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

Decarbonisation and Resource Management Programme

Open report

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University of Exeter Business School

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BRITISH GEOLOGICAL SURVEY
DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME
OPEN REPORT

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

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Hydrogen refuelling, ©*Microsoft 365*

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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 in society from currently close to zero to 446 TWh in 2050 in a 'System Transformation' scenario, or 242 TWh in a 'Leading the Way' (LW) scenario (National Grid, 2023a, 2023b).

Hydrogen can have many applications, 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 to useful energy (heat or electricity) can occur via two main pathways, combustion to release heat, or by using fuel cells (FC) to generate electricity (Shell & Wuppertal Institut, 2017).

This report explores the material supply chain for fuel cell (FC) deployment in the UK with a focus 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 Future Energy Scenarios (FES) (National Grid, 2023a, 2023b). The focus on the road transportation sector is based on the expectation that FC uptake will grow substantially in the near future (EC, 2020) and because suitable hydrogen vehicle data is readily available in the National Grid FES data (National Grid, 2023a, 2023b) enabling material demand scenario analysis. While the overall future scale of FC 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, FC 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 chemically bound energy in hydrogen into electrical energy and heat. The fuel cell process can be seen as the reverse of what happens during electrolysis. In a fuel cell hydrogen, as a di-hydrogen molecule (H_2), and oxygen (O_2) are recombined. This 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, cooling circuit, power circuit, 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 PEM fuel cell is shown in Figure 1.

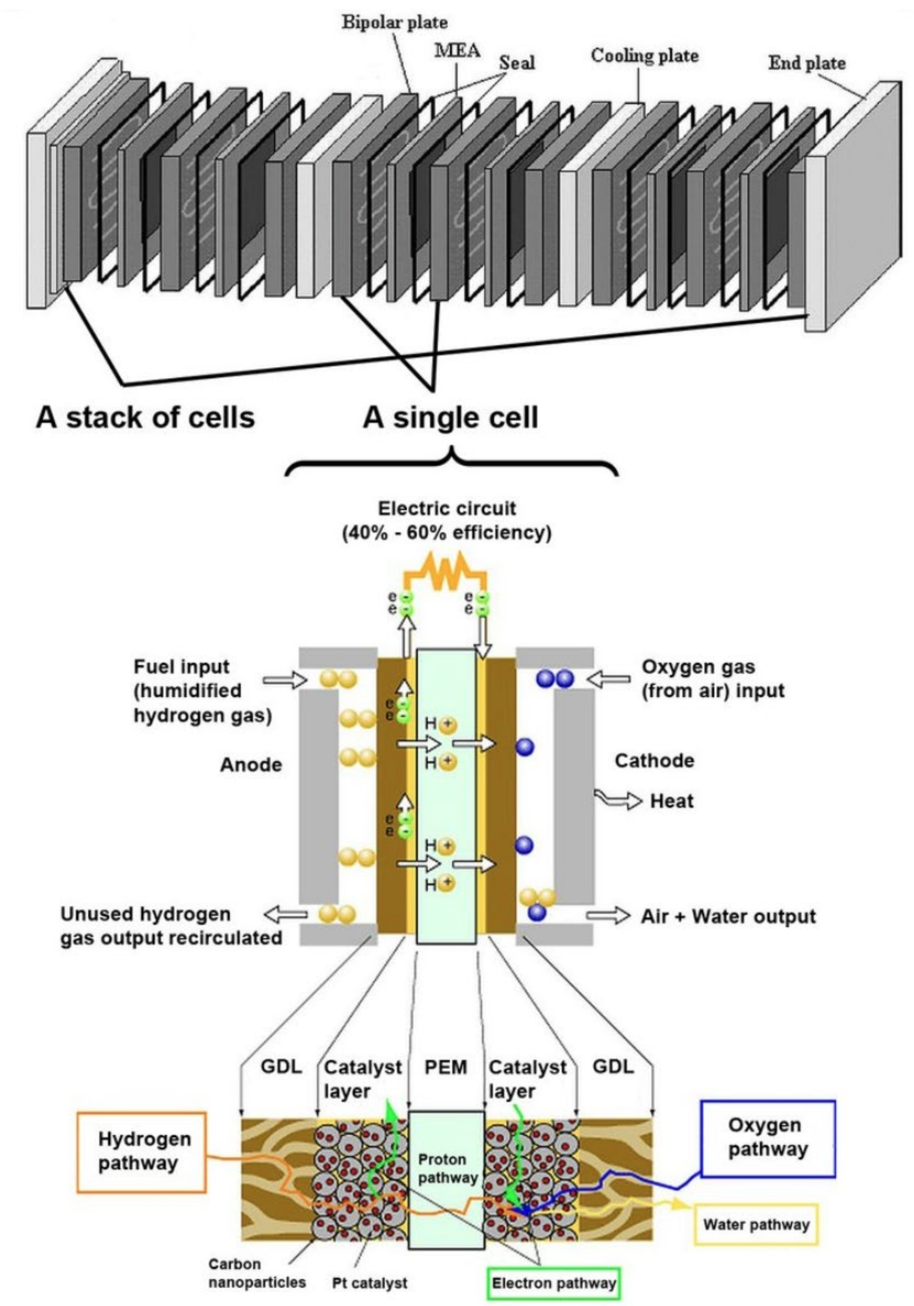


Figure 1: Principles and key components of a PEM fuel cell. Source: (Cuong, 2015).

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 for 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, p. 33).

Fuel cell type	**AFC**	**PEMFC**	**PAFC**	**MCFC**	**SOFC**
Temperature range (°C)	60-90	50-90 (LT) up to 180 (HT)	160-220	600-700	700-1,000
Electrolyte	Potassium hydroxide	Polymer membrane	Phosphoric acid	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 of 100 kW to several MW	From a couple of kW to several MW
Fuel	H2	H2, gas, syngas, biogas, methanol (external reforming)	H2, gas, syngas, biogas, methanol (external reforming)	H2, gas, syngas, biogas, methanol (internal reforming)	H2, gas, syngas, biogas, methanol (internal reforming)
Oxidant	O2 (pure)	O2	O2	O2	O2
Efficiency η_{el} (H_S)	50-60%	30-60% (depending on size and application)	30-40%	55-60%	50-70%
Investment costs USD/kW$_{el}$	200 to 700	3000 to 4000 (stationary) ~500 (mobile)	4000 to 5000	4000 to 6000	3000 to 4000
Life expectancy (h)	5000 to 8000	60 000 (stationary) 5 000 (mobile)	30 000 to 60 000	20 000 to 40 000	up to 90 000
Market development	Established for decades, but 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. AFC has a relatively low investment cost but is inferior to PEMFC with regards to output and durability. (Shell & Wuppertal Institut, 2017).

PEMFC are the most popular type of FCs (EC, 2020) and are considered likely to be a leading FC technology into the future. The PEMFC also operates at low temperatures, and has a small volume and high-power density, making it particularly suitable for mobility applications (Shell & Wuppertal Institut, 2017). They are, however, expensive due to their reliance on platinum as a catalyst.

PAFC is also a mature technology operating at medium temperatures. It is used in low volumes for decentralised power generation (small power plants) due to its high output range of up to several MWs. (Shell & Wuppertal Institut, 2017)

MCFC and SOFC operate at high temperatures. MCFC has high electrical efficiencies and can operate with both pure hydrogen and other hydrogen-containing gases. It is used in small numbers in the power plant sector. SOFC can operate at few kW to several MW. They have high electrical efficiencies but long startup times, making them useful in stationary application in power plants. SOFC have long durability and relatively low investment costs and have been considered the second most important FC type after PEMFC (Shell & Wuppertal Institut, 2017).

Despite advancements in FC 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); and
- portable power generation (<1 per cent).

Currently, PEMFC and SOFC dominate the market, both in capacity and number (Carrara et al., 2023). PEM technology is expected to be the dominant FC technology used in the road transport sector (DOE, 2022; EC, 2020; Shell & Wuppertal Institut, 2017), whereas SOFC comprise a high-temperature FC which are 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 PEMFC.

1.2 ESSENTIAL COMPONENTS AND MATERIALS

This analysis focuses on the road transport sector, which is expected to predominantly use PEMFC technology, as discussed above. 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; or (ii) they are not used in the most common configuration of the technology, (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 FC technologies which are not included here. *Graphite for FCs is typically used in synthetic form.

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

1.2.1 Proton Exchange Membrane (or polymer electrolyte) fuel cells (PEMFC)

PEMFC are similar to PEM electrolysers with some variation in design and materials used. The most important FC components are the membrane electrode assembly (MEA) (which comprise the electrolyte, gas diffusion layers acting as anode and cathode, and the catalyst) and the bipolar plates, which separate the MEAs in the FC stack (Carrara et al., 2023).

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

The most important functional raw material used in PEMFCs is platinum (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 platinum in small amounts (Carrara et al., 2023) depending on the application, but 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 platinum 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).

The IEA notes a general trend of increased demand for PGM metals in fuel cell vehicles in response to the rapid growth in hydrogen use for sustainable development (IEA, 2022b).

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

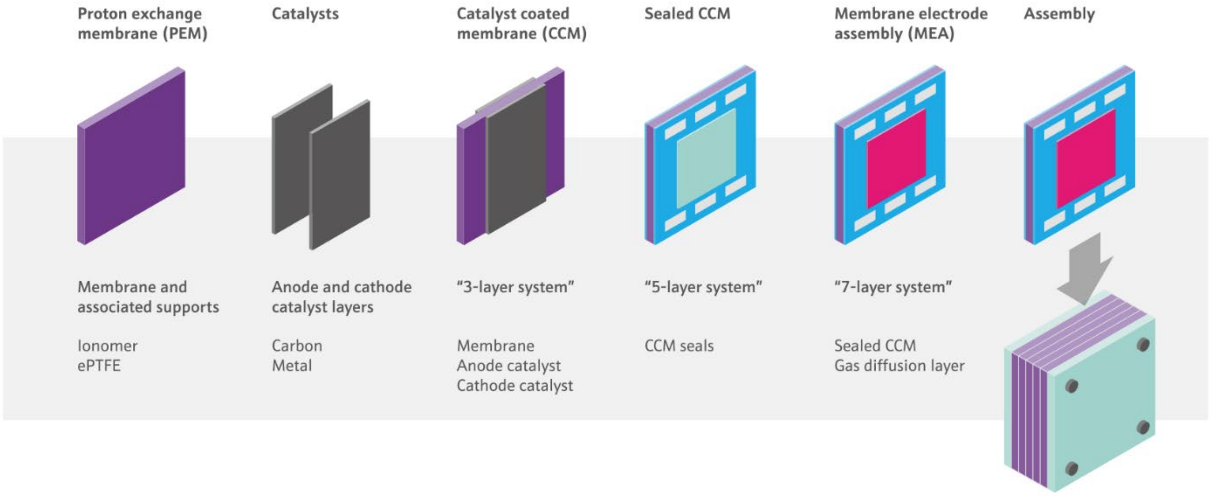


Figure 2: PEM fuel cell components. Source: (Johnson Matthey, 2023a)

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

Published lifecycle analyses shed more light on material usage in PEMFC: polymer materials in the electrolyte, including perfluorosulfonic acid (PFSA) polymers such as Nafion®; carbon fibre and steel in the gas diffusion layer; platinum and platinum-alloys as catalysts; and synthetic graphite and/or steel in the interconnect layer (also referred to as bipolar plates in PEMFC) (Mori et al., 2021; Stropnik et al., 2019) (Table 3).

