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

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Open report

University of Exeter Business School

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

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The UK Hydrogen Strategy highlights the critical role of hydrogen in the UK's net zero transition (BEIS, 2021). Beyond this, the UK National Grid Future Energy Scenarios (FES) forecasts an annual increase in demand for hydrogen by society from currently close to zero to 446 TWh in 2050 in a 'System transformation' scenario, or 242 TWh in a 'Leading the way' scenario (National Grid, 2023a, b).

Hydrogen can have many applications, including as an intermediate material for processing into other substances (including other energy carriers) or directly as an energy source. As an energy source, converting hydrogen into useful energy (heat or electricity) can occur via two main pathways: combustion to release heat or the use of fuel cells to generate electricity (Shell & Wuppertal Institut, 2017).

This report explores the material supply chain for fuel cell deployment in the UK, concentrating on the road transport sector. The objective is to estimate future material demand for different hydrogen fuel cell vehicle development scenarios, as reflected in the National Grid FES (National Grid, 2023a, b). The focus on the road transportation sector is based on the expectation that fuel cell uptake will grow substantially in the near future (EC, 2020) and because suitable hydrogen vehicle data are readily available in the National Grid FES data (National Grid, 2023a, b), enabling material demand scenario analysis.

While the overall future scale of fuel cell uptake is subject to significant uncertainty, growth is already taking place in the road transport sector in some countries. In other transportation sectors, such as rail, shipping and aviation, fuel cell technology remains mostly at an early prototype or demonstration project stage. Similarly, hydrogen use in building and for power generation currently plays only a negligible role (IEA, 2022a, 2023a).

1.1 PRINCIPLES OF OPERATION

Fuel cells convert the chemically bound energy in hydrogen into electrical energy and heat. The fuel cell process can be seen as the reverse of electrolysis. In a fuel cell, hydrogen, as a di-hydrogen molecule (H_2), and oxygen (O_2) are recombined; the reaction releases a direct electric current and produces water (H_2O) as a waste product.

A fuel cell system comprises a series of individual fuel cells organised in stacks, together with other ancillary systems including conditioning of fuel, the cooling and power circuits, control technology, safety equipment, etc. (Shell & Wuppertal Institut, 2017). The focus of this study is the fuel cell stack, which is the main demand driver for functional materials in the system. Supporting structural components are excluded.

A typical fuel cell stack consists of membrane electrode assembly (MEA). This comprises two porous, catalyst-doped electrodes (anode and cathode), an electrolyte placed between the two electrodes and a gas diffusion layer. At the anode, hydrogen is split into ions while releasing electrons, which are directed to the cathode. The electrolyte facilitates the transport of electrons between the anode and the cathode while also acting as a separator between the two electrodes. The gas diffusion layer facilitates distribution of inflowing gases as well as the removal of electrons, and processes heat (Shell & Wuppertal Institut, 2017). An overview of a proton exchange membrane fuel cell (PEMFC) is shown in Figure 1.

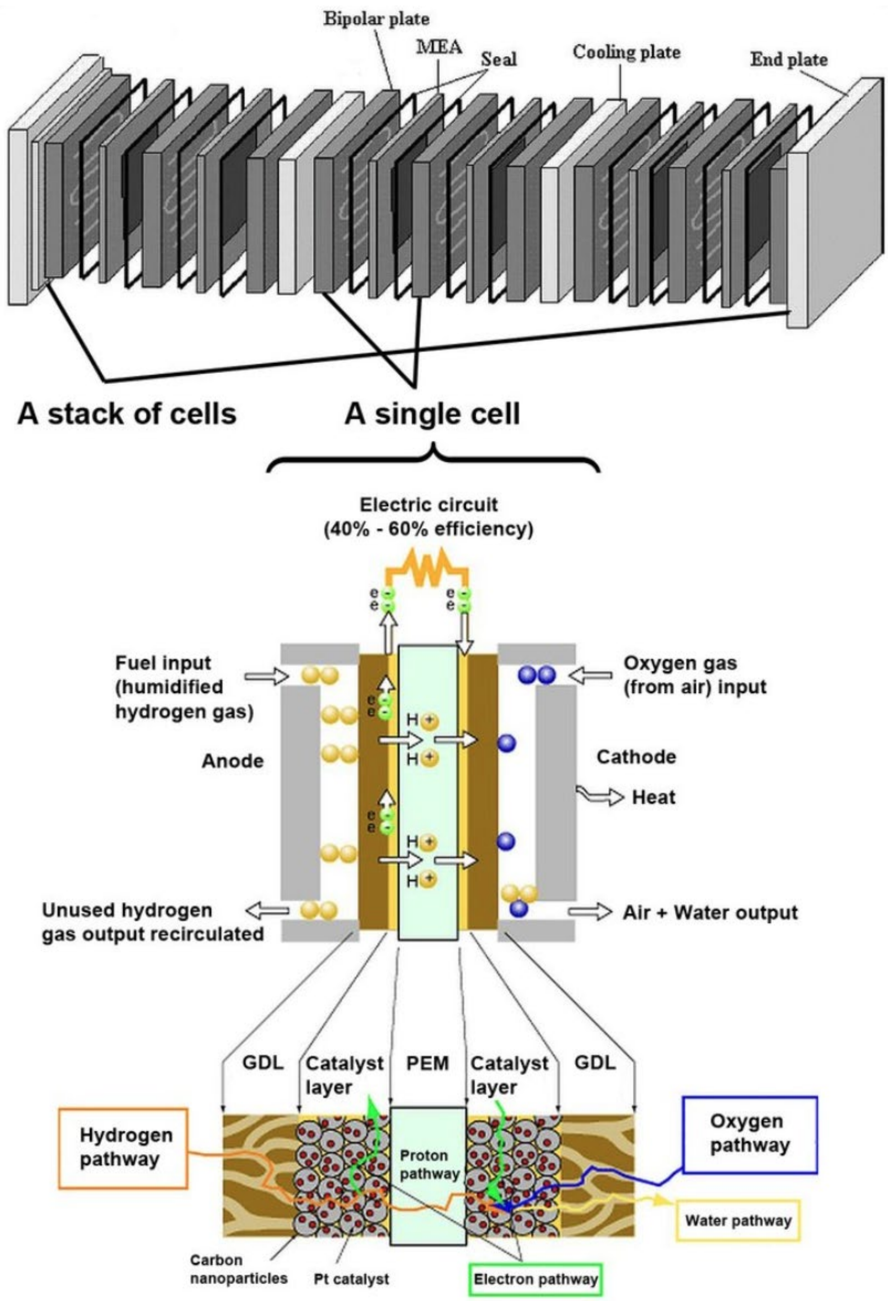


Figure 1 Principles and key components of a PEMFC. From Cuong (2015).

There are five main types of fuel cell technology:

- alkaline fuel cell (AFC)
- proton exchange membrane (or polymer electrolyte) fuel cells (PEMFC)
- phosphoric acid fuel cell (PAFC)
- molten carbonate fuel cell (MCFC)
- solid oxide (or oxide ceramic) fuel cell (SOFC)

The fuel cell types are differentiated mainly by the type of electrolyte materials used and the temperature at which they are operating (Table 1). In general, the higher the operating temperature of the fuel cell, the lower the required purity of the hydrogen used.

The efficiency of the fuel cell depends on various factors including whether it is operated with air or pure oxygen. The overall efficiencies of a fuel cell system increase if it is used in a combined heat and power (CHP) system rather than for electricity generation alone (Shell & Wuppertal Institut, 2017).

Table 1 Key features of different fuel cell types. Adapted from Shell & Wuppertal Institut, (2017).

Fuel cell type	AFC	PEMFC	PAFC	MCFC	SOFC
Temperature range (°C)	60 to 90	50 to 90 (low temperature) up to 180 (high temperature)	160 to 220	600 to 700	700 to 1000
Electrolyte	KOH	Polymer membrane	H_3PO_4	Carbonate melt	Solid ceramic oxide
Electrical performance	Up to 250 kW	From 500 W to 400 kW	Up to several 10 MW	From a couple 100 kW to several MW	From a couple of kW to several MW
Fuel	H_2	H_2, gas, syngas, biogas, CH_3OH (external reforming)	H_2, gas, syngas, biogas, CH_3OH (external reforming)	H_2, gas, syngas, biogas, CH_3OH (internal reforming)	H_2, gas, syngas, biogas, CH_3OH (internal reforming)
Oxidant	O_2 (pure)	O_2	O_2	O_2	O_2
Efficiency η_{el} (H_S)	50 to 60%	30 to 60% (depending on size and application)	30 to 40%	55 to 60%	50 to 70%
Investment costs USD/kW_{el}	200 to 700	3000 to 4000 (stationary); approx. 500 (mobile)	4000 to 5000	4000 to 6000	3000 to 4000
Life expectancy (h)	5000 to 8000	60 000 (stationary;) 5000 (mobile)	30 000 to 60 000	20 000 to 40 000	up to 90 000
Market development	Established for decades; limited to specialised applications	Early market/mature leading fuel cell type	Mature (low volume)	Early market/market introduction (especially for bigger plants)	Mature (volumes rising)
Application	Space travel; submarines	Vehicle drivetrains; space travel; micro & block-type CHP; backup power	Decentralised power generation; block-type CHP	Power plants (base load); CHP (process heat/steam)	Power plants; CHP (process heat/steam); micro & block-type CHP

The AFC is a low-temperature cell that was among the earliest developed for commercial use, with applications dating back to space travel in the 1960s. AFCs have a relatively low investment cost but are inferior to PEMFCs with regards to output and durability (Shell & Wuppertal Institut, 2017).

PEMFCs are the most popular type of fuel cells (EC, 2020) and are considered likely to be a leading fuel cell technology into the future. They also operate at low temperatures and have a small volume and high-power density, making them particularly suitable for mobility applications (Shell & Wuppertal Institut, 2017). They are, however, expensive due to their reliance on platinum (Pt) as a catalyst.

PAFCs are also a mature technology operating at medium temperatures. They are used in low volumes for decentralised power generation (small power plants) due to their high output range of up to several megawatts (Shell & Wuppertal Institut, 2017).

MCFCs and SOFCs operate at high temperatures. MCFCs have high electrical efficiencies and can operate with both pure hydrogen and other hydrogen-containing gases. They are used in small numbers in the power plant sector. SOFCs can operate at few kilowatts to several megawatts. They have high electrical efficiencies but long startup times, making them useful in stationary applications in power plants. SOFCs have long durability and relatively low investment costs and have been considered the second most important fuel cell type after PEMFCs (Shell & Wuppertal Institut, 2017).

Despite advancements in fuel cell technologies in recent years, large-scale domestic or industrial deployment has yet to take place. There are three main areas of application (EC, 2020):

- stationary power generation (67 per cent market share)
- transportation (32 per cent)
- portable power generation (less than 1 per cent)

Currently, PEMFCs and SOFCs dominate the market, both in capacity and number (Carrara et al., 2023). PEMFC technology is expected to be the dominant fuel cell technology used in the road transport sector (DOE, 2022; EC, 2020; Shell & Wuppertal Institut, 2017), whereas SOFCs comprise a high-temperature fuel cell, which is primarily considered for power-grid applications (DOE, 2022). As the focus of this report is on the road transport sector, the supply chain and material demand analysis presented below also focuses on PEMFCs.

1.2 ESSENTIAL COMPONENTS AND MATERIALS

This analysis focuses on the road transport sector, which is expected to predominantly use PEMFC technology. Table 2 summarises the key elements found in PEMFC technologies.

Table 2 Materials used in fuel cell technologies for road transport.

Technology	UK critical elements	Other
PEMFC	Platinum (Pt), palladium (Pd), cobalt (Co), graphite (C)*.	Ruthenium (Ru), iridium (Ir), aluminium (Al), copper (Cu). Polymers, incl. perfluorosulfonic acid (PFSA).

Elements in red are excluded from the detailed analysis because: (i) they are used in structural components; (ii) they are not used in the most common configuration of the technology, or (iii) no bill of materials (BOM) data are identified, likely as only very minor quantities are used. Appendix A has more reasons for exclusions and Appendix E provides an overview of materials used in fuel cell technologies that are not included here.

* Graphite for fuel cells is typically used in synthetic form.

This section is a discussion of the key PEMFC components and materials. An overview of potential fuel cell application in other sectors, which are not within the scope of this analysis, is provided in Appendix C. A brief discussion of the fuel cell technologies not within scope and the types of materials used are provided in Appendix E.

1.2.1 Proton exchange membrane (or polymer electrolyte) fuel cells

PEMFCs are similar to PEM electrolysers, with some variation in design and materials used. The most important fuel cell components are the MEA, which comprises the electrolyte, gas diffusion layers acting as anode and cathode, and the catalyst, and the bipolar plates (BPPs), which separate the MEAs in the fuel cell stack (Carrara et al., 2023).

PEMFCs use a solid polymer membrane and electrolyte, carbon materials for the porous transport layers and bipolar plates, and Pt (or Pt-based alloys) as a catalyst on both the anode and cathode (DOE, 2022).

The most important functional raw material used in PEMFCs is Pt as the main catalyst. Other platinum group metals (PGMs) such as palladium (Pd), ruthenium (Ru) and iridium (Ir) may be used as substitution for Pt in small amounts (Carrara et al., 2023) depending on the application.

The IEA notes a general trend of increased demand for PGMs in fuel cell vehicles in response to the rapid growth in hydrogen use for sustainable development (IEA, 2022b). Their use as alternatives is understood to vary and there is an incentive to limit their use as all are expensive alternatives. All PGMs are on the UK critical materials list (Lusty et al., 2021).

The use of Pt contributes to high material costs (Shell & Wuppertal Institut, 2017) and can account for up to half of the cost of a fuel cell stack (EC, 2020).

An overview of a PEM stack assembly is provided in Figure 2.

