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

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

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1 Introduction to solar photovoltaic technology

Solar power is an effectively infinite renewable energy source that potentially has a major role to play in decarbonisation (Maka and Alabid, 2022; National Grid, 2023a). The conversion of energy from the Sun into electricity requires the use of photovoltaic (PV) panel technologies. Solar PV panels are now widely used at domestic and industrial scales for generating electrical power. The electricity produced can be used directly or stored in rechargeable batteries. Solar PV panels for energy generation should not be confused with solar thermal panels, which convert solar energy into heat (Modi, 2023).

1.1 PRINCIPLES OF OPERATION

A PV cell comprises very thin wafers of semiconductor material that, when exposed to sunlight, convert the incident energy to electrons. Individual cells are linked together to make a panel, each installed in a metal frame within a glass casing. The electrons flow through a framework of wires within the panel to an inverter, which converts the direct current to an alternating current. Individual panels are connected to make a solar installation or module.

The configuration of a PV cell and its essential parts are illustrated in Figure 1.

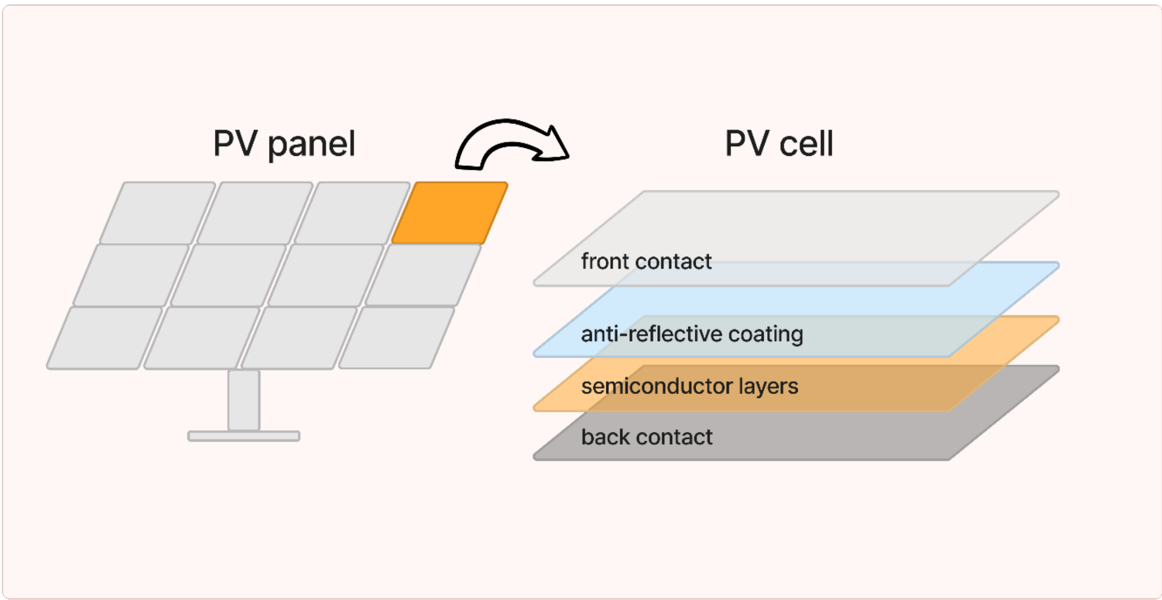

Figure 1 Simplified structure of a PV cell, based on information from European Commission et al. (2020); Maka and Alabid (2022).

The dominant semiconductor used in PVs is crystalline silicon (c-Si), which can be employed in either monocrystalline or polycrystalline forms. While monocrystalline silicon (Si) is more efficient, polycrystalline Si cells are cheaper to produce (Fraunhofer ISE, 2023; Pastuszak and Węgierek, 2022). Crystalline silicon had an overall market share of 95 per cent in 2020 (Fraunhofer ISE, 2023) (Figure 2).

Crystalline Si PV cells come in two main types: passivated emitter and rear contact (PERC) and Si heterojunction (SHJ).

The proportion of solar energy that is converted into usable electrical power, termed the ‘cell efficiency’, is currently about 20 per cent for Si cells (Gervais et al., 2021; Fraunhofer ISE, 2023). Prior to 2018, most c-Si cells used aluminium back surface field technology, which had relatively low efficiency and was gradually replaced by the PERC cell structure (Wilson et al., 2020). However, current research into the use of alternative materials and manufacturing technologies is aiming to further increase the efficiency and thus promote greater deployment of PVs; for example, through the development of the multijunction III-V/Si technology (III-V tandem solar cell on Si substrate) (Gervais et al., 2021; Fraunhofer ISE, 2023).

Thin-film solar cells are more flexible than c-Si cells and can potentially be used in a wide range of applications. Although less material is used in their production, thin-film cells have lower efficiencies and higher manufacturing costs, which has affected mass adoption (Pastuszak and Węgierek, 2022). Thin-film PVs currently account for only 5 per cent of the total market (Figure 2). Only copper-indium-gallium diselenide (CIGS) and cadmium-telluride (CdTe) thin-film cell types have been considered in this analysis; amorphous Si thin films are not included as their use has been declining over the past five years and they currently have a very small market share (Fraunhofer ISE, 2023) (Figure 2).

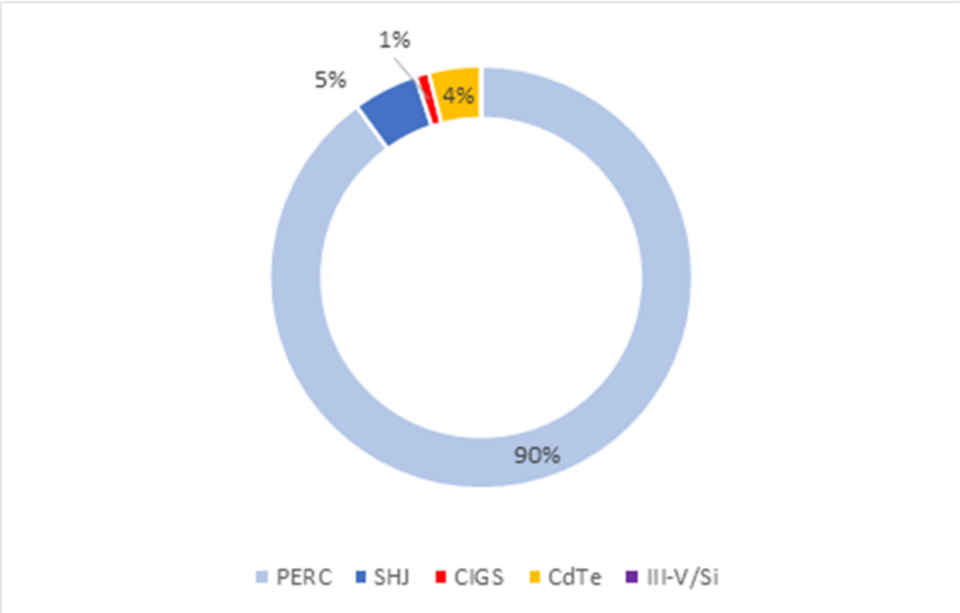

Figure 2 Market shares of different PV technologies in 2020 (Fraunhofer ISE, 2023). The market share for III-V/Si is currently close to 0 per cent BGS © UKRI 2024

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1.2 ESSENTIAL COMPONENTS AND MATERIALS

Materials that contribute to the functioning of the various cell types are analysed in this report (Table 1). Only the materials fundamental to the generation of electricity by each cell type are assessed.

Table 1 Elements used in PV technologies.

Technology	UK critical elements	Other
PERC	silicon (Si), bismuth (Bi), tin (Sn), antimony (Sb), gallium (Ga)	aluminium (Al), silver (Ag), copper (Cu), lead (Pb), boron (B)
SHJ	silicon (Si), indium (In), tin (Sn), antimony (Sb)	aluminium (Al), silver (Ag), copper (Cu), zinc (Zn), boron (B)
III-V/Si	silicon (Si), bismuth (Bi), gallium (Ga), indium (In), tin (Sn), antimony (Sb)	aluminium (Al), copper (Cu), arsenic (As), zinc (Zn), germanium (Ge)
CIGS	gallium (Ga), indium (In), tin (Sn), antimony (Sb)	aluminium (Al), copper (Cu), cadmium (Cd), selenium (Se), zinc (Zn), molybdenum (Mo), fluorine (F)
CdTe	indium (In), tin (Sn), tellurium (Te) antimony (Sb)	aluminium (Al), silver (Ag) copper (Cu), cadmium (Cd), molybdenum (Mo), fluorine (F)

Elements in red are excluded from the analysis because they are either used in structural components or they are not used in the most common configuration of the technology.

1.2.1 Passivated emitter and rear solar cells

PERCs are the most widely used current technology. Key components of the cell include:

- a front contact layer (silver (Ag) paste)
- a crystalline silicon (c-Si) substrate (phosphorus (P) doped)
- a rear contact layer (aluminium (Al) paste)

(Solar Magazine, 2023; Gervais et al., 2021) (Figure 3)

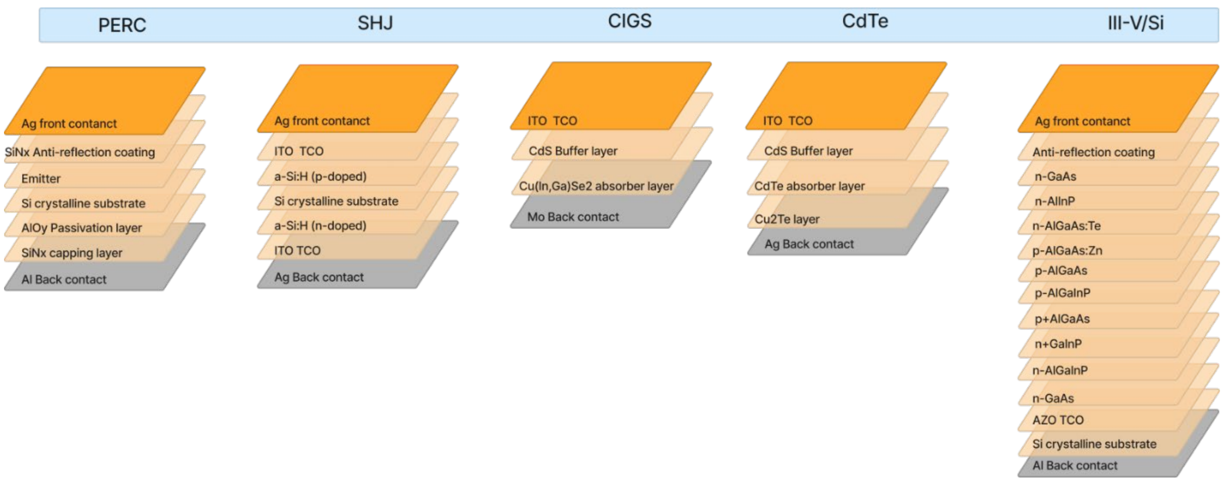


Figure 3 A simplified visualisation of the component layers in different types of PV cell. Modified from Gervais et al. (2021); Rahman et al. (2013).

