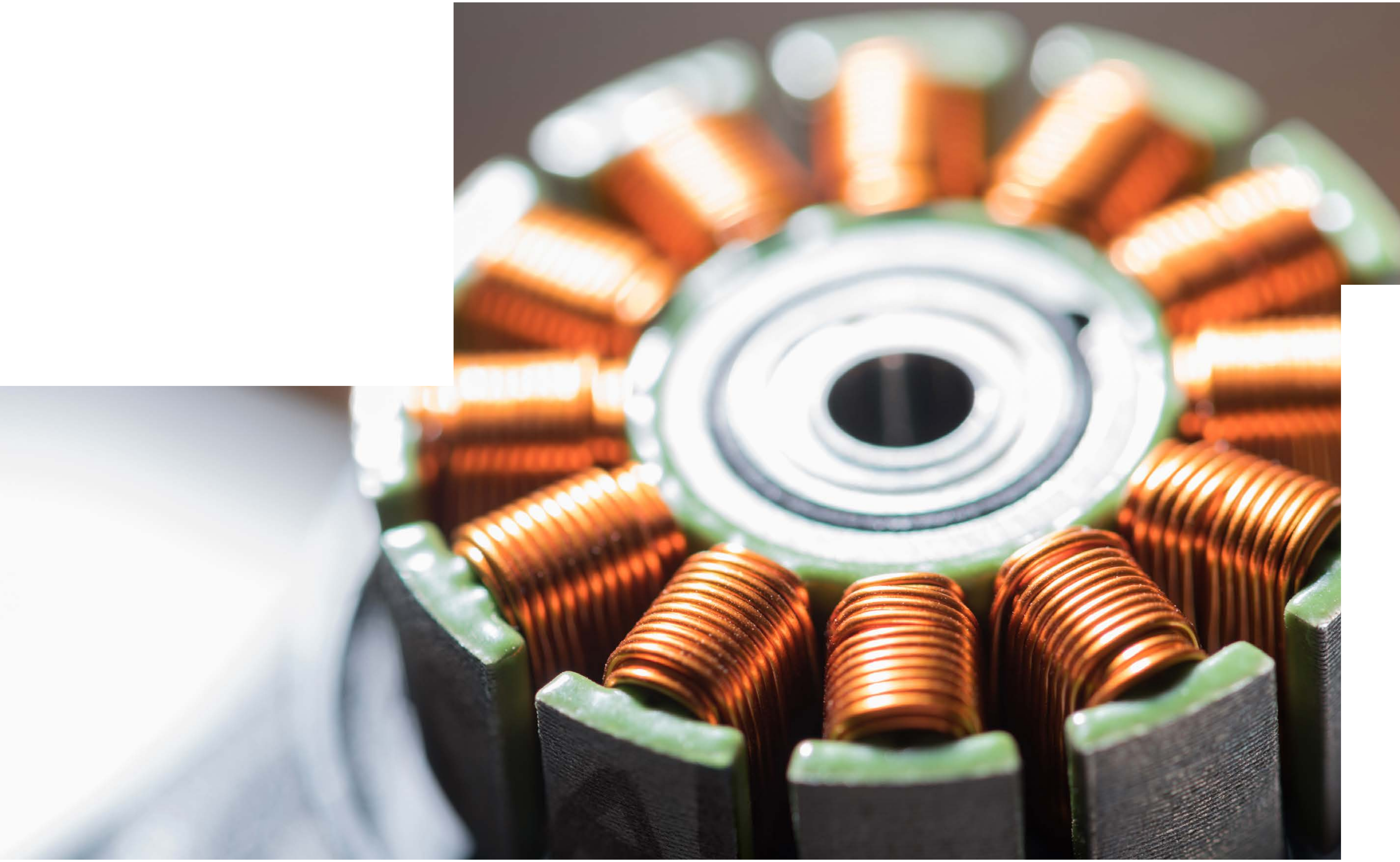
Industries consideration of all the aforementioned factors is important to become a class leading manufacturer within the UK.

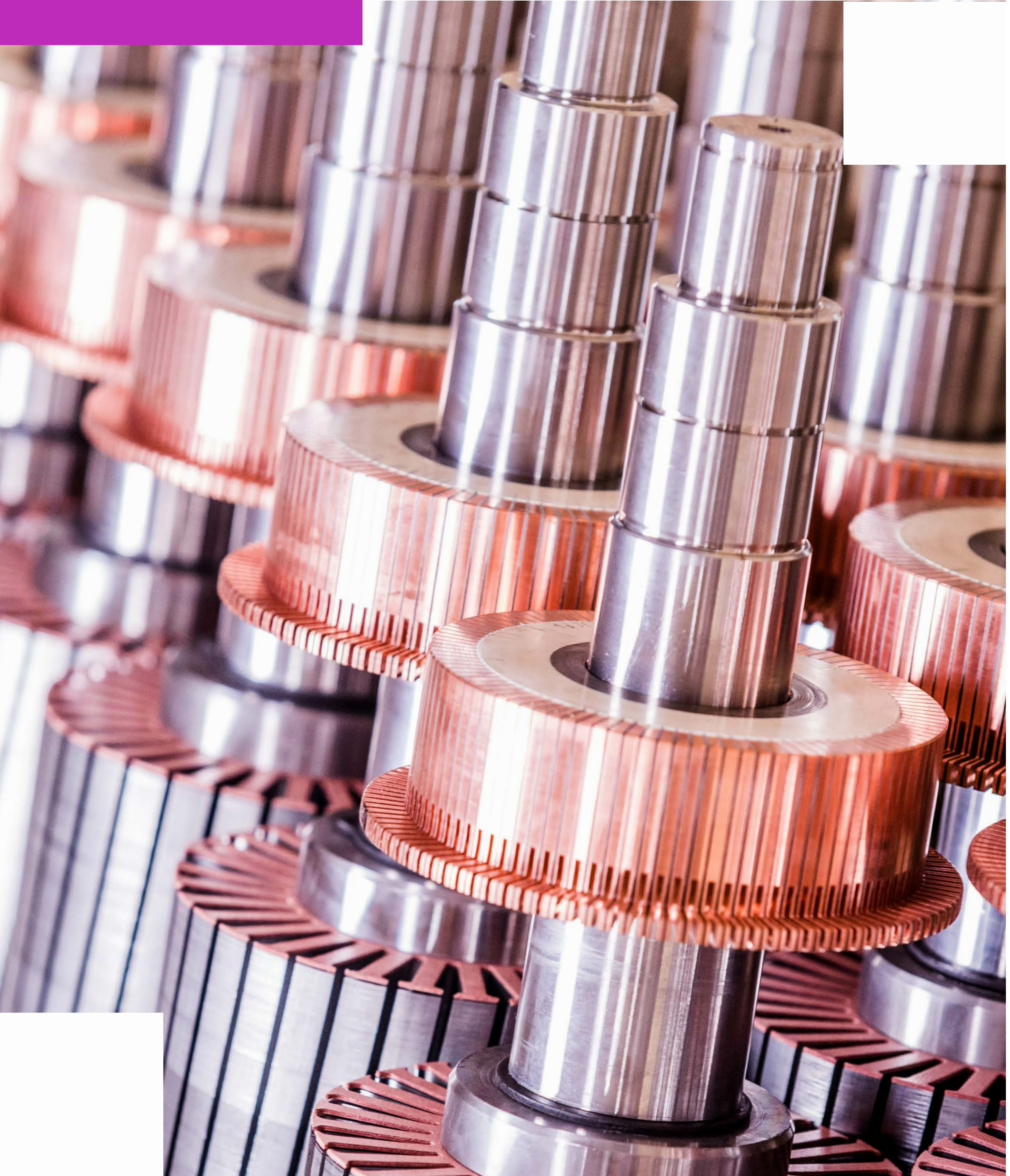
Magnets

Magnets as a discrete area are not within the scope of this report. However, discussions did mention magnets with reference to the placement of them within motors and the type of magnets utilised.

A key insight into magnetic structures used in motors found that industry prefers to specifically design and consider the placement of the permanent magnets for easy end-of-life removal. However, the cost implications of more complex mounting systems often result in the magnets being bonded in place which results in them being difficult to remove at end of life.

