UK Critical Minerals Intelligence Centre

A UK foresight study of materials in decarbonisation technologies: the case of electrolysers

Decarbonisation and Resource Management Programme

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A UK foresight study of materials in decarbonisation technologies: the case of electrolysers

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The UK Hydrogen Strategy highlights the critical role of hydrogen in the UK's net zero transition and sets out the ambition to have installed 5 GW of low-carbon hydrogen production capacity by 2030 (BEIS, 2021).

Beyond this, the UK National Grid Future Energy Scenarios (FES) forecast the annual demand for hydrogen in society may increase from currently close to zero to 446 TWh in 2050 in a 'System transformation' scenario, or 242 TWh in a 'Leading the way' scenario. The latter scenario assumes the highest proportion of green (electrolytic) hydrogen in the hydrogen mix, with 177 TWh annual demand of green hydrogen produced with electrolysis (National Grid, 2023a, b).

Achieving these ambitions will require a major scaling up of hydrogen production and decisions about different production methods. Hydrogen can be produced in different ways, but all methods require the input of either primary or secondary energy (fossil fuels, biomass or electricity) to drive a conversion process to generate hydrogen (Figure 1) (Shell & Wuppertal Institut, 2017).

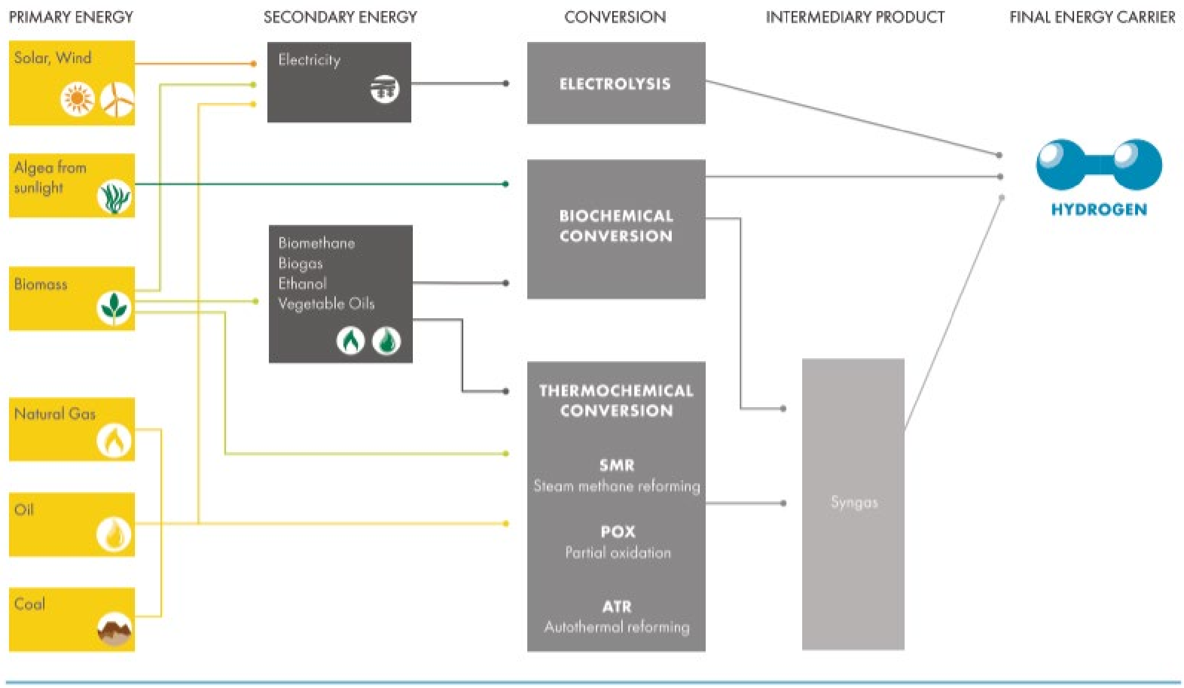


Figure 1 Different processes for producing hydrogen. From Shell & Wuppertal Institut (2017).

Electrolysis is the process of using electricity to break down water into hydrogen and oxygen. As the proportion of renewable electricity sources in energy supply increases, electrolysis offers an attractive approach to convert surplus electricity and water to low-carbon hydrogen (also referred to as 'green hydrogen'). This can then either be used directly or stored and subsequently converted to other types of energy carrier, thus offering different utilisation pathways (Shell & Wuppertal Institut, 2017).

1.1 PRINCIPLES OF OPERATION

An electrolyser consists of a direct current source and two electrodes (an anode and a cathode) coated with noble metals such as platinum (Pt). The two electrodes are separated by an electrolyte, which can be a liquid, such as potassium hydroxide (KOH) in the case of alkaline electrolysis, or a solid-state membrane, as in proton exchange membrane electrolysis. In alkaline electrolysis, the cathode loses electrons to the liquid and aqueous electrolyte solution, while the water (H_2O) is dissociated to form hydrogen (H_2) and hydroxide ions (OH^-) (Figure 2). (Shell & Wuppertal Institut, 2017).

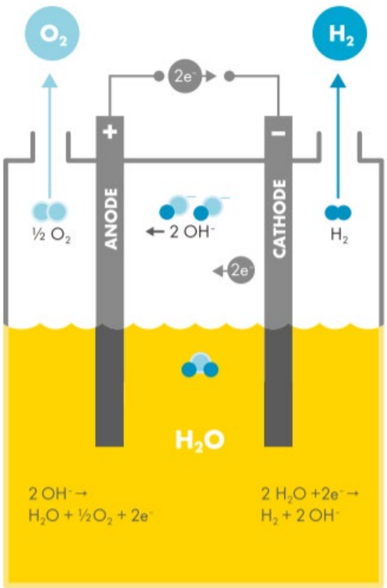


Figure 2 Principles of electrolysis. From Shell & Wuppertal Institut (2017).

There are four main types of electrolyser technology:

- alkaline electrolysers (AEL)
- proton exchange membrane (PEM) electrolysers
- solid oxide electrolyser cell (SOEC)
- anion exchange membrane electrolysers (AEM)

These are differentiated mainly by the type of electrolyte materials used and the temperature at which they operate (Figure 3). The electrolyser efficiency is measured in terms of the amount of electricity required to produce a specific quantity of hydrogen (Shell & Wuppertal Institut, 2017).

	Temperature °C	Electrolyte	Plant size		Efficiency	Purity H_2	System costs	Lifespan	Maturity level
Alkaline Electrolysis (AE)	60 – 80	Potassium-hydroxid	0.25 – 760 $Nm^3\ H_2/h$	1.8 – 5,300 kW	65 – 82%	99.5% – 99.9998%	1,000 – 1,200 €/kW	60,000 – 90,000 h	Commercially used in industry for the last 100 years
Proton Exchange Membrane Electrolysis (PEM)	60 – 80	Solid state membrane	0.01 – 240 $Nm^3\ H_2/h$	0.2 – 1,150 kW	65 – 78%	99.9% - 99.9999%	1,900 – 2,300 €/kW	20,000 – 60,000 h	Commercially used for medium and small applications (<300 kW)
Anion Exchange Membrane Electrolysis (AEM)	60 – 80	Polymer membrane	0.1 – 1 $Nm^3\ H_2/h$	0.7 – 4.5 kW	N/A	99.4%	N/A	N/A	Commercially available for limited applications
Solid Oxide Electrolysis (SOE)	700 – 900	Oxide ceramic	Until now at experimental stage in laboratories		85% (lab)	N/A	N/A	approx 1,000 h	Experimental stage

E4tech 2014; IEA 2015b; own diagram

Figure 3 Key features of different electrolyser types. From Shell & Wuppertal Institut (2017).

AELs and PEM electrolysers are the dominant electrolyser types installed globally. According to the IEA, almost 60 per cent of the total installed electrolysis capacity (687 MW) in 2022 was AEL and roughly 30 per cent was PEM, with the remaining 10 per cent other or unknown. Data for 2023 are expected to show an increased share for PEM, but with AEL remaining the dominant technology (IEA, n.d.). SOEC and AEM electrolysers are both nascent technologies, currently with limited commercial deployment (IEA, 2023, 2022a).

1.2 ESSENTIAL COMPONENTS AND MATERIALS

In this analysis, materials that contribute to the functionality of the various electrolyser types have been assessed where possible. The four electrolyser types differ in terms of the nature and size of their material requirements (Table 1).

1.2.1 Alkaline electrolysers

Alkaline electrolysis is a mature commercial technology that has been used in plants of various sizes since the 1920s. According to IEA (2022a), the largest AEL plants built today are around 10 MW, as larger plants have been shown to be uncompetitive against hydrogen produced from natural gas. The global manufacturing capacity for all electrolyser types was 8 GW/year in 2021 (IEA, 2022b) and is reported to have grown to 11 GW in 2023 (IEA, n.d.).

AELs account for 60 per cent of the global total manufacturing capacity for all electrolyser types in 2021. They are popular on account of their low capital costs, which is partly due to the fact that precious metals are not used in their manufacture. According to IEA (2022a), today's AELs use about 0.8 tonnes (t) of nickel (Ni) per MW. In addition to Ni, aluminium (Al), zirconium (Zr), steel, small quantities of cobalt (Co) and copper (Cu) catalysts are required for each AEL. A description of key materials used, identified material intensities and associated information sources is provided in Appendix A.

Table 1 Key component and material characteristics of the four water electrolyser types. Adapted from IRENA (2020).

Key characteristics		AEL	PEM	SOEC	AEM
Operating temperature		70 to 90°C	50 to 80°C	700 to 850°C	40 to 60°C
Operating pressure		1 to 30 bar	< 70 bar	1 bar	< 35 bar
Key component					
Electrolyte		KOH, 5 to 7 mol/L	PFSA membranes	YSZ	DVB polymer support with KOH or $NaHCO_3$ 1 mol/L^{-1}
Separator		ZrO_2 stabilised with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrolyte/ catalyst	oxygen side	Ni-coated perforated stainless steel	Iridium oxide	Perovskite-type (for example LSCF, LSM)	High surface area nickel or alloys
	hydrogen side	Ni-coated perforated stainless steel	Pt nanoparticles on C black	Ni/YSZ	High surface area Ni
Porous transport layer	anode	Ni mesh (not always present)	Pt-coated sintered porous Ti	Coarse Ni-mesh or foam	Ni foam
	cathode	Ni mesh	Sintered porous Ti or C cloth	None	Ni foam or C cloth
Bipolar plate	anode	Ni-coated stainless steel	Pt-coated Ti	None	Ni-coated stainless steel
	cathode	Ni-coated stainless steel	Au-coated Ti	Co-coated stainless steel	Ni-coated stainless steel
Frames and sealing		Structural elements are excluded from this analysis. See original source for details			

Note: coloured cells represent conditions or components that may vary significantly among different companies. PFSA: perfluoroacidsulfonic; PTFE: polytetrafluoroethylene; ETFE: ethylene tetrafluorethylene; PSF: poly(bisphenol-A sulfone); PSU: polysulfone; YSZ: yttria-stabilised zirconia; DVB: divinylbenzene; PPS: polyphenylene sulfide; LSCF: $La_{0.58}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$; LSM: $(La_{1-x}Sr_x)_{1-y}MnO_3$

Based on the identified information sources, Table 2 shows the AEL material intensities that have been used in the material demand analysis presented in this report.

Table 2 AEL material intensities that have been used in the material demand analysis.

Material	Present (kg/MW)	Future (kg/MW)
Nickel (Ni)	800	420
Zirconium (Zr)	100	100

1.2.2 Proton exchange membrane electrolysers

PEM electrolysers are physically smaller than AELs and are more flexible in operation (IEA, 2022a). They can respond rapidly to changes in power supply, enabling them to take advantage of low electricity prices, for example in renewable energy systems where supply and prices may vary over time (Rasmussen et al., 2019). PEM technology, however, is relatively immature compared to AEL, with shorter lifetimes and higher manufacturing costs. The scale of the largest PEM facilities is about 20 MW (IEA, 2022a).

In terms of capacity to produce PEM electrolysers, the global annual manufacturing capacity for PEM reached almost 40 per cent of the 8 GW global capacity for all electrolyser types in 2021. Forecasts indicate that PEM electrolysers will account for 22 per cent of the 65 GW global manufacturing capacity in 2030, with AELs accounting for 64 per cent and SOEC electrolysers 4 per cent (IEA, 2022b). Key functional materials used in PEM electrolysers are Pt and iridium (Ir) based catalysts, which add significantly to their cost. Additional costs are incurred through the common use of Pt-coated titanium (Ti) in the bipolar plates. A description of key materials used, identified material intensities and associated information sources is provided in Appendix A.

Based on the identified information sources, Table 3 shows the PEM electrolyser material intensities that have been used in the material demand analysis presented in this report.

Table 3 PEM electrolyser material intensities that have been used in the material demand analysis.

Material	Present (kg/MW)	Future (kg/MW)
Iridium (Ir)	0.4	0.07
Platinum (Pt)	0.3	0.03
Titanium (Ti)	528	37

1.2.3 Solid oxide electrolysers

According to IEA (2022a), SOECs are still in development and have not yet reached commercial maturity. They have lower material costs and higher efficiencies than the established technologies, thus are considered to hold significant promise. However, they are unlikely to dominate the market before 2030 due to their early stage of development and considerable uncertainty surrounds developments after that time (IEA, 2022a).

A typical SOEC electrolyser requires Ni, Zr, lanthanum (La) and yttrium (Y) as key functional materials. A description of key materials used, identified material intensities and associated information sources is provided in Appendix A.

Based on the identified information sources, Table 4 shows the SOEC material intensities that have been used in the material demand analysis presented in this report.

Table 4 SOEC material intensities that have been used in the material demand analysis.

Material	Present (kg/MW)	Future (kg/MW)
Lanthanum (La)	20	10
Nickel (Ni)	175	10
Yttrium (Y)	5	2.5
Zirconium(Zr)	40	20

1.2.4 Anion exchange membrane electrolysers

AEM electrolysers are a relatively new technology that is not yet used commercially (IEA, 2023). They may be regarded as an evolution of AELs, as both use alkaline water. AEM electrolysers provide improved material performance and durability compared to AELs. As with SOECs, AEM electrolysers can operate both in an electrolytic cell and, in reverse, in a fuel cell to generate electricity (IEA, 2023). Ni is the main catalyst material used in AEMs, but there is little information available about the detailed material composition of the AEM cell (Price, 2023).

Table 5 The key materials used in the four electrolyser technologies. Further discussion of the materials found in each technology type, material intensities and materials excluded from the analysis is provided in Appendix A.

Technology	UK critical elements	Other
AEL	Cobalt (Co)	Nickel (Ni), zirconium (Zr), aluminium (Al), copper (Cu)
PEM	Platinum (Pt)	Titanium (Ti), iridium (Ir), gold (Au), ruthenium (Ru)
SOEC	Lanthanum (La), yttrium (Y), cobalt (Co), cerium (Ce)	Nickel (Ni), zirconium (Zr), manganese (Mn), strontium (Sr), Iron (Fe)
AEM	Cobalt (Co)	Nickel (Ni)*

* Ni is the primary catalyst material used in AEM electrolysers (Price, 2023). AEM electrolysers are excluded from the quantitative material demand analysis as they are not yet commercially deployed and limited bill of materials (BOM) data are available.

Elements in red are excluded from the analysis because they are used in structural components, or they are not used in the most common configuration of the technology, or no BOM data are identified, likely because only very small quantities are used.

2 Supply chain mapping of electrolysers

The electrolyser supply chain comprises the following main stages:

- raw material extraction
- material processing
- subcomponent and precursor material manufacturing
- component and product manufacturing
- material recovery at product end-of-life

(DOE, 2022)

This study focuses on the material supply chain leading up to product manufacturing. Post-use recovery of materials has not been included in the analysis.

Seven raw materials in the supply chain of electrolysers were selected for detailed mapping, based on the most common configurations of the different electrolyser types and material intensity data from the literature. Some intermediate steps in the electrolyser supply chain could not be analysed due to a lack of published data. The analysis focuses on the electrolyser cells (stack) and excludes the broader ‘balance of plant’ ancillary and infrastructure requirements such as power and water supply, water purification, hydrogen compression and processing (IRENA, 2020). Raw materials and intermediate products excluded from the analysis are listed in Appendix A.