1.2.2 Silicon heterojunction solar cells

SHJ solar cells currently have the second-largest share of the PV market and their importance is expected to increase in the future (Fraunhofer ISE, 2023). They have larger capacity than

PERCs, but do not cost significantly more to manufacture. They may be considered as a hybrid technology between c-Si and thin-film variants.

SHJ cells generally comprise:

- a front contact layer (Ag paste)
- a c-Si substrate passivated on both sides by a thin layer of amorphous Si
- a back contact (Ag paste)

The transparent conductive oxide (TCO) layer (comprising indium-tin oxide, ITO) also has an important functional role as it improves the conduction and absorbance of light and has anti-reflecting properties (Figure 3) (Gervais et al., 2021).

1.2.3 Copper-indium-gallium diselenide and cadmium-telluride thin-film cells

The essential components of these cells are:

- an absorber layer (CIGS or CdTe)
- a transparent conductive oxide layer (TCO) composed of ITO (indium tin oxide) (front contact)
- a back electrical contact layer

(Gervais et al., 2021) (Figure 3)

1.2.4 III-V/Si thin-film tandem solar cells

These cells usually consist of III-V semiconductors on gallium arsenide (GaAs) or germanium (Ge) substrates (Figure 3). However, the use of a GaAs or Ge substrate significantly increases the cost of this technology. A gallium-indium-phosphorus/gallium arsenide (GaInP/GaAs) III-V cell on a silicon substrate is a cheaper and more efficient option, although these are currently only used in high-specification applications such as space technologies. They are likely to become available commercially after 2035 (Gervais et al., 2021; Boyer-Richard et al., 2023)

2 Supply chain mapping of photovoltaic cells

Eleven raw materials in the supply chain of PV cells were selected for detailed mapping. Figure 4 shows the different stages of the PV supply chain, the material transformations that take place at each stage for the individual materials, and the connections of these materials to the different cell technologies considered in this analysis.

Some intermediate steps in the PV supply chain could not be analysed because many key players do not publish data. Furthermore, as the focus of this study is on the PV cell, the stages of the supply chain encompassing the manufacture of the solar panel, module assembly and panel installation are not considered. Raw materials and intermediate products excluded from the analysis are listed in Appendix A.

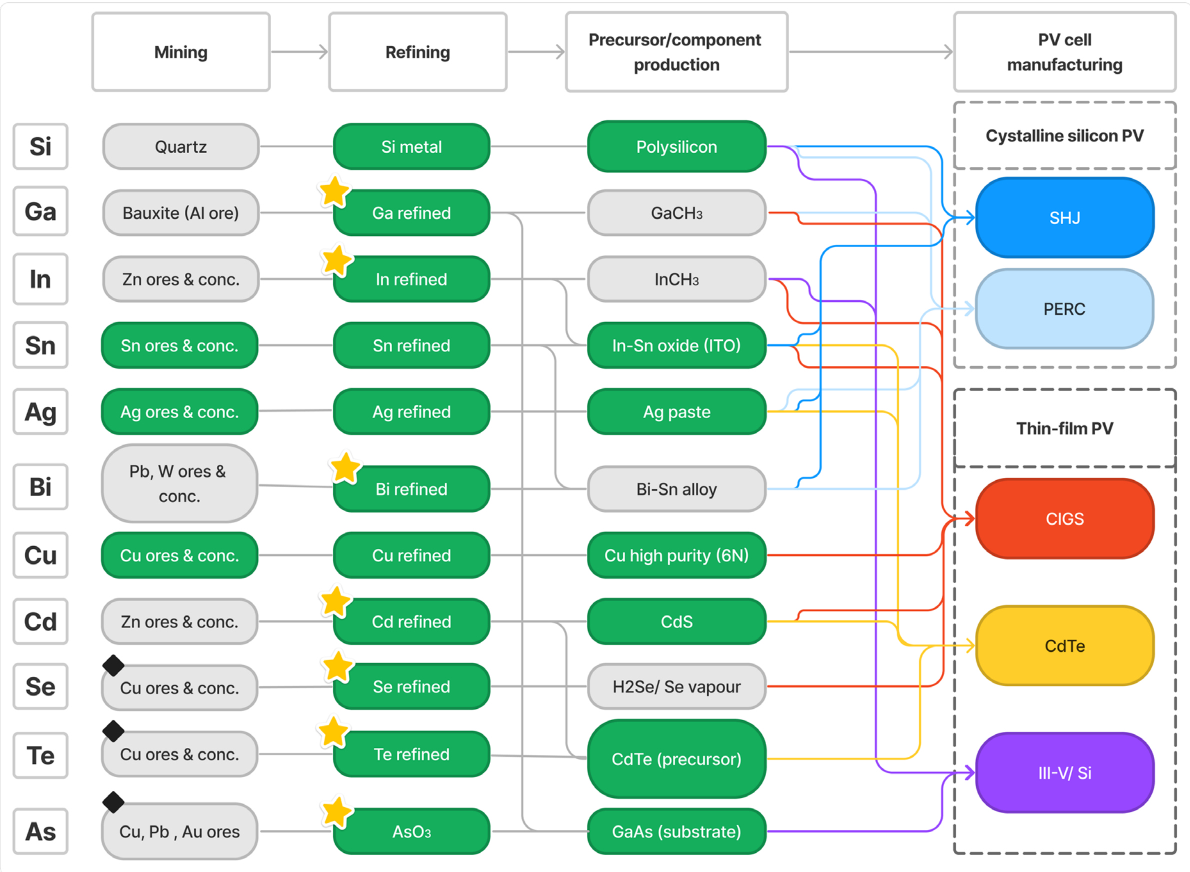


Figure 4 Supply chain mapping of PV cells, key raw materials and components. The green shading indicates materials that have been included in the analysis. A star indicates a material produced as a by-product in the refining stage. A diamond indicates that the commodity is part of the processing waste stream and not always recovered. BGS © UKRI 2024

Seven of the 11 raw materials analysed are produced mainly as a by-product of the extraction of another material that is the main product of a processing operation. They may therefore be recovered from the concentrate of the main product (for example, indium (In) and cadmium (Cd) in zinc (Zn) concentrates) or from processing waste streams (for example, tellurium (Te) and selenium (Se) in copper (Cu) anode slimes in Cu refineries). However, recovery of these by-products alongside the main product is undertaken only at a limited number of refineries; in most cases, their recovery is not economically viable and they end up being lost in the waste stream.

The metals and chemical compounds produced in the refinery provide feedstock for the manufacture of precursor intermediate materials, which are subsequently used in the manufacture of PV cells. In the case of Si, quartz is refined to Si metal that is used in various applications requiring different levels of purity. In the PV supply chain, Si is typically refined to metallurgical grade Si (about 98 per cent Si) via carbothermic reduction, which can then be used to produce polycrystalline Si (also referred to as polysilicon) (IEA, 2022a; BRGM, 2020). However, it should be noted that available Si production data includes all grades of Si metal purity and not data by each type or form of Si.

Both SHJ and PERC c-Si PV cells require:

- polysilicon semiconducting material (with a purity of more than 99.99999 per cent Si, referred to as 7N)
- Ag paste, a colloidal suspension of Ag nanoparticles in an adhesive paste for metal connections
- bismuth-tin (Bi-Sn) alloys for soldering
- ITO as a TCO in SHJ, CIGS and CdTe
- dopants, such as trimethylgallium ($GaCH_3$), boron (B) or P

Thin-film PV cells require a broader spectrum of raw materials than c-Si cells. The name of the cell type refers to the material used in the main absorber layer: for example, CIGS and CdTe PV cells. In addition, in both CIGS and CdTe cells, cadmium sulfide (CdS) is used as a buffer layer and Ag paste is used as a metal connector. Polysilicon, In and GaAs are used in III-V Si cells.

3 Supply chain bottlenecks

The range and complexity of PV cell technologies require several diverse but highly specialised manufacturing stages that involve the use of numerous raw materials from a variety of sources. However, these material sources and the appropriate manufacturing infrastructure are restricted in their geographical distribution and limited to a few countries worldwide. This production concentration contributes to an increased risk of supply disruption at any stage within the supply chain (Figure 5).

The mining stage of the PV supply chain is dominated by those countries that are the main producers of ores and concentrates of Ag, Cu and tin (Sn). The refining stage is more geographically diversified, although it is dominated by global refining hubs mostly located in Asia, notably China. In fact, China is either the largest or one of the three largest global producers of each of the elements included in this analysis.

The geographical concentration pattern changes in the midstream of the PV value chain (precursors and components), with western countries such as the USA and Germany appearing among the top producers. However, it is important to note that China is an important producer of all the precursor materials analysed. The same patterns are observed for the PV cell manufacturing stage, in which both the USA and China have prominent roles (Figure 5).

3.1 MINING AND REFINING

3.1.1 Production concentration

The global production share of materials used in PV technologies was calculated for the top three producing countries in the mining and refining stages of the supply chain. Although ores of Al (bauxite), Zn, lead (Pb) and tungsten (W) are important sources of several minor metals used in the manufacture of PVs (Cd, In, Se, Te, arsenic (As), bismuth (Bi) and gallium (Ga)), they have been excluded from this study as they are not themselves used in key functional components of PV. 'Quartz' has also been excluded as mine production data for the high-purity feedstock materials such as quartzite required to produce metallurgical Si are unavailable.

Ag, Cu and Sn were evaluated at the mining stage. Of these, the production of Sn is most concentrated, with China, Indonesia and Myanmar accounting for 68 per cent of global production. Cu is the least concentrated, with Chile, Peru and China accounting for 47 per cent of global supply (Figure 6). It is notable that China has a significant presence at the mining stage of all three commodities and is also the leading mine producer of Zn, Pb and W (sources of by-product Cd, In, Se, etc.).

Eleven materials were evaluated at the refining stage:

- As
- Bi
- Cd
- Cu
- Ga
- In
- Te
- Se
- Si metal
- Ag
- Sn

Si metal has been included as it is a key material for the manufacture of PV technologies. However, it should be noted that the data do not distinguish between low-purity (metallurgical grade, about 98 per cent Si) and high-purity (electronic grade; 99.9999 per cent Si, also referred to as 6N) Si metal. Nevertheless, the inclusion of these data serves to identify the main global sources of Si metal.