In terms of magnet design, industry considers the following points important: cost, geometry (in terms of ease to design, manufacture and assemble) and heat transfer. A deeper discussion with companies also revealed reluctance to use dysprosium-based magnets as it is believed they do not ensure supply chain security. Hence for motor design, many are remaining (for the moment) with the more available neodymium magnets.





Properties of electrical steel

Electrical steel (also known as E-steel, lamination steel, silicon electrical steel, silicon steel, relay steel, transformer steel) is an iron alloy tailored to produce high magnetic permeability and low core losses when subjected to alternating magnetic fields.

These properties make it an ideal material for use in electromagnetic devices such as motors, transformers, and generators. Electrical steel was often discussed during the company interviews as it is a critical component in the manufacture of electrical machines and that without a consistent supply there can be no motor manufacture in the UK. It is a ferromagnetic material made up of iron with additional amounts of silicon (Si) ranging from 1% to 6.5%, or with nickel-iron or cobalt-iron materials (see table on p17). These additions to the iron reduce eddy currents, increase resistivity, improve permeability and decreases hysteresis loss, which in turn decreases the dissipation of heat, an issue that results in energy wastage.

In motors, electrical steel is used in the stator and rotor cores, which are the parts of the motor that generate the magnetic field that drives the rotation of the motor shaft. The high magnetic permeability of electrical steel allows for a strong magnetic field to be generated with a relatively small amount of current, which helps to improve motor efficiency and reduce energy losses.

The low core losses of electrical steel also help to minimise the amount of heat generated in the motor core during operation. This is important, as excessive heat can lead to decreased motor efficiency and reliability, and can even cause damage to the motor over time.

Overall, the unique magnetic properties of electrical steel make it an essential material for the construction of efficient and reliable motors.

Electrical steel with 6.5% Si has the most improved magnetic and electrical properties but is brittle and has limited ductility needing additional thermomechanical processes. Subsequently, the most widely used commercially available electrical steel contains about 3.25% silicon. Iron-nickel and iron-cobalt alloys can also significantly reduce these magnetic losses to increase efficiency. (Bloch F., Waeckerle T., Fraisse H., *The use of iron-nickel and iron-cobalt alloys in electrical engineering, and especially for electrical motors*, Electrical Insulation Conference and Electrical Manufacturing Expo, EEIC, IEEE Xplore, 2007).

Using thin sheets of electrical steel further reduces eddy currents and losses to heat. A lamination stack is multiple thin sheets of metal (0.25mm to 1.0mm thickness) separated by electrically insulating layers. Electrical steel is usually manufactured in cold-rolled strips less than 2mm thick. These strips are cut to shape to make laminations which are stacked together to form the laminated cores of transformers, and the stators and rotors of electric motors. These laminations are cut to their finished shape by a punch and die or, in smaller quantities, may be cut by a laser or wire electrical discharge machining.

Name	Rolling	Orientation	Silicon content	Use
Hot rolled low silicon steel	Hot rolled	No orientation	1.0%-2.5%	Household motors and micromotors
Hot rolled high silicon steel	Hot rolled	No orientation	3.0%-4.5%	Transformer
Cold rolled grain oriented electrical steel	Cold rolled	Normal orientation/ high magnetic induction orientation		Large, medium and small transformers
Low carbon electrical steel	Cold rolled	No orientation	<0.5%	Household motors, micromotors, small transformers and ballasts
Silicon steel	Cold rolled	No orientation	0.5%-3.5%	Medium and large motors, generators and transformers

(ref. SDPX Steels, Silicon Steel)

Electrical steel magnetic properties.

Eddy currents

Two main components make up a motor or a generator (a machine) – the stator and the rotor. An iron core in a ring shape comprises the rotor along with slots that support the windings and coils. Eddy currents are induced currents in the magnetic core of the machine causing a magnetic loss or electrical loss - typically seen as heat.

Eddy currents are directly related to the material, the material's thickness, the frequency of the magnetic field induced and the density of the magnetic flux. In a machine, to suppress eddy current losses under dynamic magnetic loading, the stator and rotor are often made from electrical steel in a lamination stack.
In order to optimise a machine's efficiency, solutions to minimise eddy currents include:

- constructing the core from a stack of electrically isolated laminations thereby constraining the eddy currents to within the plane of the lamination.
- fabricating the individual laminations from high resistance electrical steel (FeSi) thereby reducing the magnetic losses.

Insulation coating – Backlack

Insulation coating (also known as Backlack) is not a metal, but as it was often discussed during the interviews it has been included as it is a critical element in the manufacture of motors.

Electrical steel is typically coated with a thin layer of insulating material to prevent electrical shorts between the steel laminations. The insulation coating is an essential part of electrical steel as it helps to minimise energy losses and improve the efficiency of electrical devices such as motors, transformers, and generators.

The insulation coating on electrical steel is made from a variety of materials, including organic and inorganic coatings. Organic coatings are typically made from materials such as varnish or epoxy, while inorganic coatings are typically made from materials such as phosphate or oxide.

The insulation coating is applied to the steel through a variety of methods, including dipping, spraying, or electroplating. The thickness of the insulation coating can vary depending on the intended application and the specific requirements of the device being constructed.

In addition to preventing electrical shorts, the insulation coating on electrical steel can help to reduce the impact of mechanical stress on the steel. This improves the durability and reliability of electrical devices over time.

Overall, the insulation coating is an essential component of electrical steel and plays a crucial role in ensuring the efficient and reliable operation of electrical devices such as motors. As it is typically applied after rolling and before coiling of the electrical steel, it is an integral part of the electrical steel fabrication.

Electrical steel lamination process

Like insulation coating, the lamination process was often discussed during company interviews and is considered a critical process.

The production of electrical steel laminations involves several stages, including steel making, hot rolling, annealing and insulation coating, before punching and stacking. Here are the general steps involved in the electrical steel lamination process:

1. **Steel making:** The first step in the production of electrical steel is to create a low-carbon steel alloy that is suitable for use in electrical devices. This involves melting iron and other alloying elements in a furnace, then refining the resulting steel to the desired composition.
2. **Hot rolling:** The steel is then hot rolled into thin sheets, which are typically between 0.2 mm to 0.5 mm in thickness. The hot rolling process helps to refine the grain structure of the steel and improve its magnetic properties.
3. **Annealing:** The hot rolled steel sheets are then annealed in a controlled atmosphere to soften the steel and relieve any residual stresses. This also helps to improve the magnetic properties of the steel.
4. **Insulation coating:** The annealed steel sheets are coated with a thin layer of insulating material to prevent electrical shorts between the steel laminations. The insulation coating is typically made from materials such as varnish or epoxy.
5. **Punching:** The insulated steel sheets are then punched into the desired shape, typically using a high-speed punch press. The punched shapes are generally either circular or rectangular and may be further processed to create laminations of various sizes and shapes.
6. **Stacking:** The punched laminations are stacked together to form the stator and rotor cores of electrical devices such as motors and generators. The laminations are usually oriented in a specific direction to optimise the magnetic properties of the core.

Stages 1 to 4 are normally completed within the steelworks, while stages 5 and 6 are usually completed at the motor manufacturing company.