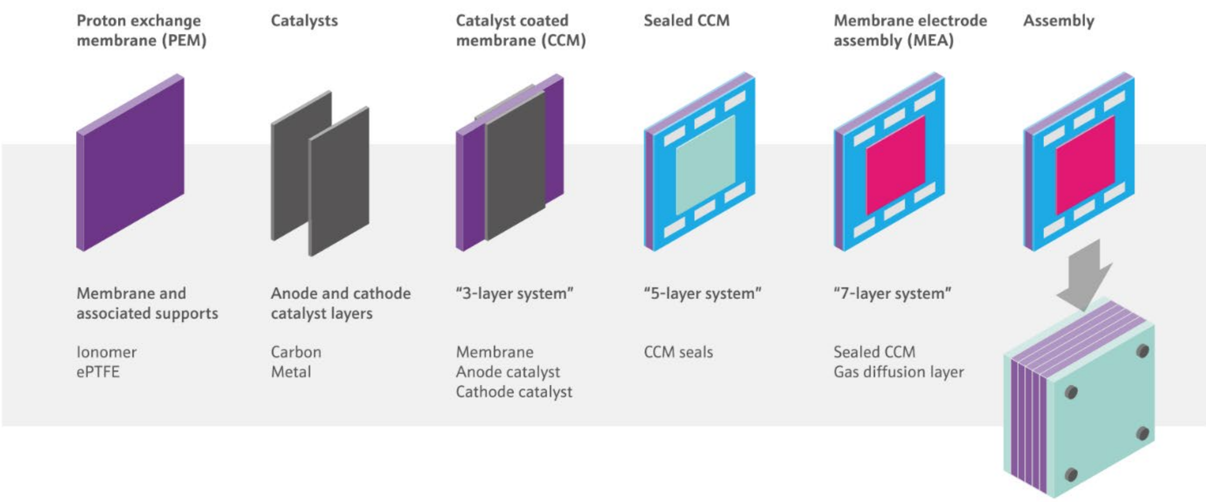


Figure 2 PEM fuel cell components. From Johnson Matthey, 2023a.

The service life of a PEMFC is typically around 5000 hours, which is equivalent to approximately 150 000 to 200 000 km travel distance for a passenger car (Shell & Wuppertal Institut, 2017).

Published life-cycle analyses shed more light on material usage in PEMFCs:

- polymer materials in the electrolyte, including perfluorosulfonic acid (PFSA) polymers such as Nafion®
- carbon fibre and steel in the gas diffusion layer
- Pt and Pt alloys as catalysts
- synthetic graphite or steel in the interconnect layer (also referred to as BPPs in PEMFCs)

(Mori et al., 2021; Stropnik et al., 2019) (Table 3)

Table 3 Materials used in PEMFCs according to Mori et al. (2021).

Component	Material
Electrolyte	PFSA — Nafion® Sulfonated polyether ether ketone (s-PEEK) Polybenzimidazole (PBI) doped with H_3PO_4 (HT-PEM)
Gas diffusion layer (GDL)	Carbon fibres Metallic mesh (steel product)
Catalyst layer	Pt and Pt alloys PTFE (Teflon) (hydrophobic agent) Carbon black (catalyst support)
Interconnect (BPPs)	Graphite Stainless steel
Sealant	Thermoplastic (PTFE) Elastomer (silicone; Viton®; EPDM)

A life-cycle assessment of a PEMFC system indicates that a PEMFC stack contains 4.5 kg of synthetic graphite per 1 kW fuel cell, noting that the BPPs typically contain synthetic graphite, graphite composites or stainless steel. The electrodes are made of carbon cloth or carbon paper in a porous gas diffusion layer (GDL) (Stropnik et al., 2019).

The same source notes that a 1 kW stack contains:

- 300 g aluminium (Al)
- 70 g PFSA (Nafion®)
- 0.75 g Pt
- 100 g chromium (Cr) steel
- 0.8 g carbon black

Mori et al. (2023) reports the use of carbon cloth and carbon black but does not include graphite. Per 1 kW stack, it suggests:

- 0.54 g Pt
- 3 g PFSA (Nafion®)
- 19.79 g copper (Cu)

This is in addition to steel (stainless and Cr-steel) and various polymers. Al is used as a base plate metal and for thermal management of the stack (EC, 2020).

Innovation has substantially reduced the Pt intensity of fuel cells, driven by the need to reduce costs. The IEA (2022b) writes that the first-generation 2014 model Mirai fuel cell electric vehicle (FCEV) used 40 g Pt, which was three-quarters less than in the 2008 prototype. The second generation Mirai reduced Pt use by a further third, while increasing power output from 114 kW to 158 kW. Japan has plans to reduce this further to 5 g per car in 2040. The US Department of Energy has set similar targets. Other sources indicate that current PEMFCs use approximately 0.5 g Pt per kilowatt fuel cell and that cerium (Ce) and Ir are used in very small, unspecified, quantities (Price, 2023).

APC (2021) notes that the use of PGMs in PEMFCs is likely to decrease significantly from the current level of 30 g per fuel cell system (0.3 g/kW, assuming a 100 kW fuel cell). Driven by cost reduction targets, the aim is to reduce the PGM loading to between 6 and 9 g (as low as 0.06 g/kW assuming a 100 kW system per vehicle)Click or tap here to enter text.. Johnson Matthey, a leading UK player in the PEMFC value chain, reports Pt intensities of 45 g per vehicle (weighted loading across all passenger and commercial vehicles) (Johnson Matthey, 2023a). Data provided by Johnson Matthey in relation to this study indicate current Pt loading of about 0.3 g/kW in light vehicles (cars), which can expect to be reduced to 0.12 g/kW in the medium term and 0.08 g/kW in the longer term. In the heavy vehicle sector, loadings are around 0.5 g/kW currently and could be halved to 0.25 g/kW by 2035. These values have been used for the Pt demand estimation (Section 5.3).

The BPPs used in PEMFCs vary in their material composition and may be made from non-porous graphite, polymer carbon (graphite composites) or polymer-metal composites and coated or non-coated metals (Carrara et al., 2023; Tang et al., 2021). The choice of BPP design depends on, amongst others, the fuel cell application. BPPs comprise almost 80 per cent of the PEMFC weight, 50 to 65 per cent of its volume and 40 per cent of the total fuel cell stack cost (Tang et al., 2021).

Tang et al. (2021) focuses on BPP designs for automobile PEMFCs and highlights the importance of low volume and lightweight fuel cell designs for transportation applications, and describes the challenges and compromises related to finding the ideal BPP material composition meeting those needs. It notes that, while the use of graphite has been the established benchmark for BPP manufacturing, metals have been identified as promising alternatives due to their lower cost, high strength, durability, thermal and electrical conductivity, and ease of manufacturing.

However, a major disadvantage of metals in BPPs is that they are corrosive. A solution could be to use non-corrosive metals such as stainless steel, Ni-based alloys, titanium (Ti), zirconium (Zr) and others, but these have high costs, which are a deterring factor. Coating lower-cost metals with these noble, non-corrosive elements may be a more feasible option. Graphite has the advantage that it is not corrosive; on the other hand, it is brittle in its pure form and its weight and volume, as well as manufacturing complexities, can be deterring factors for low-cost commercialisation.

Various solutions have been heavily researched, including the use of graphite-polymer resin composites, which have lower costs and lighter weight than metallic plates. On the negative side, such composites can result in lower electrical conductivity, which can be somewhat alleviated with the use of carbon fillers. It is noted that several types of graphite polymer composites are commercially available and that use of graphitic BPPs is still a viable option for low-cost BPPs. Some graphite composite BPP materials can also be recycled, which is an important feature.

Information about the market proportion of PEMFCs using graphite vs. metal-based BPPs has not been identified in readily available literature. However, to estimate the potential order of magnitude graphite demand associated with the different hydrogen vehicle scenarios, the following has been assumed:

- BPP weight: 0.4 kg/kW (40 kg per 100 kW vehicle fuel cell) (Tang et al., 2021; Wang et al., 2020)
- graphite content in graphite polymer composite BPPs: 80 per cent (resin content: 15 per cent, carbon black: 5 per cent) (Chen Hui et al., 2009)
- share of graphitic BPPs in the market mix: 50 per cent (assuming 50/50 share of graphitic vs. metallic BPPs (assumed fixed with no learning curve, in the absence of more reliable data)
    - resulting in average graphite content per kw PEMFC: 0.4 kg/kW × 0.8 × 0.5 = 0.16 kg/kW (160 g/kW) on average

It should be noted that this estimate is substantially lower than the indicated graphite content in a life-cycle assessment by Stropnik et al. (2019) of 4.5 kg synthetic graphite per 1 kW PEMFC. This quantity appears high given the drive towards low volume and weight fuel cells in the automobile sector.

Cu was indicated to be present in the fuel cell stack in a single identified publication (Mori et al., 2021), whereas most identified literature sources do not consider Cu to be a key functional material in the fuel cell stack (Carrara et al., 2023; DOE, 2022; IEA, 2023a). Although both Cu and Al are used in the peripheral components of the broader fuel cell system, they have been excluded from this analysis because of their relative abundance and diversified supply base. Materials and intermediate products excluded from the analysis are listed in Appendix A.

Based on the aforementioned analysis, the material intensities used for the material demand estimations presented below are summarised in Table 4.

Table 4 Material intensities used for the material demand estimations.

Material	Present (g/kW)	Future (2030) (g/kW)	Future (2050) (g/kW)
Pt (light vehicles)	0.3	0.12	0.08
Pt (heavy vehicles)	0.5	0.25	
Graphite	160		

2 Supply chain mapping of proton exchange membrane fuel cells

The scope of the supply chain mapping and material demand estimation is limited to the application of fuel cells in road transport, which is a sector where significant fuel cell growth can be expected in the near future (EC, 2020) and for which suitable data are readily available in the National Grid FES data (National Grid, 2023a, b). Consequently, the focus is on PEMFCs, which are expected to dominate the transport-related fuel cell market (DOE, 2022). This is in line with Price (2023), which assumes that other stationary and portable fuel cells will have a negligible role in future energy systems due to cost and efficiency barriers.

The fuel cell supply chain comprises the following key stages (DOE, 2022):

- raw material extraction
- material processing
- subcomponent or precursor material manufacturing
- component and product manufacturing
- recovering materials at product end of life

The focus of this study is on the material supply chain leading up to product manufacturing. Post-use recovery of materials has not been included.

The analysis examines materials in the fuel cell stack and excludes other elements of the broader fuel cell system. Pt and graphite were selected for detailed mapping as these are key functional elements used in most PEMFCs. It is understood that synthetic graphite is the dominant form of graphite used (Stropnik et al., 2019) although natural graphite may also be used (Planes et al., 2012). Synthetic graphite is made from petroleum (needle) coke (largest part) and coal-tar pitch or oil, which are not as such scarce but are by-products of the oil refining and steel industries, respectively.

Figure 3 shows the different stages of the PEMFC supply chain, the key material transformations that take place at each stage for the selected materials and the connections of these materials to relevant functional components.

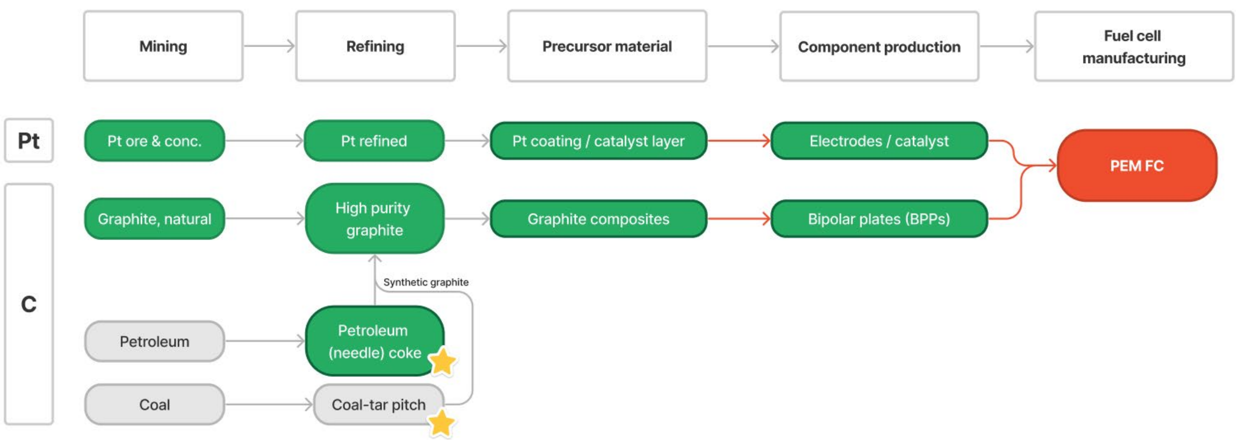


Figure 3 Simplified supply chain mapping for Pt and graphite, which is typically synthetic but may in some cases be derived from natural sources used in PEMFCs. The green shading indicates materials that have been included in the quantitative analysis of supply chain bottlenecks and/or estimation of future material demand. BGS © UKRI.

3 Supply chain bottlenecks

An overview of the global production and trade concentrations for Pt and graphite are shown in Figure 4.