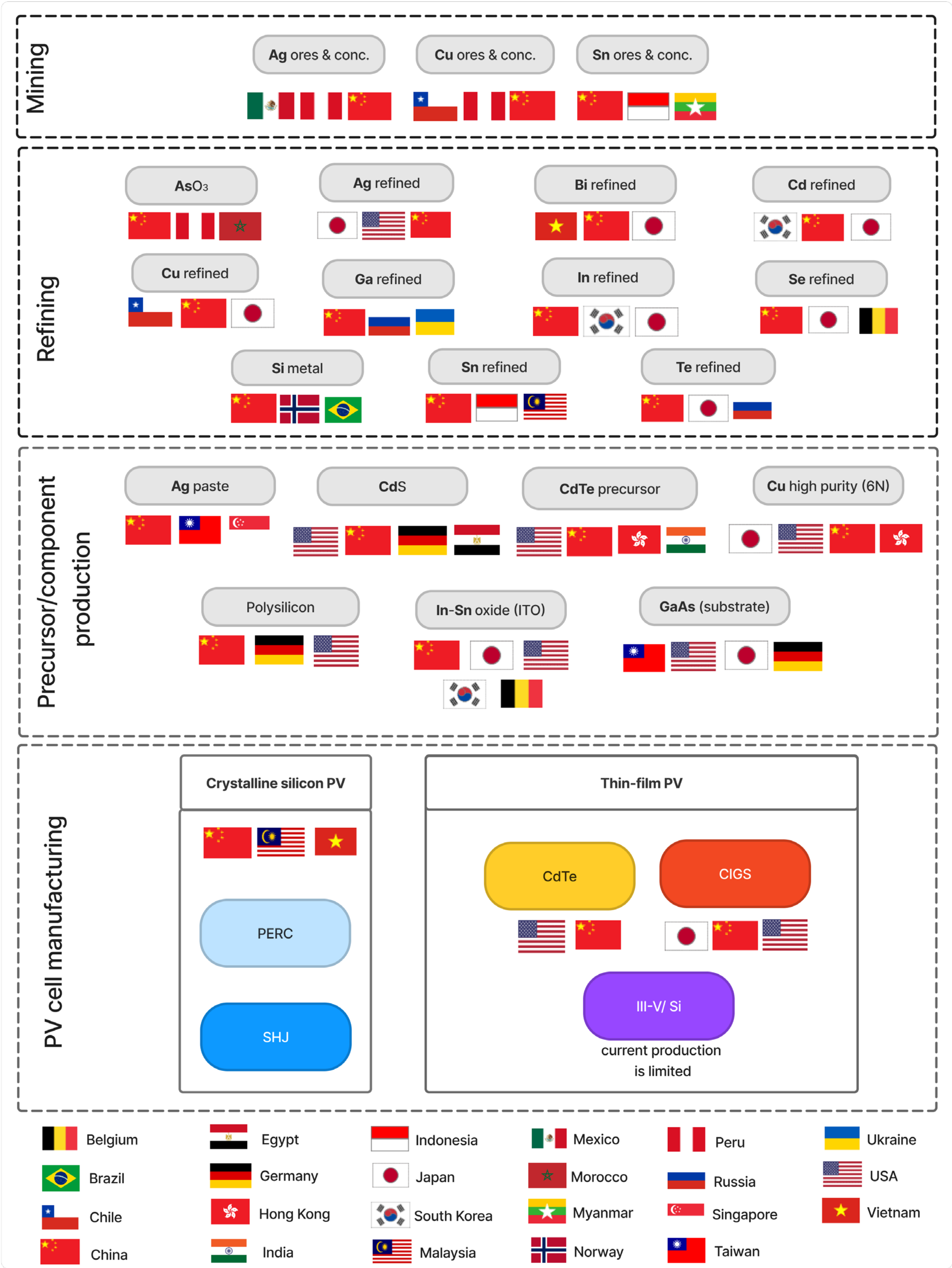


Figure 5 Geographical production concentration in the PV cell supply chain. At the mining and refining stages, the national flags show the top three producers, from left to right, based on quantitative data for 2021 from the BGS World Mineral Statistics Database (Idoine et al., 2023). At the precursor/component production and PV cell manufacturing stage, the flags highlight the location of key producers, but their order does not reflect their respective market share (data compiled and interpreted from IEA (2022a); Gervais et al. (2023); ZSW (2019); Scarpulla et al. (2023) and several company and consultancy websites). BGS © UKRI 2024

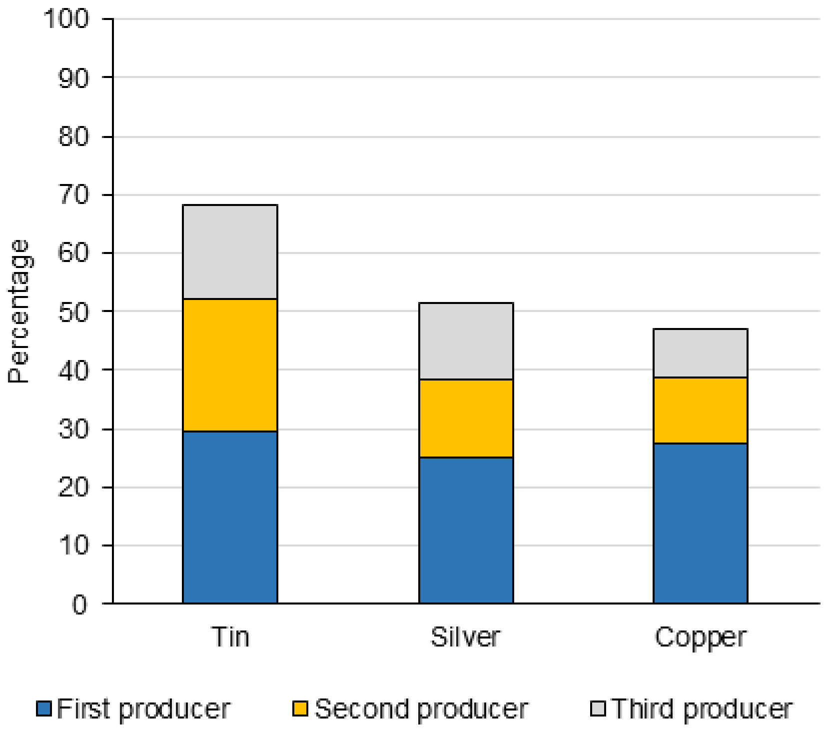


Figure 6 Global mine production of Sn, Ag and Cu showing the production shares of the top three producing countries. Data from the BGS World Mineral Statistics Database (Idoine et al., 2023). BGS © UKRI 2024

The production of all eleven materials is geographically concentrated, with 80 per cent of the global supply of seven of them derived from three countries (Figure 7). Global production of refined Cd, Cu and Se is the least concentrated of the refined materials assessed. It is important to note that China is the top producer of several refined materials:

- Ga (94 per cent of global total)
- Si metal (78 per cent)
- Te (67 per cent)
- In (61 per cent)
- As (44 per cent)
- Cu (40 per cent)
- Cd (39 per cent)
- Se (35 per cent)

It is only refined Bi and Ag where the leading producer is not China: Vietnam accounts for 40 per cent of global Bi supply, while Japan is the largest producer of refined Ag (54 per cent of global supply) (Figure 7).

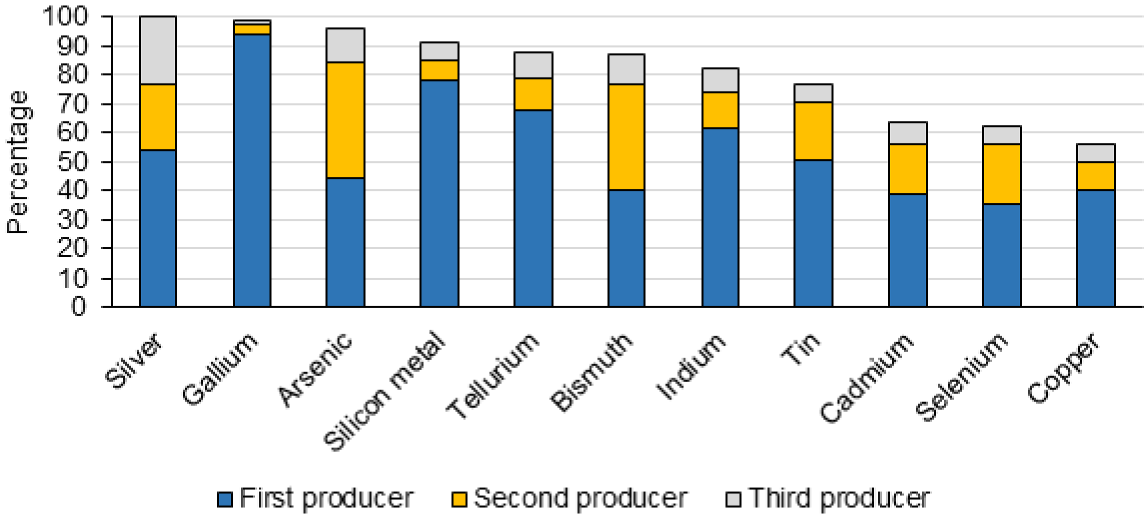


Figure 7 Global refined production of key metals used in in PV technologies showing the production shares of the top three producing countries. Data from BGS World Mineral Statistics Database (Idoine et al., 2023) and Gervais et al. (2023) for refined Ag. BGS © UKRI 2024

It should also be noted that seven of the eleven refined materials assessed (As, Bi, Cd, Ga, In, Se and Te) are recovered exclusively as by-products of mining major commodities such as Zn, Al (bauxite) and Cu.

Production concentration is calculated using the indicators recommended in the revised methodology for UK criticality assessment (Josso et al., 2023). This is derived from the production shares of the leading producers modified by a factor that reflects the environmental, social and governance (ESG) performance of those countries.

Production concentration scores for refined materials vary widely and are typically lower at the mining stage than the refining stage. This is largely due to the lower production shares held by the top producers: in other words, production is more diversified. Some are very high, on account of extreme concentration of production and poor ESG scores for the top producers. For example, refined Ga scores 8.9 because 99 per cent of global production takes place in only three countries (China, Russia and Ukraine), all of which have intermediate ESG scores. In contrast, refined Ag scores 3.2 because two of the top three producing countries (Japan and the USA) have good ESG scores, even though production is highly concentrated (Figure 8).