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

Component	Material
Electrolyte	Perfluorosulphonic acid (PFSA – Nafion) Sulfonated polyeter 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	Platinum and Pt-alloys PTFE-Teflon (hydrophobic agent) Carbon black (catalyst support)
Interconnect (bipolar plates)	Graphite Stainless steel
Sealant	Thermoplastic (PTFE) Elastomer (Silicone, Viton®, EPDM)

An LCA of a PEMFC system indicates that a PEMFC stack contains 4.5 kg synthetic graphite per 1 kW FC, noting that the bipolar plates 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 1kW stack contains 0.3 kg aluminium, 70 g Nafion®, 0.75 g platinum, 0.1 kg chromium steel and 0.8 g carbon black. Mori et al. (2023) report the use of carbon cloth and carbon black but does not include graphite. They suggest 0.54 g platinum, 3 g PFSA (Nafion®), 19.79 g copper per 1 kW stack, in addition to steel (stainless and chromium steel) and various polymers. Aluminium is used as a base plate metal and for thermal management of the stack (EC, 2020).

Innovation has substantially reduced the platinum intensity of FCs, driven by the need to reduce costs. The IEA (2022b) writes that the 1st generation 2014 model Mirai FCEV used 40 g of platinum, which was three-quarters less than in the 2008 prototype. The 2nd generation Mirai reduced platinum 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. Similar targets have been set by the US DOE. Other sources indicate that current PEMFC use approximately 0.5 g platinum per kW fuel cell and that cerium and iridium are used in very small, unspecified, quantities (Price, 2023).

The APC 2020 Fuel Cell Roadmap notes that the use of platinum group metals (PGM) in PEMFC is likely to decrease significantly from the current level of 30 g per FC system (0.3g/kW assuming 100 kW FC). Driven by cost reduction targets the aim is to reduce the PGM loading to between 6 and 9 g (i.e. as low as 0.06 g/kW assuming 100 kW system per vehicle)(APC, 2021). Johnson Matthey, a leading UK player in the PEMFC value chain, reports platinum 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 platinum loading of about 0.3 g/kW in light vehicles (cars), which can be expected 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 platinum demand estimation below.

Bipolar plates (BPPs) used in PEMFC vary in their material composition, and may be from either 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 other, the FC application. BPPs comprise almost 80 per cent of the PEMFC weight, 50-65 percent of its volume and 40 per cent of the total FC stack cost (Tang et al., 2021).

A paper by Tang et al. (2021) focusing on BPPs designs for automobile PEMFCs highlights the importance of low volume and lightweight FC 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 can be to use non-corrosive metals such as stainless steel, Ni-based alloys, titanium, zirconium, and others, but these have high costs which is 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, graphite is brittle in 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 cost 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 PEMFC using graphite vs. metal based bipolar plates 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:

- **Bipolar plate weight**: 0.4 kg/kW (Tang et al., 2021; Wang et al., 2020)(i.e. 40 kg per 100 kW vehicle FC)
- **Graphite content** in graphite polymer composite BPP: 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.
  - ➔ I.e. resulting in average graphite content per kw PEMFC: 0.4 kg/kW x 0.8 x 0.5 = 0.16 kg/kW (160 g/kW) on average.

It should be noted that the above estimate is substantially lower than the indicated graphite content in an LCA 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 FCs in the automobile sector.

Copper was indicated to be present in the FC stack in a single identified publication (Mori et al., 2021), whereas most literature sources identified do not consider copper to be a key functional material in the FC stack (Carrara et al., 2023; DOE, 2022; IEA, 2023a). Although both copper and aluminium are used in the peripheral components of the broader FC 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)**
Platinum (Pt) (light vehicles)	0.3	0.12	0.08
Platinum (Pt) (heavy vehicles)	0.5	0.25	
Graphite (C)	160		

2 Supply chain mapping of PEM fuel cells

The scope of the supply chain mapping and material demand estimation is limited to application of fuel cells in road transport, which is a sector where significant FC growth can be expected in the near future (EC, 2020) and for which suitable data is readily available in the National Grid FES data (National Grid, 2023a, 2023b). Consequently, the focus is on PEM fuel cells, which are expected to dominate the transport-related FC 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: raw material extraction; material processing; sub-component/pre-cursor material manufacturing; component and product manufacturing; and recovering materials at product end-of-life (DOE, 2022). 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. Platinum and graphite were selected for detailed mapping as these are key functional elements used in most PEMFC. 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 bi-products from oil refining and steel industries, respectively.

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

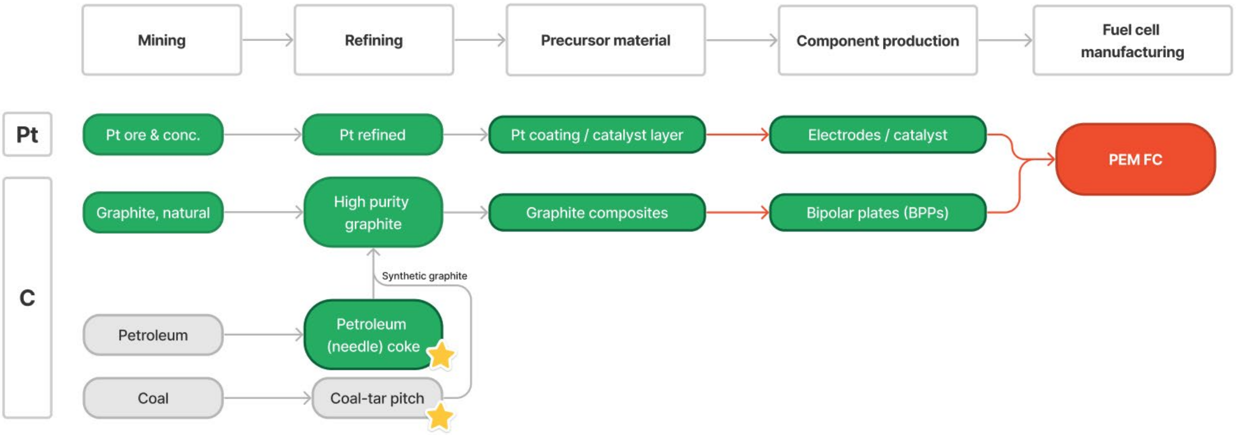


Figure 3: Simplified supply chain mapping for platinum and graphite (which is typically synthetic but may in some cases be derived from natural sources) used in Proton exchange membrane fuel cells (PEMFC). The green shading indicates materials that have been included in the quantitative analysis of supply chain bottlenecks and/or estimation of future material demand.

3 Supply chain bottlenecks

An overview of the global production and trade concentrations for platinum and graphite are shown in Figure 4 and discussed further below.

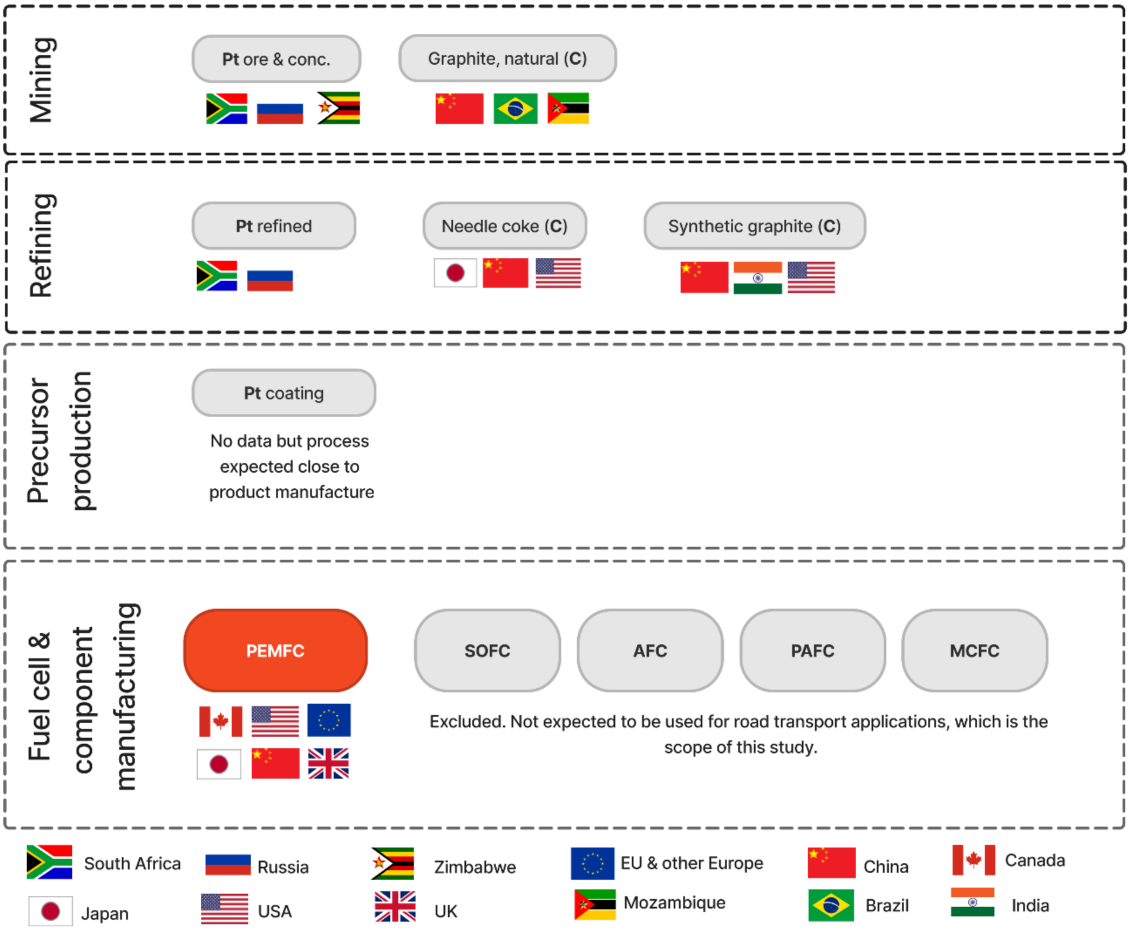


Figure 4: Geographical production concentration in the fuel cell supply chain. At the mining stage, the national flags show the top three producers, from left to right, based on quantitative data from the BGS World Mineral Statistics database (BGS, 2023). At the fuel cell component and cell manufacturing 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; Proton exchange membrane fuel cell; SOFC, Solid oxide fuel cell.