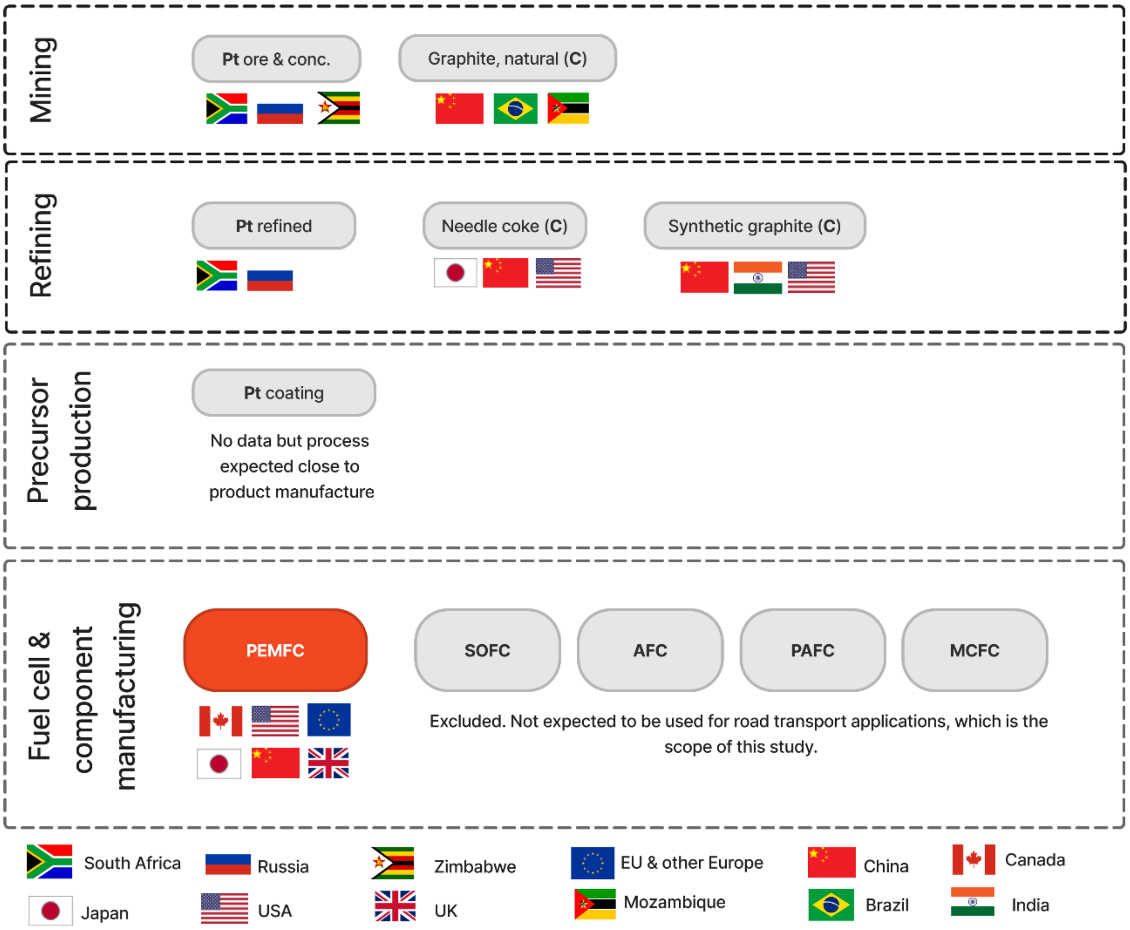


Figure 4 Geographical production concentrations in the fuel cell supply chain. At the mining stage, the national flags show the top three producers, from left to right, based on quantitative data from the BGS World Mineral Statistics Database (BGS, 2023). At the fuel cell component and cell manufacturing stage, the flags highlight the location of selected key producers, but their order does not reflect their respective market share. Data compiled and interpreted from numerous sources including: Carrara et al., 2023; DOE, 2022; Fortune Business Insights, 2021, and company websites. AFC: alkaline fuel cell; MCFC: molten carbonate fuel cell; PAFC: phosphoric acid fuel cell; PEMFC: proton exchange membrane fuel cell; SOFC: solid oxide fuel cell. BGS © UKRI.

3.1 MINING AND REFINING

3.1.1 Production concentration

At the mining stage, two materials were considered: Pt and natural graphite.

The global production of Pt is derived from three main countries(Figure 5):

- South Africa (more than 70 per cent of the total)
- Russia (12 per cent)
- Zimbabwe (8 per cent)

Mining of natural graphite is also heavily concentrated, with 64 per cent of global production in China, followed by 8 and 6 per cent in Brazil and Mozambique, respectively.

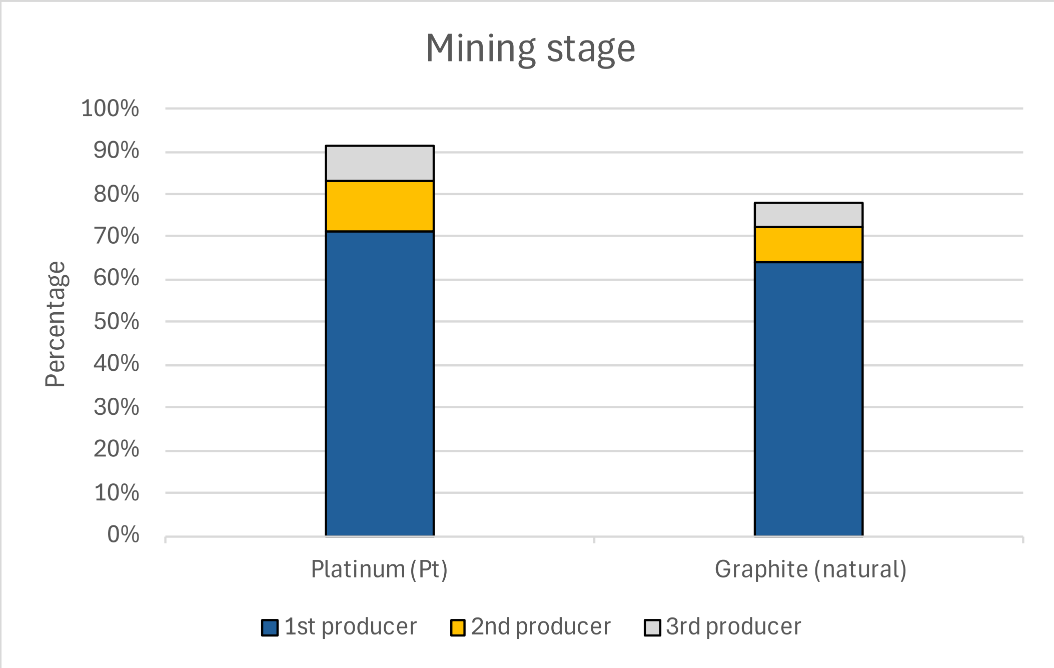


Figure 5 Global mine production of Pt and natural graphite, showing the production shares of the top three producing countries (based on five-year production average, 2017 to 2021). Data from the British Geological Survey World Mineral Statistics Database (BGS, 2023). BGS © UKRI.

Data on the production of refined Pt is not available in the public domain. However, production data for synthetic graphite and its key precursor needle coke have been obtained from Benchmark Mineral Intelligence and are reflected here with their permission (Figure 6).

Production of both needle coke and synthetic graphite is highly concentrated in the top three producing countries. Japan is the largest producer of needle coke (33 per cent), followed by China (22 per cent) and USA (22 per cent). Synthetic graphite is mostly produced in China (55 per cent) followed by India (10 per cent) and Japan (7 per cent).

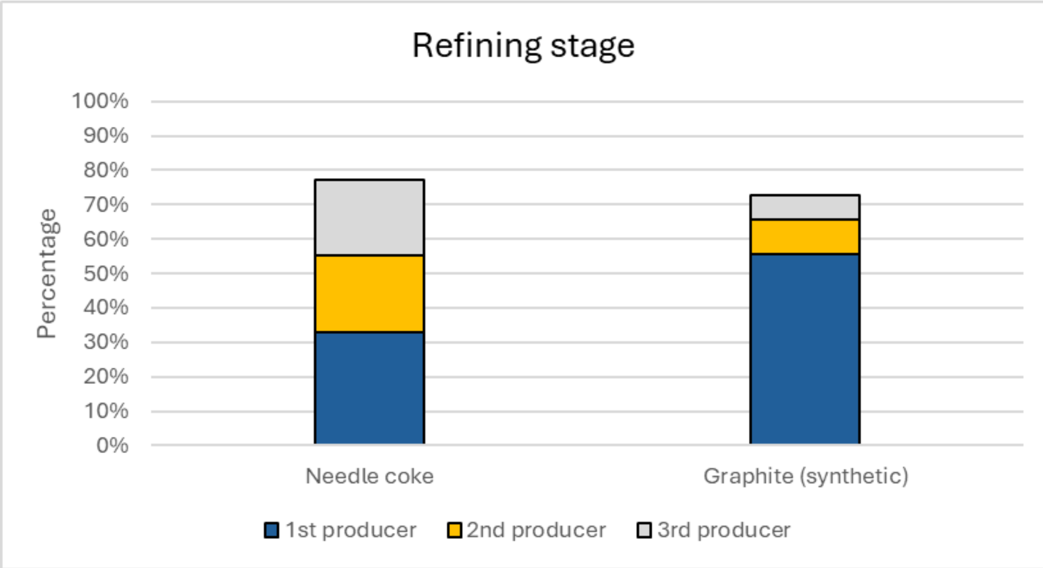


Figure 6 Global production shares of synthetic graphite and its key precursor, needle coke, showing the production shares of the top three producing countries (based on five-year production average, 2017 to 2021). Data from *Benchmark Mineral Intelligence.* BGS © UKRI.

Based on the indicator recommended in the revised methodology for the UK criticality assessment (Josso et al., 2023), the ranked production concentration scores have been determined for Pt, natural graphite, synthetic graphite and needle coke (Figure 7). The highest scores are for Pt (5.6) and natural graphite (4.8). Synthetic graphite and needle coke have lower scores (3.9 and 2.3, respectively). The relatively high value for Pt and natural graphite is derived from the concentration of production shares in three countries, all of which have low environmental, social and governance (ESG) scores.

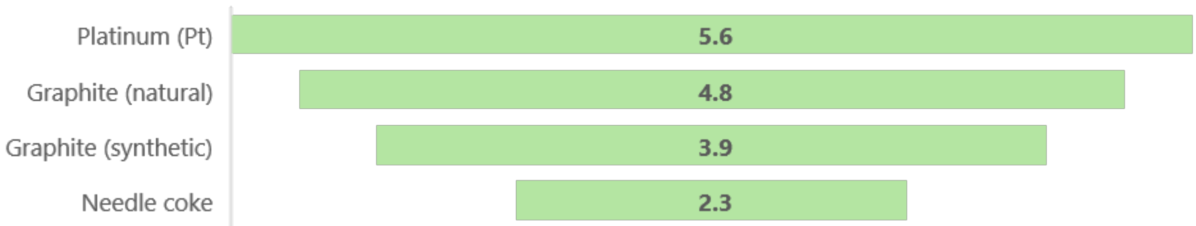


Figure 7 Ranked production concentration score (1 to 10) for key functional materials used in PEMFC technologies; Pt, natural graphite, synthetic graphite and needle coke, based on ESG-weighted Herfindahl–Hirschman index for the top three producing countries. Pt and natural graphite are of the highest concern as mining is highly concentrated in countries with relatively poor ESG scores. BGS © UKRI.

Johnson Matthey (2023a) notes that Pt mining and refining is concentrated with a small number of large, publicly quoted companies that are subject to stringent regulation and regularly report on their ESG performance. This contrasts with unregulated, commonly illegal metal production from ‘artisanal’ mining found in some other sectors. Despite their location and sometimes challenging working environment (for example, due to unstable energy supply) outputs from Pt mining operations have been resilient for over two decades.

In terms of PGM supply, Johnson Matthey (2023a) also makes the point that almost 25 per cent of Pt annually supplied to the market consists of recycled metal. In addition, substantial amounts of Pt are circulating in a ‘closed loop’ where they are not consumed in day-to-day operations but continue to be used in a non-dispersive manner (Hagelüken & Goldmann, 2022). While this reduces the demand for primary materials, these flows are largely invisible to the market. This is noted to be particularly important for Ir, where substantial amounts of Ir used in catalysts circulate in a closed loop and are not reported in supply and demand figures (Johnson Matthey, 2023a).

3.1.2 Global trade concentration and trade restrictions

As with Pt and natural graphite’s production, their trade is also geographically concentrated and subject to trade restrictions imposed by some nations. Trade concentrations for Pt and graphite (both natural and synthetic) have been calculated from UN Comtrade data (UN Comtrade, 2023) using five-year averages for 2017 to 2021 for imports and exports. Trade data for refined Pt (HS 711011), mined natural graphite (HS 250410) and artificial graphite (HS 380110) were utilised on account of their relevance to fuel cells (Table 5).

Table 5 Materials included in the analysis of trade concentration based on UN Comtrade data.

HS code	Description	Stage
711011	Metals; platinum, unwrought or in powder form	Mining
250410	Natural graphite in powder or flakes	Mining
380110	Artificial graphite	Precursor production

An overview of the trade concentrations for the included materials is provided in Figure 8. Trade in refined Pt is moderately concentrated, with 31 per cent of total imports and 25 per cent of global exports accounted for by the top three trading countries. The largest importer of Pt is China (16 per cent) and the largest exporter is Italy (10 per cent). Russia and South Africa, which have the second and third largest net Pt exports, impose export restrictions. Russia has several restrictions depending on the exact type of export, including domestic market obligation, licencing requirements and restriction on customs clearance point for exports. South Africa applies a licencing requirement in the form of application for export approval from the South African Diamond and Precious Metals Regulator (OECD, 2022a, b).

Trade in natural mined graphite is not particularly concentrated, with the largest net importing country being Canada (12 per cent), followed by Japan and India (10 and 9 per cent, respectively). China is the largest exporter of mined graphite, with 31 per cent of global exports, followed by Madagascar and Mozambique with 13 and 12 per cent, respectively. Trade in synthetic (artificial) graphite is somewhat more concentrated, with Malaysia the largest importer (34 per cent) followed by the USA (5 per cent) and Japan (4 per cent). China dominates exports of synthetic graphite with 45 per cent of global exports, with Russia and Norway following with 3 and 2 per cent of global exports, respectively.