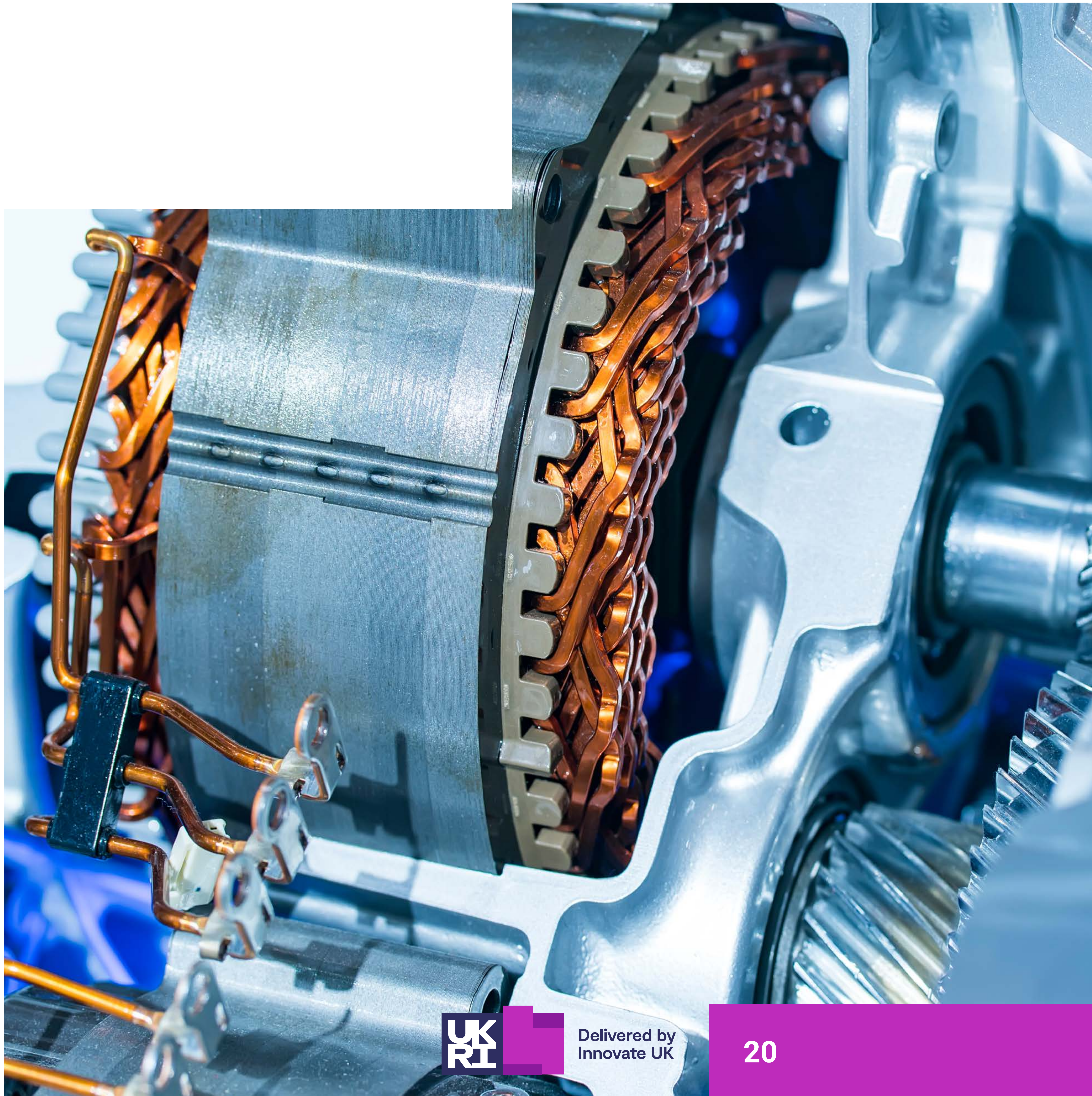
Overall, the electrical steel lamination process is a complex and highly specialised process that requires careful attention to detail and strict quality control to ensure that the resulting laminations meet the stringent manufacturing tolerances.

Motor windings, hairpins and the metals used

Traditionally, electric motor windings are copper conductive wires wrapped around the stator slots providing a path for current to flow to create a magnetic field to spin the rotor. Hairpin windings are now being created by bending a single piece of wire into a U-shape, with the two ends of the wire forming the two legs of the U. The hairpin-shaped wire is then inserted into the stator slots, and the two legs of the U are connected to adjacent stator slots to form a complete winding.

Both motor windings and motor hairpins are being designed, produced, and utilised within the UK by companies who manufacture motors.

Hairpin windings are commonly used in high-performance electric motors, such as those in hybrid and electric vehicles, as well as in industrial applications such as pumps and fans. They require specialised manufacturing techniques and equipment, which can make them more expensive to produce than traditional wire windings.



Hairpin windings offer several advantages over traditional wire windings, including:

- **Improved manufacturing efficiency:** Hairpin windings can be wound more quickly and accurately than wire windings, which can help to reduce manufacturing costs and improve production efficiency.
- **Higher power density:** Hairpin windings can offer higher power density than wire windings, due to their reduced resistance and improved cooling characteristics. This allows for higher torque output and improved efficiency.
- **Better thermal management:** Hairpin windings have improved thermal management properties compared to wire windings, allowing them to dissipate heat more effectively. This results in lower operating temperatures and better performance and reliability over time.
- **Increased mechanical strength:** Hairpin windings have increased mechanical strength compared to wire windings, which can help to reduce the risk of damage or failure during operation.

Hairpin windings also have disadvantages, including:

- **Higher manufacturing costs:** Hairpin windings require specialised manufacturing techniques and equipment, which can make them more expensive to produce than traditional wire windings.
- **Limited availability:** Hairpin windings are not as widely available as wire windings and may not be suitable for all motor applications.

The choice between hairpin windings and wire windings depends on the specific requirements of the motor application, as well as the availability and cost of each winding type. Both copper and aluminium are used as conductors for motor windings/hairpins. The choice between the two materials depends on several factors, including cost, weight, conductivity, and durability.

Industry insights into metals of the future

Scoping out industries' requirements for future metals to enable them to improve their products and services has resulted in multiple views.

Heat dissipation

Companies are working on finding solutions to reduce heat generation and/or improve heat dissipation from the windings in the motor. Interviews revealed that many in industry are considering lighter aluminium windings for use in critical applications including the aerospace sector with its requirement for lighter and/or more efficient systems and structures. This brings about a requirement to improve heat dissipation from these motors.

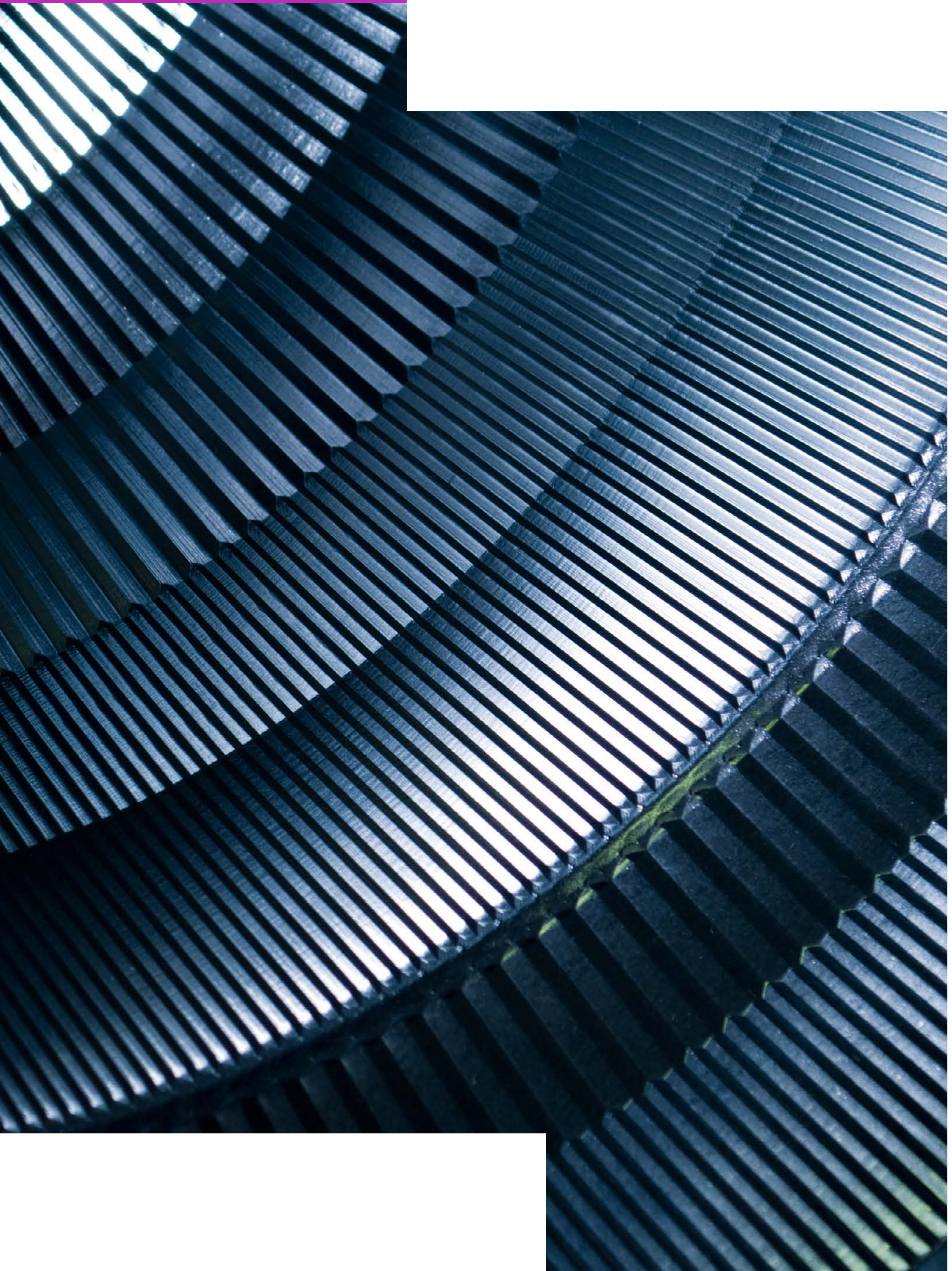
For electric motor structures, another ongoing challenge in industry is the consideration and development of smart and reliable liquid (water/oil) cooling systems for the motor. The preference is not to use a liquid cooling system due to the increase in the complexity of the motor. However, where increasing specification requirements are demanding it, industry is not only considering it but is starting to implement it.