Figure 4 shows the different stages of the electrolyser supply chain, the key material transformations that take place at each stage and the connections of these materials to the different technology types and their key functional components.

One of the seven materials analysed, Ir is a by-product of the extraction of other materials, mostly from Pt and palladium (Pd) mining and refining processes. Most Pt is derived from Pt-Pd ores mined in South Africa, although some is also a by-product of Ni mining, mostly in Russia (Gunn, 2014). Two of the seven materials are rare earth elements (REEs): La and Y. These are extracted from a variety of REE mineral ores that may contain both La and Y, as well as many of the other 17 known REEs (Wall, 2014).

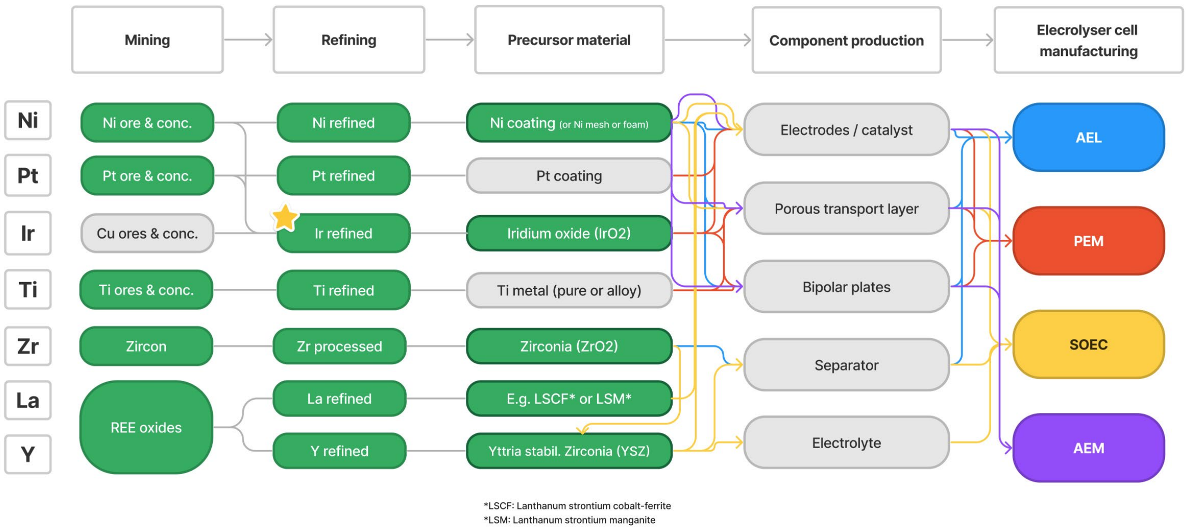


Figure 4 Simplified supply chain mapping of electrolysers, key raw materials and components. The material and component flows are based on IRENA (2020). The green shading indicates materials that have been included in the quantitative analysis of supply chain bottlenecks (production or trade concentration) or quantification of future material demand. Ni is included as a precursor material as it is expected to be mostly used in the form of the refined metal and data on refining concentration are available. Pt and Ti are also used mostly in refined metallic form; however, refining concentration data are not available. Other precursors requiring separate processing steps have not been quantified due to lack of data but are discussed qualitatively in the text. A star indicates a material produced as a by-product in the refining stage. Production data for La and Y is not available individually: they are included within total REE oxides to compare with forecast demand. BGS © UKRI.

3 Supply chain bottlenecks

Each electrolyser cell technology requires several highly specialised manufacturing stages involving the use of many raw materials. These materials, some of which are designated as critical to the UK, are derived from a wide variety of sources (Lusty et al., 2021). However, these material sources and the appropriate manufacturing infrastructure are restricted in their geographical distribution and in some cases limited to a few countries worldwide. This production concentration contributes to an increased risk of supply disruption at any stage within the supply chain.

An overview of the global production and trade concentrations for the analysed materials is provided in Figure 5.

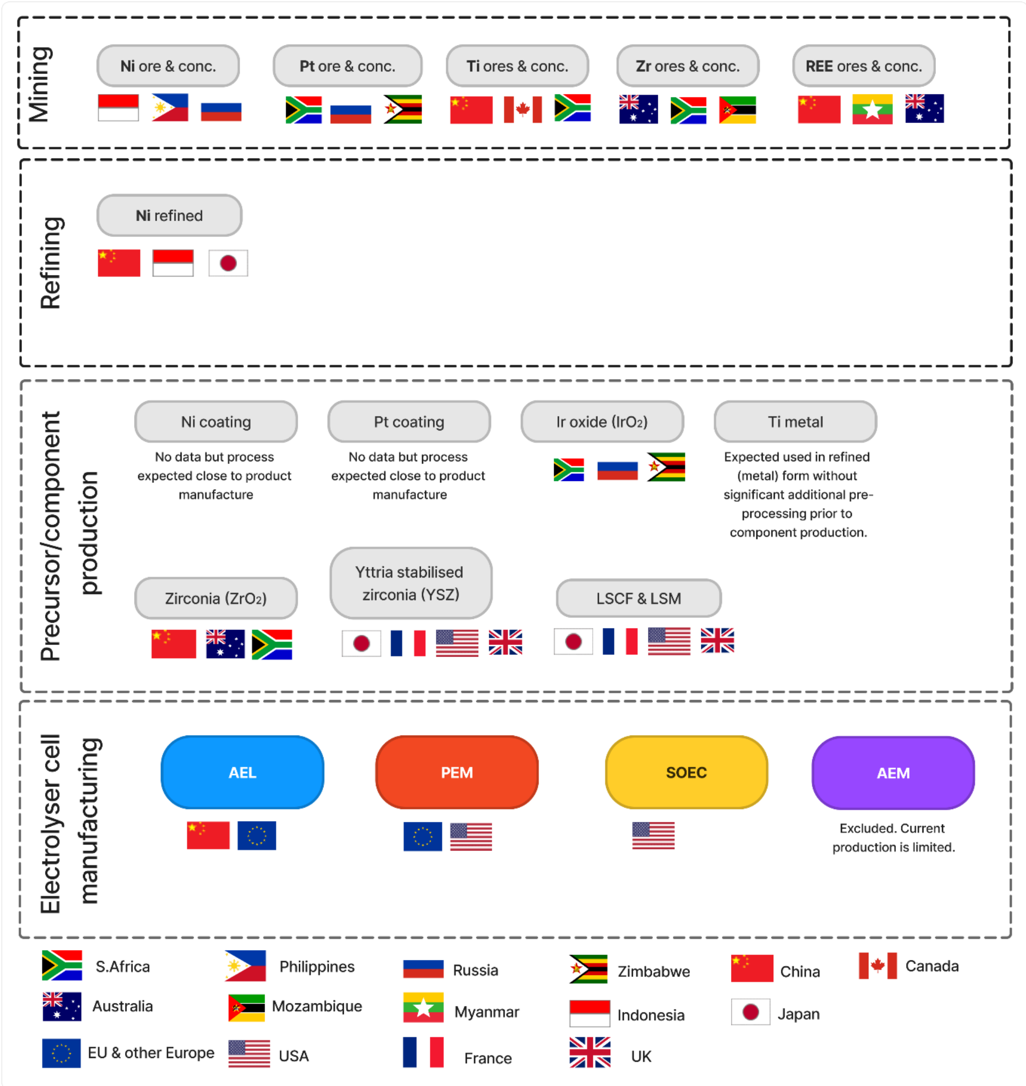


Figure 5 Geographical production concentration in the electrolyser cell supply chain. At the mining and refining stages, the national flags show the top three producers, from left to right, based on quantitative data from the BGS World Mineral Statistics Database (BGS, 2023). At the precursor/component production and electrolyser cell manufacturing stages, the flags highlight the location of selected key producers, but their order does not reflect their market share. (Data compiled and interpreted from numerous sources, including DataM Intelligence (2024); MWR (2023); Zircon-Association (2024) and several other company websites.) BGS © UKRI.

3.1 MINING AND REFINING

3.1.1 Production concentration

The global production share of key materials used in electrolyser technologies was calculated for the top three producing countries in the mining and refining stages of the supply chain.

The mining stage of the electrolyser supply chain is dominated by countries that are major producers of ores and concentrates of Ni, platinum group metals (PGMs) including Pt and Ir, Ti, zircon (ZrO_2) and REEs including Y and La.

The global production of Pt, Ir and REEs is highly concentrated, with 90 per cent of the global supply of each derived from three countries (Figure 6). The largest producer of Pt and Ir is South Africa (more than 70 per cent and 80 per cent, respectively). The second largest producer of Pt is Russia (12 per cent) and Zimbabwe (8 per cent) and the second largest producer of Ir is Zimbabwe (9 per cent), followed by Russia (less than 3 per cent). REE production is highly concentrated in China (70 per cent) and Myanmar (13 per cent). Australia is the third largest producer, with close to 7 per cent of global production. Zr production is also highly concentrated, with more than 70 per cent produced in Australia, South Africa and Mozambique. More than half (55 per cent) of Ni ore is mined in the top three producing countries, namely Indonesia, the Philippines and Russia. For Ti, the production concentration is somewhat lower, with approximately 50 per cent produced in three countries: China, Canada and South Africa.

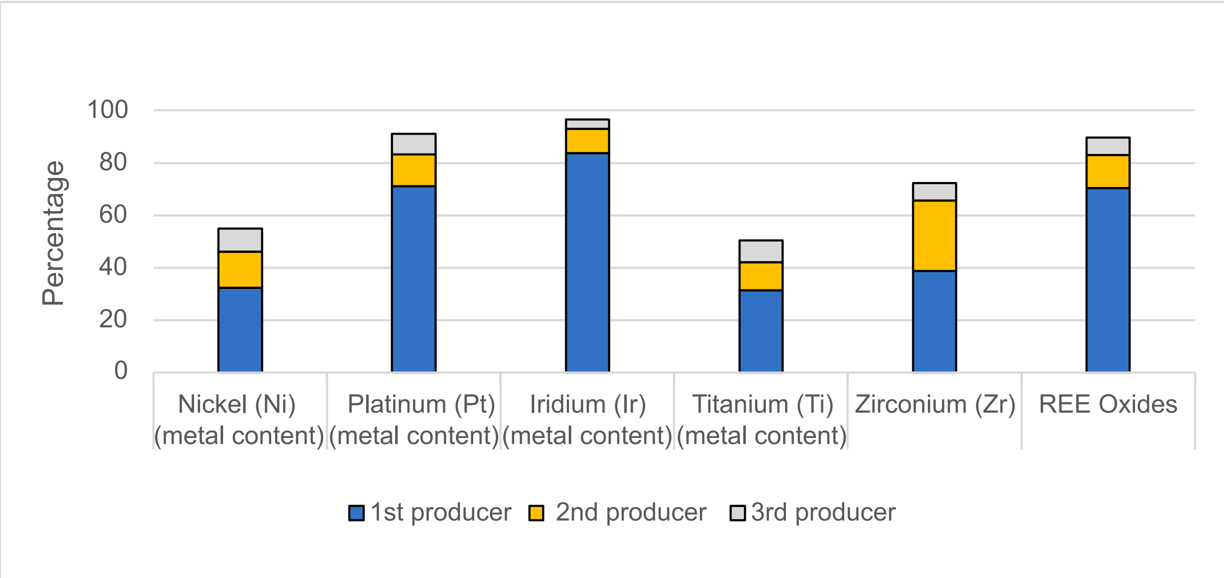


Figure 6 Global mine production of Ni, Pt, Ti, Zr and REOs showing the production shares of the top three producing countries (based on five-year production average). Data from the BGS World Mineral Statistics Database (BGS, 2023) except for Ir, which is based on USGS (2023). BGS © UKRI.

Refining stage data were only available for Ni, not for any of the other elements evaluated. Ni refining is concentrated in three countries (China, Indonesia and Japan) that together account for nearly 60 per cent of global production.

Ir is a scarce but fundamentally important material in the PEM electrolyser supply chain. The average annual global production between 2017 and 2021 was 7.7 t according to USGS (2023). Ir is produced mainly as a by-product of the extraction of other metals, in particular Ni, Pt and Pd. Consequently, the primary supply of Ir is derived from countries that produce these metals. This dependence on the mining of Pt means that continued Pt demand and investment in mining is required to secure the future supply of Ir (Johnson Matthey, 2023). It has been estimated that approximately 2000 t of Ir are available in known global mineral resources for which data for Ir grades exist (Mudd, 2023).

The two REEs Y and La could not be evaluated independently due to lack of data. Instead, the global production concentration for REE oxides (REOs) has been used as an indicator for these elements. Although production data for the individual REEs are unavailable, work conducted by BGS focusing on the geochemical signature of REE deposits indicates that global mine production consists of approximately 15 per cent neodymium (Nd), 5 per cent praseodymium (Pr), 1 per cent dysprosium (Dy) and 0.1 per cent terbium (Tb) by mass. In contrast, the mass of contained cerium (Ce) and La is about 25 to 43 per cent. This highlights an additional challenge in mine supply, as not all deposits contain viable economic concentrations of all the REEs. Many deposits are rich in Ce and La, but have lower concentrations of Dy, Nd, Pr and Tb.

Ranked production concentration scores based on the indicator recommended in the revised methodology for UK criticality assessment (Josso et al., 2023) are shown in Figure 7. These are derived from the production shares of the leading producers modified by a factor that reflects the environmental, social and governance (ESG) performance of those countries.

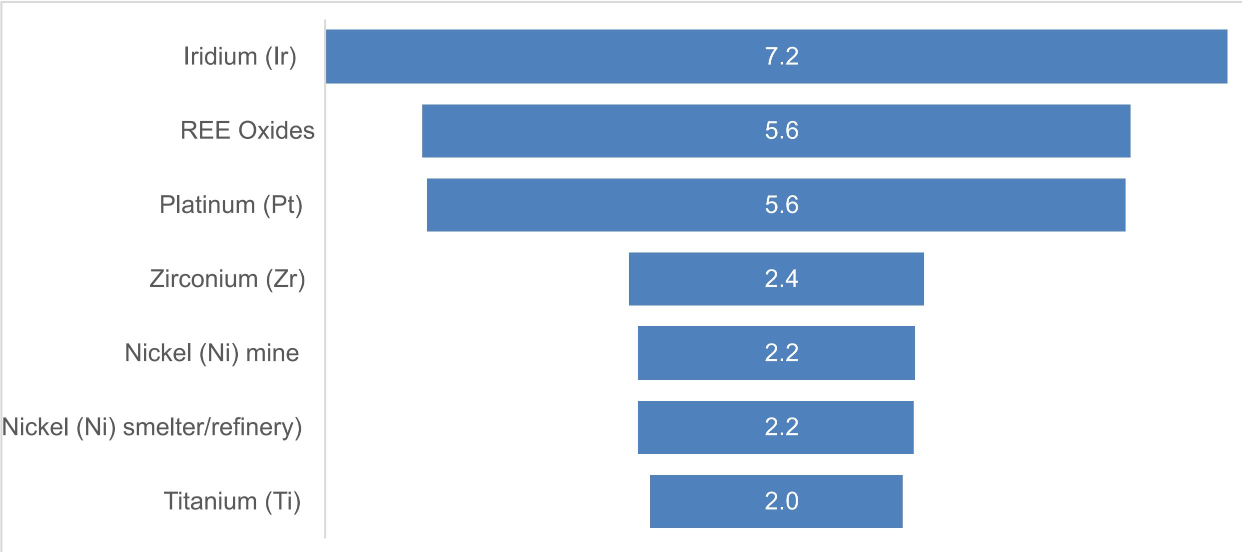


Figure 7 Ranked production concentration scores (1 to 10) for key metals (mined and refined) used in electrolyser technologies, based on ESG-weighted Herfindahl-Hirschman index for each of the top three producing countries. Ir, REOs and Pt are of greatest concern as these are highly concentrated in countries with relatively poor ESG scores. BGS © UKRI.

Based on this analysis, the materials of greatest concern are Ir, REOs and Pt. Mining of REOs is highly concentrated in China and Myanmar, both of which have poor ESG scores. Pt and Ir extraction is highly concentrated in South Africa, Russia and Zimbabwe, which also have poor ESG scores. The top mine producer of Zr is Australia, which has a relatively good ESG score. This serves to counteract the relatively poor ESG scores of the second and third largest Zr producers (South Africa and Mozambique, respectively). Mining and refining of Ni are generally less geographically concentrated, hence the relatively poor ESG scores of the top producers carry less weight and the associated supply risk for Ni is therefore relatively low. Similar considerations apply to the supply of Ti ores and concentrates.