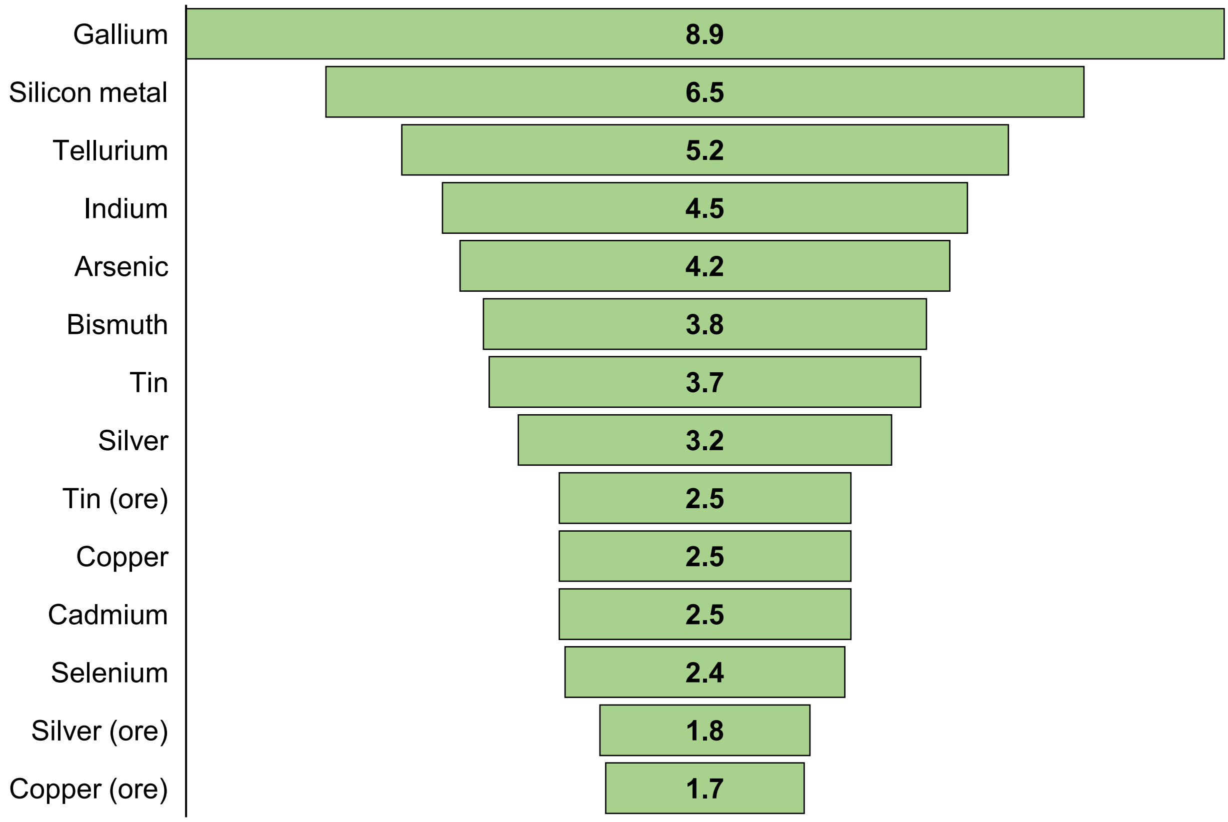


Figure 8 Ranked production concentration scores for key metals (mined and refined) used in PV technologies based on an ESG-weighted Herfindahl-Hirschman index for each of the top three producing countries. Mined metals (Sn; Cu; Ag) have lower scores on account of their more diverse supply base. Refined metals of greatest concern are those where production is highly concentrated in countries with poor ESG scores. BGS © UKRI 2024

3.1.2 Global trade concentration and trade restrictions

As with the production of mined and refined materials used in PV technologies, their trade is geographically concentrated and may be subject to restrictions imposed by trading nations. It is important to note that the trade data for some of the PV materials assessed (ores and refined metals) are not available or are reported at too low a resolution to be useful. For example, trade data for many PV materials, for example Ga, In and Bi, are heavily aggregated and are typically reported under a single Harmonized System (HS) trade code. A summary of the HS trade codes used to assess trade concentration are listed in Table 2.

Table 2 Summary of the six-digit HS trade codes used to assess trade concentration of materials used in the manufacture of PVs.

HS code	Description	Stage
260300	Copper ores and concentrates	Mining
260900	Tin ores and concentrates	Mining
261610	Silver ores and concentrates	Mining
280461	Silicon containing >= 99,99% by weight of silicon	Refining
280480	Arsenic	Refining
280490	Selenium	Refining
710610	Powder of silver, incl. silver plated with gold or platinum	Refining
740200	Copper, unrefined; copper anodes for electrolytic refining	Refining
800110	Unwrought tin, not alloyed	Refining
810720	Cadmium; unwrought powders	Refining

Trade in mined materials in the PV supply chain has been assessed for Sn, Ag and Cu. Global imports of Ag ores and concentrates are highly concentrated, with the top three importers (China, South Korea and Japan) accounting for 93 per cent of global net imports. China is the single largest net importer, with 85 per cent of the global total. Exports of Ag ores and concentrates are also concentrated, with the top three exporting nations (Peru, Mongolia and Argentina) accounting for 82 per cent of the global total. However, Peru alone is responsible for more than half (62 per cent) of global net exports of Ag ores and concentrates (Figure 9).

Global imports of Sn ores and concentrates are similarly concentrated, with the top three net importers (China, Malaysia and Thailand) accounting for 97 per cent of the total. Of these, China is the largest net importer, accounting for 80 per cent of global imports. Global exports of Sn ores and concentrates are also concentrated. Three net exporters (Australia, Myanmar and Brazil) share 62 per cent of the total. One of the top three trading nations of Sn ores and concentrates (Myanmar) has a trade restriction in place, with a licensing requirement to trade (Figure 9).

Global imports of Cu ores and concentrates are less concentrated than those of Ag and Sn, with the top three net importers (China, Japan and South Korea) accounting for 75 per cent of the total. However, as with Ag and Sn, China dominates global imports of Cu ores and concentrates with a 57 per cent share. About 42 per cent of the global exports of Cu ores and concentrates are from Peru, Chile, and Australia. Of these, Chile currently applies a 10 per cent export tax to its exports of Cu ores and concentrates.

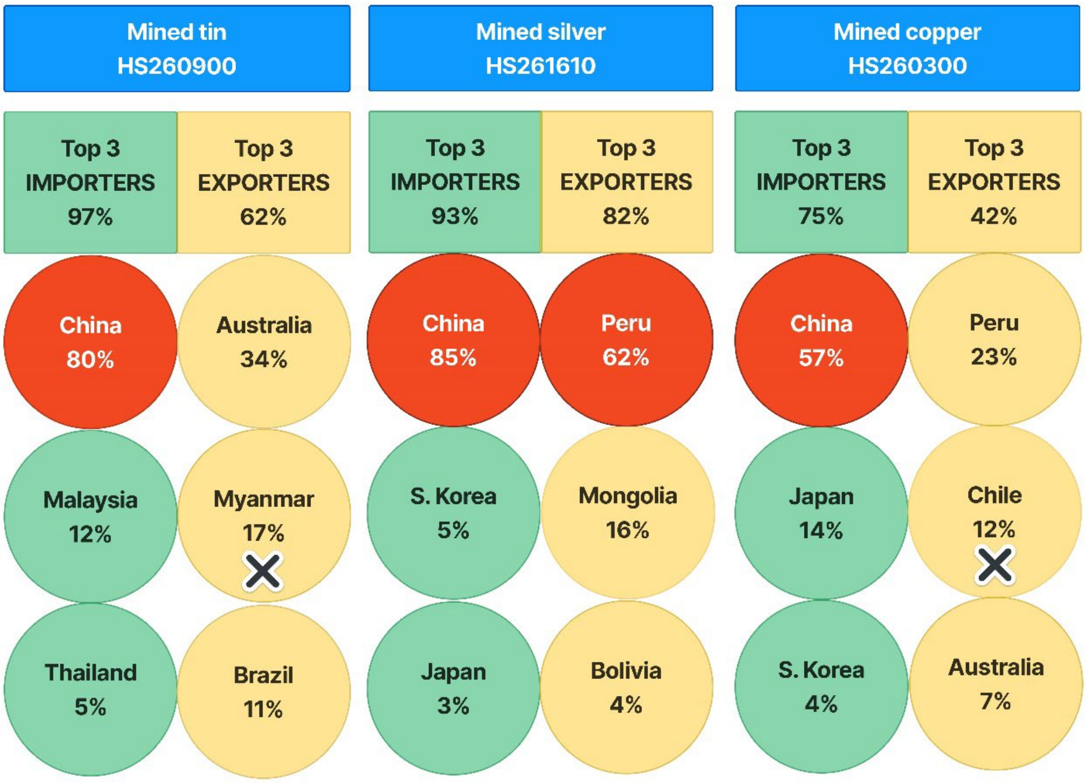


Figure 9 The top three importing and exporting countries for mined (ores and concentrates) Sn, Si and Cu with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent) while countries with a cross have active trade restrictions. (Compiled from data derived from United Nations (2023) and OECD (2020)). BGS © UKRI 2024

The global trade concentration of refined Sn, Se, As, Si (99.99 per cent Si, also referred to as 4N), Cu, Cd and Ag were assessed for the top three trading nations in each case (Figure 10). Chile currently applies a 10 per cent fiscal tax to exports of refined Cu. Zambia applies a licensing agreement to its exports of refined Cu and an export tax of 10 per cent. Note that solar grade Si (7N) is not reported in trade data.

A similar picture is seen with refined Ag, where the top three trading countries account for 61 per cent of global imports and 79 per cent of global exports. China and Japan dominate trade in refined Ag, with China accounting for 45 per cent of global imports and Japan 72 per cent of global exports. There are currently no active trade restrictions on refined Ag (Figure 10).

Global trade of refined Cd, Si (4N) and As are also highly concentrated, with the top three trading nations accounting for 74 per cent of Cd imports, 61 per cent of Si (4N) imports and 41 per cent of As imports. Global imports of Cd are dominated by India and China, which together account for 64 per cent of the total. China is also the single largest importer of refined Si (4N) globally, with 54 per cent of the total. Global exports of these refined materials are also highly concentrated with the top three countries, accounting for 48 per cent of Cd exports, 62 per cent of Si (4N) exports and 85 per cent of As exports. However, no single nation accounts for more than 30 per cent of the global total Cd and Si (4N) exports. In contrast, exports of As are dominated by China with more than 70 per cent of global exports. There are no active trade restrictions in place for Cd or Si. However, the third largest exporter of As (Namibia) applies a licensing agreement and export tax (0.25 per cent of the total export value) on its exports of As (Figure 10).

The trade of refined Sn and Se is much less concentrated: 37 per cent of global imports of Sn are shared among the top three traders, while only 26 per cent of global imports of Se are controlled by the top three. About 52 per cent of global exports of refined Sn are controlled by the top three trading countries (Indonesia, Malaysia and Peru), with Indonesia holding the largest share at 35 per cent. There are active trade restrictions on exports of refined Sn from Indonesia, which applies a licensing agreement and tax (level not specified). There are currently no active trade restrictions on exports of refined Se.