Thinner metal laminations

Companies revealed the benefits and requirement for thinner metal laminations in future structures. Although typically applied by the overseas steelworks, these improvements are important to bring about further efficiency improvements to electrical motors, generators, and transformers. Companies also highlighted the complexity of ensuring the laminations that make up a laminated stack are of a consistent thickness, of a suitable material and whose backlack is correctly applied. All of which brings about a cost implication that must be balanced against the resulting benefits. UK companies did express an interest in having UK sovereign capability for laminated electrical steel at commodity prices.

Additive manufacturing

The use of additive manufacturing is being considered to test and develop improvements to electrical machine manufacture. This area occasionally produces different dimensioned windings to test the resulting efficiency improvements.

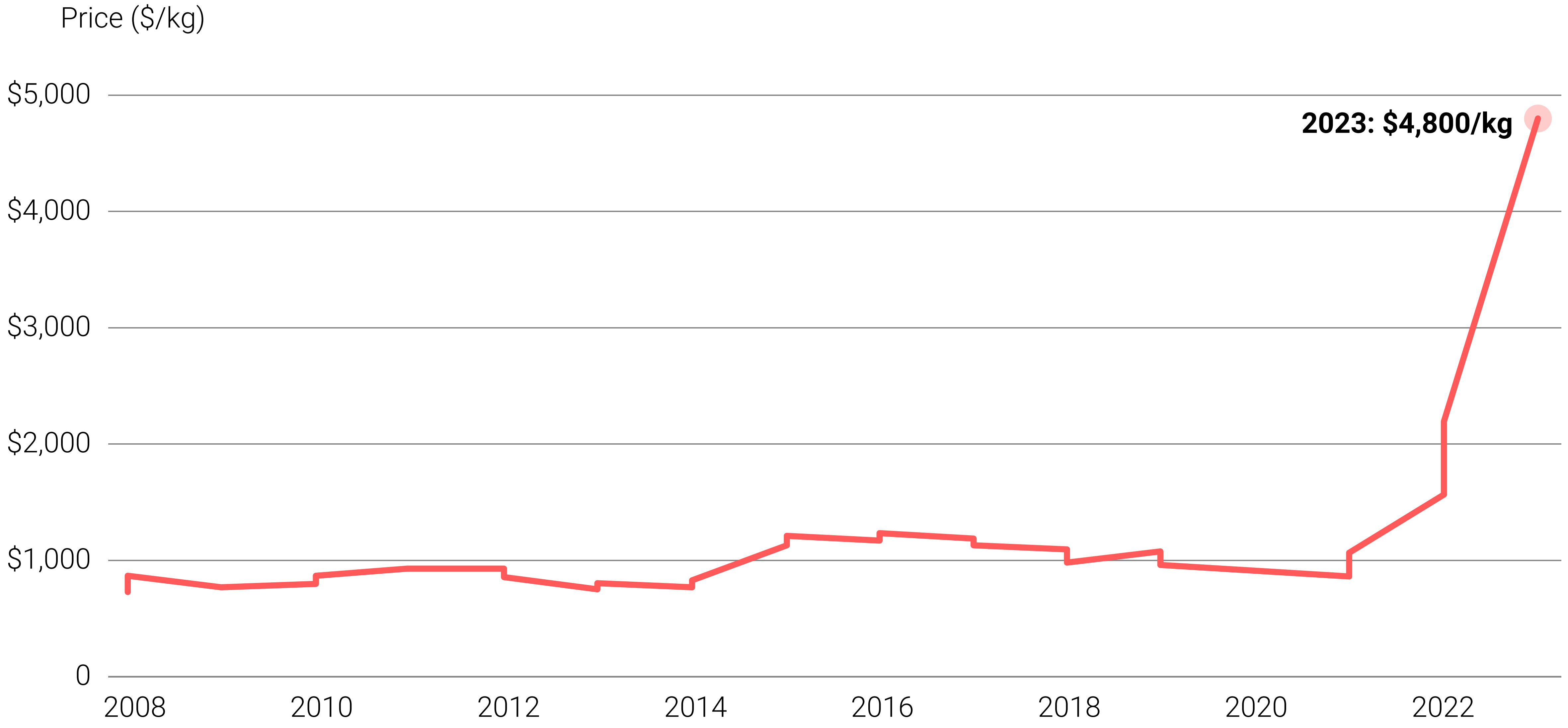


Hafnium

Hafnium is already commonly used in electronics supply chains and as an additive in nickel-based super alloys for industrial and aero gas turbine engines.

It is not currently on the UK's critical minerals list but was included in the EU Critical Raw Materials list in 2017. It is often an overlooked metal because it is a small market, but it is becoming more strategic with prices increasing from $1,200-$1,400/kg in 2022 to $4,500-$5,000/kg in 2023.

Hafnium prices increase on aerospace electronics demand



Source: www.mining.com/web/aerospace-electronic-demand-drive-hafniums-400-record-surge/

Hafnium is critical to expanding future markets. With the resurgence of aircraft production, it is again being used in aircraft engines to boost the heat resistance of nickel-cobalt alloys. For microelectronics production it is in ever growing demand by semiconductor manufacturers as hafnium tetrachloride coatings.

The aerospace, semiconductor and electronics industries are increasing their requirements for hafnium, but increasing production to match this is difficult as its production is a by-product of zirconium, whose required volumes have not increased in step with that of hafnium. Hafnium supply shortage could be eased by improvements in the recycling process and finding better methods to separate hafnium from zirconium, but these are not yet in place.

Hafnium is a technological necessity with no like for like substitution. It is commonly used in the production of semiconductors in minute quantities as a gate dielectric material in transistors due to its high dielectric constant and compatibility with silicon. In recent years, there have been efforts to find alternative materials to hafnium, particularly because of its scarcity and high cost.

One alternative material that has gained attention is zirconium dioxide (ZrO_2), which has a similar high dielectric constant to hafnium dioxide (HfO_2) and is also compatible with silicon. Other materials being researched include tantalum pentoxide (Ta_2O_5) and aluminium oxide (Al_2O_3), which also have high dielectric constants and are compatible with silicon.

The replacement of hafnium in semiconductors is not a straightforward process and requires careful consideration of various factors, including the physical and chemical properties of the alternative materials, their compatibility with existing semiconductor processes, and their ability to meet the performance requirements of modern electronic devices.

Overall, while there is ongoing research into alternative materials for hafnium in semiconductors, hafnium remains a widely used and important material in the semiconductor industry.