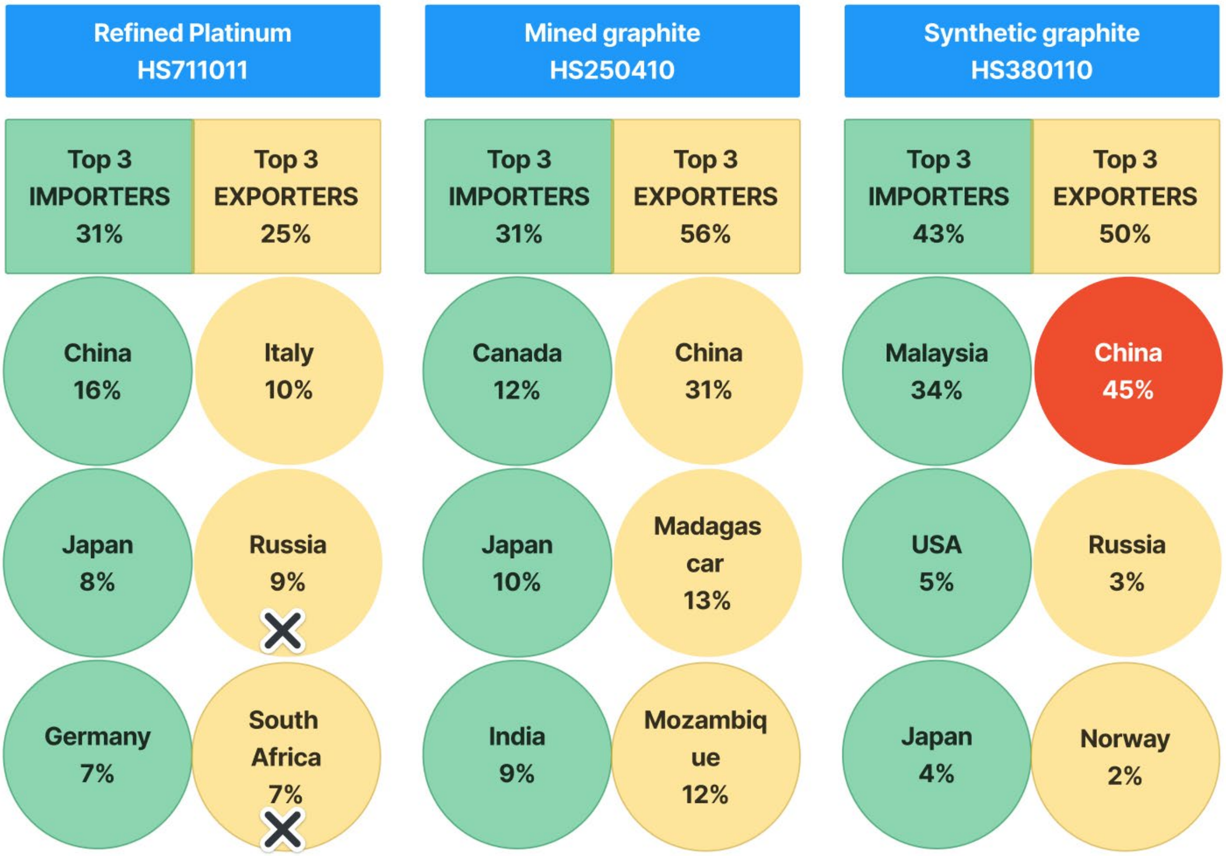


Figure 8 The top three net importing and exporting countries for refined Pt, natural graphite and synthetic graphite. Countries with a cross have active trade restrictions. Data on trade flows compiled from UN Comtrade (2023) based on 2017 to 2021 data, and active trade restrictions based on OECD (2022a) and associated dataset for the year 2021 (OECD, 2022b). BGS © UKRI.

3.2 COMPONENT AND PRODUCT MANUFACTURE

Fuel cells are a nascent technology with demand for PEMFCs currently relatively low (DOE, 2022). It is therefore difficult to acquire quantitative data at a national scale for component and product manufacture. Generally, only qualitative data are available for the main manufacturing countries.

Companies headquartered in Europe and the USA appear to have a substantial share of fuel cell stack and associated component production, although wider fuel cell system assembly largely takes place in Asia, where most fuel cell vehicle manufacturing takes place.

A material demand forecast study by the EU (Carrara et al., 2023) notes that the largest manufacturers and suppliers of fuel cell components are North America (44 per cent) and Asia (33 per cent), with the EU third (25 per cent) (based on 2019 data). Most companies produce only one component and there is little integration in the fuel cell value chain (both PEMFCs and SOFCs). An exception is the manufacturing of MEAs, which may be manufactured by those who produce the membrane and catalyst materials. A key European actor in this regard is UK-based Johnson Matthey, which is amongst the top two producers of PEMFC MEAs globally (Carrara et al., 2023).

In 2020, 85 per cent of fuel cell systems (in megawatts) were manufactured in Asia, much of it related to the production of passenger fuel cell vehicles by Toyota (Japan, 33 per cent of global fuel cell stocks) and Hyundai (South Korea), whereas China dominates in the bus and truck fuel cell vehicle segments. Some fuel cell manufacturing takes place in the USA, although their main focus is on stationary fuel cells.

Fuel cell system manufacturing remains at a low level in Europe. It accounts for only 12 per cent of global fuel cell manufacturing and is spread across numerous companies, many of which are at the early commercialisation or demonstration project stage. Several leading fuel cell technology suppliers have headquarters in Europe but engage in the fuel cell market elsewhere: examples include Bosch (Germany), Ceres (UK) and Elcogen (Estonia) (Carrara et al., 2023).

A study by the US Department of Energy (DOE, 2022) finds that the PEM industry (for both electrolysers and fuel cells) consists of relatively few suppliers, many of which are large companies (such as 3M, Dupont and Cummins) where fuel cells and electrolysers comprise only a small proportion of their business. Some of the larger PEMFC manufacturers (for example, Ballad Power in Canada) produce most of the subcomponents (electrolyte membranes; GDLs; BPPs), whereas others produce one or two components in-house. To date, few corporations have the capacity to produce fuel cell components and finished products at significant volumes, as the market and manufacturing capacities are still in the early phases of scaling (DOE, 2022). DOE (2022) also contains an overview of selected PEMFC and component manufacturers (see Appendix B).

In terms of individual PEMFC components, the following key points are pertinent to this study (DOE, 2022):

- BPPs: Europe and Asia currently hold the lead in BPP technology. Ultimately, BPPs are expected to be manufactured close to fuel cell system assembly
- catalysts: Umicore and Johnson Matthey (Europe) and Tanaka (Japan) are the world leaders in FC catalyst technologies. This is likely to continue due to the long lead times in building capacity in this area
- GDLs: four main players dominate the market: SGL and Freudenberg (Germany), Toray (Japan) and AvCarb (USA)
- membranes: USA has the global lead in membrane technology, although Europe and Asia are also strong. Large-scale production of membrane polymers may, however, be found in Asia, chiefly in China

According to a market insight report by Fortune Business Insights (2021), the PEMFC market is diversified with many smaller players. Two players, Ballard Power systems and W.L. Gore and Associates, seem to have reached significant scale in the global market, noting for example that Toyota procures fuels for its Mirai fuel cell car from W.L. Gore and Associates.

A report by the IEA on hydrogen patenting trends (IEA, 2023b) notes that the European chemical industry dominates innovation in established hydrogen technologies, whereas companies from the automotive and chemical sectors working with electrolysis and fuel cell technologies lead in new hydrogen innovation. Since 2001, the automotive use of hydrogen has received most international patenting applications compared to all other uses of hydrogen combined, with annual patent growth of 7 per cent in the past decade.

In terms of integration of fuel cell technology for automotive propulsion, the top four patent applicants are automotive original equipment manufacturers (OEMs) from Japan and Korea. The top 10 also includes two US-based and two German automotive OEMs, and one of their key suppliers (Bosch) (IEA, 2023b).

A foresight study by the European Commission (EC, 2020) concludes that, despite the high risk for the supply of key materials, the greatest supply chain vulnerability for fuel cells relates to the fuel cell assembly step, where the USA, Canada, Japan and South Korea dominate manufacturing. Less than 1 per cent of fuel cell assembly is undertaken in the EU.

4 UK supply chain in fuel cell technology

A key PEMFC player in the UK is Johnson Matthey, a British multinational company active in chemicals processing and sustainable energy technologies. Operations include production of:

- emission control and industrial catalysts
- process technologies
- fine chemicals and chemical products
- coatings
- fuel cell and battery technologies

According to the company, it is the only MEA supplier that also produces catalysts and membrane technologies in-house (Johnson Matthey, 2024). In 2021, plans were announced for new capacity at its plant in Swindon, UK, where the company will be able to manufacture fuel cell components, catalyst-coated membranes, MEAs and fuel processor catalysts (Fortune Business Insights, 2021).

Ceres is a UK-based (West Sussex) clean energy technology company with a global presence. It specialises in developing solid oxide electrolysers to produce green hydrogen and SOFCs (Wood & Optimat, 2022). According to the company website, the company maintains a strong research and development programme and licences the intellectual property for cells and stacks to manufacturing partners who hold manufacturing and marketing capabilities.

Wood & Optimat (2022), which is a report by BEIS, ‘Supply chains to support a hydrogen economy’, estimates the potential future scale of economic activity in manufacturing fuel cells based on National Grid transport-related fuel cell demand scenarios. It estimates a required fuel cell-related turnover of close to £15 billion up to 2050 to deliver the ‘System transformation’ scenario (the most ambitious scenario). It concludes that the UK supply chain is expected to win a share of this, but it is not clear how large that share will be. In terms of current fuel cell for transportation supply chain capabilities, it states that manufacturing of fuel cells has not been established in the UK yet, creating both a barrier and a future opportunity (Wood & Optimat, 2022).

5 UK future demand

5.1 SCENARIOS AND MODELLING CONDITIONS

The UK demand for materials embodied in fuel cells used in road transport has been estimated for each of the four scenarios for build-up of PEMFC capacity (gigwatts) in the UK up to 2050 based on National Grid FES data for hydrogen fuel cell vehicles (National Grid, 2023a, b).

It should be noted that road transport only makes up a small share of the potential total demand for hydrogen in the UK as reflected in the National Grid scenarios. In terms of cumulative hydrogen demand up to 2050, road transport demand ranges from about 2 per cent ('Leading the way') to 10 per cent ('System transformation') of the total hydrogen demand. The cumulative hydrogen demand across sectors until 2050 based on the National Grid scenarios is shown in Figure 9.

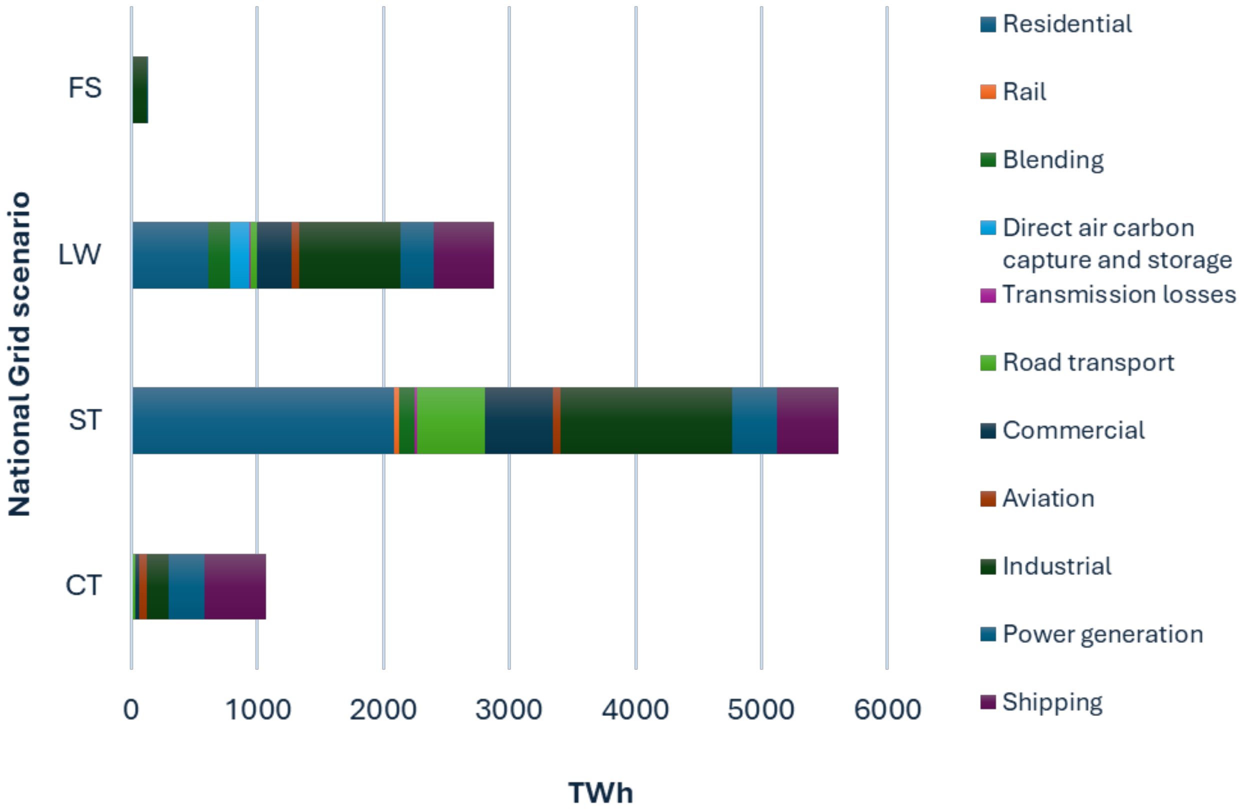


Figure 9 Cumulative hydrogen demand in terawatt hours per sector in the four National Grid FES. FS: 'Falling short'; LW: 'Leading the way'; ST: 'System transformation'; CT: 'Consumer transformation' (National Grid, 2023a, b). BGS © UKRI.

It is also important to note that not all sectors using hydrogen will rely on fuel cells for converting the hydrogen to useful energy (electricity or heat); this may also involve direct combustion or transformation into other chemical derivatives of hydrogen. No data are readily available on the potential mix of fuel cells versus other conversion technologies in the overall market mix. The

National Grid FES include data on the number of hydrogen road transport vehicles by type, where it can be assumed that the dominant hydrogen-conversion technology will be fuel cell electric based and mostly PEMFC type.

In other mobility sectors, such as rail, shipping and aviation, hydrogen technology application is less mature than in cars and may consist of a mix of fuel cells and gas combustion technologies. Power generation is another sector where the use of stationary fuel cells can be expected, although there is little data on the potential technology market mix. The main residential demand for hydrogen is expected to be in hydrogen boilers.