3.1 MINING AND REFINING

3.1.1 Production concentration

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

The global production of platinum is derived from three main countries: South Africa (>70 per cent of the total), Russia (12 per cent) and Zimbabwe (8 per cent) (Figure 5). 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.

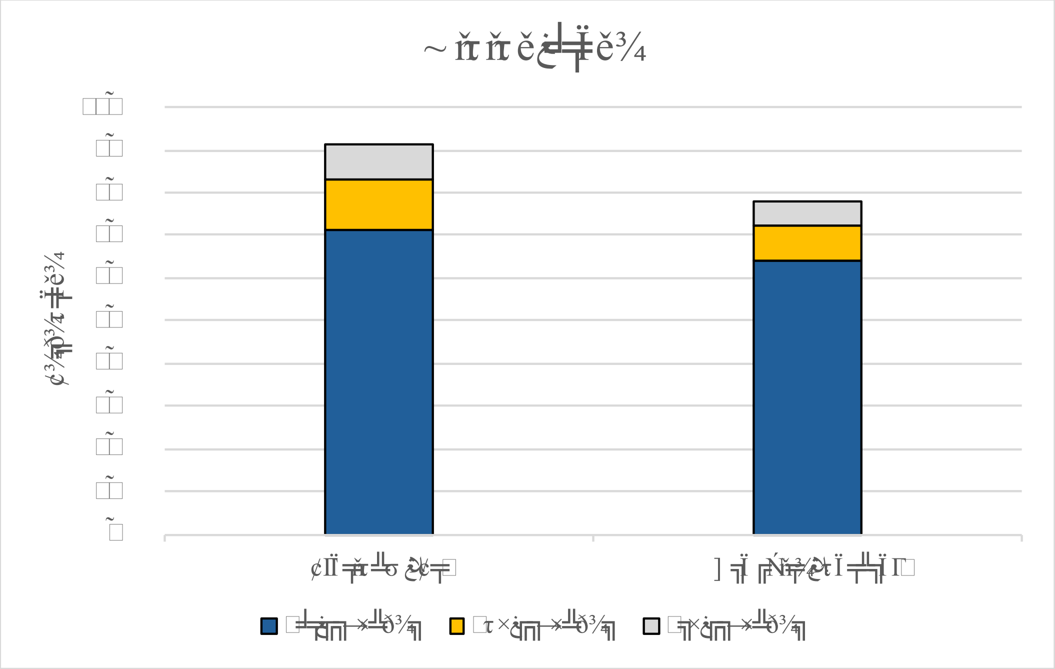


Figure 5: Global mine production of platinum showing the production shares of the top three producing countries (based on 5-year production average, 2017-2021). Data from the British Geological Survey World Mineral Statistics database (BGS, 2023).

Data on the production of refined platinum 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).

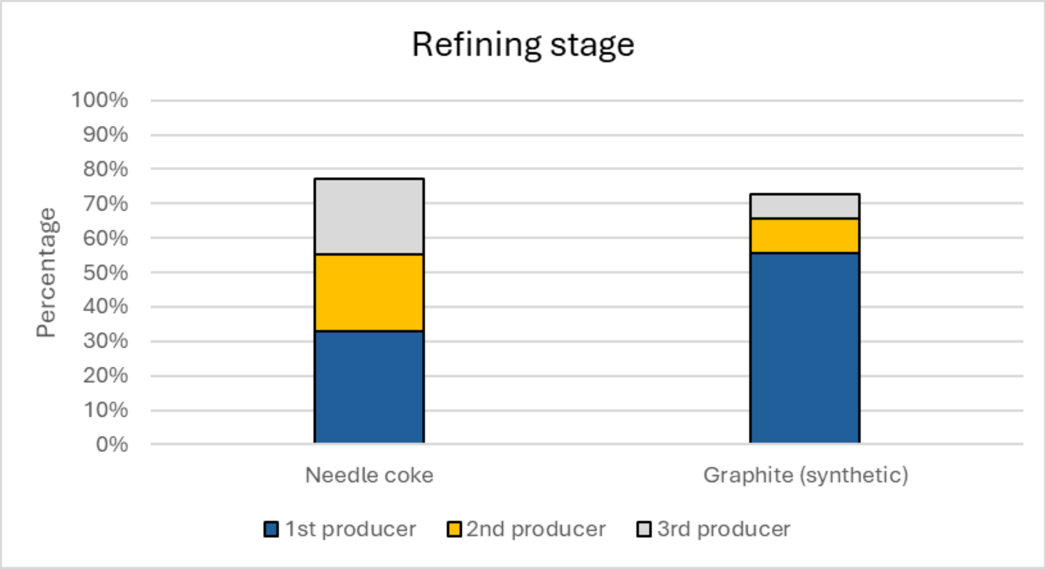


Figure 6: Global production shares of synthetic graphite and its key precursor, needle coke, showing the production shares of the top three producing countries (based on 5-year production average, 2017-2021). Data from *Benchmark Mineral Intelligence.*

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

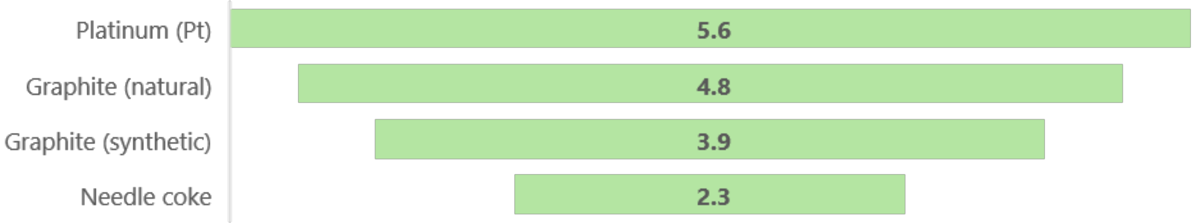


Figure 7: Ranked production concentration score (1-10) for key functional materials used in PEM fuel cell technologies; platinum, natural and synthetic graphite, and needle coke (a precursor ingredient in synthetic graphite) based on ESG-weighted HHI for the top three producing countries. Platinum and natural graphite are of the highest concern as mining is highly concentrated in countries with relatively poor ESG scores.

Johnson Matthey (2023a) notes that platinum mining and refining is concentrated with a small number of large, publicly quoted companies which are subject to stringent regulation, and which 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 the platinum mining operations have been resilient for over two decades.

In terms of platinum group metal (PGM) supply, Johnson Matthey also makes the point that almost 25 per cent of platinum supplied to the market annually consists of recycled metal. In addition, substantial amounts of platinum 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 iridium, where substantial amounts of iridium used in catalysts circulate in a ‘closed loop’ and are not reported in supply and demand figures (Johnson Matthey, 2023a).

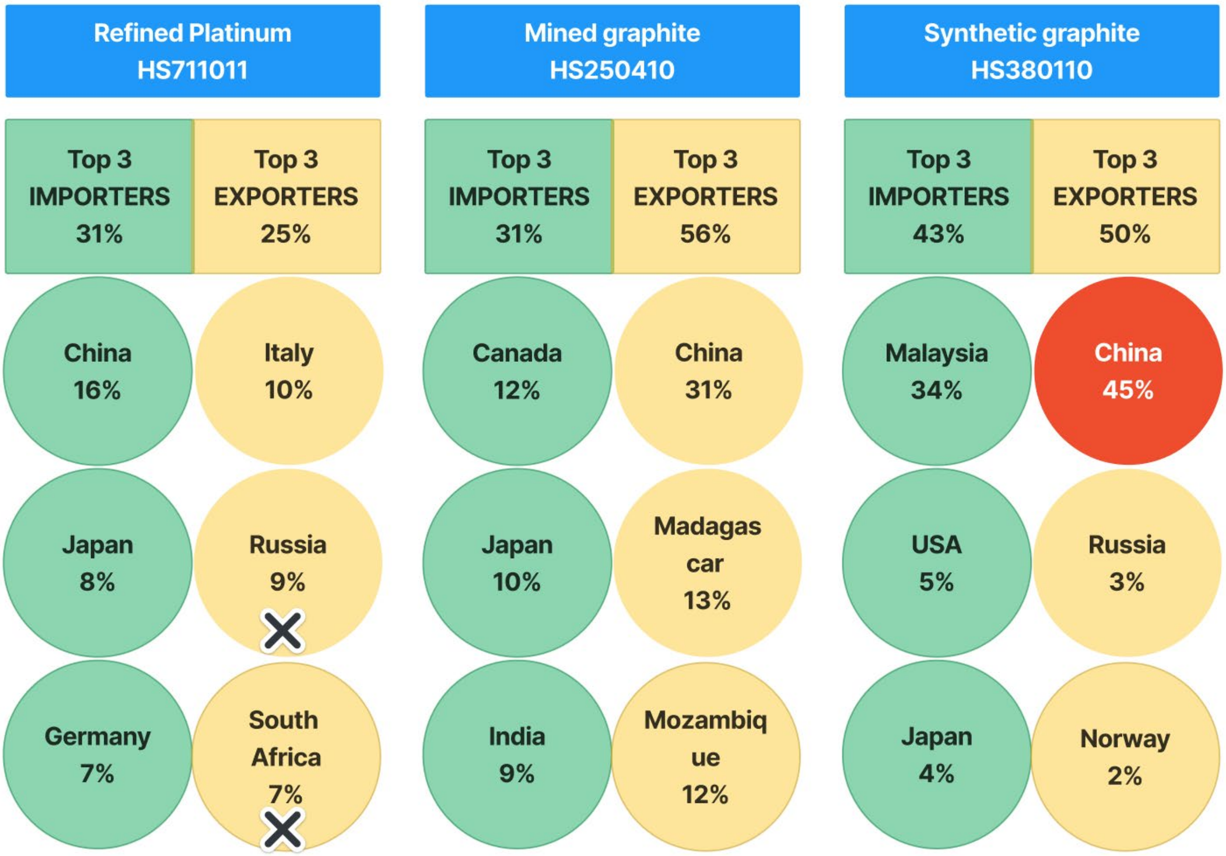
3.1.2 Global trade concentration and trade restrictions

As with the production of platinum and natural graphite, its trade is also geographically concentrated and is subject to trade restrictions imposed by some nations. Trade concentration for platinum and graphite (natural and synthetic) has been calculated from UN Comtrade data (UN Comtrade, 2023) using 5-year averages for 2017-2021 for imports and exports. Trade data for refined platinum (HS 711011), mined natural graphite (HS 250410) and artificial graphite (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. Figure Trade in refined platinum 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, respectively. The largest importer of platinum 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 platinum 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 & Precious Metals Regulator (SADPMR) (OECD, 2022a, 2022b). Trade in natural mined graphite is not particularly concentrated, with 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 each, 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.