Niobium

Niobium is used as an alloying element in steel and other metals to improve their strength and durability. In motors, niobium-based alloys could be used to make components such as gears, bearings, and other parts that need to withstand high temperatures, pressures, and stresses.

Automotive companies have increased implementation of niobium-containing moderate and high-strength low-alloy (HSLA) steel in modern passenger vehicles (10.5% in 2000 to 19.3% in 2017; Davis and Boundy, 2021), reducing the overall weight of the vehicle and resulting in increased fuel efficiency (and subsequently reduced emissions) while also improving vehicle safety ratings due to the increased strength of the steel (Heisterkamp and Carneiro, 2001; Olsson et al., 2006; Jansto,2010).

Niobium is classed by the UK Critical Minerals Strategy as a mineral with high economic vulnerability and high global supply risk because of the high concentration of niobium mine production in just a few countries, (i.e., Brazil and Canada) with a single producer and mine locality which accounts for nearly 75% of global niobium supply (Roskill Information Services Ltd., 2020b), the lack of available substitutes or significant performance loss associated with substitution (e.g. Graedel et al., 2015b; U.S. Geological Survey, 2021a), and as previously noted, its increasing implementation into modern and energy-efficient, low emission technologies.

Terbium

Terbium is a highly reactive element that is often used as an alloying element to improve the strength and durability of other metals, such as magnesium and aluminium. Terbium is also used in the production of high-performance magnets.

Terbium is a rare Earth element and is mainly produced as a by-product of the mining of other rare Earth elements in China, which makes its supply less predictable. The UK is in danger of having Terbium (and neodymium and dysprosium) supply shortages as China’s domestic needs increase.

Iron cobalt (cobalt steel)

As noted earlier, electrical steel with 6.5% Si has the most improved magnetic and electrical properties but is brittle and has limited ductility needing additional thermomechanical processes. Iron-nickel and iron-cobalt alloys significantly reduce these magnetic losses to increase efficiency. Cobalt steel has several additional advantages for use in motors:

- **High hardness:** Cobalt steel has high hardness and can retain its cutting edge even at high temperatures, making it ideal for use in high-speed motor components such as gears, bearings, and shafts.
- **Excellent wear resistance:** Cobalt steel has excellent wear resistance, which allows it to withstand the abrasive and high-stress conditions that are common in motor applications. This can help extend the lifespan of motor components and reduce the need for frequent maintenance and replacement.
- **Good heat resistance:** Cobalt steel can withstand high temperatures without losing its hardness or becoming deformed, making it ideal for use in high-temperature motor components such as rotors and stators.
- **Improved machinability:** Compared to other high-performance steels, cobalt steel is relatively easy to machine, which can help reduce manufacturing costs and lead times for motor components.

Cobalt steel has disadvantages that require consideration:

- **Cost:** Cobalt steel is more expensive than other types of steel, which can make it less cost-effective for some motor applications. The high cost of cobalt steel is due to the high cost of cobalt, which is a relatively rare and expensive metal.
- **Brittleness:** Cobalt steel can be brittle, especially at high temperatures, which can lead to cracking and failure of motor components. This can be mitigated through careful design and material selection, but it is still a potential drawback of using cobalt steel.
- **Corrosion resistance:** Cobalt steel is not as corrosion resistant as some other types of steel, which can make it less suitable for use in motors that are exposed to corrosive environments. This can be addressed using coatings or other corrosion-resistant materials, but this can add to the cost and complexity of motor production.
- **Machinability:** While cobalt steel is generally easier to machine than other high-performance steels, it can still be more difficult to machine than some other materials commonly used in motors, such as aluminium or copper. This can increase manufacturing costs and lead times for motor components.
- **Neutron activation:** Cobalt should not be used in a nuclear environment due to neutron activation.

The combination of high hardness, excellent wear resistance, good heat resistance, and improved machinability makes cobalt steel an ideal material for use in high performance motors, especially those that operate at high speeds and under harsh conditions.

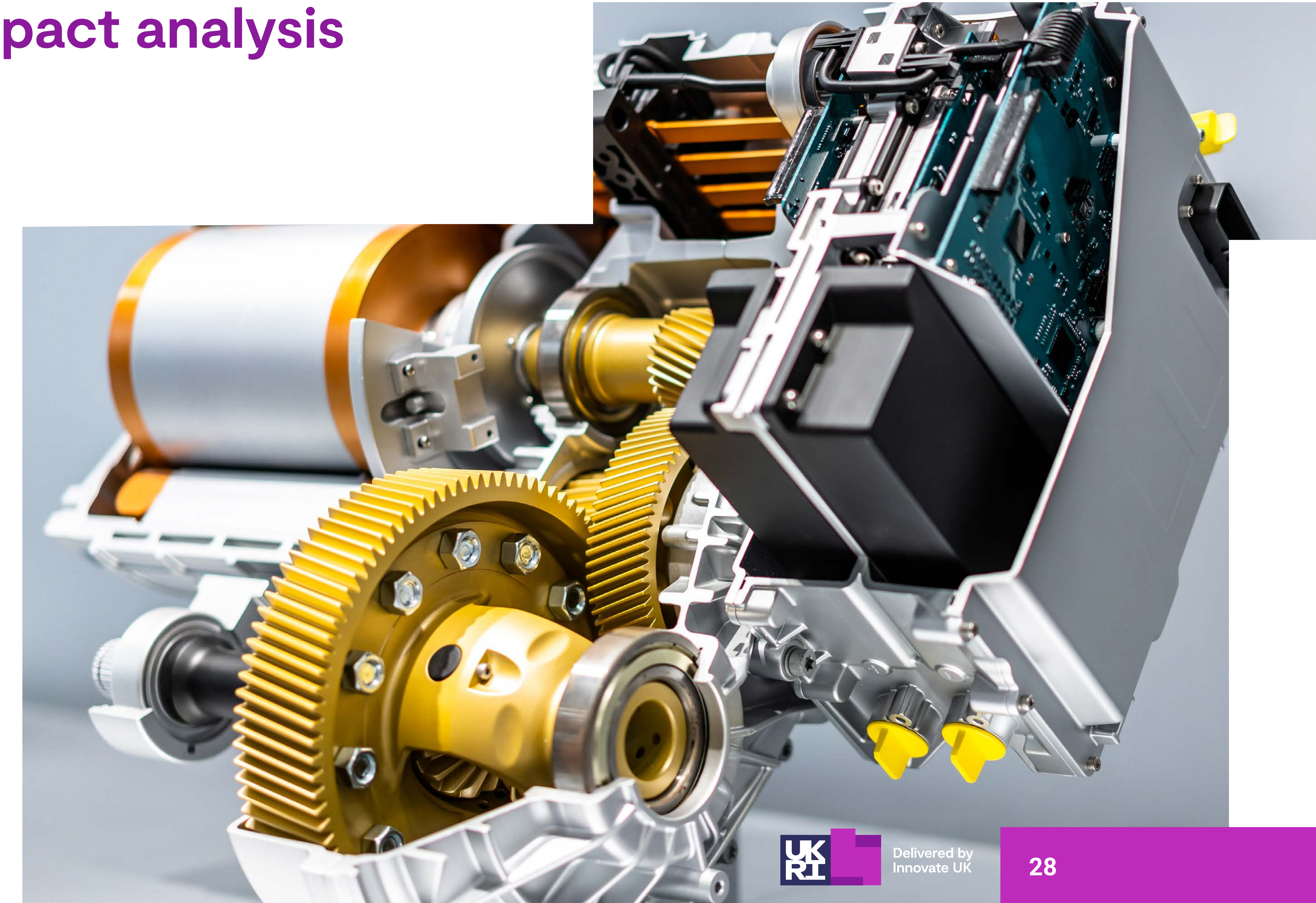
The interviews found that buyers were balancing the high cost and difficulty to source cobalt steels against its provision of increased motor performance. Currently companies are choosing to remain with silicon based electrical steels until they need the improved performance of cobalt steel or until the cost decreases.

Supply chain impact analysis

Future supply chains will require a symbiotic relationship between metals used in industry and their environmental circularity to fully transition into a climate neutral economy, which means there will be a higher demand for all types of metals.