Based on data availability and assessment of the likely relevance of fuel cells across different sectors, this analysis deals only with road transport. The rationale for excluding other sectors contributing to hydrogen demand is summarised in Appendix C. Expanding the current analysis to include other sectors should be considered at a later stage, as hydrogen end-use development trends and associated data become more visible.

The National Grid FES reports (National Grid, 2023a, b) include data on the number of different types of hydrogen vehicles in use (on the road) up to 2050. The ‘System transformation’ scenario assumes the highest number of hydrogen vehicles, almost 3.5 million, on the road by 2050. This includes cars, vans, buses, heavy goods vehicles (HGVs) and motorbikes (Figure 10).

The number of hydrogen vehicles on the road was used to calculate the annual net addition of vehicles to stock, in terms of number of vehicles. This approach does not explicitly take into account the effect of end-of-life vehicles flowing out of the system, as the underlying data are not available. Accordingly, the estimation should be regarded as conservative relative to the overall vehicle demand.

To determine the total installed fuel cell capacity required for the hydrogen electric vehicles in each of the National Grid scenarios, assumptions were made regarding the fuel cell capacity per vehicle (in kilowatts) as shown in Figure 11. The Advanced Propulsion Centre (APC) indicates that a typical fuel system in a car or van is in the range of 80 to 120 kW (APC, n.d.), which is similar to assumptions in other sources (FleetNews, 2023), so 100 kW/vehicle for cars and vans has been used in the calculations. The IEA notes that trucks require three times more power than cars (IEA, 2022b), hence 300 kW per bus and per HGV has been assumed and validated in expert interviews.

No data were identified for motorbikes. Accordingly, 20 kW per motorbike was assumed based on the weight of a motorbike being about one fifth of that of a car.

Based on these assumptions, the installed fuel cell capacity in UK hydrogen vehicles on the road would be about 17 GW in 2035 and 380 GW in 2050 in a high (‘System transformation’) scenario. For comparison, the APC has forecast demand for fuel cells in the UK to be around 14 GW by 2035, equivalent to 140 000 vehicles (Price, 2023).

In terms of the market mix of different fuel cell technologies, it is assumed that PEMFCs will be the dominant technology used for road transport. This is in agreement with other sources, such as Wood & Optimat (2022), which states that PEMFCs are generally favoured for transport applications due to their fast start-up times and other characteristics.

Material intensities for PEMFCs reflect Pt and graphite as shown in Table 4. Pt is the key functional element typically used as a catalyst in the PEMFC stack and graphite is frequently used in the bipolar plates. Assumptions on material intensities have been informed by a literature review and interviews with industry stakeholders, as indicated in previous sections.

The overall modelling logic for estimating material demand associated with fuel cells in road transport is outlined in Figure 12.

Figure 10 Number of hydrogen fuel cell vehicles on the road in the UK according to four National Grid FES scenarios. (National Grid, 2023a, b.) BGS © UKRI.

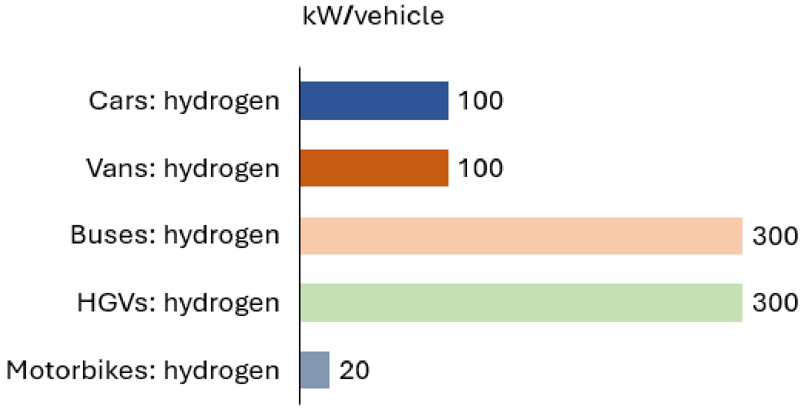


Figure 11 Assumed fuel cell capacity per vehicle used in the material demand estimations. BGS © UKRI.

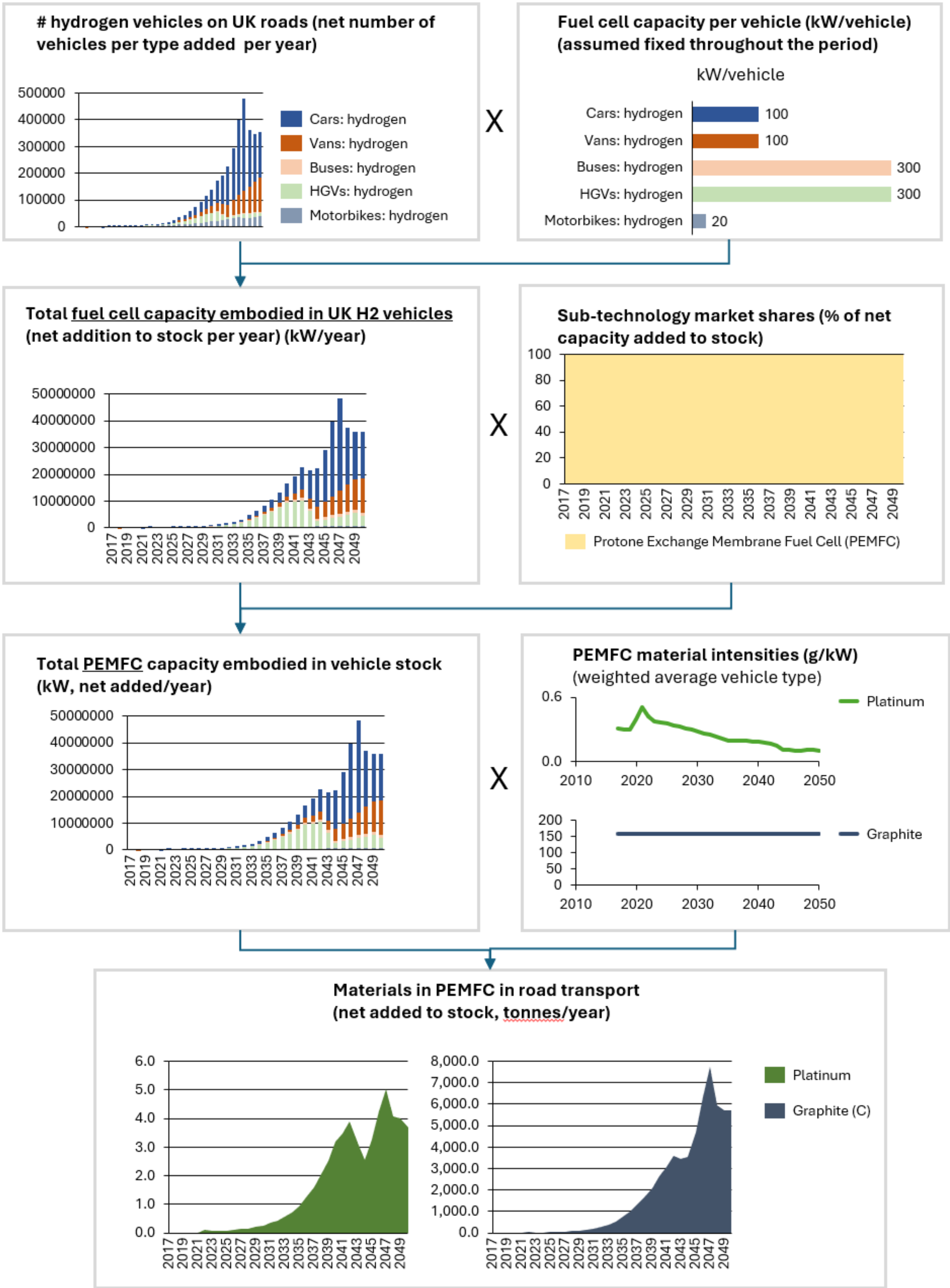


Figure 12 An outline of the modelling logic applied to estimate the embodied material demand for each of the National Grid scenarios for fuel cells installed in road vehicles. From top to bottom: the net number of fuel cell vehicles added to stock is multiplied by fuel cell capacity per vehicle (in kW). It is assumed that all fuel cells are PEMFC type. The installed fuel cell capacity in kW is then multiplied by material intensities in g/kW, resulting in an estimate for net annual material demand. BGS © UKRI.

5.2 FUTURE UK RAW MATERIAL NEEDS FOR FUEL CELLS

The future demand in the UK for Pt embedded in road vehicle fuel cells is presented in two ways:

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

The forecasts in Figure 13 show the cumulative UK Pt and graphite demand until 2050 related to fuel cells in road transport. Annual demand has also been quantified to illustrate temporal fluctuations (see Appendix D).

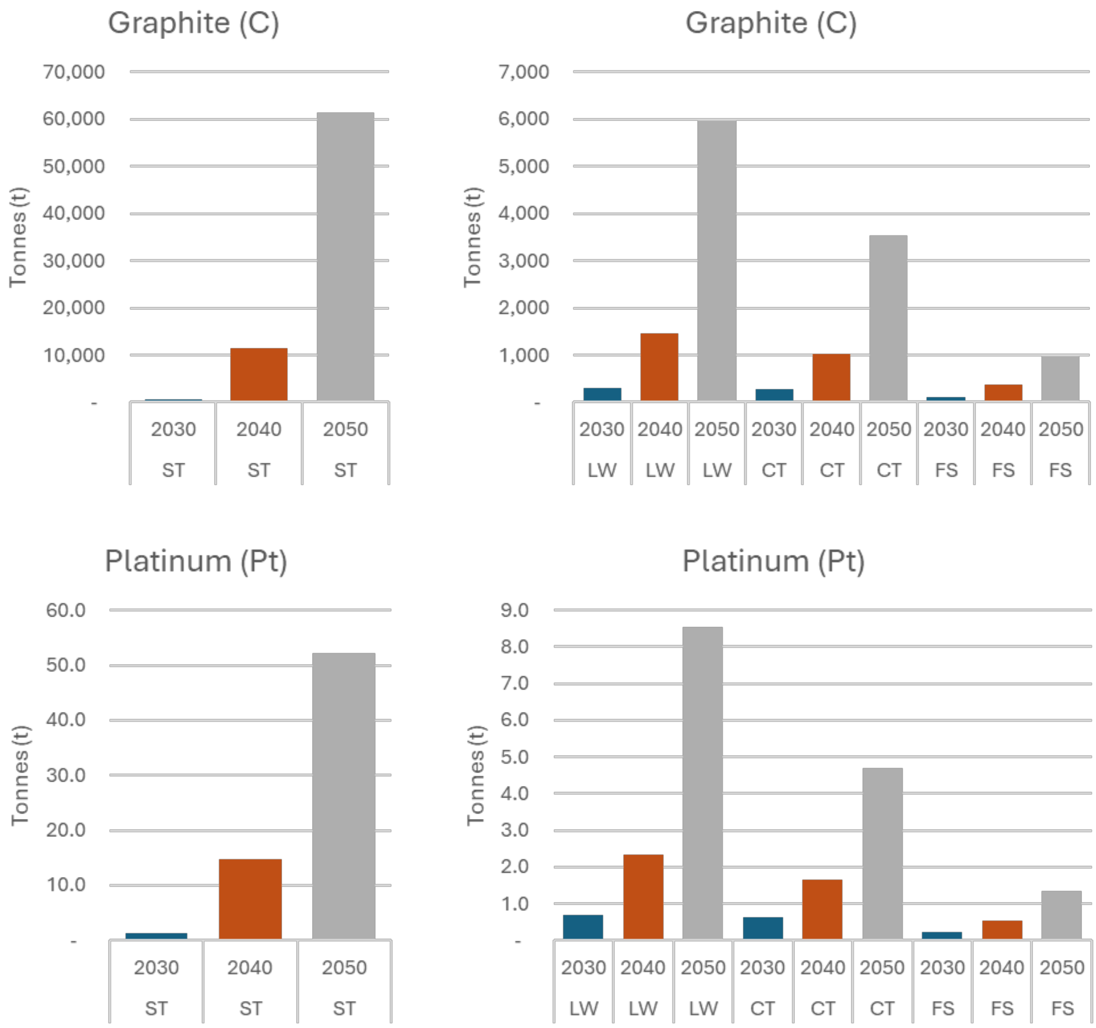


Figure 13 Cumulative forecast UK road transport-related fuel cell demand (tonnes) for graphite and Pt until 2050 under four different scenarios: ST: 'System transformation'; LW: 'Leading the way'; CR: 'Consumer transformation'; FS: 'Falling short'. BGS © UKRI.

To provide context for the estimated UK material demand, Table 6 shows the annual global Pt production for the five-year period 2017 to 2021 compared with the UK cumulative demand until 2050, and the peak UK annual demand in a 'System transformation' scenario, based on the model estimates.

Table 6 Global Pt and natural graphite production (five-year average, 2017 to 2021) compared with UK cumulative material demand for fuel cells in the 'System transformation' scenario (data from BGS (2023)). UK peak annual demand for the same scenario is also shown (peak year in brackets).

Element	Global annual production (5-year average) (tonnes)	UK cumulative demand in 2050 ('System transformation' scenario) (tonnes)	UK peak annual demand in 2020-2050 ('System transformation' scenario) (tonnes (*year*))
Pt (metal)	184	52.1	5.0 *(2047)*
Graphite*	1 125 388	61 332	7745 *(2047)*

* Natural graphite; data for synthetic graphite are not readily available.

Figure 14 shows the estimated annual UK material demand in high ('System transformation') and low ('Falling short') scenarios as a percentage of global annual production (Table 6).