Refined Platinum HS711011		Mined graphite HS250410		Synthetic graphite HS380110	
Top 3 IMPORTERS 31%	Top 3 EXPORTERS 25%	Top 3 IMPORTERS 31%	Top 3 EXPORTERS 56%	Top 3 IMPORTERS 43%	Top 3 EXPORTERS 50%
China 16%	Italy 10%	Canada 12%	China 31%	Malaysia 34%	China 45%
Japan 8%	Russia 9% ✗	Japan 10%	Madagascar 13%	USA 5%	Russia 3%
Germany 7%	South Africa 7% ✗	India 9%	Mozambique 12%	Japan 4%	Norway 2%

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

3.2 COMPONENT AND PRODUCT MANUFACTURE

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

A substantial share of FC stack and associated component production appears to be with companies headquartered in Europe and the USA, although wider FC system assembly largely takes place in Asia, where most FC vehicle manufacturing takes place.

A material demand forecast study by the EU (Carrara et al., 2023) notes that the largest manufacturers and suppliers of FC 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 FC value chain (both PEMFC and SOFC). An exception is the manufacturing of the membrane electrode assembly (MEA) 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 PEM MEAs globally (Carrara et al., 2023).

In 2020 85 per cent of FC systems (in MW) were manufactured in Asia, much of it related to the production of passenger FC vehicles by Toyota (Japan, 33 per cent of global FC stocks) and Hyundai (Korea) whereas China dominates in the buses and trucks FC vehicle segments. Some

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

A study by the U.S. Department of Energy (DOE, 2022) finds that the PEM industry (for 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 (e.g. Ballad Power, Canada) produce most of the subcomponents (electrolyte membrane, gas diffusion layer, bipolar plates), whereas others produce one or two components in house. To date, few corporations have the capacity to produce FC components and finished products at significant volumes, as the market and manufacturing capacities are still in the early phases of scaling (DOE, 2022). The DoE report 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):

- **Bipolar plates (BPP):** Europe and Asia currently hold the lead in BPP technology. Ultimately, BPPs are expected to be manufactured close to fuel cell system assembly.
- **Catalyst**: 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.
- **Gas diffusion layer (GDL)**: Four main players dominate the market: SGL and Freudenberg (Germany), Toray (Japan) and AvCarb (USA).
- **Membrane**: 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 FC car from W.L. Gore and associates.

A report by the IEA on hydrogen patenting trends (IEA, 2023c) notes that the European chemical industry dominates innovation in established hydrogen technologies, whereas companies from the automotive and chemical sectors working with electrolysis and FC 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 4 patent applicants are automotive OEMs from Japan and Korea. The top 10 also includes 2 US-based and 2 German automotive OEMs and one of their key suppliers (Bosch) (IEA, 2023c).

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 FC assembly step, where USA, Canada, Japan and South Korea dominate manufacturing. Less than 1 per cent of FC assembly is undertaken in the EU.

4 UK supply chain in fuel cell technology

A key PEMFC player in the UK is Johnson Matthey (JM), 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 SOEC electrolysers to produce green hydrogen and SOFC (fuel cells) (Wood & Optimat, 2022). According to the company website, the company maintains a strong R&D programme and licences the intellectual property (IP) for cells and stacks to manufacturing partners who hold manufacturing and marketing capabilities.

A report by BEIS on Supply Chains to Support a Hydrogen Economy (Wood & Optimat, 2022) 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 PEM fuel cell capacity (GW) in the UK up to 2050 based on (National Grid, 2023a, 2023b) scenario data for hydrogen fuel cell vehicles.

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 FES 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.

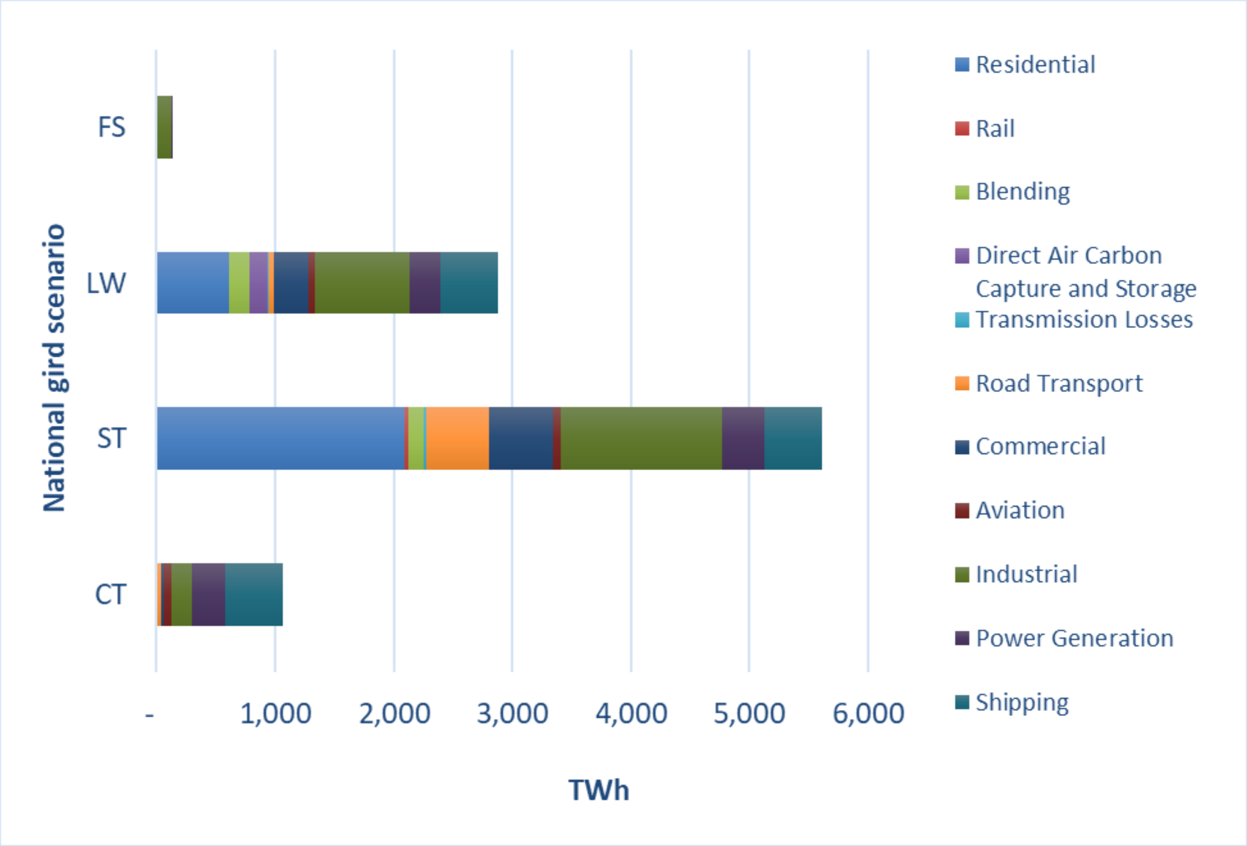


Figure 9: Cumulative hydrogen demand in TWh per sector in four National Grid (NG) future energy scenarios (FES). FS: Falling short, LW: Leading the way, ST: System transformation, CT: Consumer transformation. Data source: (National Grid, 2023a, 2023b).

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 is readily available on the potential mix of fuel cells versus other conversion technologies in the overall market mix. The national grid FES includes 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 dominantly of 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 report (National Grid, 2023a, 2023b) includes data on the number of different types of hydrogen vehicles in use (on the road) up to 2050. The ‘system transformation (ST)’ scenario assumes the highest number of hydrogen vehicles, almost 3.5 million vehicles, 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 impact of end-of-life vehicles flowing out of the system as the underlying data is not available. Accordingly, the estimation should be regarded as conservative relative to the overall vehicle demand.