Although the production of Ir and Pt is concentrated in countries with poor ESG scores, Johnson Matthey (2023) notes that PGM mining and refining is concentrated with a few large and publicly quoted companies that are subject to stringent regulation and regularly report on their ESG performances. Despite their location and challenging operational environment, for example due to unstable energy supply, outputs from the operations have been resilient for over two decades.

3.1.2 Global trade concentration and trade restrictions

As with the production of mined and refined materials used in electrolyser technologies, their trade is also geographically concentrated. In addition, trade in some materials is subject to restrictions imposed by trading nations, which can have significant effects on security of supply.

Trade concentration is calculated from import and export data derived from the UN Comtrade database for the period 2017 to 2021 (UN Comtrade, 2023). For mined minerals, data are available for Ni, Ti and Zr; for refined materials, data are available for Ni, Ti, Zr, Pt, REOs and REE metals. Data for refined Ir are not available separately; rather, it is included within aggregated data for refined Ir, osmium (Os) and ruthenium (Ru). Similarly, no data are available for the individual REEs Y and La: they are included within broader Harmonized System (HS) trade codes for REOs and REE metals, respectively. Refined Zr has been included, although it is uncertain if it only includes refined zirconium in metallic form or if it also includes the ceramic zirconia, which is the compound used in electrolysers. An overview of the materials and their respective HS codes is provided in Table 6.

Table 6 Elements and compounds included in the analysis of trade concentrations (based on UN Comtrade data) and their respective HS codes.

Material	HS code	HS code description of corresponding traded form
Nickel (Ni)	260400	Nickel ores and concentrates
Titanium (Ti)	261400	Titanium ores and concentrates
Zirconium (Zr)	261510	Zirconium ores and concentrates
REE oxides (refined)	284690	Compounds, inorganic/organic, of rare-earth metals/yttrium/scandium/mixtures of these metals, other than cerium comps.
REE metals (refined)	280530	Rare-earth metals, scandium and yttrium, whether or not intermixed or interalloyed
Nickel (Ni) refined	750210	Nickel; unwrought, not alloyed
Titanium (Ti) refined	810820	Titanium; unwrought, powders
Platinum (Pt) refined	711011	Metals; platinum, unwrought or in powder form
Iridium (Ir) refined	711041	Metals; iridium, osmium, ruthenium, unwrought or in powder form
Zirconium (Zr) refined	810920	Zirconium; unwrought, powders

An overview of the trade concentrations for the mined materials is provided in Figure 8. China is by far the largest net importer of mined Ni, with 83 per cent of the global total; 95 per cent of the total is accounted for by three countries. The largest net exporters of mined Ni are the Philippines (65 per cent) and Indonesia (21 per cent), which are also the largest producers. Both countries impose restrictions on the export of mined Ni, the Philippines in the form of a fiscal tax and Indonesia in the form of export prohibition (OECD, 2022a, b).

Trade in mined Ti is less concentrated, with 57 per cent of net imports in China (34 per cent), USA (13 per cent) and Germany (10 per cent) and 53 per cent of net exports from the top three countries (Mozambique, South Africa and Ukraine, respectively).

China is by far the largest importer of mined Zr minerals with 64 per cent of the global total, followed by Spain (7 per cent) and India (5 per cent). The top three exporting countries for Zr minerals account for 53 per cent of the global total, with South Africa the largest (33 per cent), followed by Mozambique (10 per cent) and Senegal (9 per cent). Senegal applies export restrictions in the form of a fiscal tax on exports equivalent to 3 per cent of the sales price.

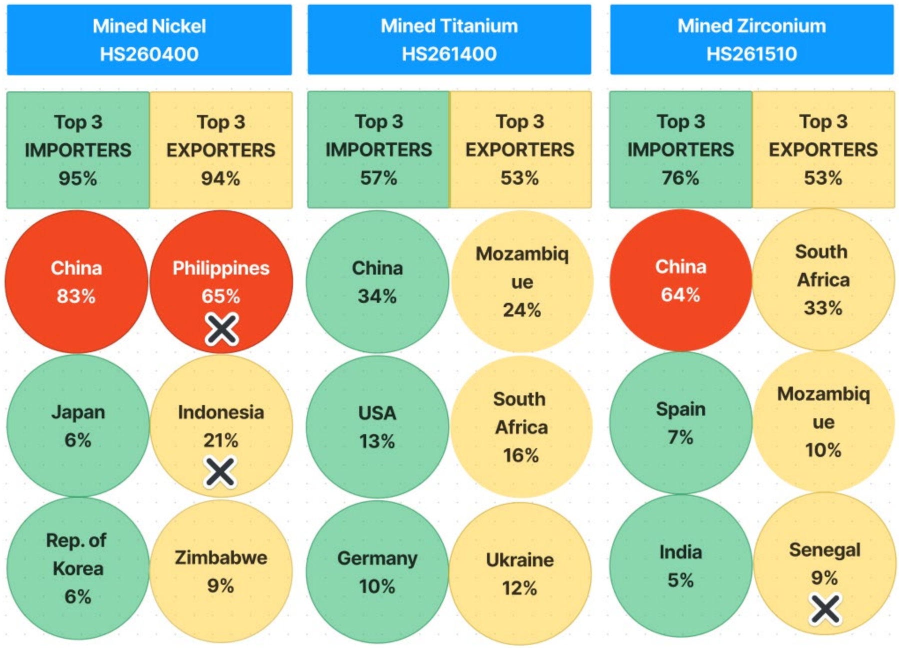


Figure 8 The top three net importing and exporting countries for mined (ores and concentrates) materials of relevance to electrolyser supply chains, showing each country's share of total global trade flows. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent), whilst countries with a cross have active trade restrictions. Data on trade flows compiled from UN Comtrade (2023) based on 2017 to 2021 data, and active trade restrictions based on OECD (2022a) and associated dataset OECD (2022b) for the year 2021. BGS © UKRI.

An overview of the trade concentrations for the refined materials is provided in Figure 9. Imports of refined Ni are less concentrated than for mined Ni ores. China is the largest single importer of refined Ni with 26 per cent of global imports, followed by the USA (10 per cent) and Germany (8 per cent). One of the main reasons why China is the largest importer is that it is the world's largest producer of steel, which is the main use of Ni (Elshkaki et al., 2017). The largest exporters of refined Ni are Russia (18 per cent), Canada (17 per cent) and Norway (14 per cent).

Imports of refined Ti are moderately concentrated, with 35 per cent of total net imports accounted for by three countries (USA, UK and South Korea). Japan is the largest net exporter of refined Ti (31 per cent), followed by Kazakhstan (18 per cent) and Ukraine (6 per cent).

The largest importers of refined Zr are the USA, France and Malaysia, together accounting for 49 per cent of the global total. The dominant net exporter of refined Zr is South Africa, with 45 per cent of global exports, followed by China (7 per cent) and 'other Asian' countries (8 per cent).

Trade in refined Pt is also moderately concentrated, with 31 per cent of global imports and 25 per cent of exports accounted for by three countries. The largest importer of Pt is China (16 per cent) and the largest exporter is Italy (10 per cent). Exports from Russia and South Africa, the second and third largest net Pt exporters, are both subject to trade restrictions. Russia has several restrictions depending on the exact type of export, including domestic market obligation, licencing requirements and restrictions on customs clearance point for exports. South Africa applies a licencing requirement in the form of a requirement for export approval from the South African Diamond and Precious Metal Regulator (OECD, 2022a, b).

Figure 9 The top three net importing and exporting countries for refined materials of relevance for electrolyser supply chains, showing each country's respective share of total global trade flows. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent), while countries with a cross have active trade restrictions. Data on trade flows compiled from UN Comtrade (2023) based on 2017 to 2021 data and active trade restrictions based on OECD (2022a) and associated dataset (OECD, 2022b) for the year 2021. BGS © UKRI.

Japan, the USA and China together account for 44 per cent of aggregated Ir, Os and Ru imports (three of the six PGMs), although the proportion of Ir within this total is not known. South Africa is the dominant exporting nation, with 29 per cent of global exports, followed by Belgium (11 per cent) and Germany (9 per cent)[1]. South Africa has export restrictions related to Ir, Os and Ru in the form of licencing requirements.

Two trade categories are shown for refined REE: one for refined compounds (REOs) (HS284690) and one for REE metals (HS280530). HS284690 represents the separation stage of refining before refined metal production.

The trade of refined (separated) REE compounds is moderately concentrated with the top three exporting nations (USA, Malaysia and Russia) accounting for 54 per cent of the global total. Of

[1] UN Comtrade data erroneously indicated Thailand as the largest exporter of Ir, Os and Ru based on a very large export year in 2017 (and none in the following years) resulting in a high five-year average. This data point was removed and is not reflected here.

these, the USA is the single largest exporter, accounting for 30 per cent of the global total. Imports of REE compounds are less concentrated, with the top three importers (China, Germany and Japan) accounting for only 28 per cent of the global total. Even though a significant amount of REE refining capacity exists in China, it does not appear as a top exporter of REE compounds. This is likely due to domestic consumption of these materials to manufacture magnets and refined REE metals, of which China is a major global exporter. Trade in refined REE metals is therefore highly concentrated, with China the largest and dominant exporter with 71 per cent of global exports, followed by Vietnam with 7 per cent. Japan is the dominant importer of REE metals, with 63 per cent of global imports, followed by Norway and India, each with 5 per cent.

It should be noted that trade data for Malaysia for refined REE metals have been excluded from the analysis, as it appears the reported trade data actually represent imports of REE mineral concentrates from Australia, not refined metals.

The key points derived from the analysis of the global trade in materials required for electrolyser technologies are:

- China is the largest net importing country for all the mined materials evaluated (Ni, Ti, Zr and REEs) and, of these, Ni and Zr imports are most concentrated in China
- of the mined materials, imports and exports of mined Ni are the most concentrated globally, with China and the Philippines dominating net imports and exports, respectively
- South Africa and Mozambique are important exporting countries for mined Ti and Zr
- trade in refined materials is generally less concentrated than for mined products, with only export of refined Zr from South Africa exceeding 45 per cent of the global total
- where trade restrictions are imposed, they are almost always applied to exports, with the most common restrictions being licence agreements or export taxes
- it is difficult to assess the direct impact of a particular trade restriction as this will depend on its type, magnitude, and duration. Imposition of a trade embargo or quota is likely to have a greater impact than levying an export tax for a short period. The dynamic character of export restrictions also contributes additional uncertainty to the supply chain
- the most significant risk to supply is where global trade is dominated by a few countries (for example, China accounts for 83 per cent of global imports of mined Ni and 64 per cent of mined Zr) and the risk may increase if restrictions are applied to trade

3.2 COMPONENT AND PRODUCT MANUFACTURE

It is difficult, or in some cases impossible, to acquire quantitative data at a national scale for component and product manufacture. Generally, only qualitative data are available for the main manufacturing countries. However, the geographical concentration pattern appears to change in the midstream of the electrolyser value chain (precursors, components and product assembly), with companies from western countries, such as Europe and the USA, having a larger role than in the mining and refining stages. This is confirmed by IRENA (2020), which contains a list of the key players involved in the manufacturing of water electrolyser systems globally and their manufacturing sites (see Appendix B). Many of the locations are in Europe, the USA, Australia and Japan. Three Chinese players are listed, all with focus on AEL manufacturing.

IEA (2023) provides an insight into the potential geographical concentration of future electrolyser manufacturing. The electrolyser landscape is still characterised by competition between several technology families of varying levels of maturity, with no single design currently dominating the market. It also provides a geographical overview of current and planned electrolyser manufacturing capacities for different types of electrolysers (Figure 10), which indicates that alkaline electrolysis can be expected to remain the dominant technology up to

2025. However, investment in the manufacturing capacity of PEM electrolysers and SOECs is taking off, based on patenting activities in the period 2011 to 2020 (IEA, 2023).

As shown in Figure 10, about half of current AEL manufacturing capacity is located in China, with the rest in Europe. Planned AEL expansion capacity will increase Europe's share to about two-thirds of the global total by 2025, with about one-third in China and a small amount in Japan. For PEM electrolysers, the USA is likely to become the dominant manufacturer, with about half of planned manufacturing capacity, and approximately 40 per cent in Europe. For SOECs, the planned manufacturing capacity is likely to be mostly located in Europe (about 70 per cent) with the remainder in the USA. AEM electrolyser technology remains to be proven commercially. Any manufacturing capacity is likely to be installed in the EU but is likely to be on a small scale within the timeframe of this study.

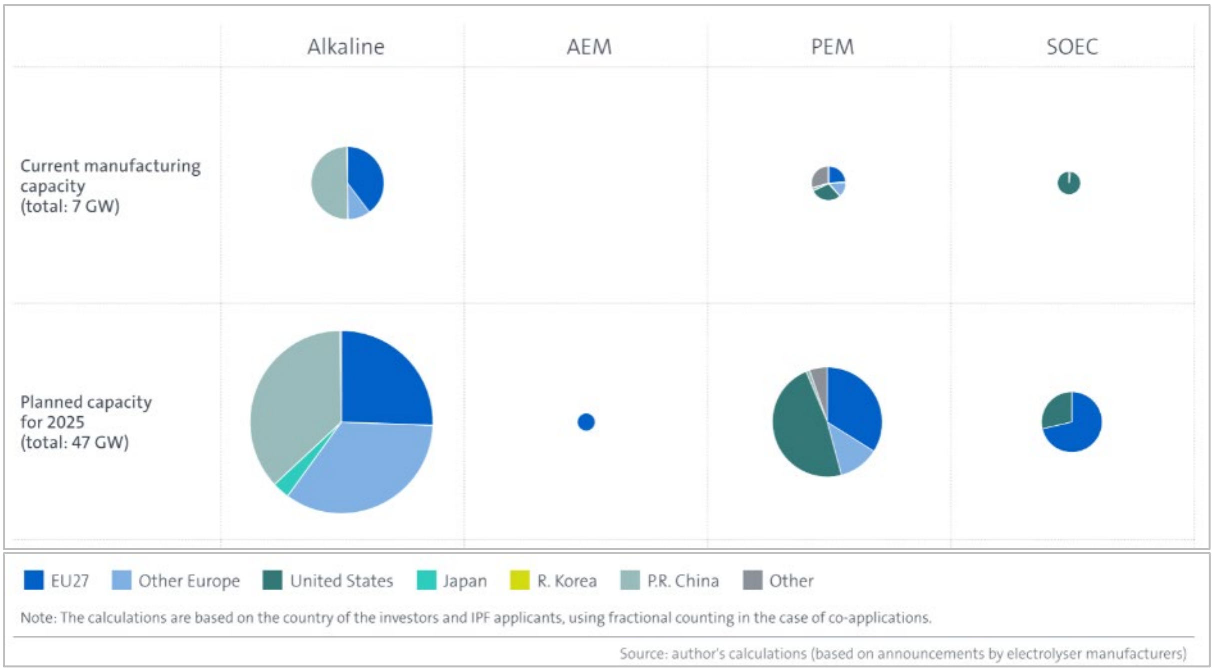


Figure 10 Current and planned manufacturing capacity related to electrolysers. From IEA (2023).

Based on company announcements, the global manufacturing capacity for electrolysers could exceed 130 GW per year by 2030 (IEA, 2023). Europe and China are expected to lead this growth, with each having about 20 per cent of the total. However, only 10 per cent of plans have reached a final investment decision and 25 per cent have no specified location. There is therefore still substantial uncertainty about the development of future electrolyser manufacturing capacity (IEA, n.d.).

There is limited readily available information about the overall electrolyser industry structure and level of integration in the value chain. However, a study by the US Department of Energy found that the PEM industry (for electrolysers and fuel cells) is largely made up of a small number of suppliers, many of which are large companies (including 3M, Dupont and Cummins) where fuel cell or electrolysers comprise a small proportion of their business. Some of the larger manufacturers produce most of the subcomponents (electrolyte; gas diffusion layer; bipolar plates) whereas others produce one or two components in-house. In the SOEC value chain, it is reported that the production of processed materials, subcomponents and end products is currently dominated by a small number of commercial developers, with the same companies that develop the electrolyser or fuel cell stack and system often importing key materials and generating processed (precursor) materials (DOE, 2022).