PEMD is a rapidly growing industry that is becoming increasingly important as the world transitions to renewable energy sources and electric transportation. The supply chain for PEMD includes several critical components and materials that can be subject to various risks and challenges.

Overall, the supply chain for PEMD components and materials is subject to various risks and challenges, including geopolitical tensions, manufacturing disruptions, and environmental and human rights concerns. Efforts to promote responsible sourcing, recycling, and localisation can help mitigate these risks and increase resilience in the PEMD supply chain.



Supply chain impact analysis interview highlights

Electrical steel

As steel producers try to increase production capacity, the rapid growth of market demand due to electric motors and vehicles could potentially cause material demands to outpace supply from 2025. (Vittori C., Evans G., Fini M., *Electrical steel – Another temporary supply chain shortage or a threat to OEMs' electrification plans?* S&P Global Mobility, 2021)

Electric steel manufacturing clusters are concentrated in China, Japan and South Korea, and exported to other regions, usually in the form of steel coils. Limited access to these materials was raised as a current and future concern and there was a consensus request for the UK to have an increase in production and supply of electrical steels.

Laminated steel suppliers

Industry feedback highlighted the need for more laminated steel suppliers within the UK to help address the gaps and needs of businesses that are currently resorting to buying their steel from offshore businesses. Not having UK suppliers was reportedly resulting in time lags to arriving shipments, and price and quality variations. It is recommended that this area is explored in further detail to determine if the manufacturing processes of laminated steel can be developed in the UK to bring about economic benefits and new opportunities for businesses.

Rare Earth metals

PEMD components such as the permanent magnets used in electric motors, often contain rare Earth metals such as neodymium and dysprosium. These metals are subject to supply chain risks, including geopolitical tensions and export restrictions, as a significant portion of the world's supply is produced in China. In the long term, recycling and the development of alternative materials could mitigate these risks.

Semiconductors

The production of PEMD components such as power electronics and motor controllers rely heavily on semiconductors. The semiconductor industry is subject to supply chain risks, including manufacturing disruptions, raw material shortages, and geopolitical tensions. The recent semiconductor shortage has highlighted these risks and highlighted the need for increased resilience and diversity in the semiconductor supply chain.

Recycling and remanufacturing

For electrical machines typically both their metal content and their manufacturing processes were discussed. This included optimising their design for future remanufacturing, or recycling at end of life. Interviewees highlighted a wish to consider the future remanufacturing and recycling of materials and machines to optimise future use of metals by designing structures so that they can be easily dismantled in order to separate the individual components (e.g. magnets, windings, steel) and minimise cross contamination of the metals. Three areas were highlighted for development:

- **Magnets** – their removal from electrical machines and improved methods and processes of recycling.
- **Electrical machines** – with improved initial manufacturing design to simplify their end of life for dismantling and recycling.
- **Windings** – consideration during production to improve the separation or the metal windings from their encapsulating resin and removal of contaminating materials.

Battery materials

PEMD applications such as electric vehicles and renewable energy storage systems rely heavily on batteries. The production of battery materials such as lithium and cobalt can be subject to environmental concerns, geopolitical tensions, and human rights issues in the mining and processing of these materials. Efforts to promote responsible sourcing and recycling of battery materials can help mitigate these risks.

Conclusion

The International Energy Agency estimates that by 2040 global demand for rare Earth elements for energy transition could rise more than sevenfold.

Lithium demand could be 13 times higher, and demand for cobalt and graphite could be anywhere between six and 30 times higher, depending on how battery technologies evolve. Rare Earths, lithium, cobalt, and graphite are also used by other industries that will continue to compete with energy transition technologies for supply.

For physical, regional, and political reasons there is likely to be a limit to the metals (and other critical minerals) that will be readily available, possibly limiting government and company ambitions for the products required by consumers and needed to achieve net zero.

Interviewees said that they wanted:

- More UK suppliers of laminated steel.
- Improved methods to produce lamination stacks.
- Copper wire for windings with a range of cross-sectional areas.
- Ability to consider remanufacturing and recycling when designing electrical machines with reference to:

  Magnets – their removal and recycling.
  Electrical machines – their ease to dismantle and recycle.
  Windings – their separation from encapsulating resin.

As Power Electronics, Machines and Drives (PEMD) become increasingly important, efforts to localise and diversify the supply chain can help mitigate risks and increase resilience. This includes investing in domestic production of critical components and materials, promoting recycling and circular economy practices, and reducing dependence on a single source or supplier.

Future undertakings

This report provides insight into the critical metals in use in PEMD. To further understand and promote these requirements, future peer assisted discussion and group networking will be considered, alongside any further reports focusing deeper on sub areas of this report.

Next steps

Peer group forums through the Innovation Network to identify solutions to issues raised.

Further reports focused on selected areas of this report that are critical to PEMD.

- Determine which metals have the greatest relevance to the UK.

Identify possible solutions to address supply chain gaps and promote these to the relevant industries.

- Where is the UK involved in metals manufacture/production/processing?
- What are the risks and dependencies of the existing supply chain?
- Which areas of this supply chain should be improved?
- How can the UK improve its manufacturing/production/processing of metals to build and strengthen its supply chain?

Promote methods to improve future metal supplies including:

- Considerations needed now for future remanufacturing and recycling.
- Minimisation of future contamination of critical metals.

Discussion on how physical, regional and political influences will impact metals critical to PEMD, and how these impacts can be minimised.

Acknowledgements

We acknowledge and thank the contributions made by the following organisations: Bristol University, C Brandauer, Custom Interconnect, Electrified Automation, Equipmake, MicroChip and WMG

Appendix 1

Metallurgy and work hardening

Metallurgy involves both the science side and the technology side of metals. More specifically the way chemical metallurgy, which is the science behind how metals are produced, and physical metallurgy, which is the engineering behind how the components are used in the final product for both consumers and manufacturers. This includes sizing, dimensioning, cutting and laminating the steels.

In metallurgy there is a process called work hardening, also known in materials science as strain hardening. The process is used to increase the hardness of a metal, either induced deliberately or accidentally, and it involves things like hammering, rolling, drawing, or any other physical process to achieve a ductile product.

Strain hardening strengthens a metal or polymer by plastic deformation, and can be desirable or undesirable, depending on the context of what is intended to be achieved. Initial deformations on the metal can, at first, make the metal weaker and more brittle, but continuous induced deformations at a granular level can then increase the overall strength.