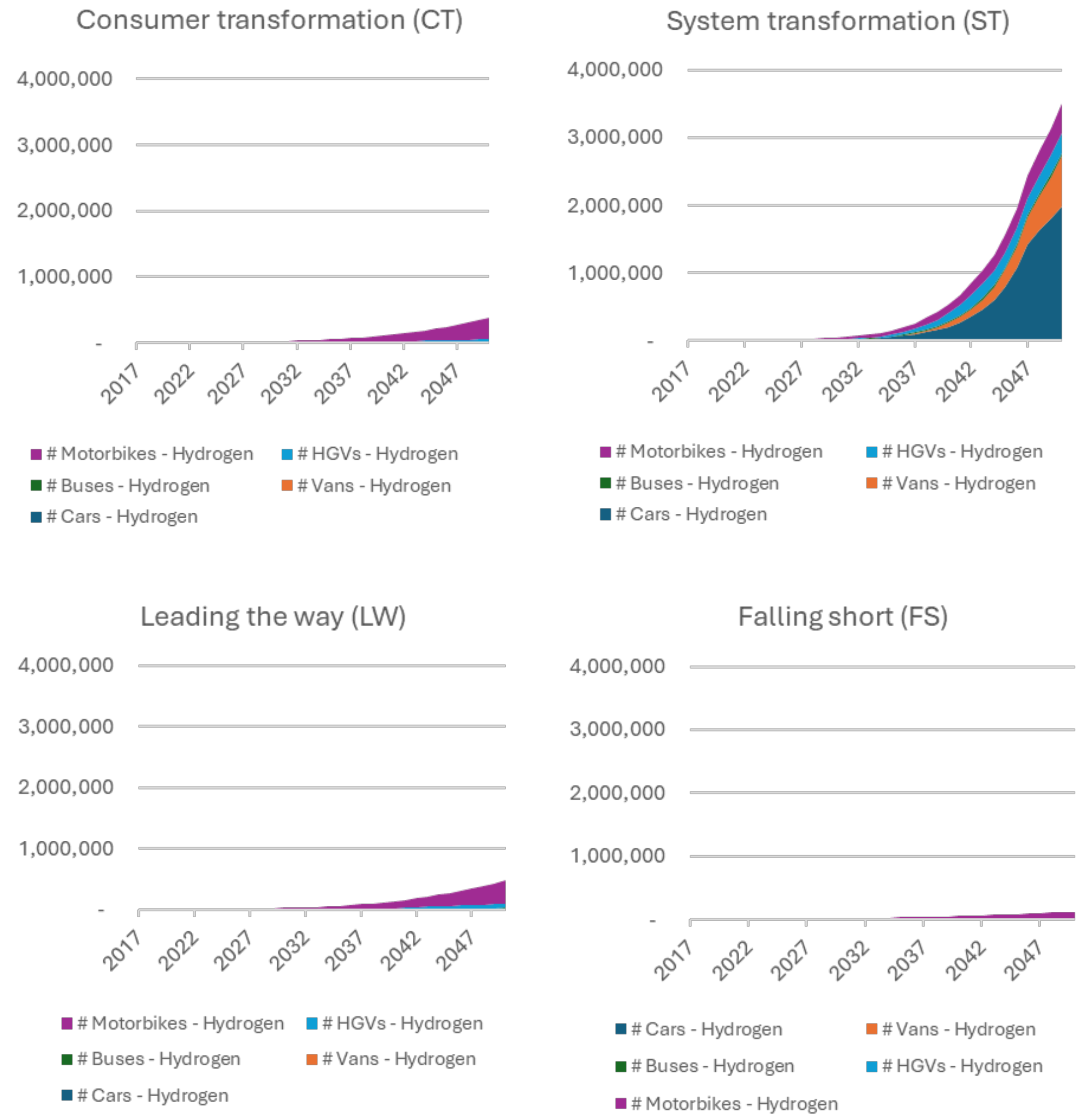


Figure 10: Number of hydrogen fuel cell vehicles on the road in the UK according to four National Grid FES scenarios. Data source: (National Grid, 2023a, 2023b).

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 FC capacity per vehicle (in kW) 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 80-120 kW (APC, n.d.), which is similar to assumptions in other sources (FleetNews, 2023); hence 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 was 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.

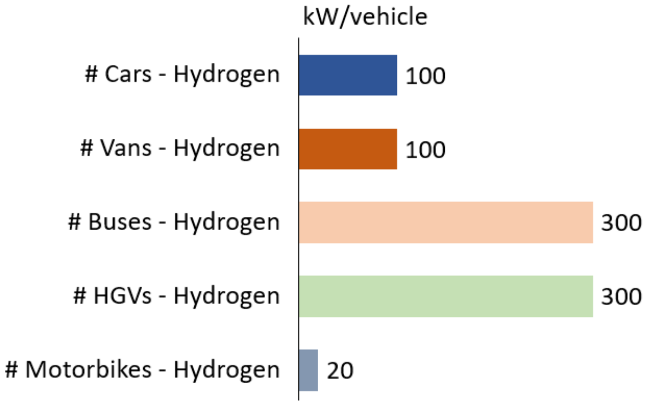


Figure 11: Assumed fuel cell capacity per vehicle used in the material demand estimations.

Based on these assumptions, the installed FC 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 Advanced Propulsion Centre (APC) has forecast demand for fuel cells in the UK to be around 14 GW by 2035 (or equivalent to 140 000 vehicles) (Price, 2023).

In terms of the market mix of different FC technologies, it is assumed that PEMFC will be the dominant technology used for road transport. This is in agreement with other sources, such as Wood & Optimat (2022) who state that PEM fuel cells are generally favoured for transport applications due to their fast startup times and other characteristics.

Material intensities for PEMFC reflect platinum and graphite as reflected in Table 4. Platinum 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.

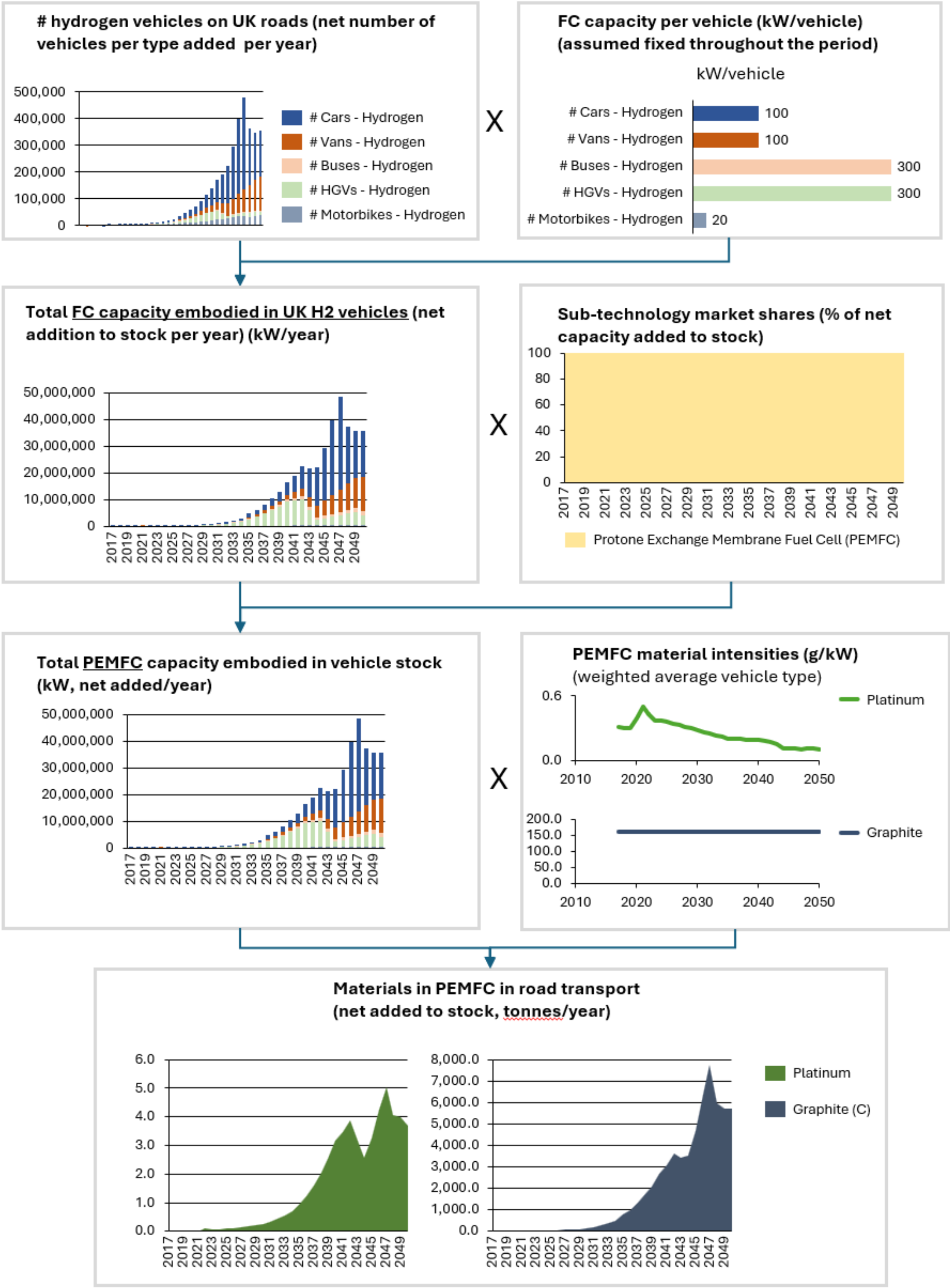


Figure 12: An outline of the modelling logic applied to estimate the embodied material demand for each of the national grid scenarios for fuel cells installed in road vehicles. From top to bottom: the net number of FC vehicles added to stock is multiplied by FC capacity per vehicle (in kW). It is assumed that all FCs are PEMFC type. The installed FC capacity in kW is then

multiplied by material intensities in g/kW, resulting in an estimate for net annual material demand.

5.2 FUTURE UK RAW MATERIAL NEEDS FOR FUEL CELLS

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

(i) as the cumulative quantity (in tonnes) required between 2020 to 2050 for each of the National Grid Future Energy scenarios (annual quantities provided in Appendix D); and

(ii) the annual quantity as the percentage of current annual global platinum and synthetic graphite production (based on average annual production between 2017 and 2021).

The forecasts in Figure 13 show the cumulative UK platinum (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).

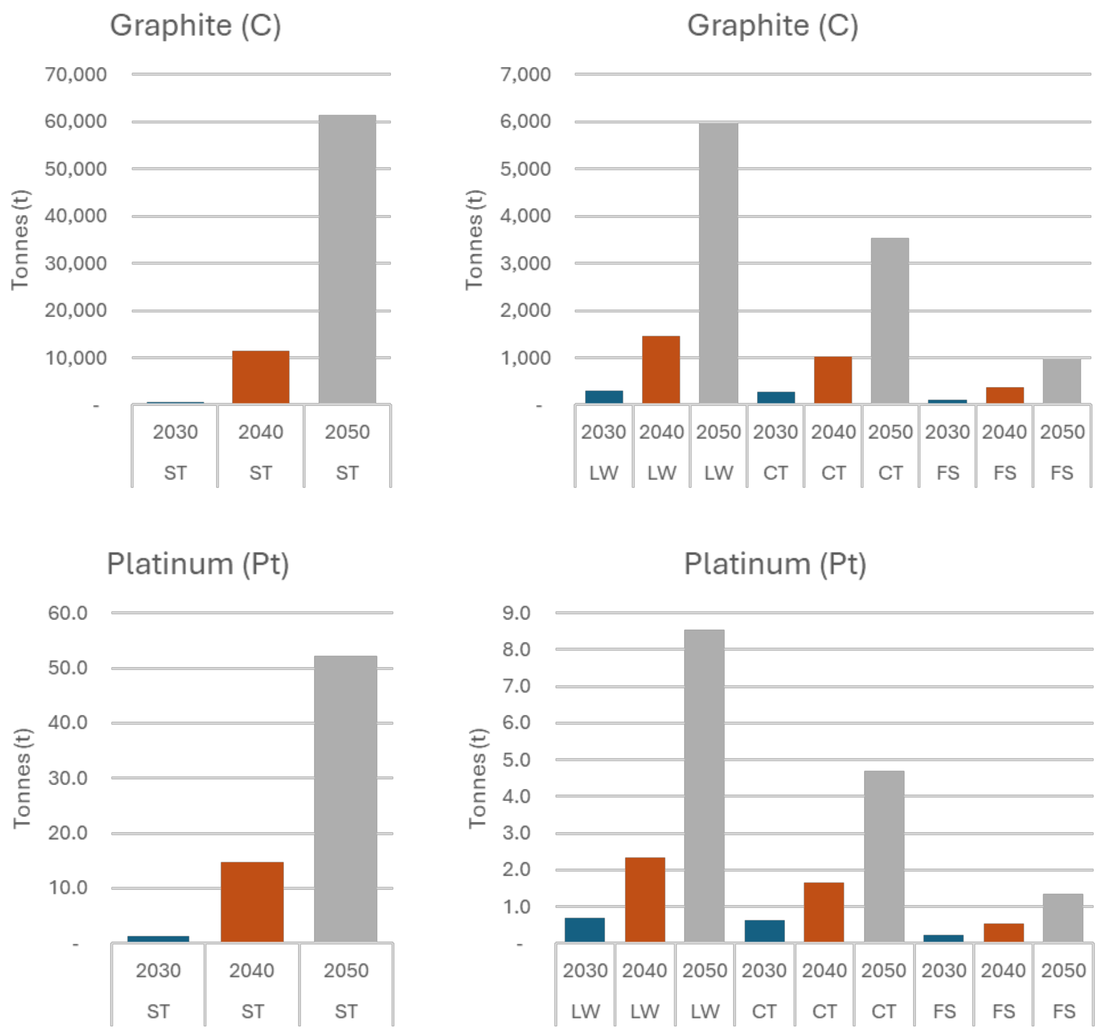


Figure 13: Cumulative forecast UK road transport-related fuel cell demand (tonnes) for graphite and platinum until 2050 under four different scenarios: System transformation (ST), Leading the way (LW); Consumer transformation (CT) and Falling short (FS).