(a)

(b)

Figure 10 The top three importing and importing and exporting countries for (a) refined Cu, Ag, As, Si (4N); (b) Cd, Sn and Se, with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (i.e. with a global share exceeding 40 per cent), while countries with a cross have active trade restrictions (compiled from data derived from United Nations (2023) and OECD (2020)). BGS © UKRI 2024

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

- imports of mined materials (Ag, Sn and Cu) are typically more heavily concentrated than exports of mined materials
- China is the single largest importer of mined materials (Ag, Sn and Cu), accounting for more than 50 per cent of global imports in each case

- exports of refined materials (As, Cd, Cu, Se, Si, Ag and Sn) are typically more concentrated than imports of the same materials, except for Cd and Se. Refined Ag, As and Cu exports are the most concentrated, with the top three trading nations responsible for 70 per cent or more of the global total
- China is the single largest importer of four of the seven refined materials evaluated (Cu, Si, Si and Se)
- where trade restrictions are imposed, they are almost always applied to exports, with the most common restrictions being licence agreements or export taxes
- it is difficult to assess the direct impact of a particular trade restriction as this will depend on its type, magnitude and duration. Imposition of a trade embargo or quota is likely to have a greater effect than levying an export tax for a short period. The dynamic character of export restrictions also contributes additional uncertainty to the supply chain
- the most significant risk to supply is where global trade is dominated by a few countries (for example, China accounts for 85 per cent of global imports of mined Ag). The risk may increase if restrictions are applied to trade; for example, China recently applied export licensing to refined Ga, which led to price increases and some international traders being cut out of the market (MMTA, 2023)

3.2 COMPONENT AND PRODUCT MANUFACTURE

It is difficult, or in some cases impossible, to acquire quantitative data at a national scale for component and product manufacture. Generally, only qualitative data is available for the main manufacturing countries.

The production of polysilicon, an important step in the supply chain of c-Si PV cells, is highly concentrated in China. Based on the latest announcements on new polysilicon plants (Bernreuter Research, 2023), it is estimated that China now produces more than 90 per cent of polysilicon globally, a significant increase from its 30 per cent market share in 2010 (IEA, 2022a). After China, Germany and the USA are the largest producers.

ITO sputtering targets, which are used to produce thin films, are manufactured by several companies, dominantly in Asia (China, Japan and South Korea), although production capacity also exists in Belgium and the USA (Anderson, 2018; Lin et al., 2019). A major competitor for the emerging PV market is the use of ITO in the manufacture of flat-panel displays such as televisions, computers, phones and other mobile devices. This application currently accounts for about 56 per cent of global In consumption, compared to 8 per cent consumed by PV cell manufacturers.

Although Ag ore and concentrate production is dominated by Mexico and Peru, 86 per cent of Ag paste is manufactured in China, followed by Taiwan and Singapore (Gervais et al., 2023). Ag paste is essential for c-Si and CdTe PV cell types. The restricted global supply capacity for Ag paste production, the highly concentrated market and high ESG risks along the supply chain are considered potential limiting factors for the implementation of solar energy technologies (Zhang et al., 2021; Gervais et al., 2023).

Manufacturing of precursor components for thin-film cells is dominated by a small number of companies. Most of those producing high-purity Cu, CdS and CdTe sputtering targets and GaAs substrate are located in Japan, the USA, Taiwan and China, and are closely linked to the global semiconductor industry (Verified Markets Reports, 2023a, b; Mordor Intelligence, 2023; Research Reports World, 2022). However, India, Egypt, Germany and Hong Kong also have some production of these high-tech components.

Manufacturing of all PV cell types is dominated by China (84 per cent), followed by Malaysia (4 per cent) and Vietnam (3 per cent) (Gervais et al., 2023). C-Si cells are predominant, with over 95 per cent of market share in 2021 (IEA, 2022a). As a result, production of c-Si cells is highly concentrated in China and the Asia-Pacific region. In contrast, the thin-film cells sector (CdTe and CIGS), representing about 5 per cent of the global PV cell market, includes other important producers. The US-based company First Solar, a leading producer of CdTe cells, benefits from its vertically integrated supply chain, which includes Te sourced from a refinery in Utah, where Te has been recovered as a by-product since 2022 (Rio Tinto, 2022). Manufacturers of CIGS cells are located in Japan, China and the USA. Production of III-V/ Si cells is currently very limited, but they are included in this analysis because of forecast future demand growth (Gervais et al., 2021).

4 UK supply chain in solar photovoltaic technology

The UK has only a minor presence in the PV supply chain. It has no major participants in PV manufacturing and is completely absent from the upstream sector, with no mining or refining of PV raw materials. The UK has a small presence in the semiconductor industry, dominantly supplying the automotive industry (House of Commons, 2022).

Precursors that can be used for III-V/Si PV cells are manufactured by Wafer Technology Ltd. based in Milton Keynes. Their products include semiconducting materials for GaAs wafers and substrate (Wafer Technology Ltd., 2023). The company is a subsidiary of IQE Plc, a leading semiconductor company with headquarters in Cardiff and further manufacturing facilities in the USA and Taiwan.

MicroLink Devices UK Ltd is currently developing a solar cell fabrication facility in Baglan Bay, Wales, to produce high-efficiency solar cells based on GaAs technology used in spacecraft and aircraft, as well as in land-based applications (MicroLink Devices UK Ltd., 2023, 2022).

Oxford PV, a spin-out from Oxford University, is developing next-generation solar cells based on the perovskite mineralogical structure, a technology that is not currently in wide use. While their research and development team is based in Oxford, their new industrial-scale solar cell plant is located in Germany (Oxford Photovoltaics Ltd., 2023).

It is clear that most solar PV technology is manufactured overseas and UK-based installations are highly dependent on imports of solar cells and solar modules. UK direct demand for mined and refined materials for PV components is very small, reflecting the current size of UK domestic manufacturing capacity. The only company currently producing commercial solar panels used for housing in the UK is GB-Sol, with a current manufacturing capacity of 25 MW (GB-Sol, 2023, 2024). In contrast, there are numerous installation companies in the UK but these are wholly reliant on imported modules and panels.

5 UK future demand

5.1 MARKET SHARE SCENARIOS AND MODELLING CONDITIONS

Understanding technology transformation is of fundamental importance for forecasting embedded material demand, as the bill of materials associated with each technology and the market shares of those technologies are likely to change substantially in the future. The technological evolution of the PV market has previously been modelled in a range of scenarios up to 2050 (Chen et al., 2023; European Commission et al., 2020; Hallam et al., 2022; Lopez-Pascual et al., 2022)

For the purposes of this analysis, a conservative technology evolution scenario is considered from 2020 onwards, based on Gervais et al. (2021). More aggressive scenarios usually depend on rapid advances in research that lead to increased deployment of emerging technologies such as III/V-Si and the phasing out of thin films by 2035 (Clark, 2023; Fischer et al., 2023; Gervais et al., 2021; Gómez et al., 2023). In this study, future demand and material challenges associated with a gradual technological transition have been analysed. This is considered to provide a reliable indication of potential bottlenecks in the PV supply chain.

In the adopted scenario, mature PV cell types (c-Si) are expected to remain market leaders for the next 20 to 30 years. However, next-generation multijunction PV cells offer significantly increased efficiency (Fischer et al., 2023). Accordingly, as production costs fall, SHJ technology is expected to attain a market share of 40 per cent by 2035 (Figure 11) (Louwen et al., 2016). The CIGS and CdTe thin-film technologies are assumed to become irrelevant by mid-2030, both economically and technologically, as the price differential of crystalline modules compared with thin films is maintained or increased (PVinsights.com, 2024; Fraunhofer ISE, 2023) (Figure 11). The use of critical raw materials such as Si, In, Ga, Bi, Se, Te and Sn may have negative impacts on the rapid deployment of PV technologies due to the high supply risk and by-product status of several of these elements (Gervais et al., 2021; Zimmermann, 2013).

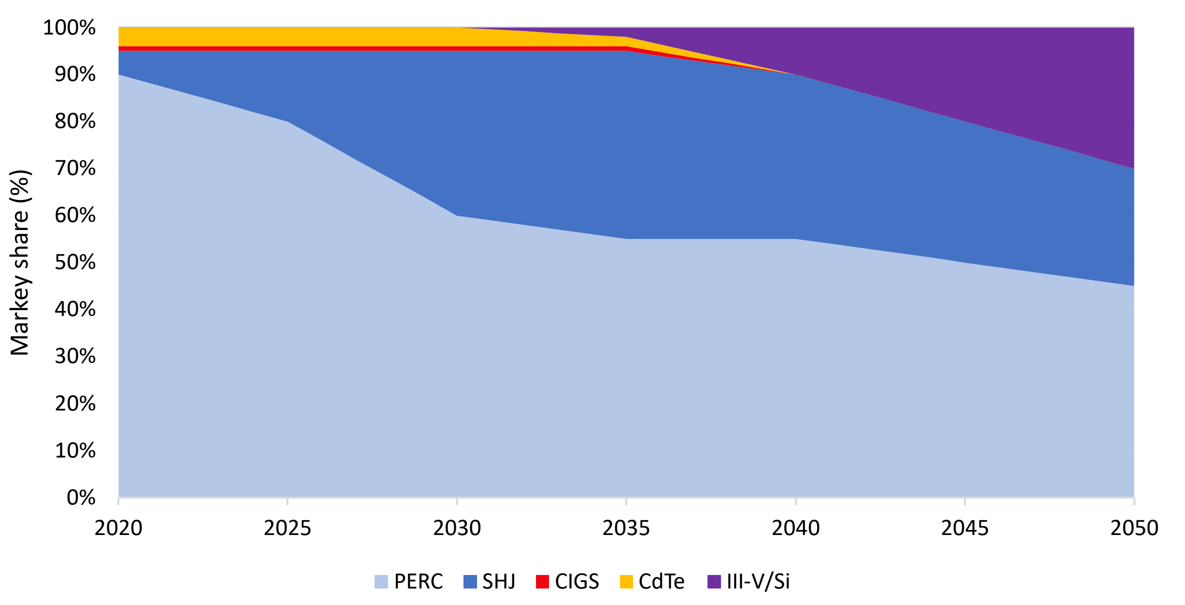


Figure 11 Evolution of the PV cells market between 2020 and 2050 showing the technology transformation that is likely to take place (data from Gervais et al. (2021) and Fraunhofer ISE (2023)). The market shares shown were used in the material demand calculations. (PERC: passivated emitter and rear cell; SHJ: Si heterojunction cells; CIGS: copper-indium-gallium diselenide cells; CdTe: cadmium-telluride; III-V/Si: III-V tandem solar cell on Si substrate.) BGS © UKRI 2024

Commercialisation of III-V/Si solar cells is unlikely to start before 2035 but is forecast to grow rapidly to a 30 per cent market share by 2050 (Gervais et al., 2021; Fraunhofer ISE, 2023). However, their economic viability will depend on significant technological improvement as the GaAs wafer substrate and epitaxy of the III-V solar cell stack are expensive to manufacture. The cost difference between III-V/Si and PERC is assumed to remain disadvantageous to the former until 2050. PERC is therefore likely to remain the dominant cell type between 2020 and 2050, with an estimated market share in 2050 of 45 per cent (Figure 11).