Many of the players listed in Appendix B are understood to be active in both component manufacturing and subsequent electrolyser stack manufacturing. Given the growing maturity and large projected growth in electrolyser manufacturing, Wood Mackenzie (2023) expects significant changes in the industry. These may include:

- consolidation of players and technologies
- increased product segmentation and standardisation
- evolution of business models with either high or low levels of vertical integration
- a value chain that is largely 'electrode-centric', which is likely to be vital

In relation to key precursor materials, iridium oxide (IrO_2), which is used as a catalyst in PEM electrodes, is produced from refined Ir metal through a chemical oxidation process. The production of Ir and Ir-based products is a niche market often handled by companies active in other PGM processing. While details of IrO_2 manufacturing are not readily available, key players active in PGM mining and refining as well as further PGM processing include:

- Anglo American Platinum Ltd. (South Africa)
- Sibanye Stillwater (South Africa)
- Norilsk Nickel Group (Russia)
- Zimplats Holdings Ltd (Zimbabwe)

(DataM Intelligence, 2024)

Many PGM-processing companies are in South Africa, which is the largest producer of PGMs with over 70 per cent of global mined production (BGS, 2023).

Zirconia (ZrO_2) is a ceramic compound derived from the mineral zircon via chemical processing (Zircon-Association, 2024). The global production of ZrO_2 is closely tied to the mining and processing of zircon, which is highly concentrated in Australia and South Africa. China imports a significant amount of zircon sand and has become a leading processor of zircon and a major producer of ZrO_2 and other Zr chemicals (Zircon-Association, 2024).

Specialised precursor materials include yttria-stabilised zirconia (YSZ), an electrolyte material used in SOEC. YSZ is produced from ZrO_2 and yttria (Y_2O_3) and is typically manufactured by companies specialised in advanced ceramics technologies. The YSZ market and manufacturing are understood to be relatively diverse with key players distributed globally. Examples include:

- Tosoh Group (Japan)
- Saint-Gobain Group (French multinational)
- 3M (American multinational)
- Dyson Technical Ceramics (UK based, part of the Dyson group)
- CeramTec (Germany)

(MWR, 2023)

Other specialised precursor ceramics used in certain SOECs include lanthanum-strontium-cobalt ferrite (LSCF) and lanthanum-strontium manganite (LSM). Both compounds are advanced ceramics used for their electrochemical properties. Some of the companies that manufacture YSZ also manufacture LSCF and LSM.

4 UK supply chain related to electrolysers

The UK has an ambition to become a world leader in the production of green hydrogen from electrolysis (BEIS, 2021; Hydrogen UK, 2023). The UK has no presence in the mining and refining of the key functional materials used for electrolysers, but is active at a relatively small scale in the component and assembly stages of the electrolyser supply chain.

ITM Power is a leading manufacturer of PEM electrolysers, with a global presence. It operates a semi-automated, 1 GW/year capacity factory in Sheffield. This is one of the largest operations of its kind in the world (Hydrogen UK, 2023; hydrogenfuelnews.com, 2019).

There are several other UK-based companies active in the manufacture and supply of electrolysers or electrolyser components, although most of these are understood to operate at a small scale. A report published by BEIS on 'Supply chains to support a hydrogen economy' (Wood & Optimat, 2022) states that, globally, there are approximately 20 suppliers of commercially available AELs or PEM electrolysers working at industrial scale, but only one of these (ITM Power) is UK based. The report also finds that investment in electrolyser manufacturing capacity in the UK is extremely minimal and there is a risk of the UK being outcompeted by European and other countries in capturing shares of the electrolyser supply chain, noting that 55 per cent of current electrolyser manufacturing is in China. Based on this and given the UK's green hydrogen ambitions, further expansion of electrolyser manufacturing in the UK is found to be justified (Hydrogen UK, 2023).

Other companies active in the UK electrolyser supply chain include (Wood & Optimat, 2022):

- Ceres: a West Sussex-based clean-energy technology company with a global presence, which specialises in developing SOECs to produce green hydrogen and solid oxide fuel cells
- Clean Power Hydrogen Group (CPH2): active in the development of an alternative PEM technology called the Membrane-Free Electrolyser™
- Supercritical Solutions: active in the development of membrane-free high-pressure electrolysers, reported to use only mass-produced industrial metals (no REE metals or Ir)

Hydrogen UK has estimated that the UK electrolyser supply chain, of which manufacturing of electrolysers and components would be a part, could be worth up to £5 billion by 2030 and £30 billion by 2050 (Hydrogen UK, 2023). They recommend that efforts be made to further invest in domestic manufacturing of electrolyser stacks to lower the cost of hydrogen in the UK and create high-value jobs, stating: '…the UK has shown its potential for manufacturing electrolysers, with companies such as ITM Power, however, without short term action could lose out to demand for electrolysers from abroad and simultaneously rely on imported electrolyser stacks.' (Hydrogen UK, 2023).

The Scottish government has commissioned work to support the deployment of a strong electrolyser supply chain in Scotland, analysing the electrolyser-related supply chain opportunities, strengths, weaknesses and threats (Scottish Government, 2023). It states that previous (2020) Scottish hydrogen assessments had identified the relative immaturity of the supply chain as a possible limiting factor for maximising hydrogen production benefits, but notes that, since then, several Scottish companies have started working in the electrolyser system. For example, Ames Goldsmith Ceimig, based in Dundee, specialises in the formulation, synthesis and manufacturing of catalysts and compounds from PGM metals for PEM electrolysers and fuel cells.

5 UK future demand

5.1 SCENARIOS AND MODELLING CONDITIONS

The UK demand for materials embedded in electrolysers has been estimated for each of the four scenarios for the development of electrolyser capacity (in GW) in the UK up to 2050, as outlined by the National Grid (2023a, b). In addition to installed capacity, assumptions related to the electrolyser technology market share and product lifespans have been applied to estimate the gross demand (inflow) of electrolyser capacity (in GW) for each electrolyser type. The embodied material demand was then calculated from the electrolyser demand and the related material intensities for each demand scenario. The overall modelling logic is outlined in Figure 11.

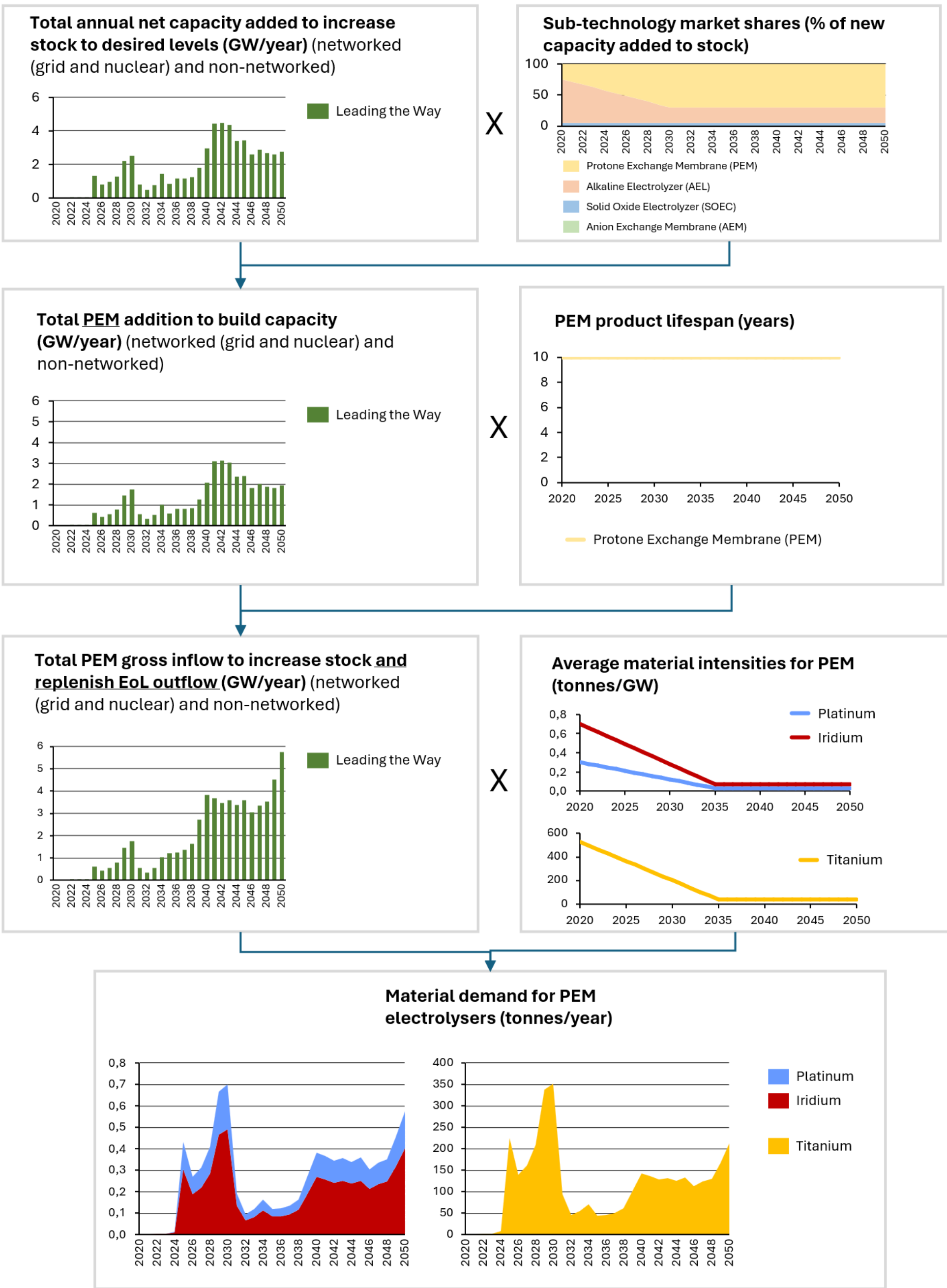


Figure 11 An outline of the modelling logic to estimate the embodied material demand for each of the National Grid scenarios for installed electrolyser capacity. BGS © UKRI.

The installed capacity of electrolysers in the UK between 2020 and 2050 is derived from the National Grid FES (National Grid, 2023a, b). The total cumulative installed electrolyser capacity in 2050 ranges from 1.59 GW in the ‘Falling short’ scenario to 55.21 GW in the most ambitious ‘Leading the way’ scenario, including networked, nuclear and non-network electrolyser capacity (Figure 12).

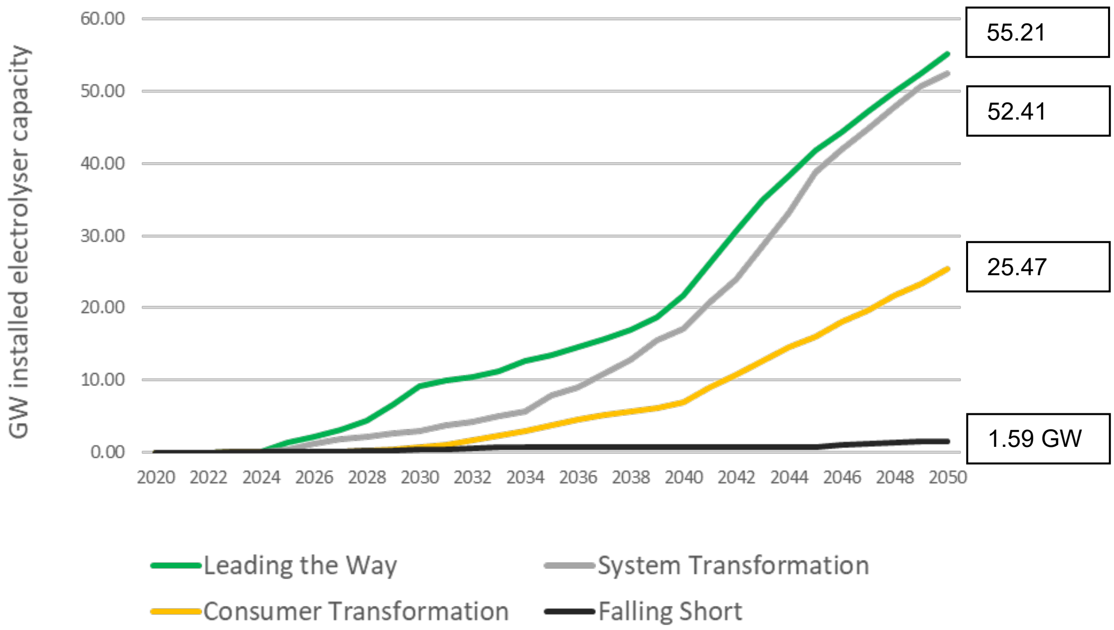


Figure 12 The cumulative installed electrolyser capacity in the UK based on four different scenarios (National Grid, 2023a, b).

Understanding technology transformation in the rapidly changing electrolyser market is of fundamental importance for forecasting embedded material demand, as the BOMs associated with each technology and the market shares of those technologies are likely to change substantially in the future.

At the global level, AELs and PEM electrolysers are expected to remain the leading electrolyser technologies until at least 2030. In 2021, approximately 70 per cent of globally installed capacity was AELs, with PEM electrolysers about a quarter. The remainder was divided between SOECs and AEM electrolysers. The IEA has predicted that, by 2030, total installed capacity could be split equally between AELs and PEM electrolysers (IEA, 2022b). As noted, SOECs and AEM electrolysers are still not in commercial use, although the first demonstration-scale SOEC plants have been commissioned (IEA, 2023). However, it unlikely that SOECs will become widely used before 2030 (IEA, 2022a).

A scoping report on the material requirements for a UK hydrogen economy (Price, 2023) expects that UK composition of electrolyser technologies will deviate somewhat from global projections. It also expects PEM electrolysers will make up a larger share of the UK market, reaching 70 per cent by 2030. This is attributed to the flexibility of PEM electrolysers’ operation in terms of their suitability for use with renewable power generation and the UK’s high level of ambition in that regard.

The technology market share assumptions used for the modelling of UK future electrolyser material demand are shown in Figure 13. In line with Price (2023), it is assumed that PEM electrolysers will reach a share of 70 per cent by 2030, from a current level assumed to be 25 per cent based on global market shares. Given the uncertainty around the commercial deployment of SOECs, it is assigned a market share of 5 per cent throughout the whole period. AEM electrolysers are excluded from the demand analysis on account of their technological infancy and lack of material intensity data.

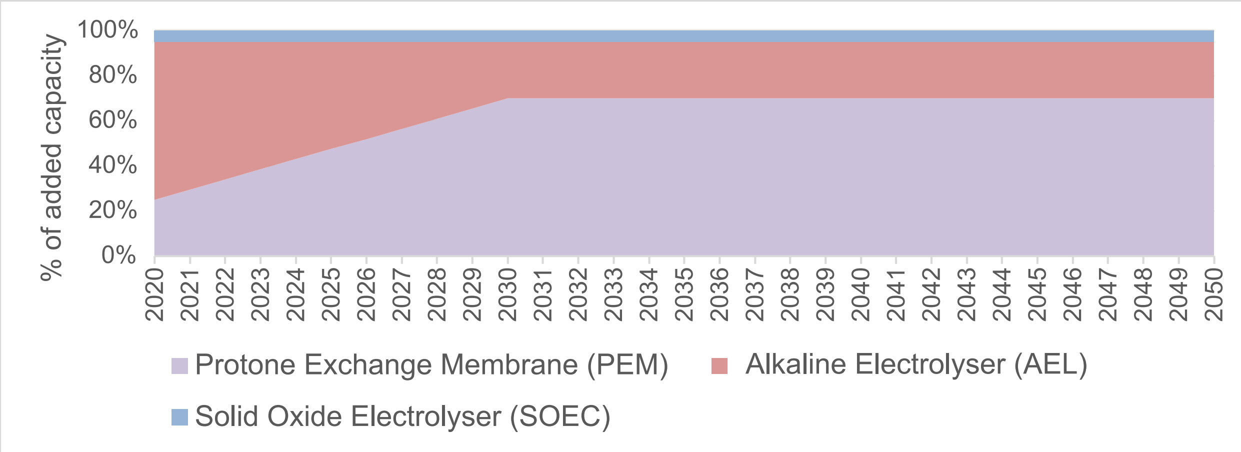


Figure 13 Electrolyser market share assumptions used in the modelling of UK embodied material demand. AEM electrolysers are excluded from the demand analysis on account of their technological infancy and lack of material intensity data. BGS © UKRI.