To provide context for the estimated UK material demand, Table 6 shows the annual global platinum production for the five-year period 2017-2021 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 platinum and natural graphite production (5-year average, 2017-2021) compared with UK cumulative material demand for fuel cells in the ‘system transformation’ scenario (data from BGS World Mineral Statistics database, 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 as data is not readily available for synthetic graphite

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).

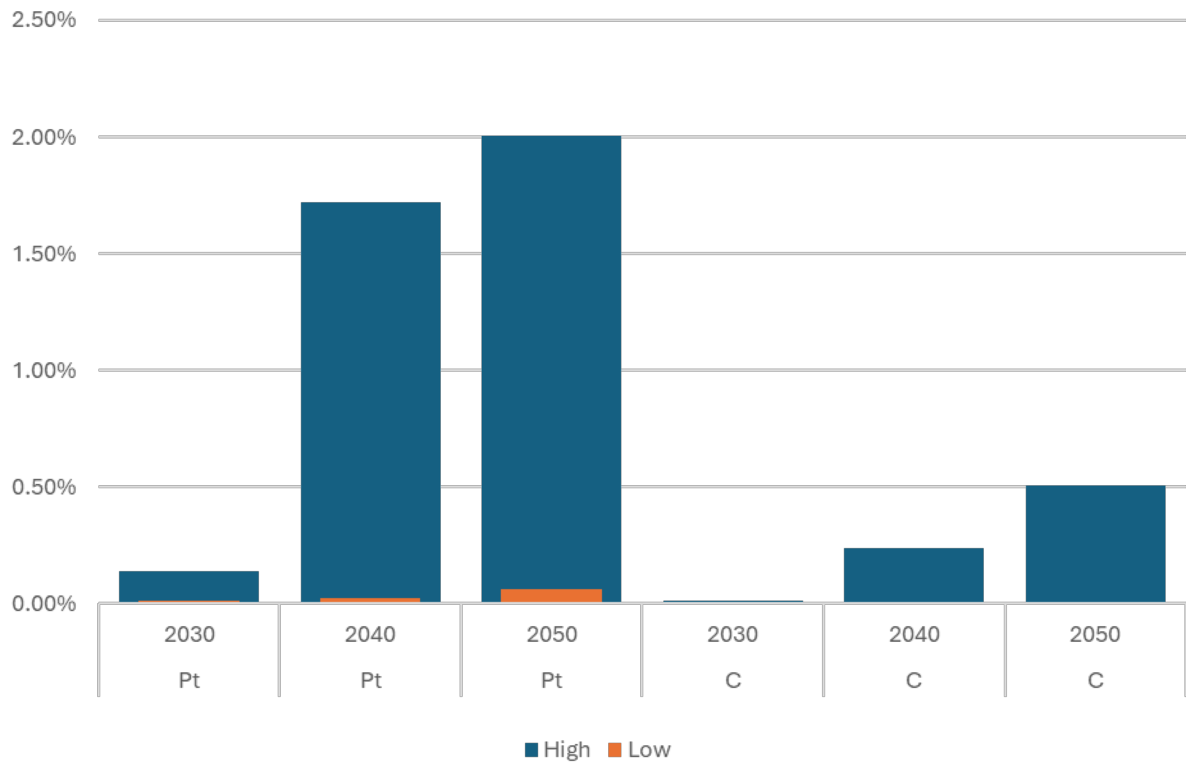


Figure 14: The estimated annual UK demand for platinum (Pt) and graphite (C) in fuel cells used in road vehicles in 2030, 2040, 2050 as a percentage of current global annual production (as reflected in Table 6). The lower values (orange) reflect demand in the ‘falling short’ scenario and the higher value (blue) demand in the ‘system transformation’ scenario.

Figure 14 indicates that annual UK road transport-related FC platinum demand in a high scenario may increase to approximately 2 per cent of current global annual platinum 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 platinum production. The corresponding cumulative platinum demand is 1.2 tonnes by 2030, 14.8 tonnes by 2040 and 52.1 tonnes by 2050 in a high scenario (Figure 13). In the other three scenarios, the cumulative UK demand up to 2050 is well below 10 tonnes. 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.

The estimates for platinum appear aligned with those of Price (2023) which indicated a cumulative platinum demand for vehicle-related FC of about 7 tonnes FC 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 platinum scale up.

The relatively low share of fuel cell platinum material demand as a fraction of global supply is reasonable, because: a) transport-related fuel cell technology represents only a small share of the overall fuel cell and hydrogen economy and b) platinum is also used in many other technologies, chiefly autocatalysts, which are outside the scope of this study (Figure 15).

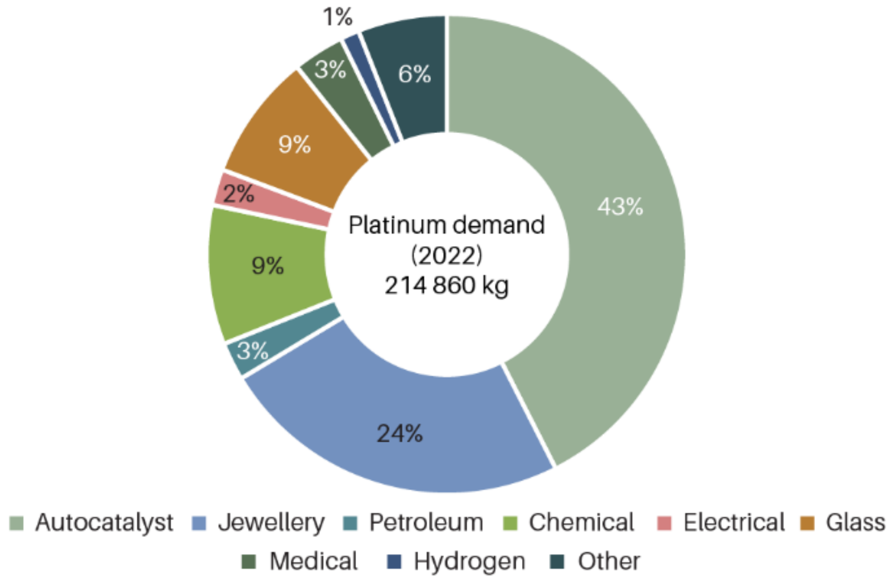


Figure 15: Global platinum demand by sector in 2022 (Price, 2023).

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

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

Forecasts by Johnson Matthey indicate that 70-80 per cent of platinum consumption for hydrogen applications will be for FCEVs with 20-30 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 (2023b) reports that there were 72 000 hydrogen fuel cell electric vehicles (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) provide 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, 2023b) 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 does 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).

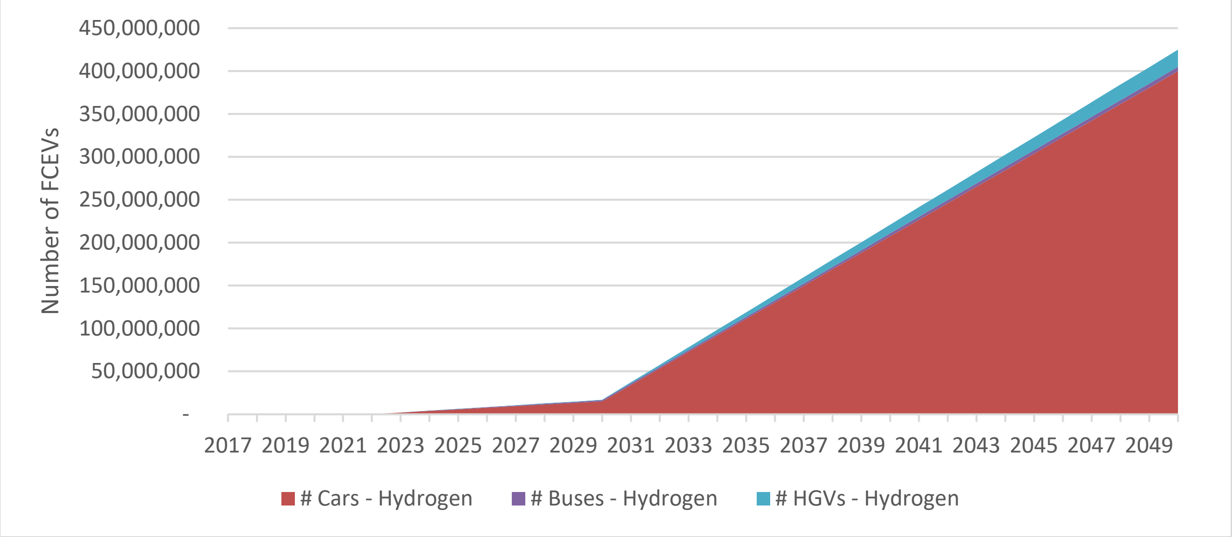


Figure 16: Assumed development of the number of fuel cell electric vehicles on the road globally up to 2050. Data based on IEA (2023b) (historic) and Samsun et al. (2022) (future).

For simplicity, all other modelling parameters and assumptions were kept the same as for the UK estimations (i.e. fuel cell capacity per vehicle, dominance of PEMFC and 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 platinum and graphite compared with the calculated global demand, based on the selected global ramp-up scenario.