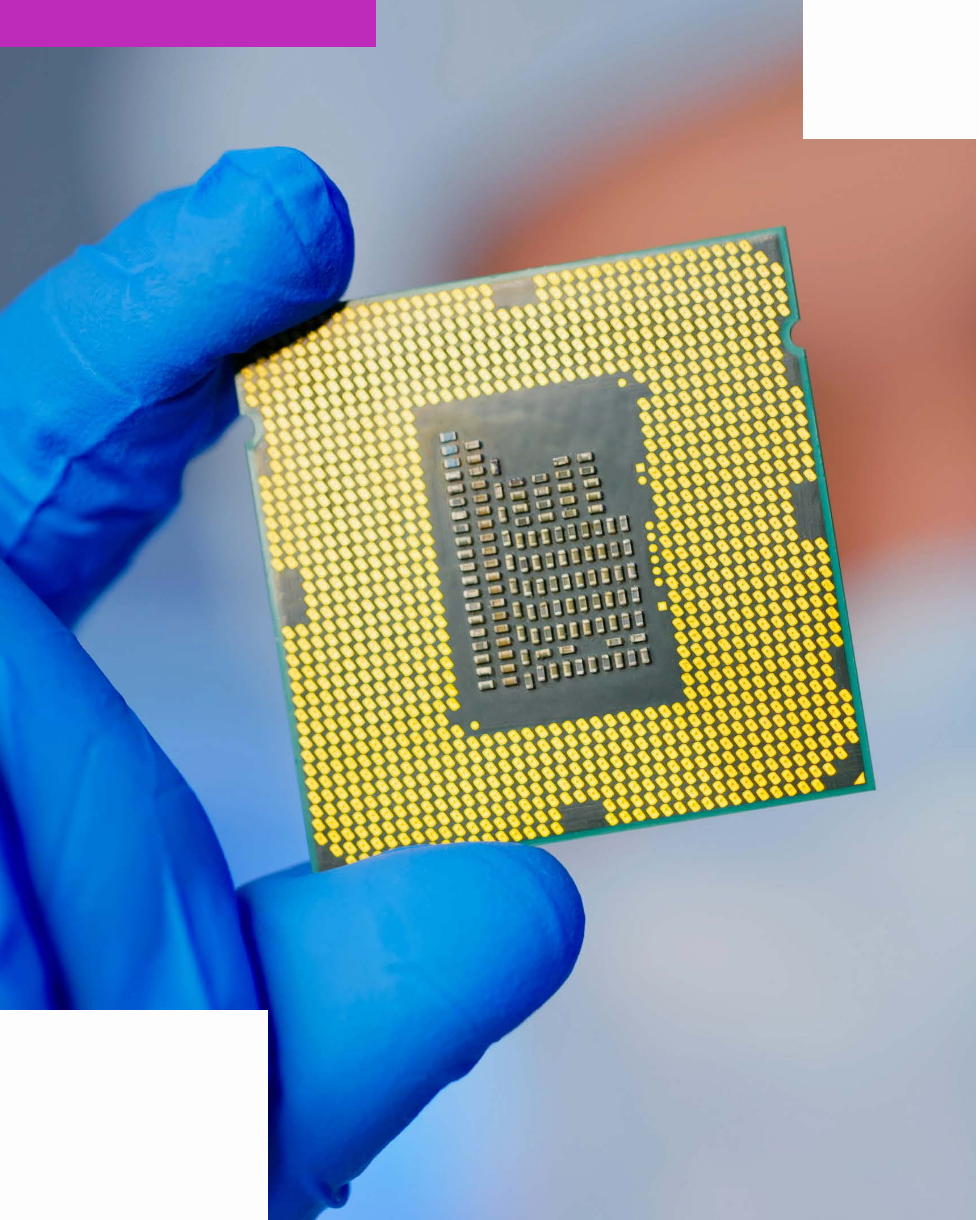
Taking aluminium alloys as an example inducing work hardening can result in different degrees of strain hardening (see table on p34), depending on the heat treatments applied, aluminium-magnesium alloy composite, how pure the aluminium is, and the solid state of the solution dispersed in the hardening process.

Work hardening for aluminium alloys can be plotted as functions of two properties, these being true stress and true strain, which in engineering terms are parabolic, and can be described as:

$$\sigma = k\varepsilon n \qquad (1)$$

where σ is the true stress, k is the stress at unit strain, ε is the true strain, and n is the strain-hardening exponent.

Alloys that are non-heat treatable can present initially in two state conditions: cold worked or hot worked and can have rates of strain hardening much lower than materials in annealed temper.



Temper designations for strain-hardened alloys.

(Total Materia, 2007)

Temper	Description
F	As fabricated. No control over the amount of strain hardening; no mechanical property limits.
O	Annealed, recrystallised. Temper with the lowest strength and greatest ductility.
H1	Strain hardened. H12, H14, H16, H18. The degree of strain hardening is indicated by the second digit and varies from quarter-hard (H12) to full-hard (H18), which is produced with approximately 75% reduction in area. H19. An extra-hard temper for products with substantially higher strengths and greater strain hardening than obtained with the H18 temper.
H2	Strain hardened and partially annealed. H22, H24, H26, H28. Tempers ranging from quarter-hard to full- hard obtained by partial annealing of cold worked materials with strengths initially greater than desired.
H3	Strain hardened and stabilised. H32, H34, H36, H38. Tempers for age-softening aluminium-magnesium alloys that are strain hardened and then heated at a low temperature to increase ductility and stabilise mechanical properties.
H112	Strain hardened during fabrication. No special control over the amount of strain hardening but requires mechanical testing and meets minimum mechanical properties.
H321	Strain hardened during fabrication. Amount of strain hardening con- trolled during hot and cold working.
H321	Strain hardened during fabrication. Amount of strain hardening con- trolled during hot and cold working.
H323, H343	Special strain hardened, corrosion-resistant tempers for aluminium- magnesium alloys.

For cold worked tempers, there is a difference caused by the strain required to produce such a temper. If this strain happens to equal ε0, then equation 1 becomes:

$$\sigma = k(\varepsilon 0 + \varepsilon)n \quad (2)$$

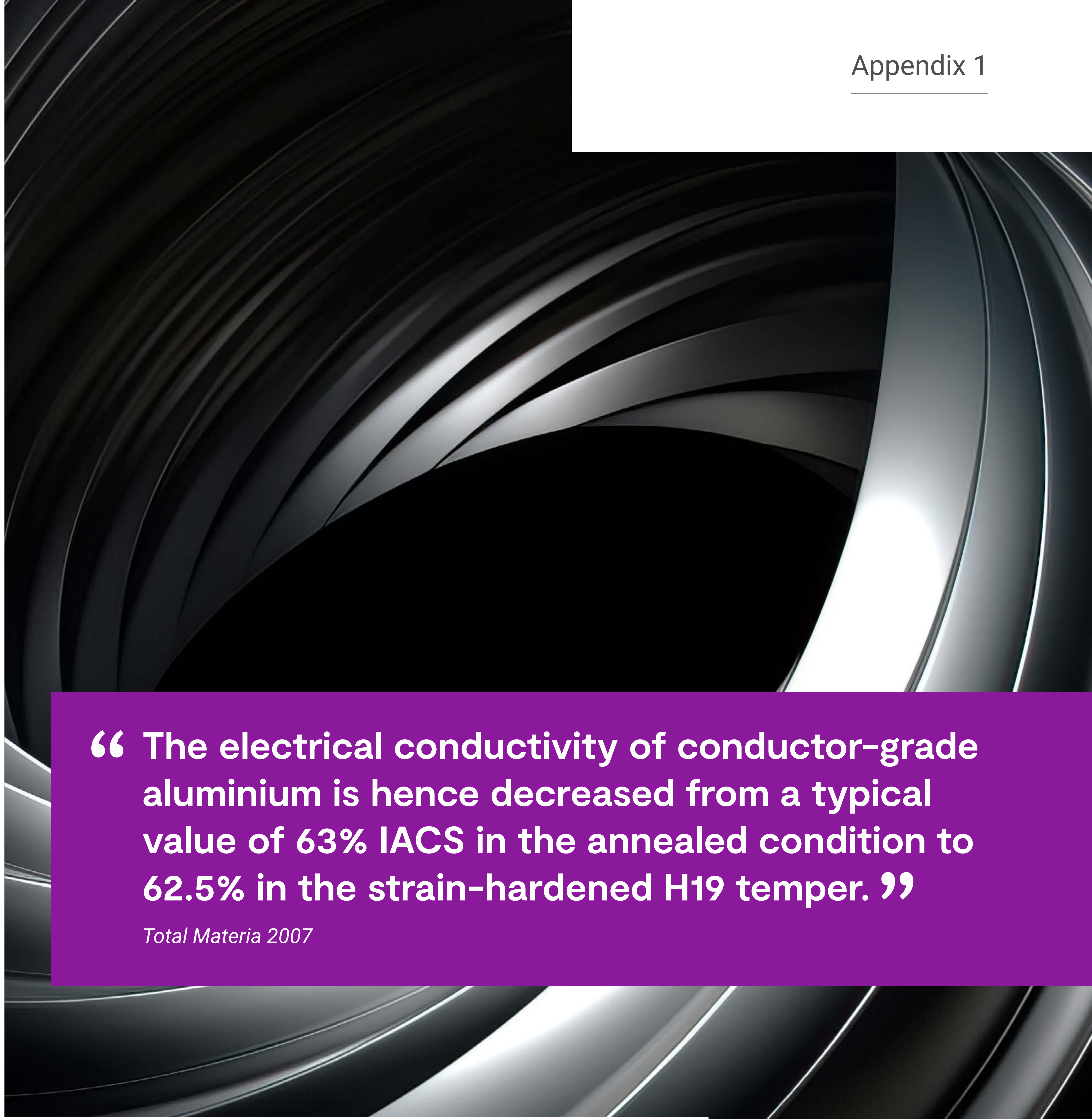
Similarly, products that undergo hot working conditions would face a similar strain and have similar outcomes, with the resulting strain assumed to be equivalent to that achieved by cold worked alloys.