The future metal requirements of PERC, SHJ, CIGS and III-V/Si are calculated from a variety of material efficiency measurements adapted from Gervais et al. (2021). These measurements are based on a range of factors, including:

- increased module efficiency
- improved material usage
- novel module designs
- production processes

Due to limited data availability, the metal requirement for CdTe cells is calculated using the material intensity figures required for a PV module, with an average efficiency of 20 per cent. No allowance is made for future improvements in material usage and product design.

5.2 FUTURE UK RAW MATERIAL NEEDS FOR PHOTOVOLTAIC CELLS

The installed capacity of PVs in the UK from 2010 to 2022 is based on data reported by the Department for Energy Security and Net Zero (DESNZ, 2023) (Figure 12). Data for 2023 to 2050 are derived from the National Grid's Future Energy Scenarios (National Grid, 2023b) (Figure 12).

The forecast models are based on the operational capacity of PVs. The average lifespan of a PV is assumed to be 30 years; installed PV capacity that reached the end of its life during the analysis period was accounted for in the calculations.

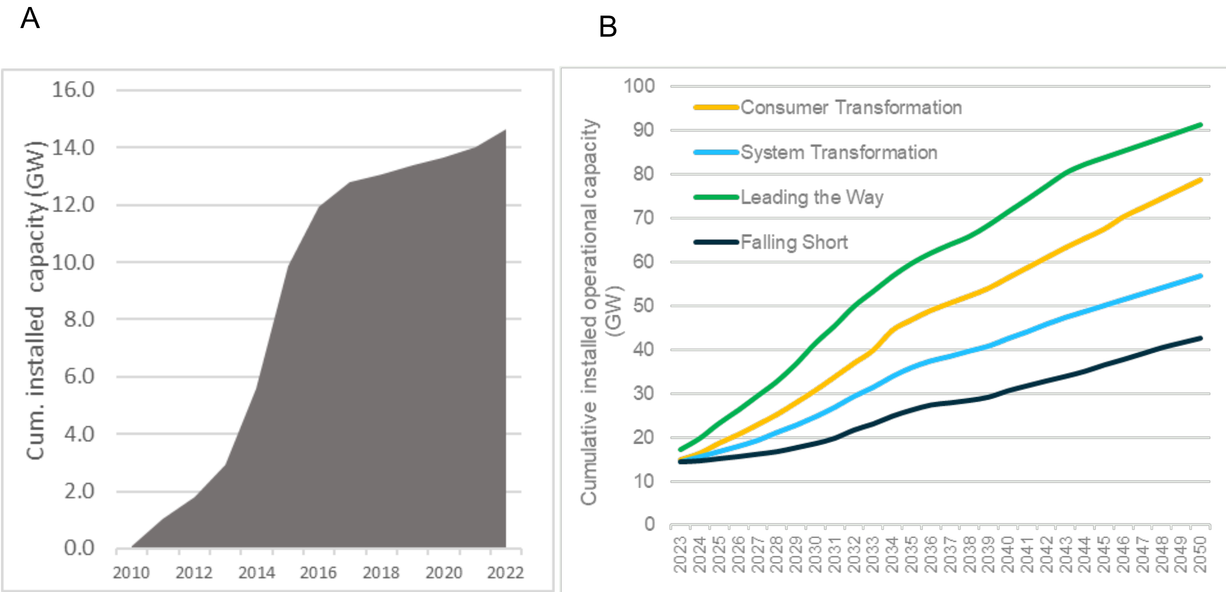


Figure 12 A: cumulative installed PV operational capacity up to 2022 (DESNZ, 2023); B: future cumulative operational installed PV capacity based on four different scenarios (National Grid, 2023b; DESNZ, 2023). BGS © UKRI 2024

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

- as the quantity (in tonnes) required between 2020 to 2050 for each of the National Grid Future Energy Scenarios
- as the percentage of current global metal production (based on average production between 2017 and 2021)

The forecasts in Figure 13 show the cumulative UK demand between 2020 and 2050. Annual demand for each element has also been quantified to illustrate temporal fluctuations (Appendix B).

It is important to note that current global production for some materials, such as Si and Cu, is already very large, amounting to several million tonnes of each per annum (Table 3). In contrast, some minor metals used in PV, such as In, Bi and Se, are produced in much smaller quantities, measured in hundreds or thousands of tonnes. Overall demand for the majority of elements included in the analysis increases up to 2040 (Si, Cu, In, Ga, As), although the required production increase for elements such as Si and Cu are orders of magnitude greater than for minor metals (Table 2).

For a few elements, demand decreases up to 2050, with Ag, Cd, Te and Se forecast to peak in 2030. Thereafter, demand for Ag decreases gradually towards 2050, with more drastic reductions for Cd, Te and Se, for which it is estimated there will be no new PV demand in 2050. This is driven by the technology shift away from CdTe and CIGS thin-film PVs towards SHJ and III-V/Si cells.

However, for several other minor metals, such as Sn, Bi, Ga, In and As, demand continues to increase into the 2040s. Sn and In are essential for most PV technologies and their demand rises with increased PV deployment over time. For Ga and As, the increase in demand stems from the market penetration of III-V/Si cells after 2040. The replacement of solders in current use by Bi-Sn alloys is the key factor in the forecast demand growth for Bi (Figure 13). The annual demand decreases slightly for all materials from 2046 to 2050 due to a decline in newly installed solar capacity in all scenarios.

Comparison of these projections with current global production levels highlight the scale of future demand increases required for many PV materials (Figure 14). For example, the UK alone would require up to 4 per cent of current global Ga production by 2040 and up to 7 per cent by 2050. For Bi, the UK would require up to 3 per cent of current global production by 2030 and up to 1 per cent by 2050. Comparison of UK demand and global production for other elements used in PV technologies highlights similar potential supply concerns, including In (in 2040 and 2050), Te (2030), Si (2030, 2040 and 2050), As (2050) and Ag (2030 and 2040).

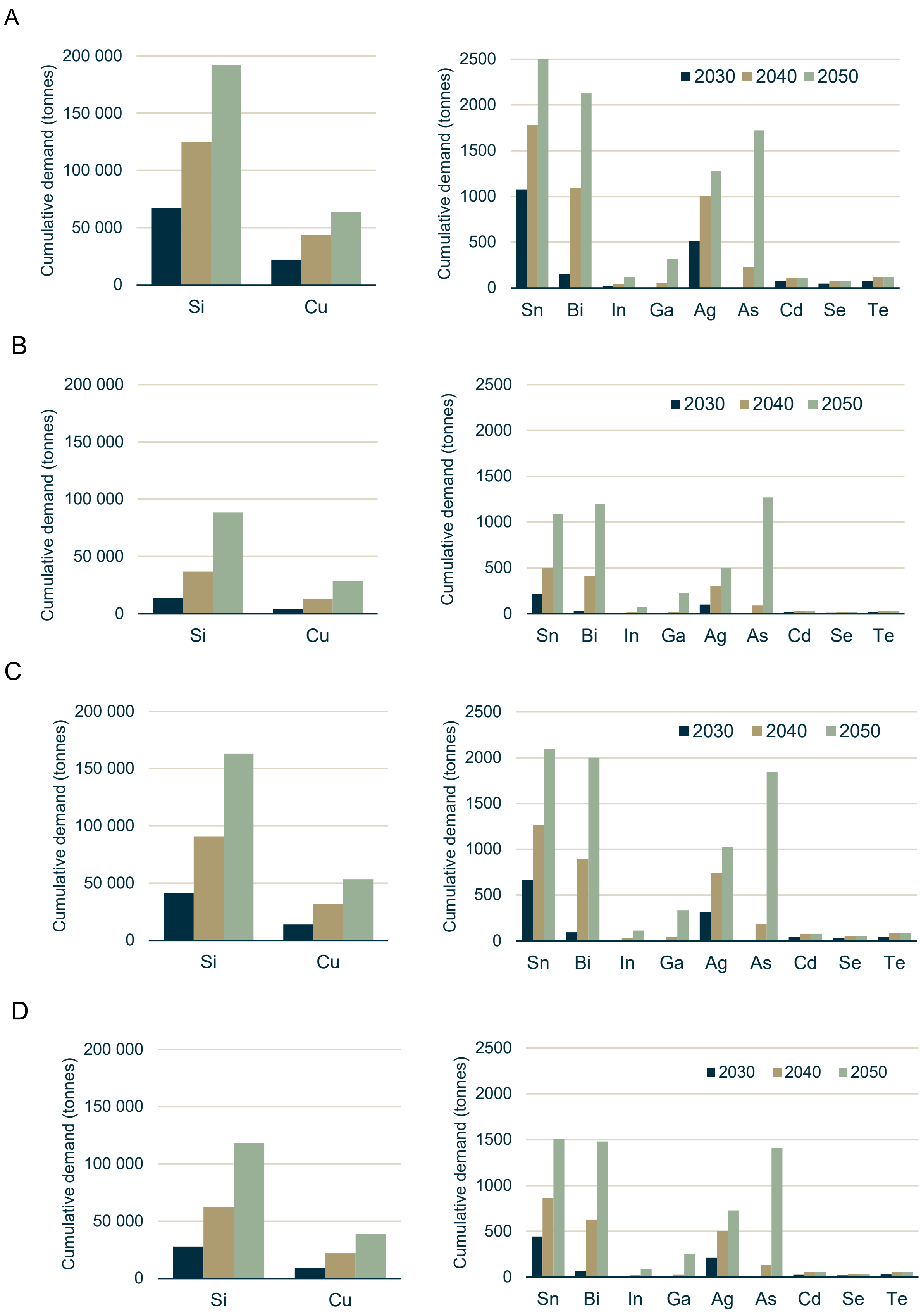


Figure 13 Cumulative forecast UK PV demand (tonnes) for the elements considered in this study between 2020 and 2050 under four different scenarios. A: 'Leading the way'; B: 'Falling short'; C: 'Consumer transformation'; D: 'System transformation.' BGS © UKRI 2024

Table 3 Global metal production (five-year average, 2017 to 2021) for the elements assessed in this analysis (data from (Idoine et al., 2023)).