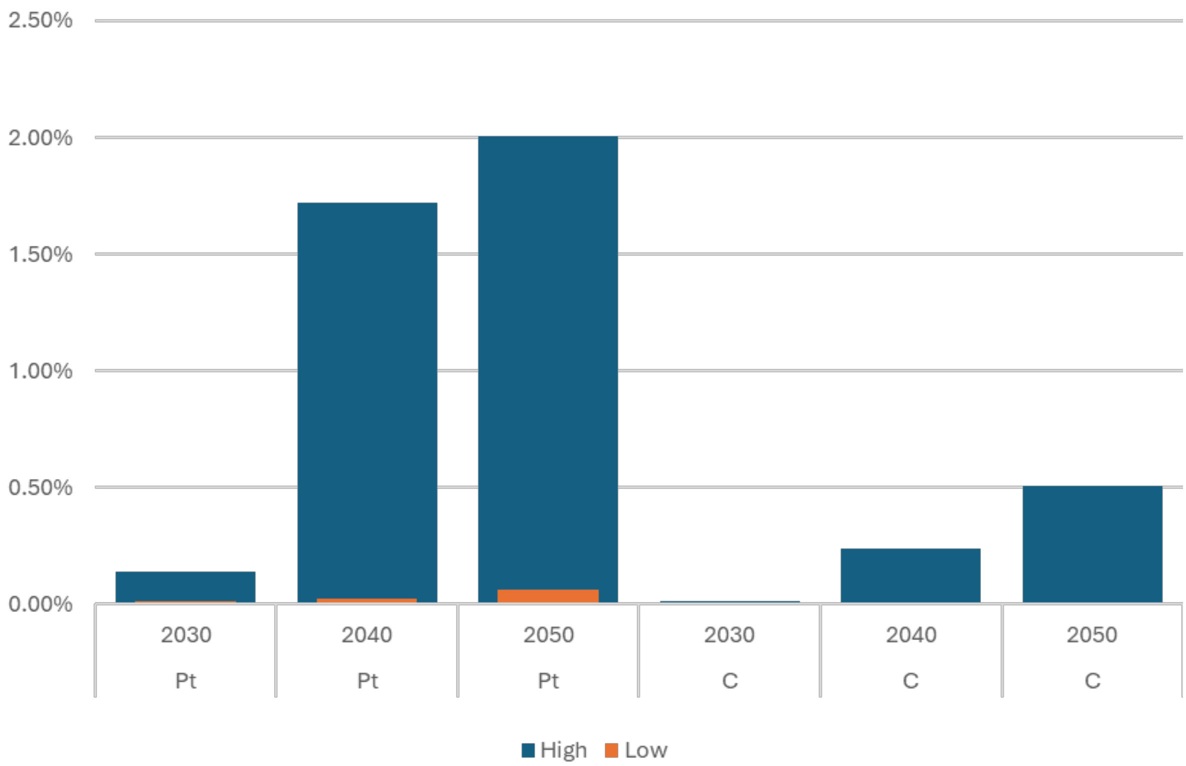


Figure 14 The estimated annual UK demand for Pt and graphite (C) in fuel cells used in road vehicles in 2030, 2040 and 2050 as a percentage of current global annual production (as reflected in Table 6). The lower values (orange) reflect demand in the 'Falling short' scenario and the higher value (blue) demand in the 'System transformation' scenario. BGS © UKRI.

Figure 14 indicates that annual UK road transport-related fuel cell Pt demand in a high scenario may increase to approximately 2 per cent of current global annual Pt production in 2050. Peak annual demand will occur in 2047, when the net addition of new hydrogen vehicles on the road is highest; this will equate to 2.7 per cent of current global Pt production.

The corresponding cumulative Pt demand in a high scenario (Figure 13) is:

- 1.2 t by 2030
- 14.8 t by 2040
- 52.1 tonnes by 2050

In the other three scenarios, the cumulative UK demand up to 2050 is well below 10 t. Annual graphite demand in a high scenario indicates a small fraction of global production of natural graphite, equivalent to approximately 0.5 per cent in 2050.

These estimates for Pt appear aligned with those of Price (2023), which indicates a cumulative Pt demand for vehicle-related fuel cells of about 7 t of fuel cells by 2035. The same study also concluded that existing supply chains (mine production and recycling) should be able to comfortably meet forecast demand for PEM-related Pt scale-up.

The relatively low share of fuel cell Pt material demand as a fraction of global supply is reasonable, because:

- transport-related fuel cell technology represents only a small share of the overall fuel cell and hydrogen economy
- Pt is also used in many other technologies, chiefly autocatalysts, which are outside the scope of this study (Figure 15)

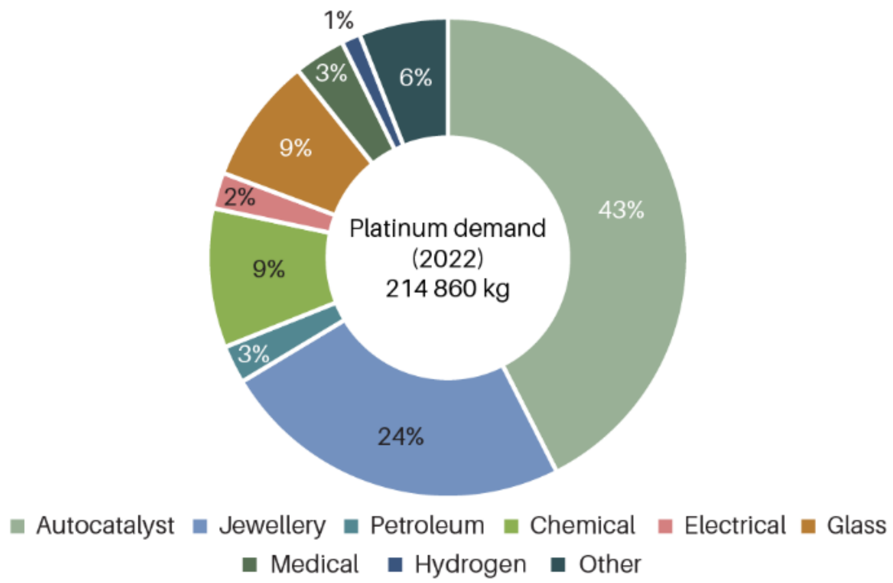


Figure 15 Global Pt demand by sector in 2022 (Price, 2023)

The future fuel cell Pt demand estimates should also be considered in the context of global demand for Pt used in autocatalysis, which was over 91 t in 2022, corresponding to 43 per cent of global Pt demand (Price, 2023).

Rasmussen et al. (2019) analyses global dynamic material flows of Pt across different scenarios, highlighting the impact of different developments in vehicle technology uptake on Pt demand. For example, the dominance of electric vehicles would reduce Pt demand substantially as autocatalyst demand dropped. In contrast, significant uptake of hydrogen fuel cell vehicles would substantially increase Pt demand. It is noted in all the analysed scenarios up to 2050 that increased use of Pt due to fuel cell demand will make up for and eventually exceed the decrease resulting from the phasing out of petrol and diesel engines (Rasmussen et al., 2019).

Forecasts by Johnson Matthey indicate that 70 to 80 per cent of Pt consumption for hydrogen applications will be for FCEVs, with 20 to 30 per cent used for electrolytic purposes (Johnson Matthey, 2023a).

5.3 UK DEMAND PROJECTIONS VS. GLOBAL DEMAND

Increasing fuel cell capacity in the UK will be dependent on global supply chains for key components and materials. It is therefore important to consider the UK demand in the context of anticipated global demand for fuel cells and associated key functional materials.

It must be noted that there is considerable uncertainty when it comes to predictions of future fuel cell vehicle demand, especially beyond 2030.

IEA (2023c) reports that there were 72 000 hydrogen FCEVs on the roads globally in 2022, a 40 per cent increase from the 51 000 vehicles in 2021. Of the FCEVs, about 80 per cent are cars, 10 per cent trucks and 10 per cent buses.

Samsun et al. (2022) provides perspectives on the global development of fuel cell vehicle deployment based on a review of roadmaps, targets and plans in numerous countries.

To produce global fuel cell-related material demand projections comparable with those made for the UK, the global demand was modelled using historic IEA figures (IEA, 2023c) and the worldwide fuel cell vehicle estimates provided by Samsun et al. (2022). This assumes a linear ramp-up of FCEV numbers between 2030 and 2050. As the global data do not reflect motorbikes, these have been excluded, while light commercial vans are assumed to be included in the car data. The derived timeseries is shown in Figure 16. For comparison, the National Grid 'System transformation' scenario assumes 3.5 million FCEVs on the road in the UK in 2050 (Figure 10).

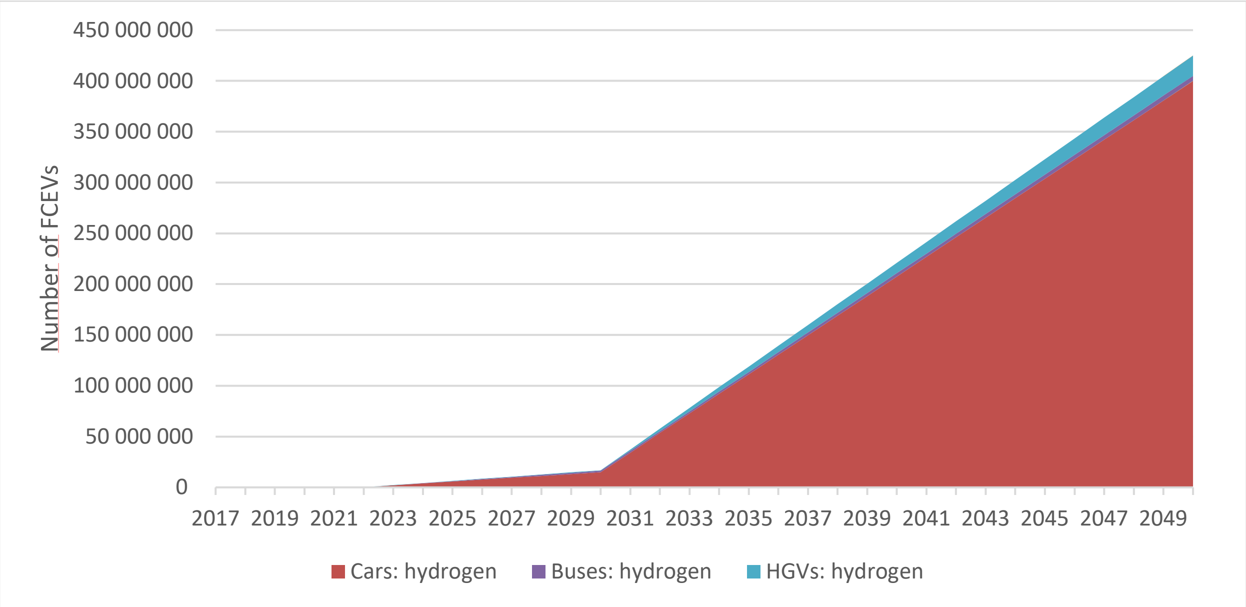


Figure 16 Assumed development of the number of FCEVs on the road globally up to 2050. Data based on IEA (2023c) (historic) and Samsun et al. (2022) (future). . BGS © UKRI.

For simplicity, all other modelling parameters and assumptions were kept the same as for the UK estimations (fuel cell capacity per vehicle; dominance of PEMFC; material intensities). However, it is important to note that these are subject to many uncertainties and may differ between regions.

Figure 17 shows the calculated UK cumulative vehicle fuel cell-related demand for Pt and graphite compared with the calculated global demand, based on the selected global ramp-up scenario.

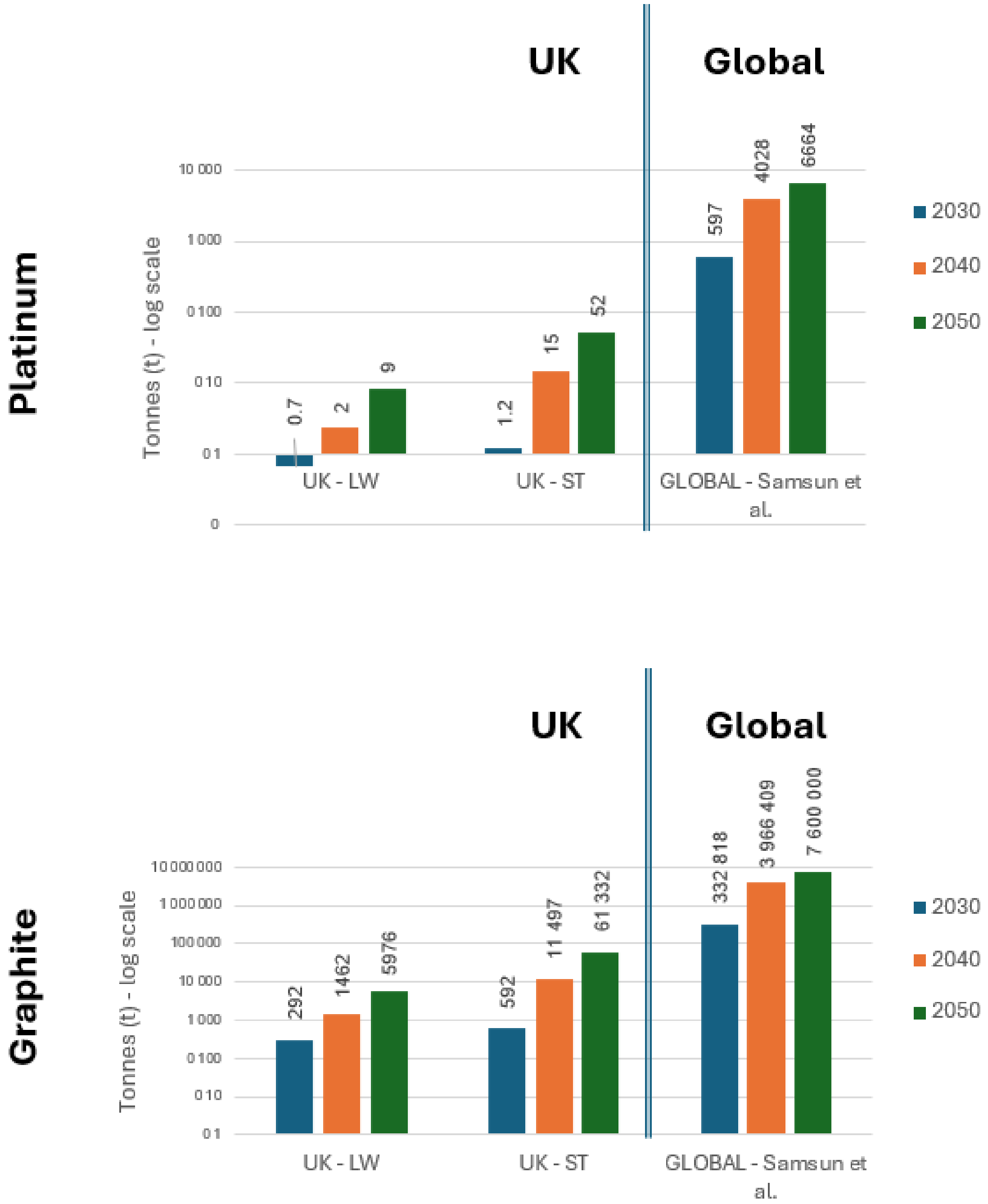


Figure 17 Estimated cumulative UK demand for Pt and graphite (in the 'Leading the way' (LW) and 'System transformation' (ST) scenarios) compared with global demand for fuel cells in road transport. BGS © UKRI.