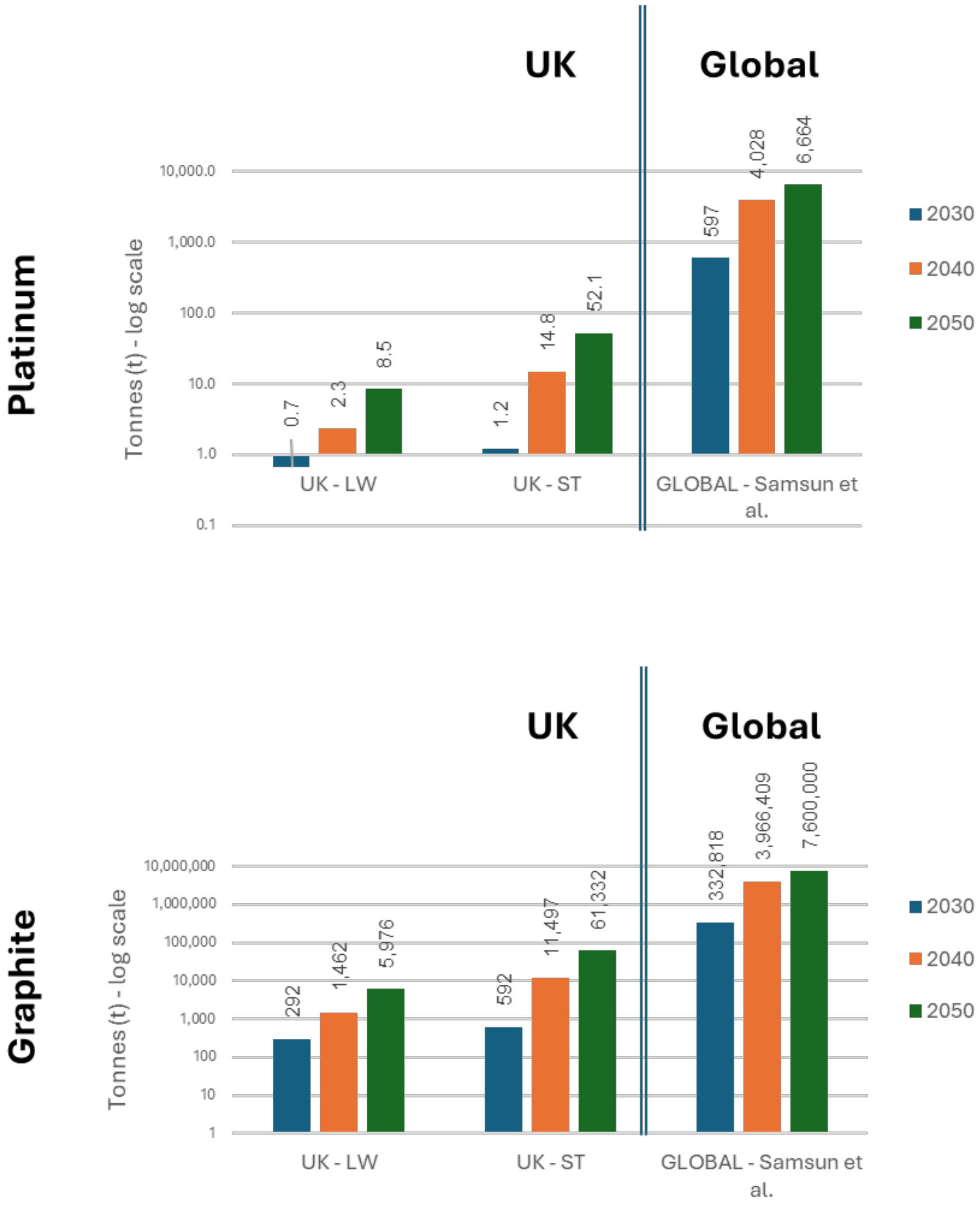


Figure 17: Estimated cumulative UK demand for platinum and graphite (in the ‘leading the way’ (LW) and ‘system transformation’ (ST) scenarios) compared with global demand for FCs in road transport.

The UK demand for platinum 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 tonnes of platinum for about 425 million FCEVs on the road. This is equivalent to approximately 15.7 g platinum per vehicle. The UK cumulative demand of 52.2 tonnes for roughly 3.5 million vehicles in a system transformation scenario is similarly equivalent to 14.9 g platinum per vehicle. The slight difference between the UK and global relative platinum consumption per vehicle has to do with the different number and ratios of types of vehicles (e.g. heavy and light), as all other modelling assumptions were kept the same. These values appear consistent with assumptions by Johnson Matthey which indicate average platinum intensities as low as 15 g/vehicle by 2050 (Johnson Matthey, 2023a).

In terms of annual demand, the global scenario peaks at over 400 tonnes of platinum per year after 2030 (for >20 million FCEVs added to stock annually). This falls to about 240 tonnes per year in 2050 as a result of continuing reductions in material intensity. It is, therefore, clear that the current annual platinum production of about 180 tonnes 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 platinum. Although the UK will remain a relatively small player in the global FCEV landscape, it may be challenging to secure the sustainable platinum supplies required to meet its deployment targets (BEIS, 2021, National Grid, 2023a, 2023b).

The estimated cumulative global demand for graphite for road vehicle PEMFC until 2050 is in the order of 7.6 million tonnes, 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 PEMFC with bipolar plates made of graphite. The graphite estimate should be taken as a rough order of magnitude estimate which is subject to considerable uncertainty, as noted previously.

6 Discussion and conclusions

Fuel cells (FC) 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 (FC) deployment in the UK with a focus on the road transport sector.

Of the different FC types available in the market, PEMFC are particularly suitable for use in vehicles and other mobility applications due to their small volume and high-power intensity. Hence, PEMFC is expected to be the dominant FC technology for road transport and other mobility applications. A key functional element in PEMFC is platinum (Pt) which is required as a catalyst in the FC electrolyte, contributing to a high cost of PEMFC. Other metals, such as palladium (Pd), ruthenium (Ru), iridium (Ir), and cobalt (Co), may be found in some PEMFC variations or as substitutes for small amounts of platinum. Other elements in PEMFC include carbon-based materials and synthetic graphite, perfluorosulfonic acid (PFSA) polymers, aluminium, and steel.

This study focuses on platinum and graphite as the key functional materials in PEMFC and for which data is available. This permits estimation of platinum 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 was available for the bill of materials (BoM) as the quantities used in PEMFC is assumed to be very low.

Forecast material demand associated with FC deployment up to 2050, based on the National Grid Future Energy scenarios (FES) for hydrogen vehicle uptake, was determined and compared with forecast global FC demand for the same period.

Supply bottlenecks for the embedded platinum 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; and
- **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:

- Estimated UK demands for platinum and graphite in FC vehicles up to 2050 are relatively low in comparison to today's global production capacities.
- However, over 90 per cent of platinum production is concentrated in three producing countries: South Africa (>70 per cent of global total), Russia (12 per cent) and 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 platinum (DOE, 2022). It has, however, been noted that PGM mining and refining is concentrated with few large and publicly quoted companies subject to stringent regulation and ESG reporting requirements (Johnson Matthey, 2023a).
- On the positive side, the UK has a well-established supply chain for PGM metals 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 platinum (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 platinum, and China for natural and synthetic graphite. The FC 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 (FC stack) Asian vehicle-producing countries (Japan and South Korea) dominate the market. An EU foresight study finds the highest FC supply chain vulnerability to be the assembly step, where 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 platinum demand, and there is substantial competing demand from other sectors. Hence, high levels of competition for the required materials can be expected worldwide.

The outlook carries several forecasting uncertainties because:

- The scope of the study is limited to road transport which is expected to only represent a small fraction of the total hydrogen demand in the future. In other sectors where fuel cell deployment can be expected, including rail, shipping and aviation, FC deployment is less developed than in road vehicles and may comprise a mix of fuel cells and gas combustion technologies. Similarly, stationary FC deployment in power generation is yet to take off at scale and future developments are uncertain.
- Significant technology advancements have been seen in FC 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, FC electric vehicle platinum 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 platinum loadings per kW FC capacity.
- The underlying road transport related fuel cell demand scenarios display significant variation in expected demand for hydrogen vehicles. The high ‘system transformation’ scenario assumes significantly higher demand for fuel cell electric vehicles (FCEVs) compared with the second highest (‘leading the way’) scenario. 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 its high efficiency.

Regardless of these uncertainties, even under those scenarios with lower levels of FC uptake in road transport, future UK demand for platinum 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 FC vehicles and contribute to increased demand. On the other hand, further breakthroughs in battery technology could put a halt to FC vehicle market penetration.

7 Recommendations

Analysis of the FC-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.

- **Methodology recommendations**
    - **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 is limited. This includes missing data on the bill of materials (BOM) 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 and thus undermine the reliability of forecasts of material demand for FCs. Developing BOMs for signature products could further improve data visibility.
    - **Overcoming the uncertainty gap**: the current study works backwards from future demand scenarios for innovation technologies which are subject to significant learning curves. This affects their material composition and relative mass requirements, hence resulting in significant variance between the derived forecasts. A frequent refresh of the study could further reduce uncertainty.
    - **Refreshing outlook on wider potential application space:** Given the nascent stage of the fuel cell development and the expectation, that other markets than transport, could move out of the experimentation stage in the next couple of years, it is recommended to repeat this type of analysis with a clear focus on looking into further sectors (e.g. rail, aviation, off grid energy storage, etc.).

  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 where 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 create a solid foundation for proactive and reliable decision making in the future.

- **Security of supply recommendations**
    - **Scale-up of the FC-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 platinum mining in a few publicly registered companies with strong ties to the UK (e.g. South Africa and Zimbabwe) facilitates effective monitoring of ESG risks and performance throughout the value chain.
    - **Maintaining and strengthening the UK’s strong position** in the PGM value chain will help mitigate supply chain risks related to the sourcing of platinum required for FC and other applications and can support the development of a strong FC value chain in the UK.
    - **The platinum supply** chain should not be considered in isolation, but also in the context of other PGMs, which are by-products of platinum mining and are essential for related technologies such as electrolysers. Continued production of platinum is required to ensure supply of these by-products, such as iridium, rhodium, palladium (Johnson Matthey, 2023b). The net-demand for platinum might fall in the future due to decreased use in autocatalysts. If this drop in platinum demand is not replaced by new markets such as for FCs, the supply of iridium 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.
    - **There is already an established recycling industry** for platinum globally (Johnson Matthey, 2023a, 2023b). Nonetheless, there is an opportunity, in collaboration with leading UK FC players to explore options to strengthen the management of 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.

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 FC-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 reuse and recycling to maintain necessary stocks within the UK.