To estimate the total demand for electrolyser stacks based on aspirations related to future total installed capacity, it is important to consider the product lifespan of the different electrolyser stack types. A short-lived stack needs to be replaced more often than a long-lived stack in order to maintain the same installed capacity.

The stack lifespan varies considerably between the different electrolyser types. Although reliable data are sparse and the operating conditions of individual plants will vary, AELs are considered to be the most durable, with a typical lifespan of 20 years. This compares with 10 years for PEM electrolysers and two to four years for SOECs (Price, 2023). In the demand projection model, it has been assumed that AEL and PEM electrolyser stack lifetimes will remain largely unchanged, whereas the SOEC lifespan will improve by 5 per cent annually to reach approximately eight years by 2040 (Figure 14). This is generally consistent with a state-of-the-art electrolyser performance target for 2050 presented by IRENA (2020), which is about nine years for SOECs.

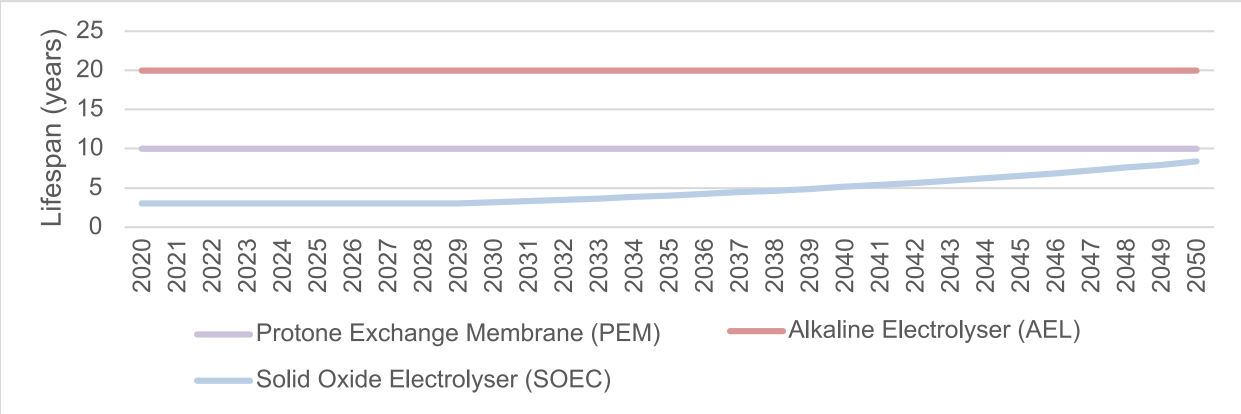


Figure 14 Lifespan assumptions for different electrolyser types included in the material demand analysis. BGS © UKRI.

Current and future material intensity data have been derived from several sources, with the IEA and the International Renewable Energy Agency (IRENA) being among the most important. Life cycle assessment studies from journal articles and various industry reports have also been used. Selected industry stakeholders in the UK have been consulted for further validation and data insights. Additional information about the sources used is provided in Appendix A. The material intensities used in the analysis are shown in Figure 15.

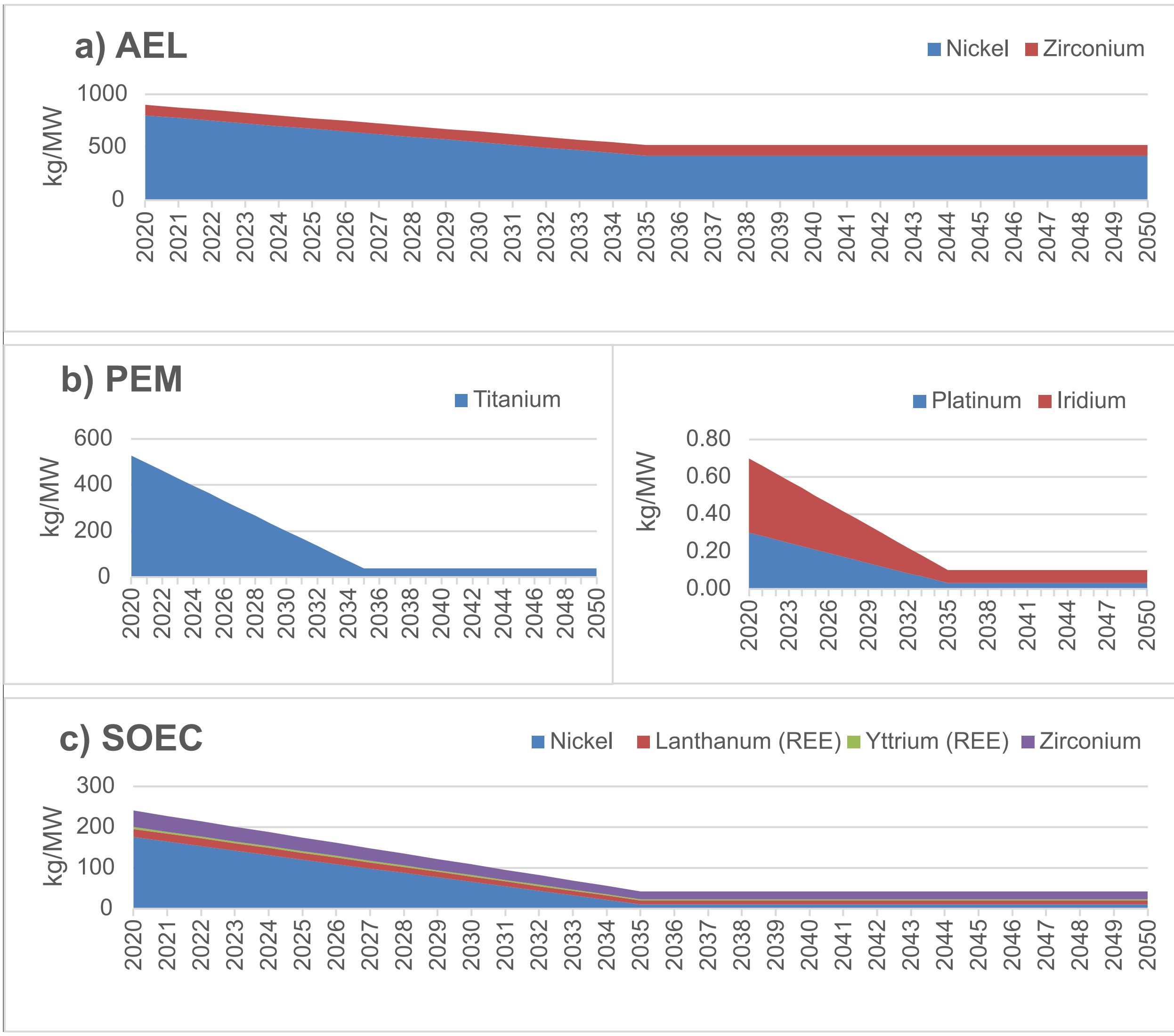


Figure 15 Material intensity (kg/MW) assumptions applied for the estimation of future electrolyser material demand. AEL: alkaline electrolyser; PEM: proton exchange membrane electrolysers; SOEC: solid oxide electrolysers. BGS © UKRI.

5.2 FUTURE UK RAW MATERIAL NEEDS FOR ELECTROLYSERS

The future UK demand for the selected elements embedded in electrolyser cells is presented in two ways:

- as the cumulative quantity (in tonnes) required between 2020 to 2050 for each of the National Grid FES (annual quantities provided in Appendix C)
- the cumulative quantity as the percentage of current annual global metal production (based on average annual production between 2017 and 2021)

Figure 16 shows the cumulative UK material demand between 2020 and 2050 related to electrolysers. Annual demand for each element has also been quantified to illustrate temporal fluctuations (Appendix C).

It is instructive to compare the estimated UK material demand with the current global production (Table 7).

Table 7 Global metal production compared with UK cumulative material demand to 2050 and UK peak annual demand in a high demand scenario ('Leading the way'). Production data are five-year averages (2017 to 2021). Data from BGS World Mineral Statistics Database (BGS, 2023). Global production for iridium is based on USGS (2023). The year in which peak UK demand is forecast is also shown.

Element	Global production (five-year average) (tonnes)	UK cumulative demand in 2050 ('Leading the way' scenario) (tonnes)	UK peak annual demand in 2020 to 2050 ('Leading the way' scenario) (tonnes (*year*))
Ni (metal)	2 423 024	8191	622 *(2045)*
Ti (metal)	6 558 489	3545	352 *(2030)*
Zr (mineral)	1 227 641	1911	157 *(2045)*
Ir (metal)	7.7	5	0.4 *(2050)*
Pt (metal)	184	3	0.2 *(2030)*
REOs	244 723	88	6 *(2045)*

It is also important to note that current global annual production for some materials, such as Ni and Ti, is already very large, amounting to several million tonnes of each per annum. In contrast, some metals used in electrolysers, in particular Pt and Ir, are produced in much smaller quantities. For most of the analysed materials (Ni; Ti; Zr; REEs), the cumulative UK electrolyser demand appears to be very small in relation to annual global production. This is not unreasonable, considering that electrolyser technology will only play a role in the hydrogen economy, which is forecast to represent only a small fraction of the total clean-energy transformation. Furthermore, most of those materials required for electrolysers are also used in larger amounts in other technologies not considered in this study.

It should be noted, however, that peak annual UK demand for Ir, which is currently produced globally in small quantities (7.7 t/year), may reach nearly 5 per cent of current global production by 2050 (Figure 17). Ir demand falls towards 2040, reflecting reduced material intensities, but increases again towards 2050 due to the increasing number of end-of-life electrolysers that will need replacing to maintain installed capacity. In comparison, the proportion of UK annual demand for Pt is only about 0.1 per cent of global production, so does not seem to pose the same challenges. The relatively large Ir demand is partly due to the high expected share of PEM electrolysers in the UK market.

Johnson Matthey (2022) does not view Ir supply as a barrier to growing PEM electrolyser capacity, with Ir intensities potentially decreasing by 80 per cent by 2030. It is also crucial to plan for electrolysers' end-of-life to ensure effective recycling of materials.

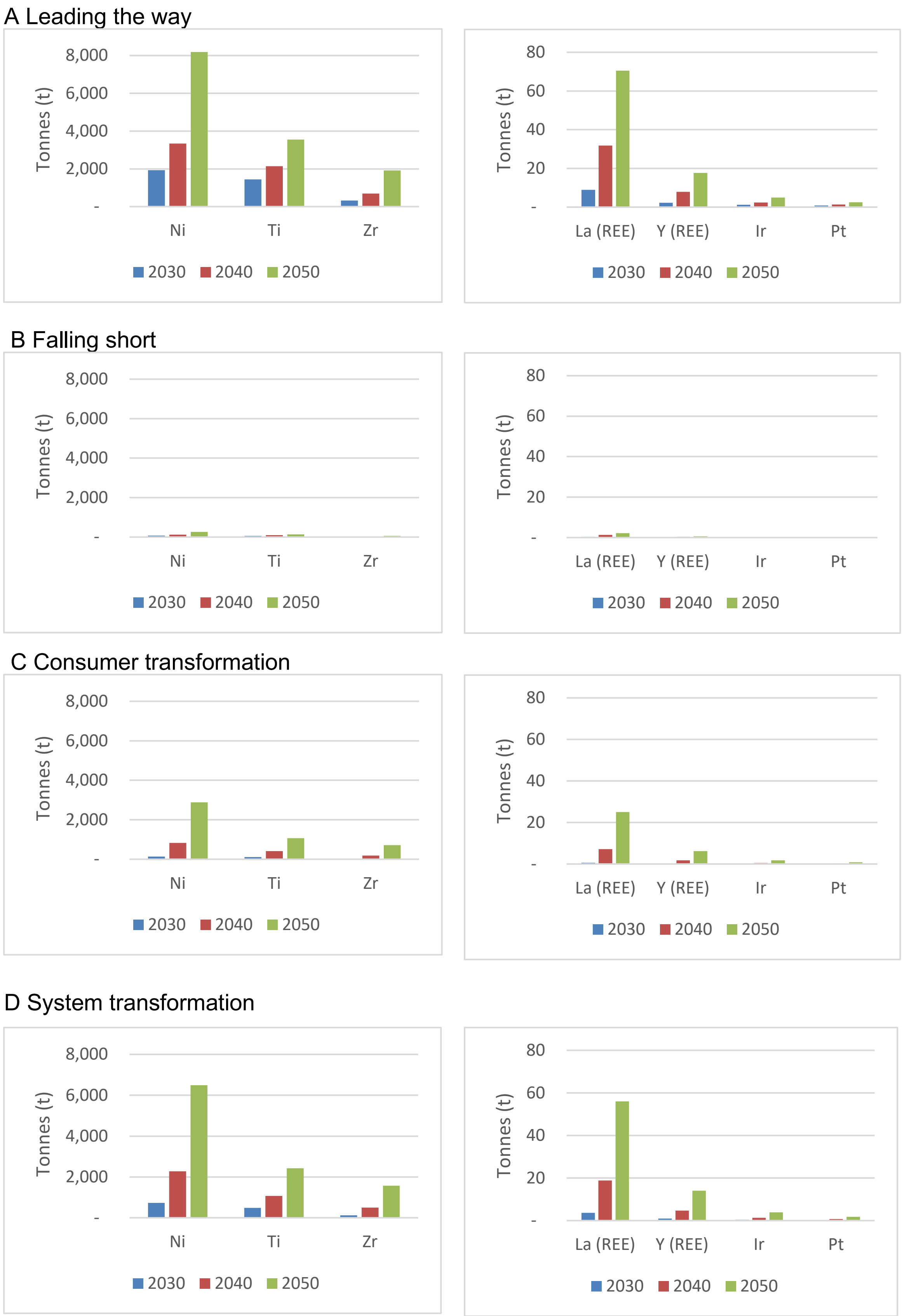


Figure 16 Cumulative forecast UK electrolyser demand (tonnes) for the elements considered in this study between 2020 and 2050 under four different scenarios. A: 'Leading the way'; B: 'Falling short'; C: 'Consumer transformation'; D: 'System transformation'. (National Grid, 2023a.) BGS © UKRI.

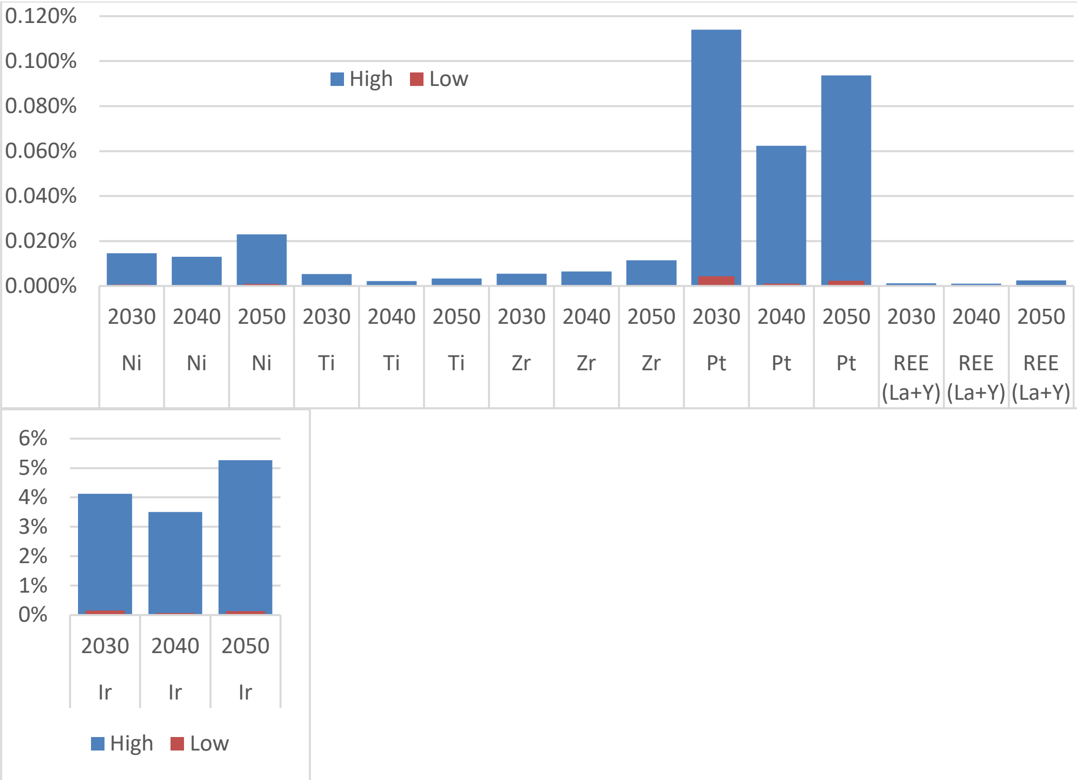


Figure 17 Estimated annual UK demand in 2030, 2040 and 2050 as a percentage of current global annual metal production. The global metal production figures used (five-year average, 2017 to 2021) are reflected in Table 7. Data sources: BGS (2023) & National Grid (2023a). BGS © UKRI.