The UK demand for Pt and graphite for PEMFCs in the highest demand scenario will be orders of magnitude lower than the global demand, equivalent to less than 1 per cent of global cumulative demand to 2050.

The global scenario indicates a cumulative demand up to 2050 of 6664 t of Pt for about 425 million FCEVs on the road. This is equivalent to approximately 15.7 g Pt per vehicle. The UK cumulative demand of 52.2 t for roughly 3.5 million vehicles in a ‘System transformation’ scenario is similarly equivalent to 14.9 g Pt per vehicle. The slight difference between the UK and global relative Pt consumption per vehicle has to do with the different number and ratios of types of vehicles (for example, heavy or light), as all other modelling assumptions were kept the same. These values appear consistent with assumptions by Johnson Matthey, which indicate average Pt intensities as low as 15 g/vehicle by 2050 (Johnson Matthey, 2023a).

In terms of annual demand, the global scenario peaks at over 400 t Pt per year after 2030 (for more than 20 million FCEVs added to stock annually). This falls to about 240 t per year in 2050 as a result of continuing reductions in material intensity. It is therefore clear that the current annual Pt production of about 180 t would not be adequate for this number of FCEVs.

If the most aggressive FCEV scenarios should start to materialise, high levels of competition can be expected for the required Pt. Although the UK will remain a relatively small player in the global FCEV landscape, it may be challenging to secure the sustainable Pt supplies required to meet its deployment targets (BEIS, 2021; National Grid, 2023a, b).

The estimated cumulative global demand for graphite for road vehicle PEMFCs until 2050 is in the order of 7.6 million t, based on forecasts in Samsun et al. (2022), assuming 425 million FCEV vehicles on the road globally in 2050. This is equivalent to almost 18 kg graphite per vehicle on average, which also includes the assumption that only 50 per cent of FCEVs contain PEMFCs with BPPs made of graphite. The graphite estimate should be taken as a rough order of magnitude estimate that is subject to considerable uncertainty, as noted previously.

6 Discussion and conclusions

Fuel cells are expected to play an important role in the hydrogen economy as an energy conversion technology that transforms hydrogen to useful energy in the form of electricity and heat. This report explores the material supply chain for fuel cell deployment in the UK, with a focus on the road transport sector.

Of the different fuel cell types available in the market, PEMFCs are particularly suitable for use in vehicles and other mobility applications due to their small volume and high-power intensity. PEMFCs are therefore expected to be the dominant fuel cell technology for road transport and other mobility applications.

A key functional element in PEMFCs is Pt, which is required as a catalyst in the fuel cell electrolyte, contributing to the high cost of PEMFCs. Other metals, such as Pd, Ru, Ir and Co, may be found in some PEMFC variations or as substitutes for small amounts of Pt. Other elements in PEMFCs include carbon-based materials and synthetic graphite, PFSA polymers, Al and steel.

This study focuses on Pt and graphite as the key functional materials in PEMFCs and for which data are available. This permits estimation of Pt and graphite demand in PEMFC used in UK road transport up to 2050. Other PEMFC materials were excluded because they are used in structural rather than functional components or are used in small amounts in less common PEMFC configurations. For some materials, no relevant data were available for the bill of materials (BOM) as the quantities used in PEMFCs are assumed to be very low.

Forecast material demand associated with fuel cell deployment up to 2050, based on the National Grid FES for hydrogen vehicle uptake, was determined and compared with forecast global fuel cell demand for the same period.

Supply bottlenecks for the embedded Pt and graphite were evaluated on the basis of 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

6.1 KEY CONCLUSIONS OF THE ANALYSIS

Estimated UK demands for Pt and graphite in fuel cell vehicles up to 2050 are relatively low in comparison to today’s global production capacities. However, over 90 per cent of Pt production is concentrated in three producing countries:

- South Africa (over 70 per cent of global total)
- Russia (12 per cent)
- Zimbabwe (8 per cent)

This high concentration adds to the risk of supply chain disruptions. Furthermore, these countries have relatively low ESG scores and may not be considered long-term sustainable sources of Pt (DOE, 2022). It has, however, been noted that PGM mining and refining is concentrated with a few large and publicly quoted companies that are subject to stringent regulation and ESG reporting requirements (Johnson Matthey, 2023a).

On the positive side, the UK has a well-established supply chain for PGMs with a long history of refining and recycling, as well as strong bilateral relations with key regions, including South Africa (Price, 2023).

Trade is substantially less concentrated, with China being the largest importer of Pt (16 per cent) and Italy the largest exporter (10 per cent).

Mining of natural graphite is also highly concentrated, with 64 per cent of global production in China. Similarly, 55 per cent of synthetic graphite is produced in China. Japan is the largest producer of needle coke, the key precursor ingredient for synthetic graphite, with 33 per cent of global production.

In terms of value chain configurations and potential bottlenecks, the mining as well as the refining stages require careful monitoring due to a high dependency on southern Africa and Russia for Pt, and China for natural and synthetic graphite. The fuel cell component manufacturing stage activities are largely carried out in North America (44 per cent), Europe (25 per cent) and Asia (33 per cent). In terms of product assembly (fuel cell stack) Asian vehicle-producing countries (Japan and South Korea) dominate the market. An EU foresight study finds the highest fuel cell supply chain vulnerability to be the assembly step, where the USA, Canada, Japan and South Korea dominate, with less than 1 per cent manufactured in the EU (EC, 2020).

In the global context, the UK demand for fuel cells for the road sector and embedded materials will be orders of magnitude lower than the global demand. Currently, autocatalysts are a key source of Pt demand and there is substantial competing demand from other sectors. High levels of competition for the required materials can therefore be expected worldwide.

6.2 FORECASTING UNCERTAINTIES

The scope of the study is limited to road transport, which is expected to represent only a small fraction of the total hydrogen demand in the future. In other sectors where it can be expected, including rail, shipping and aviation, fuel cell deployment is less developed than in road vehicles and may comprise a mix of fuel cells and gas combustion technologies. Similarly, stationary fuel cell deployment in power generation is yet to take off at scale and future developments are uncertain.

Significant technology advancements have been seen in fuel cell technologies in recent years and further learning curves can be expected in terms of efficiency, materials used, material intensities and costs. These developments may significantly alter the future technology market mix and consequently the material demand. For instance, FCEV Pt intensities have been reduced considerably to date and are expected to be further reduced to levels corresponding to a half to a third of current Pt loadings per kilowatt fuel cell capacity.

The underlying road transport-related fuel cell demand scenarios display significant variation in expected demand for hydrogen vehicles. The high scenario (‘System transformation’) assumes significantly higher demand for FCEVs compared with the second highest scenario (‘Leading the way’). This reflects the underlying assumption in the ‘Leading the way’ and ‘Consumer transformation’ scenarios that battery electric vehicles will be the dominant road transport technology due to their high efficiency.

Regardless of these uncertainties, even under those scenarios with lower levels of fuel cell uptake in road transport, future UK demand for Pt and graphite up to 2050 is likely to be substantially higher than at present. Developments in other competing sectors, such as battery electric vehicles, and potential supply chain challenges hindering growth in those sectors, may also have an impact on the uptake of fuel cell vehicles and contribute to increased demand. On the other hand, further breakthroughs in battery technology could put a halt to fuel cell vehicle market penetration.

7 Recommendations

Analysis of the fuel cell-related transport supply chain leads to various recommendations aimed at ensuring access to the materials required to achieve the UK's ambitions related to the production and deployment of PEMFCs.

7.1 METHODOLOGY RECOMMENDATIONS

These 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 at present, when rapid technology development is taking place at a time of dynamic geopolitics and unstable market forces. Continual review of these foresight studies is pivotal to creating 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 because the availability, quality and relevance of publicly available data are limited. This includes missing data on the BOMs and material composition, together with limited availability of data on refining and mining capacities, especially for by-products and secondary products. These data deficiencies relate both to the present time and, more significantly, to the future, thus undermining the reliability of forecasts of material demand for fuel cells. Developing BOMs for signature products could further improve data visibility.

7.1.2 Overcoming the uncertainty gap

The current study works backwards from future demand scenarios for innovation technologies that are subject to significant learning curves. This affects their material composition and relative mass requirements, resulting in significant variance between the derived forecasts. A frequent refresh of the study could further reduce uncertainty.

7.1.3 Refreshing outlook on wider potential application space

Given the nascent stage of fuel cell development and the expectation that markets other than transport could move out of the experimentation stage in the next couple of years, it is recommended that this type of analysis is repeated with a clear focus on looking into further sectors (for example, rail; aviation; off-grid energy storage, etc.).

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 forecast increase in fuel cell technology deployment in the UK. Particular focus should be on trade-related partnering agreements at the national level. At the same time, effective schemes should be established to facilitate re-use and recycling to maintain necessary stocks within the UK.

7.2.1 Scale-up of the fuel cell technology

Scaling up fuel cell technology will require an undisrupted supply of raw and refined materials. However, these materials are commonly sourced from countries with poor ESG ratings and inherently high geopolitical risk. Restrictions on trade further exacerbate the material supply risk. However, the concentration of Pt mining in a few publicly registered companies with strong ties to the UK, such as South Africa and Zimbabwe, facilitates effective monitoring of ESG risks and performance throughout the value chain.

7.2.2 Maintaining and strengthening the UK's position

The UK's strong position in the PGM value chain will help mitigate supply chain risks related to the sourcing of the Pt required for fuel cells and other applications. It can also support the development of a strong fuel cell value chain in the UK.

7.2.3 Platinum supply

The Pt supply chain should not be considered in isolation, but in the context of other PGMs, which are by-products of Pt mining and are essential for related technologies such as electrolysers. Continued production of Pt is required to ensure supply of these by-products, such as Ir, Pd and rhodium (Rh) (Johnson Matthey, 2023b).

The net demand for Pt might fall in the future due to decreased use in autocatalysts. If this drop in demand is not replaced by new markets such as fuel cells, the supply of Ir would be reduced, leading to a bottleneck for growth in electrolyser technology. Closely monitoring the changing PGM demand and supply chain is therefore important to identify potential bottlenecks in the future.

7.2.4 Recycling

There is already an established recycling industry for Pt globally (Johnson Matthey, 2023a, b). Nonetheless, there is an opportunity, in collaboration with leading UK fuel cell players, to explore options to strengthen the management of the existing stock of assets where PGMs are embedded. This would increase material productivity and revalorisation of end-of-life components and materials within the FC value chains.

7.3 LOCAL CAPABILITY RECOMMENDATIONS

7.3.1 Establishing fuel cell manufacture in the UK

The UK is home to Johnson Matthey, which is a key global player in the PEMFC value chain with focus on industrial catalysts and key fuel cell components. However, manufacturing of fuel cells has not yet been established in the UK (Wood & Optimat, 2022), creating both a barrier and a future opportunity to support developments in that direction. Developing local capabilities in fuel cell design and manufacturing would ensure participation in the anticipated scaling opportunities, leveraging a unique starting position alongside Johnson Matthey.

7.3.2 Investment in fuel cell technology innovation

Investment is required to ensure that assumed learning curves towards lower fuel cell cost, lower Pt intensities and higher durability will materialise. If these learning curves do not materialise, further bottlenecks to fuel cell deployment in the UK and worldwide are likely to develop.

7.3.3 Maximise resource productivity

Given the absence of mineral reserves of Pt in the UK, a focus on maximising resource productivity of existing stock can reduce the dependencies on foreign powers and ease peak-pricing challenges. This can be achieved through optimised post-use revalorisation schemes, including material recycling of PGMs in existing product and component stocks, (for example, autocatalysts) and exploring initiatives that go beyond recycling, including component re-use (for example, anodes and cathodes). These approaches would benefit from a UK-focused programme to incentivise private sector investment backed up by an improved regulatory regime.

Appendix A PEMFC material excluded from the detailed supply chain and material demand analysis

The study focuses on the use of fuel cells in the road transport sector, which will predominantly deploy PEMFCs. Other fuel cell types and associated materials are excluded.

Material	Function	Reason for exclusion
Al	Base plate (structural and heat management) (functional)	A relatively abundant metal with a diversified supply base. Partly structural
Co, Ir, Pd, Ru	Catalyst material as possible substitution for parts of Pt	Mentioned in EU foresight studies as a potential replacement for Pt. However, no BOM data are identified in literature, likely as the material is not consistently present in most common configurations or because quantities are very small
Cu	Unspecified	Mentioned in one PEMFC life-cycle assessment literature source without specifying function, but not commonly used as functional material in the cell. Commonly used in the ancillary parts of the fuel cell system

Appendix B Overview on component manufacturers

Overview of selected global PEMFC and component manufacturers. (DOE, 2022).