Work hardening characteristics for aluminium alloys are said to vary considerably with temperature, where for example at cryogenic temperatures the strain hardening is much greater than at room temperature. This gain in strength by working at -195°C is about 40%, which also makes the material more brittle because of the significant reduction in ductility.

Work hardening characteristics of aluminium alloys at high temperatures can vary with temperature and strain rate, as rolling temperatures increase until about 700°C, with little effect on strain hardening at temperatures above that stated. The exact relationship between material strength and temperature is a variation of the method used, the amount of deformation caused, the time it underwent the work and at what temperature, and many other factors.

Both the physical and chemical properties of aluminium alloys are affected by strain hardening, but these changes can be quite small and only of academic research importance. However, changes to the resistance of stress induced corrosion of the alloys, and the effects of strain hardening, are of commercial importance.

Effects of strain hardening on aluminium's electrical conductivity are generally small and can be less than heat treatments applied on various aluminium alloys.



> **“The electrical conductivity of conductor-grade aluminium is hence decreased from a typical value of 63% IACS in the annealed condition to 62.5% in the strain-hardened H19 temper.”**
>
> *Total Materia 2007*

Appendix 2

Corrosion

Metals can also fall to potential failures due to corrosion, thermal expansion, and reactions to water. If water gains entry to the wiring/cable at any point due to storage, environment, accidental damage, or joint termination failures. For example, the reaction of water with aluminium could produce a chemical reaction: hydrogen gas ($2Al + 3H_2O \rightarrow 3H_2 + Al_2O_3$), and the effect on the aluminium conductor could lead to damage or structure failure of the insulation.

The table details the difference between rust and corrosion. An example of this is galvanic corrosion (bimetallic corrosion) that is an electrochemical process in which one metal corrodes in preference to another metal that is in the presence or in contact with an electrolyte. Two dissimilar metals immersed in a conductive solution, electrically connected, exploiting the primary cells to generate electrical voltage to power devices.

An example of galvanic corrosion can occur in galvanized iron, where a sheet of iron or steel covered with zinc coating is attacked, with the protective zinc coating breaking, the underlying steel remains unaltered/untouched/not affected, with the zinc being corroded because of it being a less noble metal.

Galvanic corrosion can occur on metals such as aluminium and copper when in contact with each other.

Difference between rust and corrosion.

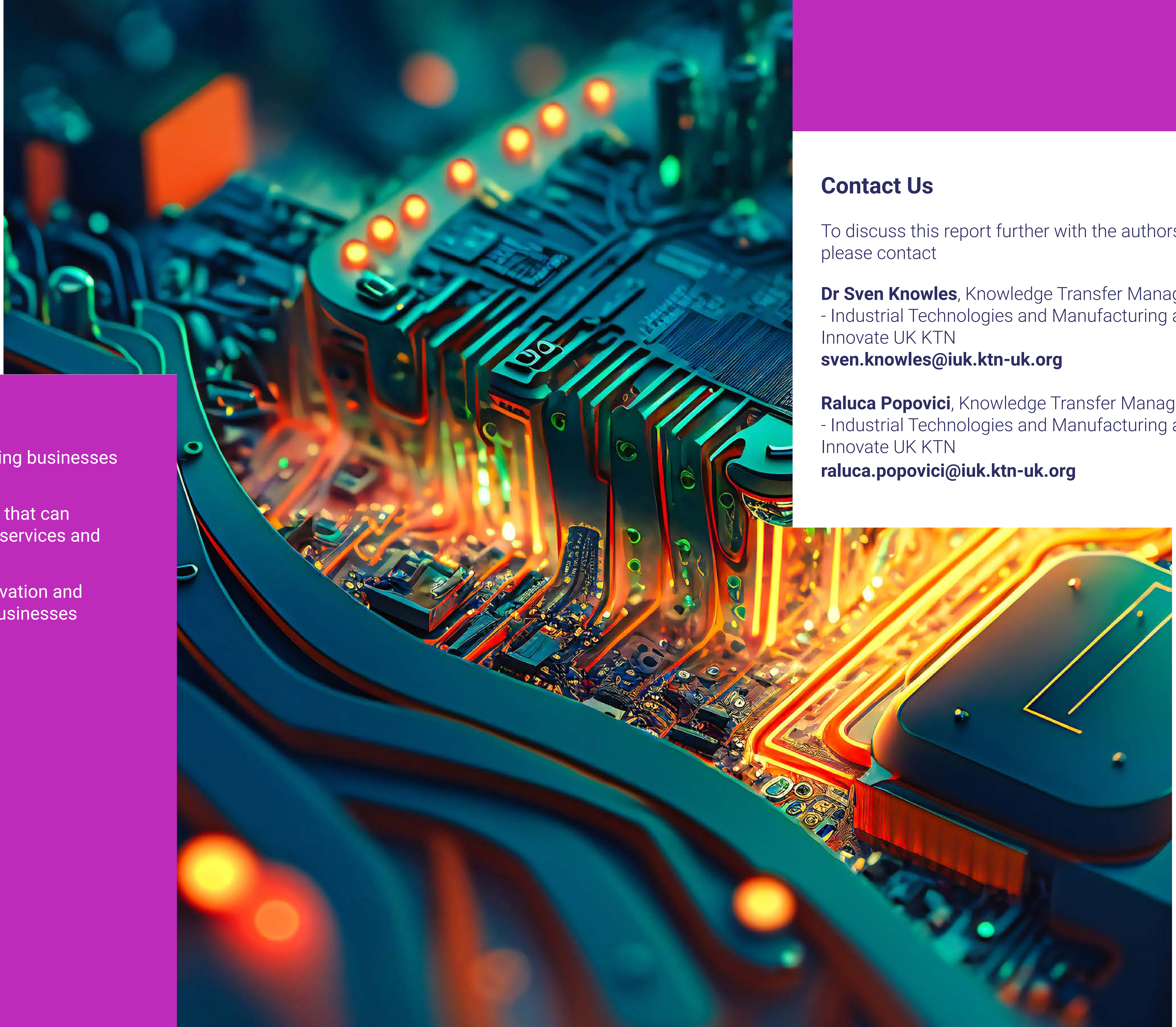
Corrosion	Rust
Corrosion is the process of deterioration of materials because of chemical, electrochemical or other reactions.	Rusting is a part of corrosion and is a chemical process which results in the formation of red or orange coating on the surface of metals.
Corrosion can occur on different surfaces such as skin, wood, metals, etc.	Rusting usually occurs on surfaces of iron and its alloys.
Corrosion can occur when the substance is exposed to air or chemicals.	Rusting mainly occurs when a metal is exposed to air and moisture.
Corrosion results in the formation of the oxides of metal or salts.	Only iron oxide is formed when rusting takes place.
Corrosion can occur in materials like polymers and ceramics and this type is known as degradation.	
Galvanic corrosion	

Delivered by
Innovate UK

Accessibility

To request copies of this report in large print or in a different format, please contact the Equality, Diversity and Inclusion team at UKRI:

01793 444000
equality@ukri.org



Contact Us

To discuss this report further with the authors, please contact

Dr Sven Knowles, Knowledge Transfer Manager - Industrial Technologies and Manufacturing at Innovate UK KTN
sven.knowles@iuk.ktn-uk.org

Raluca Popovici, Knowledge Transfer Manager - Industrial Technologies and Manufacturing at Innovate UK KTN
raluca.popovici@iuk.ktn-uk.org

Innovate UK drives productivity and economic growth by supporting businesses to develop and realise the potential of new ideas.

We connect businesses to the partners, customers and investors that can help them turn ideas into commercially successful products and services and business growth.

We fund business and research collaborations to accelerate innovation and drive business investment into R&D. Our support is available to businesses across all economic sectors, value chains and UK regions.

Innovate UK is part of UK Research and Innovation.
For more information visit innovateuk.ukri.org

Follow us

Telephone: 01793 361000
Email: support@iuk.ukri.org
innovateuk.ukri.org