- **Local capability recommendations**
    - **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. Build-up of local fuel cell design and manufacturing capabilities for FC would ensure participation in expected scale game leveraging a unique starting position with Johnson Matthey
    - **Investment in FC technology innovation** is required to ensure that assumed learning curves towards lower FC cost, lower platinum intensities and higher durability will materialise. If these learning curves do not materialise, further bottlenecks to FC deployment in the UK and worldwide are likely to develop.
    - **Given the absence of mineral reserves** of platinum in the UK, a focus on maximising resource productivity of existing stocks 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 PGM in existing product and component stocks, e.g. autocatalysts, and exploring initiatives that go beyond recycling, including component reuse, e.g. anodes and cathodes. These approaches would benefit from a UK-focused programme to incentivise private sector investment backed up by an improved regulatory regime.

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Appendix A

PEMFC materials 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 PEM fuel cells. Other fuel cell types and associated materials are excluded.

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

Appendix B

Overview on component manufacturers.

Overview of selected PEMFC and component manufacturers globally. Source: DOE, p. (2022, p. 16).

Company	Headquarters	Manufacturing locations	Products
3M	US (St Paul, MN)	Minnesota and Wisconsin, US	Membrane, Ionomer
Advent	Greece (Athens), US (MA, Boston)	Greece, MA US	Membrane, MEA
Ballard Power Systems	Canada (Burnaby, BC)	Canada (BC), Denmark	PEMFC, MEA*, BPP*
BASF	Germany (Ludwigshafen)	Germany	MEA, Catalyst
Chemours	US (Wilmington, DE)	US (South Carolina)	Membrane, Ionomer
Horizon Fuel Cell	Singapore	Singapore, China	PEMFC
Hydrogenics – subsidiary of Cummins (Cummins 2019)	Canada (Mississauga, Ontario)	Canada (Ontario)	PEMFC
Intelligent Energy	UK (Loughborough)	UK	PEMFC
Ion Power	US (New Castle, DE)	US (Delaware and Pennsylvania)	MEA
Johnson Matthey	UK (London)	US (Pennsylvania), UK	MEA, Catalyst
Plug Power, Inc. (“Plug Power | Green Hydrogen & Fuel Cell Solutions”)	US (Latham, NY)	New York, US	PEMFC, MEA*
Solvay	Belgium (Brussels)	US (NJ), Italy	Membrane, Ionomer
TANAKA	Japan (Tokyo)	Japan	Catalyst
Umicore	Belgium (Brussels)	China, US, Germany, Denmark, Korea	Catalyst
W.L. Gore	US (Newark, DE)	US (Delaware), 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 FC sectoral applications

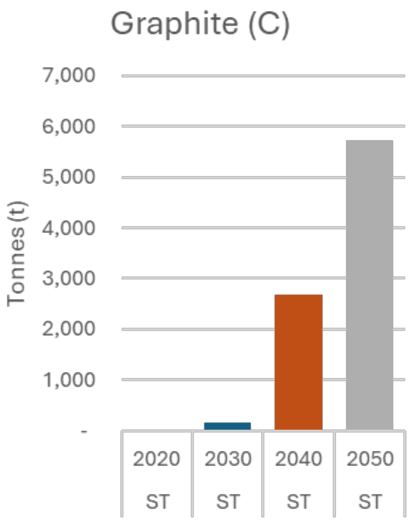
Sector	**Fuel Cell (FC) relevance – preliminary analysis / assumptions**	**Assumed FC Sub-technology relevance (share) in context of the study**				
		PEMFC	**SOFC**	**AFC**	**MCFC**	**PAFC**
Residential	NG: The residential H_2 demand appears to refer primarily to “residential hydrogen demand for heat” (National Grid, 2023b)(National Grid, 2023b) via H2 gas boilers or combined boiler and ASHP systems. This cumulated demand is 1784 TWh in ST and 455 TWh in LW, 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 ST scenario assumes use of H_2 for railways. While not stated in the FES2023 report, it is likely this will include FCs. There are various H_2 projects being developed internationally, some which are close to commercialisation (source). The UK HydroFlex H_2 train uses PEMFC of 100kW. However, it is uncertain how to estimate the installed FC capacity based on the NG TWh demand, or which assumptions the NG has applied in this regard. Generally, rail H2 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 FC relevance.	N/A	N/A	N/A	N/A	N/A
Direct Air Carbon Capture and Storage	NG (FES2023, p.153) 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 FC power generation via stationary FC plants. In the absence of data, this sector is excluded from the FC foresight analysis.	Excluded due to lack of readily available data.				
Transmission Losses	No FC relevance.	N/A	N/A	N/A	N/A	N/A
Road Transport	H_2 for road transport expected by NG to pick up after 2030, mainly in the ST scenario. While not explicit in the NG report, it is assumed here that FC will dominate for H_2 vehicles, as direct combustion of H_2 is less efficient. It is furthermore assumed that PEMFC will be the dominant sub-technology, due to their suitable characteristics (high power density, low operating temp., quick start up, etc.) and current trends.	**100%**				
Commercial	NG (FES2023, p.94) 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.” Hence, no FC relevance assumed for this study.	N/A	N/A	N/A	N/A	N/A

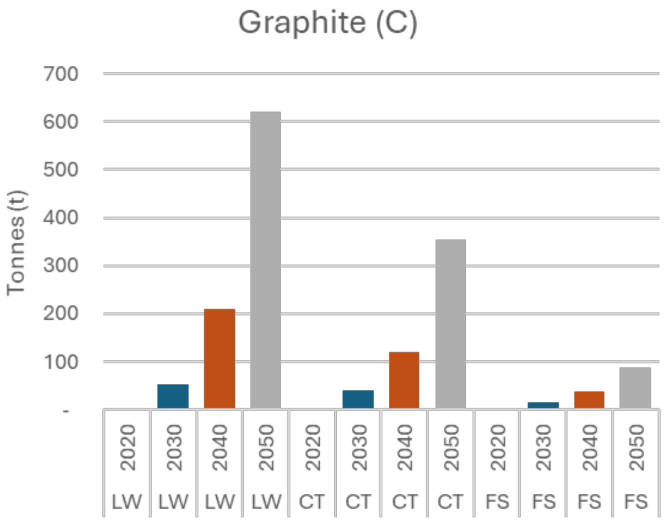
Aviation	The NG CT, ST and LW scenarios all assume substantial H2 demand for aviation, without specifying further the underlying assumptions in terms of number of airplanes or technology (FC vs. combustion). Excluded for now in the absence of data / qualified assumptions.	Excluded due to lack of readily available data.				
Industrial	For Industrial hydrogen demand (EC.17) NG does not specify in much more detail how this will be used or to what extent this will involve fuel cells but indicates (p.92) this will initially include substituting natural gas with H2 for ind. processes. Although stationary FCs 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	NG (FES2023, p.153) 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 FCs are likely, however there is no data on the assumed installed FC capacity to meet this H2 demand. Excluded for now in the absence of data / qualified assumptions.	Excluded due to lack of readily available data.				
Shipping	The NG CT, ST and LW scenarios all assume substantial H2 demand for shipping, without specifying further the underlying assumptions in terms of number of ships or technology (FC vs. combustion). Excluded for now in the absence of data / qualified assumptions.	Excluded due to lack of readily available data.				

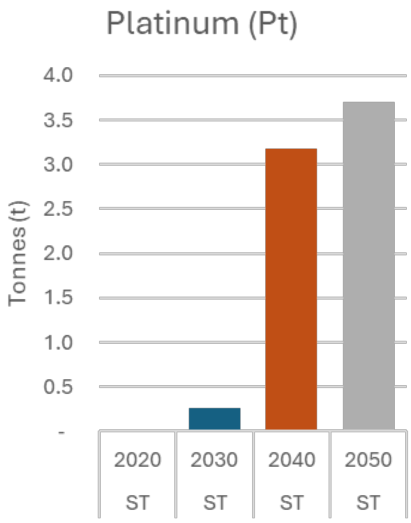
Appendix D

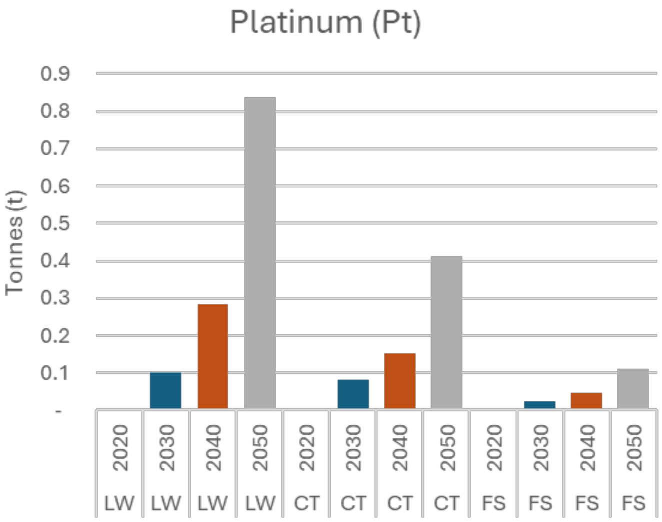
Annual demand as function of scenario

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









Appendix E

An overview of FC technologies and associated key material use not covered within the scope of this analysis (i.e. applicable to other sectors than road transport).

The following table summarises the key elements found in the FC technologies which are outside the scope of this study, i.e. technologies other than PEMFC.

Table: Materials used in fuel cell technologies other than PEMFC.

Technology	UK critical elements	Other
AFC	Platinum (Pt), palladium (Pd)	Silver, manganese (Mn), nickel (Ni)
PAFC	Platinum (Pt), graphite (C)	
MCFC	Lithium (Li)	Nickel (Ni), chromium (Cr)
SOFC	Lanthanum (La), yttrium (Y), cerium (Ce), gadolinium, samarium (Sm), cobalt (Co)	Nickel (Ni), zirconium (Zr), manganese (Mn), strontium (Sr), iron (Fe), chromium (Cr)

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

The below sections briefly describe the materials used in FC technologies which are outside the scope of this report, as they are not expected to be used in road transport applications.

Alkaline fuel cell (AFC)

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

Phosphoric acid fuel cell (PAFC)

PAFC is a mature technology but is used commercially in low volumes (Shell & Wuppertal Institut, 2017). Modern PAFC include platinum 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).

Molten carbonate fuel cell (MCFC)

The MCFC uses 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 (Li_2CO_3, K_2CO_3) and the electrodes consist of nickel (Ni) materials. The anode is made of nickel, commonly alloyed with chrome or aluminium, and the cathode consists of lithiated nickel oxide. Hence, key functional materials include lithium, nickel, and chrome.

Solid oxide (or Oxide ceramic) fuel cell (SOFC)

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