Element	Global production (five-year average) (tonnes)
Cu (smelter)	17 064 904
Si (metal)	3 035 036
Sn (smelter)	372 476
As	54 374
Ag	27 252
Cd	25 750
Bi	4910
Se	3549
In	813
Te	530
Ga	379

Figure 14 Annual UK demand in 2030, 2040 and 2050, as a percentage of current global metal production (five-year average, 2017 to 2021). Data from BGS World Mineral Statistics Database (Idoine et al., 2023). The minimum and maximum values represent outputs of the different scenarios. BGS © UKRI 2024

5.3 GLOBAL DEMAND VS UK DEMAND PROJECTIONS

The global material demand projections used in this analysis are sourced from the data published by the IEA (International Energy Agency, 2023). The demand projections are presented in a similar way to that of the modelling in this study, showing minimum and maximum values based on the different stated policy scenarios used by the IEA (Figure 15)

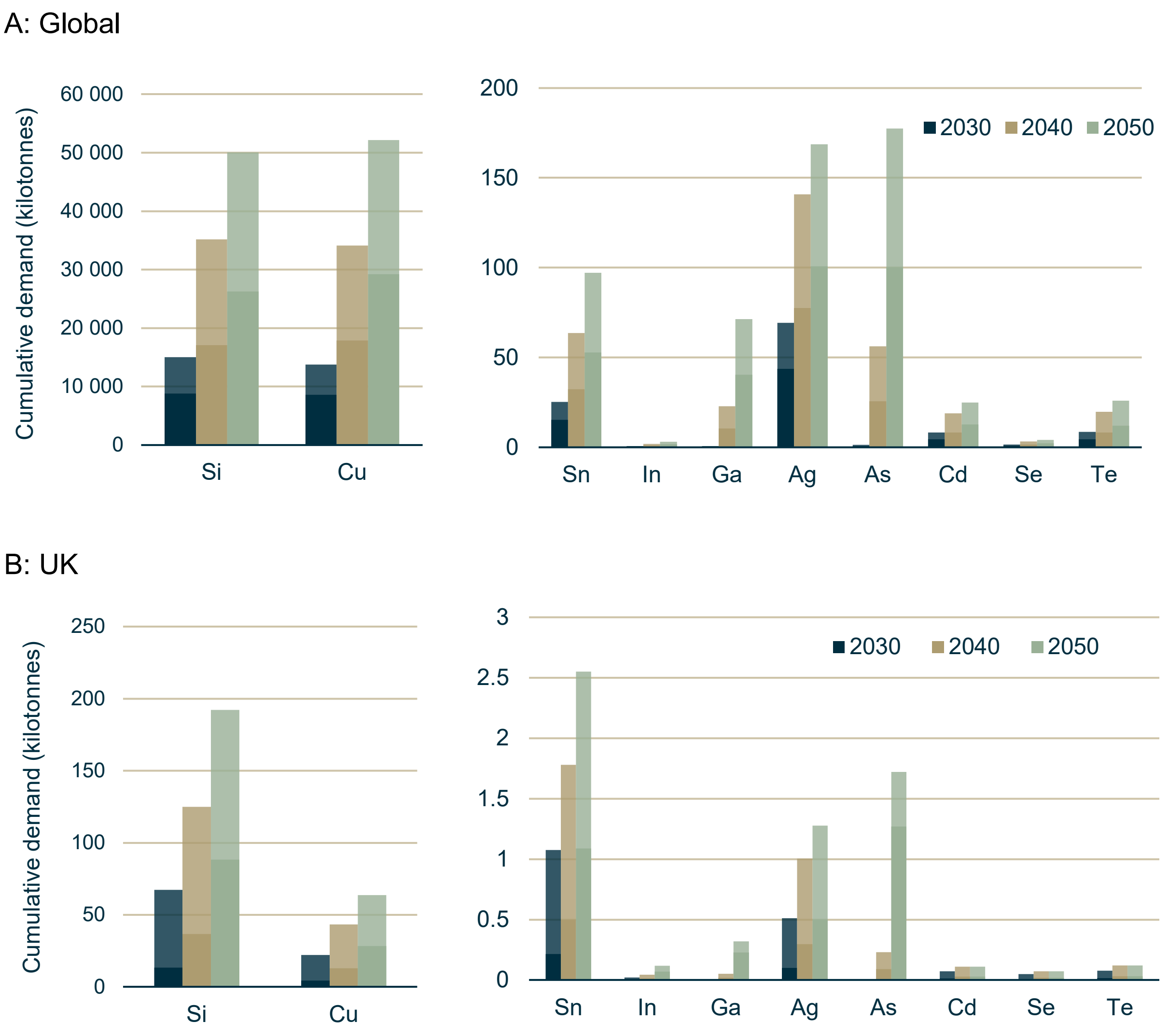


Figure 15 Material demand between 2020 and 2050 for selected elements (in kilotonnes) embedded in PV cells globally (A) and in the UK (B). The data for the non-UK demand projections, shown in A, are based on the IEA estimates for different scenarios (International Energy Agency, 2023). The maximum and minimum values derived from the following scenarios are shown: 'Stated policies'; 'Announced pledges'; 'Net zero emissions by 2050'. UK materials demand for PVs is shown in B; the maximum and minimum values derived from the following scenarios are shown: 'Leading the way'; 'Falling short'; 'Consumer transformation'; 'System transformation'. (National Grid, 2023b.). BGS © UKRI 2024

The results show that the global demand is roughly two to three orders of magnitude larger than in the UK. The UK demand projections are comparably high for Sn, In and Se, ranging from 1 to 4 per cent of global demand for Sn and In and between 1 and 3 per cent of global demand for Se, from 2030 to 2050. The UK demand projections for Cu and Si are much smaller, ranging between 0.2 to 0.5 per cent of global demand for Si and between 0.1 and 0.2 per cent of global demand for Cu. Bi data were not available on the global level and could therefore not be included for this comparison.

UK demand will be orders of magnitude lower than the global demand. As a result, there will be high levels of competition for these materials as the energy transition takes place worldwide. Given that PVs will be a key renewable technology, likely to be responsible for about 25 per cent of the electricity mix by 2030 (IEA, 2022b), there is serious concern about meeting future global material demand for PV technology. A broad array of challenges — technical, social, political and economic — need to be faced in order to achieve the required major increases in production and secure reliable, long-term supplies for the PV supply chain. Moreover, meeting such conditions and expanding production infrastructure may take many years (Petavratzi and Gunn, 2022). Although the UK will remain a relatively small player in the global PV landscape, it may be challenging to secure sustainable material supplies that underpin its deployment targets.

6 Discussion and conclusions

PV technology will make an increasingly important contribution to global renewable energy supply up to 2050 and beyond. PVs require a wide range of materials, many of which are already considered to be critical to the UK and several that are by-products of the production of other commodities.

This study analysed the global supply chains and UK demand requirements up to 2050 for 11 elements embedded in PV technologies:

- As
- Bi
- Cd
- Cu
- Ga
- In
- Se
- Si
- Ag
- Te
- Sn

Forecast PV demand in the UK for these materials up to 2050, based on the National Grid Future Energy Scenarios, was determined and compared with forecast global PV demand for the same period.

Supply bottlenecks for these materials 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 producers
- trade concentration, derived from analysis of national trade data and trade restrictions currently imposed by the main trading nations

Wherever possible, this analysis used quantitative data from authoritative sources; however, there are significant issues concerning the availability and quality of data. For example, data for assessing the production of precursor materials are limited. Consequently, no systematic quantitative analysis of supply risk could be undertaken.

Asian countries, notably China, Japan and South Korea, are major players across the PV supply chain. In China, there is a particularly high degree of vertical integration as it is a leading producer of raw materials, precursors and PV cells.

Refining is the largest bottleneck in the production stage of the supply chain. The supply risks associated with Ga, Si, Te and In are particularly high because refining is concentrated in a small number of countries with poor ESG ratings. Despite the lack of comprehensive data that would allow the quantification of market concentration in the midstream supply chain, the qualitative assessment produced here reveals that the production of precursors and PV cells is also restricted to a handful of businesses operating in a few jurisdictions. This is exemplified by China, which strongly dominates this part of the supply chain for the c-Si PV market.

Seven of the eleven materials assessed are recovered exclusively as by-products of other major commodities. Their future supply will therefore be strongly influenced by the markets for these main commodities and by the availability of adequate capacity to recover the by-products. Such capacity is currently small and restricted to a few countries.

The investigation of trade revealed that China dominates global imports of mined and refined PV materials, accounting for 50 per cent or more of the total for six of the ten elements that can be tracked with trade data. Global exports of Ag (mined and refined), As and Cu (refined) are also highly concentrated and are dominated by a few nations.

Several PV raw material producers have some form of trade restriction in place, most commonly a licensing agreement or export tax. These are not considered to be serious constraints on supply, especially because many of these nations trade only relatively small volumes of these materials. This could, however, change rapidly if major traders adopt different policies in response to shifting economic or geopolitical influences.

Analysis of future global and UK demand for PV technologies and associated material requirements was undertaken using a conservative technology evolution based on Gervais et al. (2021) and Fraunhofer ISE (2023). Significant technological changes in PV cell design are expected during the assessment period, driven by improved energy generation efficiencies in the new technologies coupled with lower production costs. However, at present, Si-based technologies are expected to dominate the market up to 2050. III-V/Si cells are expected to have a market share of about 30 per cent by 2050, whereas thin-film CIGS and CdTe technology will be phased out as a result of their cost and technical disadvantages.

Demand for most of the materials considered is expected to increase greatly in the future. This will be driven by the PV deployment plans set in the UK and globally for renewable energy generation. Projections for Ga, Bi and Te demand in the UK are high compared with current consumption. The current limited production in the UK cannot satisfy domestic demand and the gap between UK demand and supply will grow further in the future.

Furthermore, based on projected PV capacity by the IEA, global material is two to three orders of magnitude greater than for the UK. For example, 190 kt of Si will be required to meet UK PV demand in 2050 compared to global demand of about 50 million tonnes. Current global production of Si metal is approximately 3 million tonnes per annum (Table 2), but most is used in other applications (for example, chemicals or alloys), with only about 5 per cent consumed by the solar energy sector (SCRREEN, 2023). Accordingly, a massive expansion in production capacity will be required to meet the increased demand, not only for Si but also for several other PV materials. Ensuring the UK has access to secure and sustainable material supplies in the face of serious global competition will be a formidable challenge.

In contrast, there are few current issues with the adequacy of the installed manufacturing capacity of PV modules. This has increased significantly in the past five years, resulting in lower PV prices and an inventory buildup in certain regions such as Europe, where current demand is small compared to Asia (Chase, 2023). The current market conditions and geographical demand discrepancies are likely to change the manufacturing industry landscape in the future. Those regions with the highest demand already monopolise the PV cell and precursor materials market and will be best placed to respond to future growth both at home and overseas. This may lead to reductions in the already limited manufacturing capacity elsewhere, thus to increased production concentration in the PV supply chain.

Although not addressed in this study, another factor that will have a potentially major impact on the deployment of solar energy and its contribution to meeting net zero targets is the implementation of a swift connection to the UK national grid. However, it has been noted that connecting a renewable project to the transmission network can currently take more than 10 years (Lawson, 2023). This could jeopardise future renewable technology uptake in the UK, as well as discourage private investment in renewable technologies such as solar energy.

7 Recommendations

This assessment has led to the following key recommendations relating to the future deployment of PV technology in the UK.