5.3 GLOBAL DEMAND VS UK DEMAND PROJECTIONS

Building electrolyser capacity in the UK will be highly dependent on global electrolyser supply chains for key components and materials. Increased competition can be expected in securing the necessary supplies to meet green hydrogen ambitions, so it is important to consider the UK demand in the context of anticipated global demand for electrolysers and associated key functional materials.

The National Grid anticipates approximately 9 GW of installed electrolyser capacity by 2030 and 55.2 GW by 2050 in a 'Leading the way' scenario (National Grid, 2023a, b). Considering the need to replace end-of-life electrolysers, aggregated UK demand exceeding 73 GW may be required by 2050.

In comparison, the IEA Sustainable Development Scenario (SDS) anticipates global installed electrolyser capacity to be about 140 GW in 2030, 530 GW in 2040 and 1400 GW in 2050 (IEA, 2022a). IRENA has indicated that global electrolyser capacity needs to grow to 350 GW by 2030 to meet clean hydrogen demand and to 5000 GW by 2050 to stay on a 1.5°C pathway scenario (IRENA, 2022a). In line with the 1.5°C pathway scenario, the global demand for electrolysers in 2030 would be 70 times the aggregated UK demand, which is about 1 per cent of forecast aggregated demand of 5000 GW in 2050.

The larger European economies have set targets for deployment of electrolyser technologies: these include the EU, with a strategic objective of 40 GW installed capacity by 2030, and France, Germany, Spain and Italy, with national targets between 5 and 10 GW by 2030 (IRENA, 2022b). The US Department of Energy reports up to 1000 GW electrolyser capacity required in the USA by 2050 to meet their decarbonisation goals and approximately 6000 GW capacity globally, assuming the largest share of electrolysers will be PEMs (DOE, 2022).

To produce material demand projections comparable with those made for the UK, the global electrolyser demand was modelled using the IEA SDS scenario (1400 GW by 2050) (IEA, 2022a) and the IRENA 1.5°C pathway scenario data (IRENA, 2022a), respectively. The 1.5°C pathway scenario assumes linear ramp-up of installed electrolyser capacity of 350 GW by 2030 and 5000 GW by 2050. For simplicity, all other modelling parameters and assumptions were kept the same as for the UK estimations, although it is important to note that these are subject to considerable uncertainty and may differ across regions. For example, IRENA assumes a high market share for AELs (around 90 per cent) (IRENA, 2022a) in contrast to PEM electrolysers, which have been forecast to reach a 70 per cent share in the UK by 2030. Given the different materials used in each cell, the overall material demand is very sensitive to variations in the mix of electrolyser types.

Figure 18 shows the calculated cumulative UK demand for selected electrolyser materials against the calculated global demand, based on the electrolyser ramp-up scenarios. The comparison for all the materials analysed is given in Appendix D.

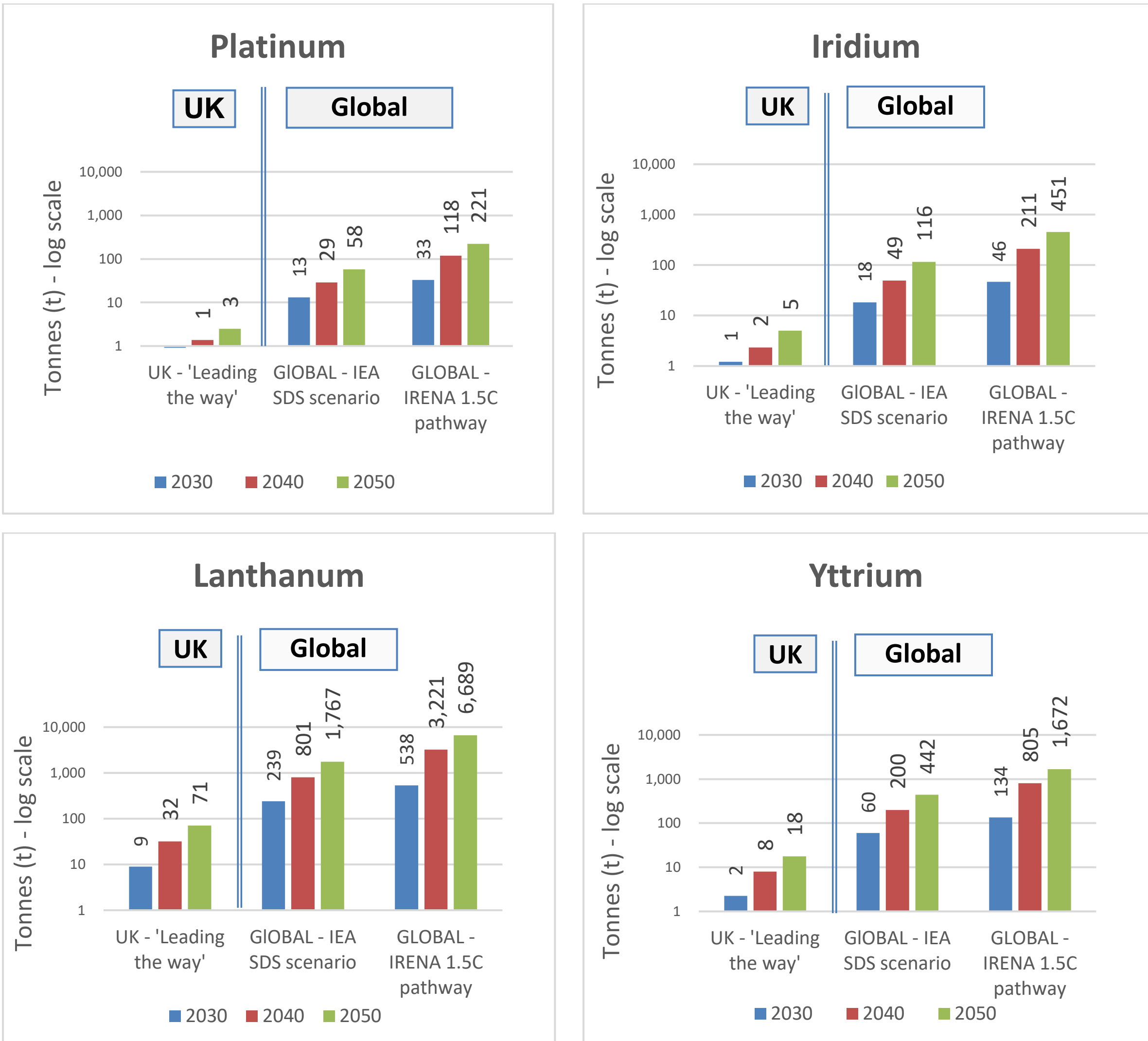


Figure 18 Estimated UK and global material demand for selected electrolyser materials. (Appendix C gives an overview of all materials included in the analysis). BGS © UKRI.

This analysis demonstrates that the UK demand for electrolysers and embodied materials will be orders of magnitude lower than the global demand. The total UK electrolyser demand under the ‘Leading the way’ scenario (55.2 GW or 73 GW considering end-of-life replacement) is about 1 per cent of global electrolyser demand in the IRENA electrolyser scenario, assuming 5000 GW cumulative installed capacity by 2050. Similarly, the cumulative UK demand for embedded materials is about 1 per cent of the global material demand for electrolysers. There is therefore likely to be serious competition for some materials, especially those currently produced in small quantities, as energy transition efforts ramp up worldwide. Although the UK will remain a relatively small player in the global electrolyser landscape, it may be challenging to secure sustainable material supplies that underpin its deployment targets.

Building electrolyser capacity in the UK will be highly dependent on global electrolyser supply chains for key components and materials. Increased competition can be expected in securing the necessary supplies to meet green hydrogen ambitions; it is therefore important to consider the UK demand in the context of anticipated global demand for electrolysers and associated key functional materials.

6 Discussion and conclusions

Electrolyser technology will make an increasingly important contribution to global renewable energy supply up to 2050 and beyond. Electrolysers requires a wide range of materials, several of which are already considered to be critical to the UK and some that are by-products of the production of other commodities. This study analysed the global supply chains and UK demand requirements up to 2050 for seven elements embedded in different electrolysers technologies (Figure 4): Ir, Ni, Pt, Ti, Zr and the REEs La and Y. Of these, Pt, La and Y are included in the UK critical minerals list (Lusty et al. 2021). Al, Ce, Co, Cu, Au, Mn, Ru and Sr were excluded from the analysis because of at least one of the following reasons:

- their use is in structural rather than functional components
- they are not used in the most common configurations of the technologies involved
- no data were available for the relevant BOM

Forecast electrolysers material demand to 2050, based on the National Grid FES, was determined and compared with forecast global electrolysers material demand for the same period.

Supply bottlenecks for the included materials were evaluated based on two key parameters:

- production concentration, derived from analysis of national production data and the ESG ranking of the main producing countries
- trade concentration, derived from analysis of national trade data and trade restrictions currently imposed by the main trading nations

The key conclusions of this analysis are:

- future UK material demand for electrolysers technology is small in comparison with current global production levels
    - Ir is an exception: future annual UK demand could equate to as much as 5 per cent of current global production by 2050
- high geographical concentration of both production and trade gives rise to significant supply risk: for most metals evaluated, the top three producers collectively account for more than 50 per cent of current global production, increasing to as much as 90 per cent in some cases (Ir and Pt)
- both the mining and refining stages of the electrolysers value chain have a high dependency on a few key countries, notably China and Russia, in addition to countries in southern Africa, including South Africa, Zimbabwe and Mozambique
- the precursor, component and product manufacturing stages activities are largely undertaken in Europe and North America
- poor ESG scores for key producing countries of Ir, Pt and REEs are of particular concern as they are frequently cited as a core inhibitor for the rapid scaling-up of many decarbonisation technologies (DOE, 2022)
- UK demand for electrolysers and embodied materials will be orders of magnitude lower than the global demand, so high levels of competition for the required materials can be expected worldwide
- although some electrolyser technologies are mature and long established, significant future advancements in other technologies, such as AEM and SOEC, are forecast, which will be driven by innovation leading to changes in the future technology mix, with longer usage cycles and significantly reduced material intensities

There is also considerable uncertainty relating to the underlying energy and electrolyser demand scenarios. Variations in expected energy generation demand need to be considered alongside the potential of hydrogen as an alternative fuel in a wide range of applications, including energy storage, propulsion, heat generation and input into chemical processes, to fully evaluate future material demand.

Regardless of these uncertainties, future demand for the analysed materials in almost all scenarios is likely to increase significantly in the short term, at both the UK and global scales. This is largely driven by commitments to decarbonise a wide range of applications for which hydrogen could constitute an energy carrier and storage solution. In the UK, the planned scenario for wind power generation and other renewables is likely to further push demand for electrolyser capacity as off-grid storage to accommodate peak loads, which in turn favours the deployment of PEM technology due to its superior properties under non-constant load profiles. Consequently, larger volumes of critical materials, chiefly Pt and Ir, will be required. This may pose a significant bottleneck for future scaling-up of the technology (IRENA, 2020).

Figure 19 illustrates the relative material accumulation by technology and the materials embedded in each. It clearly shows the dominance of Ni, Ti and Zr in absolute terms. Given the UK's aspiration for wind energy to have a primary share of renewable energy generation, Ti will require a closer look.

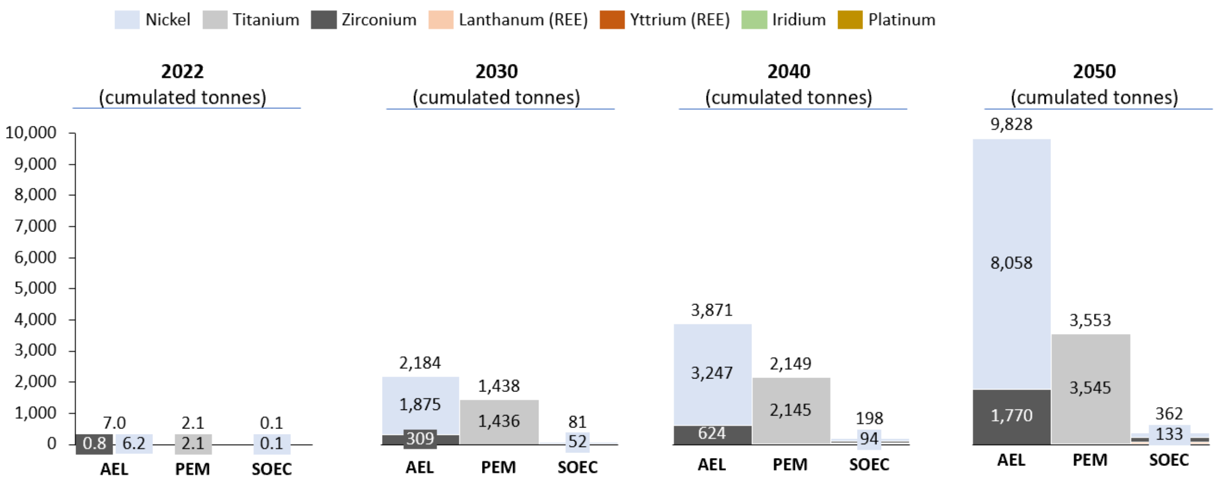


Figure 19 The cumulative mass (tonnes) of the materials evaluated in this study embodied in different electrolyser technologies in 2022 compared with forecasts for 2030, 2040 and 2050. BGS © UKRI.

Figure 20 displays the value of the materials used in the various currently installed electrolyser technologies and future projections of those values. Ir stands out as a significant cost to 2050, even when taking into account optimisation through thrifting (using less metal) and improved efficiencies.

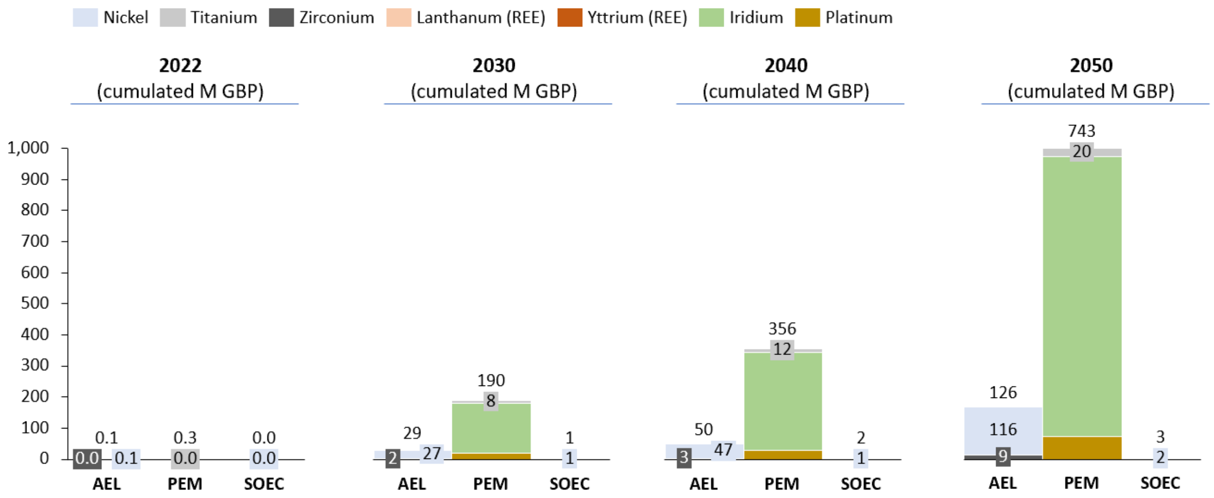


Figure 20 The aggregate value (in £millions) of the materials evaluated in this study embodied in different electrolyser technologies in 2022 compared with forecasts for 2030, 2040 and 2050 at today's prices. Material prices used and respective sources are provided in Appendix E. BGS © UKRI.