Company	Headquarters	Manufacturing	Products
3M	St Paul, Minnesota, USA	Minnesota and Wisconsin, USA	Membrane; ionomer
Advent	Athens, Greece; Boston, Massachusetts, USA	Greece; Massachusetts, USA	Membrane; MEA
Ballard Power Systems	Burnaby, British Columbia, Canada	British Columbia, Canada; Denmark	PEMFC; MEA*; BPP*
BASF	Ludwigshafen, Germany	Germany	MEA; catalyst
Chemours	Wilmington, Delaware, USA	South Carolina, USA	Membrane; ionomer
Horizon Fuel Cell	Singapore	Singapore; China	PEMFC
Hydrogenics	Mississauga, Ontario, Canada	Ontario, Canada	PEMFC
Intelligent Energy	Loughborough, UK	UK	PEMFC
Ion Power	New Castle, Delaware, USA	Delaware and Pennsylvania, USA	MEA
Johnson Matthey	London, UK	Pennsylvania, USA; UK	MEA; catalyst
Plug Power, Inc. (‘Plug Power | Green Hydrogen & Fuel Cell Solutions’)	Latham, New York, USA	New York, USA	PEMFC; MEA *
Solvay	Brussels, Belgium	New Jersey, USA; Italy	Membrane; ionomer
TANAKA	Tokyo, Japan	Japan	Catalyst
Umicore	Brussels, Belgium	China; Denmark; Germany; South Korea; USA	Catalyst
W.L. Gore	Newark, Delaware, USA	Delaware, USA; Japan	Membrane

Included companies were mentioned by at least four market reports and could be found in the BNEF database, and/or they are known to the DOE’s Hydrogen and Fuel Cell Technologies Office as a manufacturer of fuel cell components. Note that manufacturing locations listed are specifically for fuel cell components, and the list may not be complete for a given company.

* Component is produced for use in company end products but is not sold directly

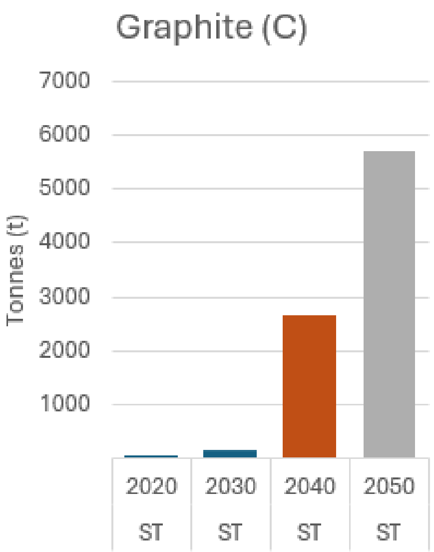
Appendix C Overview on potential fuel cell sectoral applications

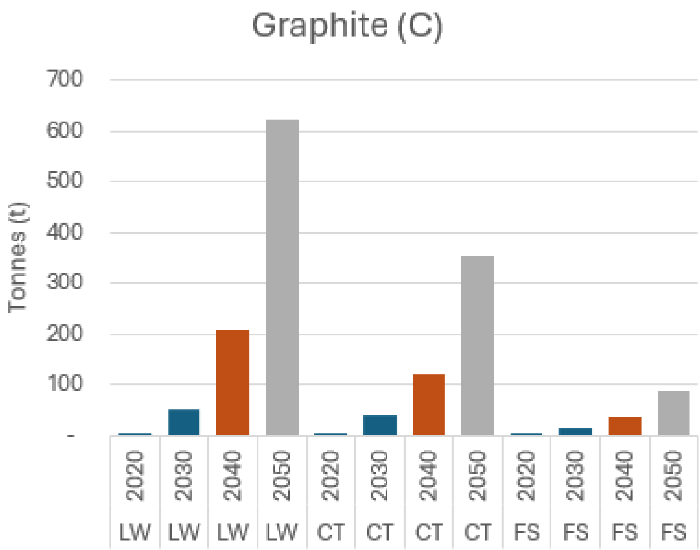
Sector	Fuel cell relevance – preliminary analysis / assumptions	Assumed fuel cell subtechnology relevance (share) in context of the study				
		PEMFC	**SOFC**	**AFC**	**MCFC**	**PAFC**
Residential	The residential H_2 demand appears to refer primarily to 'residential hydrogen demand for heat' (National Grid, 2023b)via H_2 gas boilers or combined boiler and ASHP systems. This cumulated demand is 1784 TWh in 'System transformation' and 455 TWh in 'Leading the way', which corresponds to 85 per cent and 75 per cent of total H_2 residential demand in these scenarios, respectively.	N/A	N/A	N/A	N/A	N/A
Rail	Primarily, the 'System transformation' scenario assumes use of H_2 for railways. While not stated in the FES2023 report, it is likely this will include fuel cells. There are various H_2 projects being developed internationally, some which are close to commercialisation (source). The UK HydroFlex H_2 train uses PEMFCs of 100 kW. However, it is uncertain how to estimate the installed fuel cell capacity based on the National Grid TWh demand, or which assumptions the National Grid has applied in this regard. Generally, rail H_2 application is in early stages of maturity and scale-up is uncertain.	Excluded due to lack of readily available data				
Blending	Relates to blending of H_2 into the gas network. No significant fuel cell relevance.	N/A	N/A	N/A	N/A	N/A
Direct air carbon capture and storage	National Grid (2023b) states: 'Leading the Way also sees some hydrogen use to power direct air carbon capture and storage.' It is not stated if this is expected to involve direct fuel cell power generation via stationary fuel cell plants. In the absence of data, this sector is excluded from the fuel cell foresight analysis.	Excluded due to lack of readily available data				
Transmission losses	No fuel cell relevance.	N/A	N/A	N/A	N/A	N/A
Road transport	H_2 for road transport expected by National Grid to pick up after 2030, mainly in the 'System transformation' scenario. While not explicit in the National Grid report, it is assumed here that fuel cells will dominate for H_2 vehicles, as direct combustion of H_2 is less efficient. It is furthermore assumed that PEMFCs will be the dominant subtechnology, due to their suitable characteristics (high power density; low operating temperature; quick start-up, etc.) and current trends.	100%				
Commercial	National Grid (2023b) states: 'Commercial hydrogen use is expected to be almost exclusively for heat and hot water, with some additional small potential fuel switching to hydrogen in the catering sector' therefore no fuel cell relevance assumed for this study.	N/A	N/A	N/A	N/A	N/A
Aviation	The National Grid 'Consumer transformation', 'System transformation' and 'Leading the way' scenarios all assume substantial H_2 demand for aviation, without further specifying the underlying assumptions in terms of number of aeroplanes or technology (fuel cell vs. combustion). Excluded for now in the absence of data or qualified assumptions.	Excluded due to lack of readily available data				

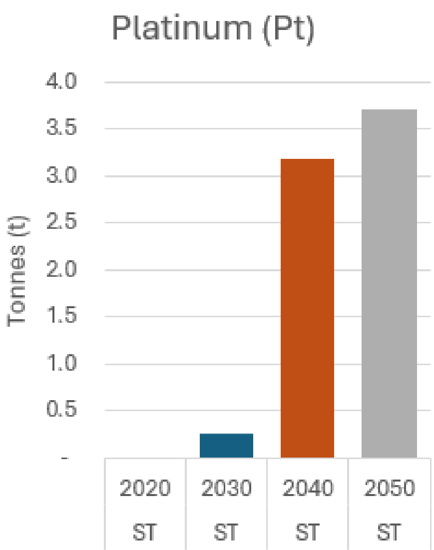
Industrial	For industrial hydrogen demand National Grid (2023b) does not specify in much more detail how this will be used or to what extent this will involve fuel cells but indicates this will initially include substituting natural gas with H_2 for industrial processes. Although stationary fuel cells may play a role, we assume here that this mainly involves hydrogen boilers and other industrial processes.	N/A	N/A	N/A	N/A	N/A
Power Generation	National Grid (2023b) states: 'Volumes of hydrogen used for power generation are fairly low, across the scenarios, but this plays a key role in supporting security of supply, particularly in Consumer Transformation, supplying electricity at times of peak demand or during lulls in renewable generation output.' Use of stationary fuel cells is likely, however there are no data on the assumed installed fuel cell capacity to meet this H_2 demand. Excluded for now in the absence of data or qualified assumptions.	Excluded due to lack of readily available data				
Shipping	The National Grid 'Consumer transformation', 'System transformation' and 'Leading the way' scenarios all assume substantial H_2 demand for shipping, without specifying further the underlying assumptions in terms of number of ships or technology (fuel cell vs. combustion). Excluded for now in the absence of data or qualified assumptions.	Excluded due to lack of readily available data				

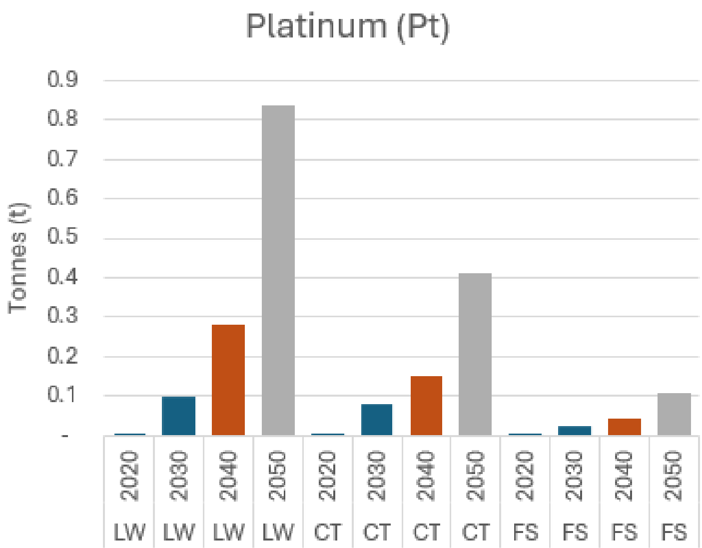
Appendix D Annual demand as a function of scenario

Annual forecast demand (tonnes) for Pt and graphite up to 2050 compared with 2020 under four different scenarios: ST: System transformation; LW: Leading the way; CT: Consumer transformation (CT); Falling short (FS). BGS © UKRI.









Appendix E Overview of fuel cell technologies and key material use not covered in this analysis

An overview of fuel cell technologies and associated key material use not covered within the scope of this analysis (that is, applicable to other sectors than road transport).

This table summarises the key elements found in fuel cell technologies that are outside the scope of this study (technologies other than PEMFCs).

Technology	UK critical elements	Other
AFC	Pd, Pt	Mn, Ni, Ag
PAFC	Pt, graphite	
MCFC	Li	Cr, Ni
SOFC	Ce, Co, Gd, La, Sm, Y	Cr, Fr, Mn, Ni, Sr, Zr

Elements in red are excluded from the detailed analysis because the fuel cell technology is not covered within the sectoral scope of this report. Appendix A outlines reasons for sectoral exclusions.

The following sections briefly describe the materials used in fuel cell technologies that are outside the scope of this report, as they are not expected to be used in road transport applications.

ALKALINE FUEL CELLS

AFCs use a simple electrolyte (potassium hydroxide solution) and low-cost base metal catalysts typically consisting of nickel (Ni) or Ni alloys (Shell & Wuppertal Institut, 2017; McLean et al., 2002). However, reportedly Pt and Pa may also be used as an anode catalyst and Pt, Pd, silver (Ag) and manganese dioxide (MnO_2) in the cathode catalyst (Ferriday & Middleton, 2021).

PHOSPHORIC ACID FUEL CELLS

PAFCs are a mature technology but are used commercially in low volumes (Shell & Wuppertal Institut, 2017). Modern PAFCs include Pt and graphite composites in the anode and cathode and carbon fibre paper in the gas diffusion layer. The catalyst layer is PTFE (Teflon) bonded. Graphite composites plates are used in the electrolyte reservoir and bipolar plates (Jiang & Li, 2022).

SOLID OXIDE FUEL CELLS

The material composition of SOFCs resembles that of solid oxide electrolysers, which commonly include the elements Ni, Zr, lanthanum (La) and yttrium (Y) (IEA, 2022b) as well as cerium (Ce) cand other rare earth elements (REEs). This technology is, therefore, of potential importance to the recycling industry on account of European reliance on imported REEs (Mori et al., 2021). Ni is used in the anode, whereas the cathode side commonly includes the compounds strontium-lanthanum manganite (LSM) or lanthanum-strontium-cobalt ferrite (LSCF). Y and Zr are found in the electrolyte in the form of yttria-stabilised zirconia (YSZ), which may also be used for doping nickel in the anode. Ce may be found in the electrolyte doped with gadolinium (Gd) or samarium (Sm). Steel and doped lanthanum chromate is used in the interconnect (bipolar plates). (Mori et al., 2021)

MOLTEN CARBONATE FUEL CELLS

MCFCs use a carbonic melt as the electrolyte and expensive noble metal catalysts are not required. However, materials resistant to corrosion and high temperatures are necessary (Shell & Wuppertal Institut, 2017).

According to Mehmeti et al. (2016) the electrolyte uses carbonates (lithium carbonate, Li_2CO_3; potassium carbonate, K_2CO_3) and the electrodes consist of nickel (Ni) materials. The anode is made of Ni, commonly alloyed with chromium (Cr) or aluminium (Al), and the cathode consists of lithiated nickel oxide. Hence, key functional materials include Ni, Cr and lithium (Li).

Acronyms and abbreviations

AFC	Alkaline fuel cell
APC	Advanced Propulsion Centre
ASHP	Air-source heat pump
BEIS	Department for Business, Energy and Industrial Strategy
BOM	Bill of materials
BPP	Bipolar plates
CHP	Combined heat and power
ESG	Environmental, social and governance
FCEV	Fuel cell electric vehicle
FES	(UK National Grid) Future Energy Scenarios
GDL	Gas diffusion layer
HGV	Heavy goods vehicle
HS	Harmonized System (trade codes)
IEA	International Energy Agency
LSCF	Lanthanum-strontium-cobalt ferrite
LSM	Strontium-lanthanum manganite
MCFC	Molten carbonate fuel cell
MEA	Membrane electrode assembly
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cel
PFSA	Perfluorosulfonic acid
PGM	Platinum group metal
PTFE	Polytetrafluoroethylene (trade name Teflon)
REE	Rare earth element
SOFC	Solid oxide fuel cell
YSZ	Yttria-stabilised zirconia

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