7.1 DIVERSIFY THE SUPPLY CHAIN

Diversification of the PV supply chain through investment in projects aiming to scale-up the supply of materials and components would reduce UK and global supply risks. New mining and refining projects are urgently needed to meet the high levels of projected demand for Ga, Bi and Te. The UK Government could assist through providing technical assistance for capacity building, training and knowledge sharing, particularly in developing countries. It could also support overseas investment by UK companies.

The midstream PV supply chain is currently concentrated in a few countries and the projected high level of future demand is likely to be met through expansion in those countries where demand growth would be greatest, such as in Asia and the USA. To prevent and mitigate supply risks in midstream supply chains, investment by UK companies should be actively encouraged and supported. For example, support could be given to projects funded through InnovateUK that enables them to prove commercially feasible. Establishment of trade agreements with important producing nations and assistance with collaborative research and development would help to build resilience against security of supply issues.

7.2 INCREASE DOMESTIC MANUFACTURING

The UK has limited domestic manufacturing capacity for precursors and PV cell manufacture. Supporting growth in this sector would assist the UK in meeting its demand for secure and sustainable supplies and assist in mitigating competing demand challenges. Subsidies and tax incentives would support the domestic sector and de-risk manufacturing investment. Developing a skilled workforce would be essential to support the growth of UK manufacturing capacity in this sector.

7.3 DEVELOP A PHOTOVOLTAIC CIRCULAR ECONOMY

The average lifespan of PV panels is about 30 years and the first installations took place around 2010. Rapid deployment of solar PVs would lead to significant stock build up, which at some point in time would reach end-of-life. Developing a circular economy for PV cells is likely to play a prominent role in supply in the future for the re-use and recovery of components and materials in which the UK can participate, if policy, infrastructure and technology advancements align.

7.4 IMPROVE DATA AND INFORMATION AVAILABILITY

This assessment provides many useful insights on potential material bottlenecks associated with the growth of solar energy. However, the robust estimation of future material demand and identification of supply issues depend on reliable data of many types. Improving data availability and quality, developing infrastructure for harmonised data and new data generation, and ensuring key data providers are fully engaged are of fundamental importance.

7.5 MONITOR THE MARKET

Like other decarbonisation technologies, the solar energy sector is dynamic and market conditions, geopolitical challenges, techno-economic changes and other social and environmental factors can rapidly affect any part of the supply chain. Ongoing monitoring, together with the development of stocks and flows models supported by scenarios analysis, can provide critical insight into future material challenges and contribute to the development of effective mitigation strategies.

Appendix A

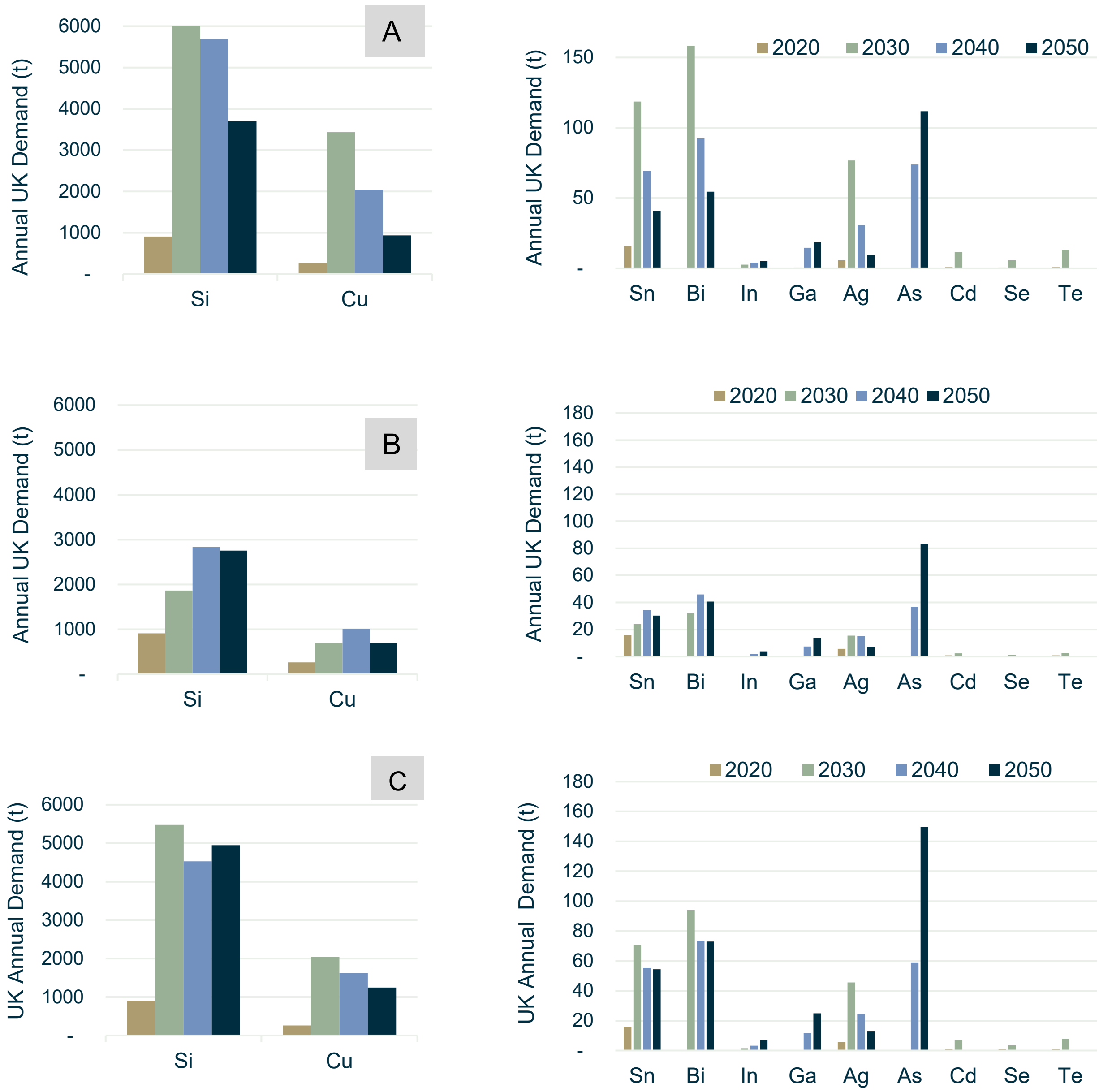
PV raw materials and components excluded from the analysis. TCO: transparent conductive layer; PERC: passive emitter rear cell; SHJ: stereo heterojunction; ITO: indium-tin-oxide; CIGS: copper-indium-gallium diselenide cells; CdTe: cadmium-telluride; III-V/Si: III-V tandem solar cell on Si substrate; c-Si: crystalline Si.

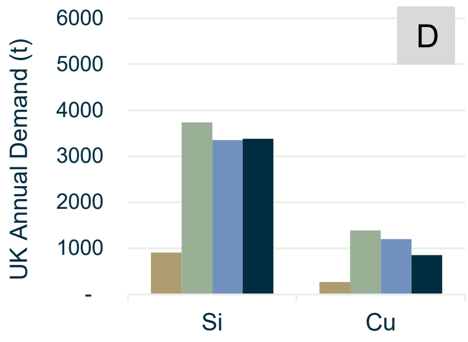
Component	Function	Reason for exclusion
Raw materials		
Aluminium (Al)	Used in III-V/Si and in panel frames	Demand in technology is negligible compared to use in structural material, which is not considered in this study
Antimony (Sb)	Sb-grade glass and solders	Not part of the main technology
Boron (B)	Dopant in c-Si semiconductors (PERC; SHJ)	Increasingly replaced by Ga, which we have considered here
Fluorine (F)	F-doped SnO2 as TCO in CdTe, CIGS	ITO more commonly used
Germanium (Ge)	Sometimes used as a layer in III/V-Si cells	Not commonly used in thin-film PV
Lead (Pb)	Used for soldering	Not part of the main technology
Molybdenum (Mo)	Back contact layer in CdTe and CIGS	No production data
Zinc (Zn)	ZnO can be used as TCO in CIGS and SHJ, as well as a dopant in GaAs	ITO is more commonly used

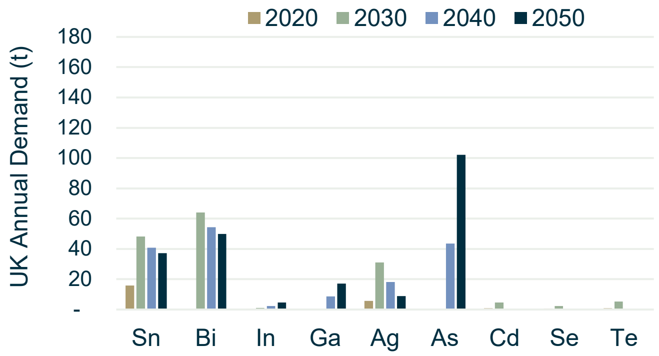
Component	Function	Reason for exclusion
Precursor materials		
AsH_3	Precursor for GaAs substrate	GaAs substrate was chosen as the key precursor stage
Bismuth-tin alloy	Used for soldering in SHJ and PERC	Listed in supply chain map, but no further data available
Boron tribromide	Dopant in c-Si semiconductors (PERC; SHJ)	Increasingly replaced by Ga, which we have considered here
Crystalline Ge wafer	Can be used as layer in III-V/Si	Not commonly used in technology
Fluorine-doped tin oxide	TCO in CdTe, CIGS	Not commonly used in thin-film PV
Hydrogen selenide (H_2Se); Selenium vapour	Precursor in CIGS	Listed in supply chain map, but no further data available
Trimethylgallium ($GaCH_3$)	Used as sputtering precursor to make semiconductors (for example, GaAs) or doping	Listed in supply chain map, but no further data available
Trimethylindium ($InCH_3$)	Sputtering precursor to make semiconductors (for example, Al-In-P)	Listed in supply chain map, but no further data available
Zinc oxide (ZnO)	TCO in CIGS	Indium-tin oxide is more commonly used
PV cells		
Aluminium-back surface field c-Si	Similar technology to PERC, but lower efficiency	Likely to be marginalised by more efficient PERC
Amorphous silicon	Alternative solar cell technology, still used in small electronic devices such as pocket calculators	Use likely to phase out

Appendix B

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




D
UK Annual Demand (t)
6000
5000
4000
3000
2000
1000
-
Si
Cu


2020
2030
2040
2050
UK Annual Demand (t)
180
160
140
120
100
80
60
40
20
-
Sn
Bi
In
Ga
Ag
As
Cd
Se
Te

Acronyms and abbreviations

BGS	British Geological Survey
c-Si	Crystalline silicon
CIGS	Copper-indium-gallium diselenide
ESG	Environmental, social and governance
HS	Harmonized System (trade codes)
IEA	International Energy Agency
ITO	Indium-tin oxide
PERC	Passivated emitter and rear contact
PV(s)	Photovoltaics(s)
SHJ	Silicon heterojunction
TCO	Transparent conductive oxide

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