7 Recommendations

This analysis leads to several recommendations aimed at securing the materials required to achieve UK's ambitions for the production of green hydrogen using electrolysers.

7.1 METHODOLOGY RECOMMENDATIONS

The following methodology challenges should be addressed by further investment in material observatories to provide the necessary fact base for private and public sector decision making and policy development. This is particularly important during the current period of rapid technology development, heightened geopolitical competition and unstable market forces. Continual review of these foresight studies is pivotal to create a solid foundation for active and reliable decision making in the future.

7.1.1 Reducing the visibility gap

The analysis has shown that the estimation of material demand using a back-casting approach (from product to component) and refined and raw materials is difficult, owing to limited data availability. This includes missing data on BOMs and material composition and the limited availability of data on refining and mining capacities, especially for by- and co-products. These data deficiencies exist for both present day and, more importantly, future scenarios.

7.1.2 Overcoming the uncertainty gap

There is significant uncertainty surrounding the future electrolyser technology mix, which will have implications for their material demand. There is therefore a considerable degree of variance built into each derived forecast.

7.2 SECURITY OF SUPPLY RECOMMENDATIONS

A concerted effort at a national level is required to explore policy options to ensure access to those materials needed to meet the major increase in electrolyser technology deployment in the UK. Particular focus should be on trade-related agreements at the intra-national level. At the same time, effective schemes should be established to facilitate re-use and recycling to maintain necessary stocks within the UK.

Scale-up of electrolyser technology will require an undisrupted supply of raw and refined materials. However, these materials are often sourced from jurisdictions with poor ESG ratings and high geopolitical risk, many of which already impose trade restrictions via licencing and tax requirements.

The assumed technological progress indicates substantial cost-improvement potential and an option to reduce relative dependencies by investigating alternative material supplies, including in existing stock in the UK via post-use circular revalorisation options.

The co-dependence of certain critical raw materials used in electrolysers, notably Ir and REEs, requires consideration of the net demand for the by-product and the aligned demand for the primary products. For example, the net demand for Pt might decrease in the future due to decreased use in autocatalysts, while the demand for its by-product, Ir, could soar as a key enabler of electrolyser technologies. The improved management of existing stocks of Pt and Ir through revalorisation could ease the burden.

In the absence of new mining output, Ir could become a bottleneck for future growth in PEM electrolyser capacity. However, Johnson Matthey (2022) argues that this can be avoided through joint innovation efforts across the sector to improve electrolyser efficiencies, reduce Ir intensities by an order of magnitude and plan for material recycling at electrolysers' end-of-life.

7.3 LOCAL CAPABILITY RECOMMENDATIONS

To further de-risk the dependence on purely import-reliant feedstock, an improvement of post-use revalorisation of the installed asset base should be a key priority in addition to further innovation in electrolyser technology to achieve higher resource productivity of the embedded materials.

The UK is currently home to relatively few companies in the electrolyser value chain. Most of these are involved in cell manufacturing, while a few are component manufacturers. Steps should be taken to expand the UK capacity across the value chain.

Investment is essential to ensure that the anticipated technological advancements—such as reduced electrolyser costs, decreased material intensities, and enhanced durability—are realised. IRENA (2020) points out that innovation to extend durability is crucial to reduce electrolyser cost and performance. Should the assumed technological learning curves not materialise, this will result in further bottlenecks to electrolysers' deployment.

Given the absence of UK mineral reserves and the long lead times for developing those known overseas, it is important to focus on maximising the resource productivity of existing stocks. This can be achieved via optimised post-use revalorisation schemes, including component re-use and material recycling. These approaches would benefit from a UK-focused programme to incentivise private sector investment, backed up by an improved regulatory regime.

Appendix A

This discussion supplements the main text by elaborating on:

- the material composition of the electrolyser technologies for which material demand has been estimated (AEL; PEM; SOEC)
- the selection of materials included in the analysis
- key data sources and judgements made in the estimation of the material intensity data used

The main functional electrolyser components and the key materials found in each technology type are based on IRENA (2020). Material intensities have been derived from a wide variety of literature sources.

ALKALINE ELECTROLYSERS

Various sources highlight Ni and Zr as key functional materials in alkaline electrolysers. Ni is typically found as coating on stainless steel in the electrode and bipolar plates and in the form of a mesh in the transport layer. ZrO_2 is used in the separator (IEA, 2022a; IRENA, 2020).

According to IEA (2022b), today's most advanced AELs use (per 1 MW AEL):

- 0.8 t Ni
- about 100 kg Zr
- 0.5 t Al
- more than 10 t steel
- smaller amounts of Co and Cu catalysts

IEA (2022a) notes that Ni reduction can be expected but not eliminated. It does not provide potential future values. Other sources also reference Ni intensity of 800 kg/MW (Lundberg, 2019; Price, 2023). Another indicates a lower Ni intensity of 420 kg/MW (Wasserstoff Kompass, 2022). In the absence of a dedicated future estimate, the 420 kg/MW has been used as the potential future Ni material intensity in this analysis.

A Zr intensity of 100 kg/MW has been kept constant into the future, in the absence of data indicating the level of potential reduction.

Based on the identified sources, the following AEL material intensities have been used in the material demand analysis.

Material	Present (kg/MW)	Future (kg/MW)
Ni	800	420
Zr	100	100

Steel and Al, which are mainly used for structural purposes, and Cu, which is typically used in electrical connections and wiring, are excluded from the analysis. This is based on the notion that these materials are commonly available in the market and not considered at risk of supply disruption.

Functional materials that have been **excluded** from the material demand estimation:

Material	Function	Reason for exclusion
Co	Used as catalyst in some AELs	The use of Co in AELs is not the most common configuration so has been excluded Co has not been identified amongst the AEL material intensities in literature
Pt	Used as catalyst in some AELs	The use of Pt in AELs is not the most common configuration so has been excluded Pt has not been identified amongst the AEL material intensities in literature

PROTON EXCHANGE MEMBRANE ELECTROLYSERS

Key functional materials used in PEM electrolysers include Ti-based materials, noble metal catalysts and protective coatings, including Pt and Ir, which can withstand the acidic environment of the PEM. Pt is used to coat the Ti bipolar plates and in the cathode electrode, and Ir is used as a catalyst in the anode electrode. Ti is also used in the porous transport layer. Ti can represent half of the stack cost for PEM (IRENA, 2020).

The IEA states that current PEM catalysts use around 0.3 kg Pt and 0.7 kg Ir per MW and that reductions to about one-tenth of these amounts are possible in the next decade, driven by the need to reduce costs (IEA, 2022a). Discussions with a leading UK actor in the supply chain for catalysts used in electrolyser technologies, conducted as part of this study, indicated that current Ir intensities for PEM electrolysers are closer to 0.4 t/GW (which is the value used for Ir in the material demand estimation below). It was also noted that Ru may be used in some configurations of PEM electrolysers.

Alternative sources indicate Pt intensity as low as 0.1 kg/MW and Ir as low as 0.4 kw/MW (Price, 2023). Bareiß et al. (2019), based on a PEM stack lifecycle assessment, indicates current PEM Pt levels of 0.075 kg/MW with near-future potential of 0.01 kg/MW, and current Ir levels of 0.75 kg/MW with near-future potential of 0.037 kg/MW.

The IRENA and IEA reports discuss the importance of Ti in PEM stack costs but do not provide material intensity data. However, Bareiß et al. (2019) indicates Ti use of 528 kg/MW currently and near-future potential of 37 kg/MW. These values have been used for the PEM material demand analysis. In an alternative source, Wasserstoff Kompass (2022) only indicates Ti intensity of 28 kg/MW for the PEM, although the background data is not presented.

Based on the identified sources, the following PEM material intensities have been used in the material demand analysis.

Material	Present (kg/MW)	Future (kg/MW)
Ti	528	37
Pt	0.3	0.03
Ir	0.4	0.07

Au is sometimes used as a catalyst in PEM electrolysers (IRENA, 2020), although this is understood to be a niche configuration that is not widely used. Au has, therefore, been excluded from the estimates of future material demand.

Functional materials that have been excluded from the material demand estimation.

Material	Function	Reason for exclusion
Au	Used as catalyst instead of Pt	Not the most common configuration so has been excluded Au has not been identified amongst the PEM material intensities in literature

SOLID OXIDE ELECTROLYSERS

SOECs contain a somewhat broader palette of materials than AELs and PEM electrolysers, although configurations are understood to vary between manufacturers. The electrolyte typically includes YSZ, a compound consisting of the REE Y, and ZrO_2, a derivative of element Zr. IRENA (2020) also indicates that the electrolyte/catalyst configuration varies but may consist of Ni or YSZ on the hydrogen side and the compounds LSCF or LSM on the oxygen side. It is therefore evident that La, Sr, Co and Mn are used in some configurations of SOECs. In addition, Ni is used on the anode side of the porous transport layer in the form of mesh or foam, while Co-coated stainless steel may be used in the bipolar plates. The use of these compounds varies between manufacturers.

IEA (2022a) provides material intensities for individual elements, stating that the primary mineral demands of SOECs are:

- Ni: 150 to 200 kg/MW
- Zr: around 40 kg/MW
- La: around 20 kg/MW
- Y: less than 5 kg/MW

The IEA report expects that better design can contribute to halving of each of these quantities in the next decade, with technical potential to reduce Ni content to below 10 kg/MW. Based on this, the following SOEC material intensities have been used in the material demand analysis.

Material	Present (kg/MW)	Future (kg/MW)
Ni	175	10
La	20	10
Y	5	2.5
Zr	40	20

Häfele et al. (2016) provides material intensity data for SOEC. It indicates a Ni content similar to that specified by the IEA and also provides quantities per MW stack for the compounds YSZ, LSCF, and LSM and for yttria-doped ceria (YDC) (YDC data is not given in IEA (2022a) or (IRENA, 2020)). As these compounds are not broken down into individual elements, they are not directly comparable to the IEA data and have not been used in the analysis.

In terms of the LSCF and LSM compounds, these are generally understood to be composed of dominantly La, with minor amounts of the other elements.

Functional materials that have been excluded from the material demand estimation:

Material	Function	Reason for exclusion
Co	May be in LSCF in the electrolyte	Use understood to vary based on manufacturers No material intensity data identified
Mn	May be in LSM in the electrolyte	Use understood to vary based on manufacturers No material intensity data identified
Sr	May be in LSCF or LSM in the electrolyte	Use understood to vary based on manufacturers No material intensity data identified
Ce	In blocking layer according to Häfele et al. (2016)	Indicated in Häfele et al. (2016) as part of a YDC compound but no other information found

Appendix B

Selected global key players in electrolyser system manufacturing. Source: IRENA (2020), p 83.

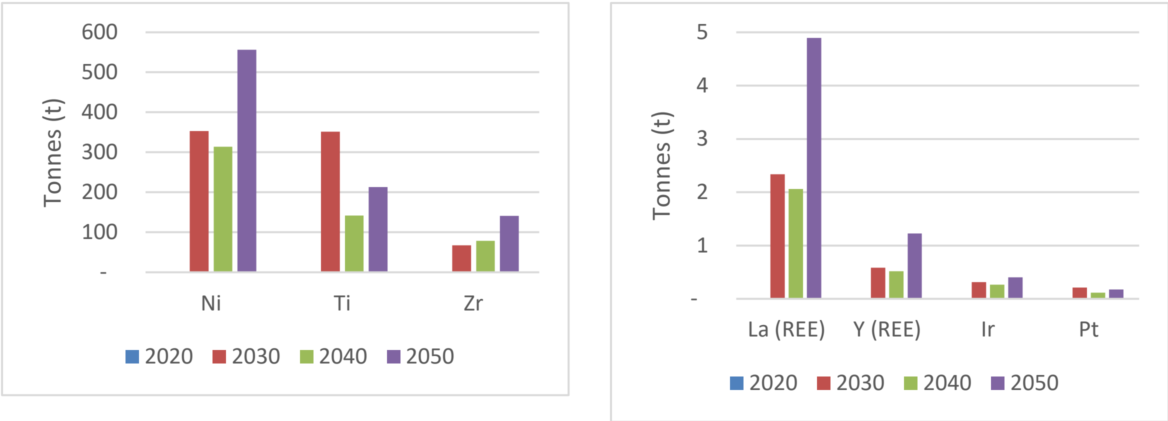
COMPANY	MANUFACTURING SITE	ELECTROLYSER TYPE
AQUAHYDREX	AUSTRALIA, USA	ALKALINE
ASAHI KASEI	JAPAN	ALKALINE
AREVAH_2	FRANCE, GERMANY	PEM
CARBOTECH	GERMANY	PEM
COCKERILLL JINGLI	CHINA	ALKALINE
CUMMINS - HYDROGENICS	BELGIUM, CANADA, GERMANY	PEM AND ALKALINE
DENORA	ITALY, JAPAN, USA	PEM AND ALKALINE
ENAPTER	ITALY	AEM
GINER ELX	USA	PEM
GREEN HYDROGEN SYSTEMS	DENMARK	ALKALINE
HALDOR TOPSOE	DENMARK	SOLID OXIDE
HITACHI ZOSEN	JAPAN	ALKALINE AND PEM
HONDA	JAPAN	PEM
HYDROGENPRO	NORWAY	ALKALINE
iGAS	GERMANY	PEM
ITM	UK	PEM
KOBELCO	JAPAN	ALKALINE AND PEM
KUMATEC	GERMANY	ALKALINE
MCPHY	FRANCE, ITALY, GERMANY	ALKALINE
NEL Hydrogen	DENMARK, NORWAY, USA	PEM AND ALKALINE
PERIC	CHINA	ALKALINE
PLUG POWER	USA	PEM
SHANGHAI ZHIZHEN	CHINA	ALKALINE
SIEMENS ENERGY	GERMANY	PEM
SOLIDpower	ITALY, SWITZERLAND, GERMANY, AUSTRALIA	SOLID OXIDE
SUNFIRE	GERMANY	SOLID OXIDE
TIANJIN	CHINA	ALKALINE
TELEDYNE	USA	PEM
THYSSENKRUPP UHDE	GERMANY	ALKALINE
TOSHIBA	JAPAN	SOLID OXIDE

Based on IRENA analysis.

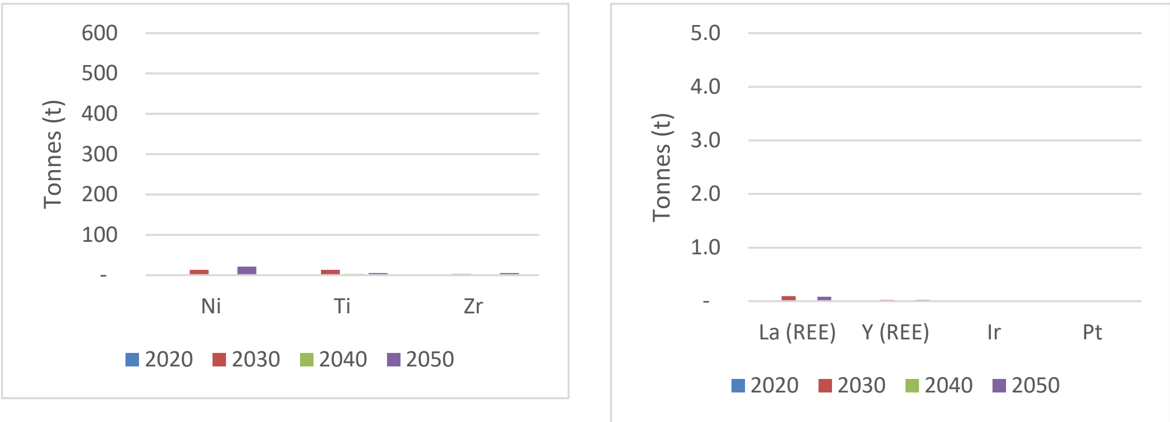
Appendix C

Annual forecast demand (tonnes) for the elements considered in this study up to 2050 and compared with 2020 under four different scenarios: A: ‘Leading the way’; B: ‘Falling short’; C: ‘Consumer transformation’; D: ‘System transformation’. BGS © UKRI.

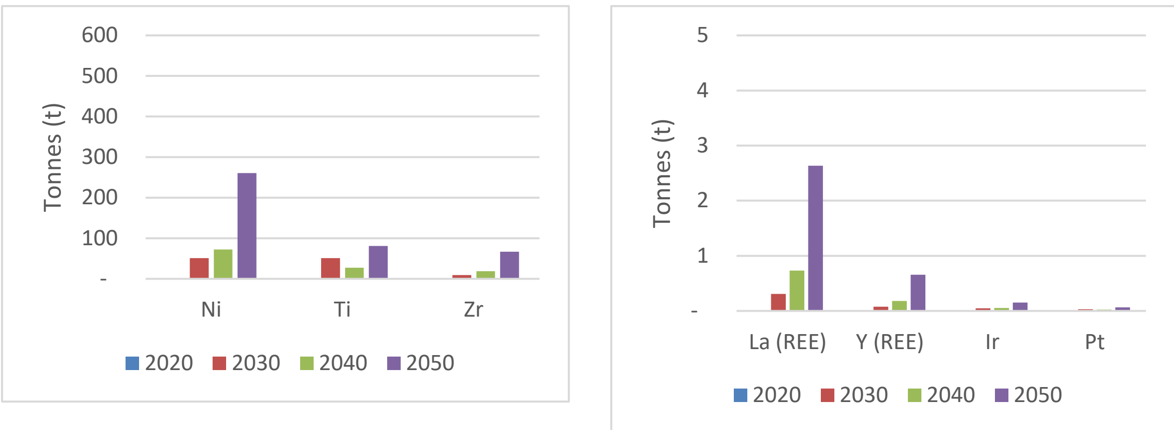
A



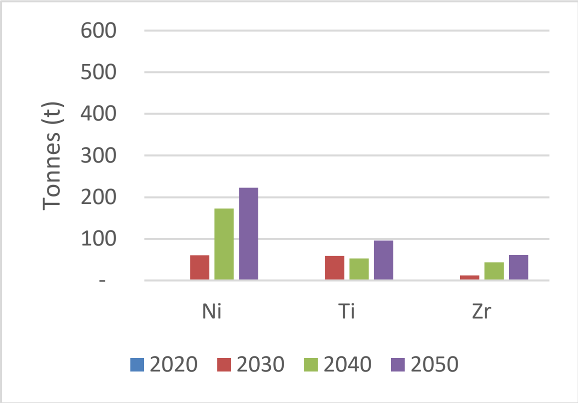
B

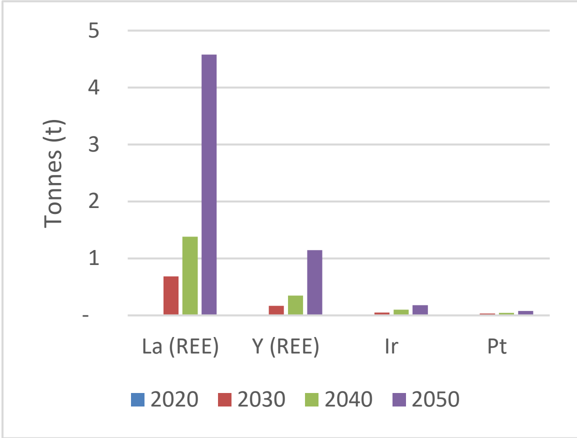


C



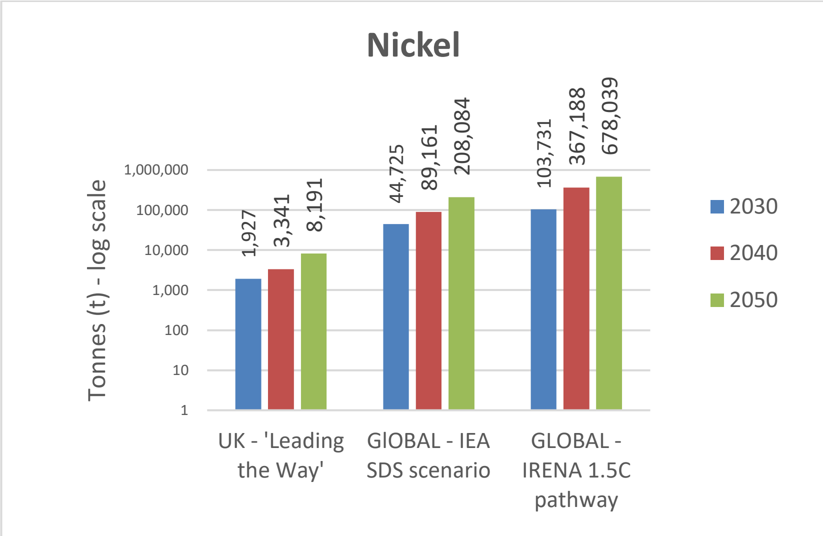
D

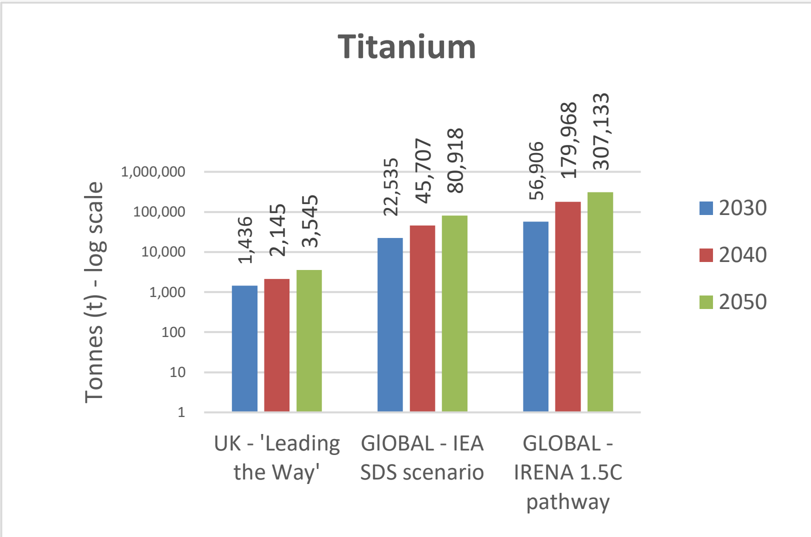

Tonnes (t)
600
500
400
300
200
100
-
Ni
Ti
Zr
2020
2030
2040
2050

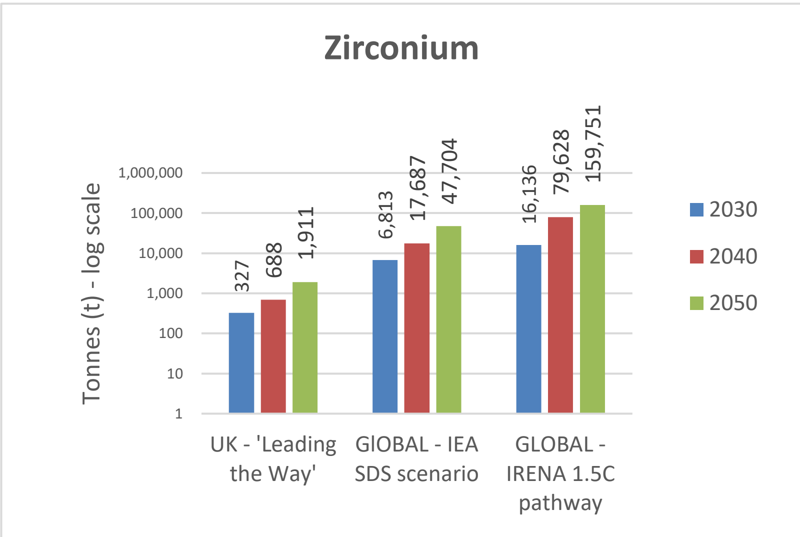

Tonnes (t)
5
4
3
2
1
-
La (REE)
Y (REE)
Ir
Pt
2020
2030
2040
2050

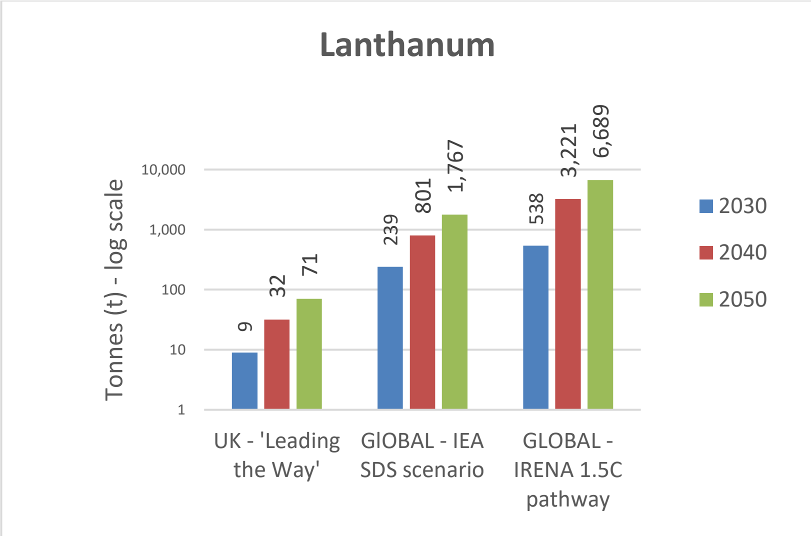
Appendix D

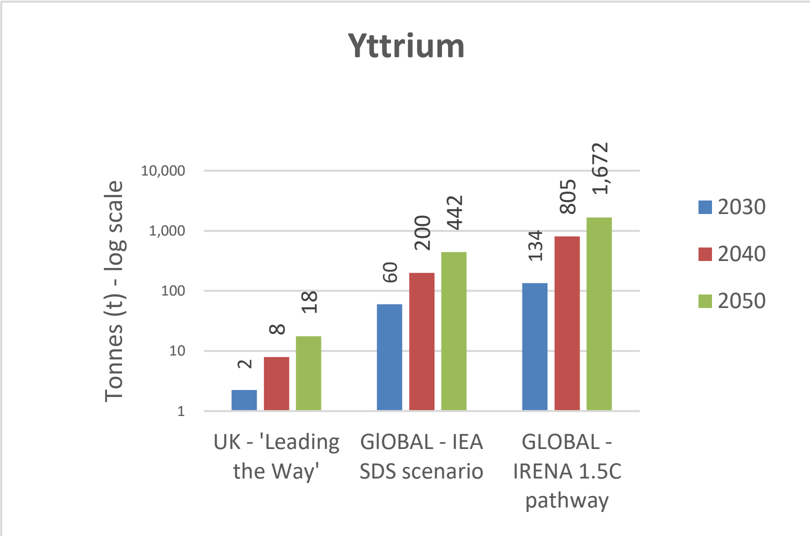
The estimated future UK and global material demand (in tonnes) for selected elements embedded in electrolysers. BGS © UKRI.

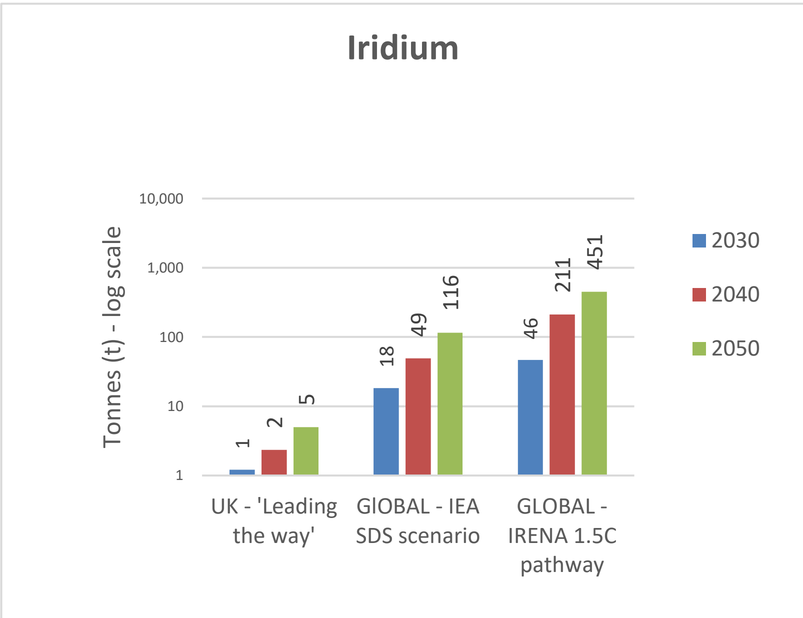


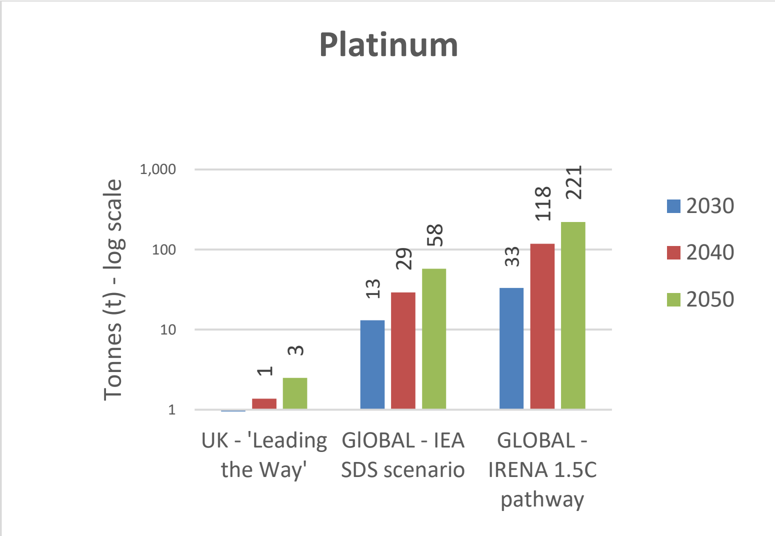





Lanthanum
Tonnes (t) - log scale
10,000
1,000
100
10
1
9
32
71
239
801
1,767
538
3,221
6,689
UK - 'Leading the Way'
GlOBAL - IEA SDS scenario
GLOBAL - IRENA 1.5C pathway
2030
2040
2050


Yttrium
Tonnes (t) - log scale
10,000
1,000
100
10
1
2
8
18
60
200
442
134
805
1,672
UK - 'Leading the Way'
GlOBAL - IEA SDS scenario
GLOBAL - IRENA 1.5C pathway
2030
2040
2050


Iridium
Tonnes (t) - log scale
10,000
1,000
100
10
1
1
2
5
18
49
116
46
211
451
UK - 'Leading the way'
GlOBAL - IEA SDS scenario
GLOBAL - IRENA 1.5C pathway
2030
2040
2050


Platinum
Tonnes (t) - log scale
1,000
100
10
1
1
3
13
29
58
33
118
221
UK - 'Leading the Way'
GlOBAL - IEA SDS scenario
GLOBAL - IRENA 1.5C pathway
2030
2040
2050

Appendix E

Material prices used in the analysis (23 February 2024). Conversion factors: 1 tonne = 35 840 ounces; US$1 = £0.79.

Commodity	£/tonne	$/tonne	$/ounce	Price data source
Ir	149 194 83 4	188 854 221	5269.37	Iridium price today | Historical iridium price Charts | SMM Metal Market
La	445	563		Lanthanum oxide price today | Historical lanthanum oxide price charts | SMM Metal Market
Ni	14 439	18 277		#1 import nickel price today | Historical #1 import nickel price charts | SMM Metal Market
Pt	24 300 713	30 760397	858.27	Platinum price today | Historical platinum price charts | SMM Metal Market
Ti	5672	7180		Titanium sponge price today | Historical titanium sponge price charts | SMM Metal Market
Y	4783	6055		Yttrium oxide price today | Historical yttrium oxide price charts | SMM Metal Market
Zr	5284	6688		Zirconium dioxide Zr(Hf)O_2 ≥ 99.5% price today | Historical Zirconium dioxide Zr(Hf)O_2 ≥ 99.5% price charts | SMM Metal Market

Acronyms and abbreviations

AC	Alternating current
AEL	Alkaline electrolyser
AEM	Anion exchange membrane (electrolyser)
BGS	British Geological Survey
BOM	Bill of materials
ESG	Environmental, social and governance
FES	Future Energy Scenarios
HS	Harmonized System (trade codes)
IEA	International Energy Agency
LSCF	Lanthanum-strontium-cobalt ferrite
LSM	Lanthanum-strontium manganite
PEM	Proton exchange membrane (electrolyser)
PGM	Platinum group metal
SOEC	Solid oxide electrolyser cell
YDC	Yttria-dosed ceria
YSZ	Yttria-stabilised zirconia

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