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Can local mineral reserves support the path towards energy independence? A resource assessment of recyclable perovskite photovoltaics

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Abstract

Solar energy is a renewable alternative to the fossil fuels on which the European Union and global energy systems are reliant. Perovskite solar cells (PSC) are a promising next generation photovoltaic technology due to their high power conversion efficiencies as well as their potential for simple manufacturing routes and low cost. This letter assesses whether decentralised PSC manufacturing could be complemented by decentralised material supply, using the European Union's own reserves and secondary raw-material streams. Using data from the Raw Mineral Information System and Urban Mine Platform, three perovskite module designs are evaluated for their potential electricity generation. Terawatt-hour deployment would be most constrained by demands for titanium dioxide, indium, caesium, aluminium, graphite, tin and silver with restrictions in annual energy production of 0 TWh – 10,200 TWh. In contrast, the reported reserves of fluorine, zirconium, lead and phosphorus would theoretically be able to produce 35,000 TWh – 217,300,000 TWh per year, which is significantly higher than current energy demands. Under full waste recovery, however, secondary sources of titanium dioxide, lead, tin, aluminium, nickel and phosphorus could support the manufacturing of enough modules to support 31,000 TWh – 209,100,000 TWh. Although this is limited by current end-of-life recycling input rates, the concentration of waste in electronic and electrical equipment is often similar or higher than that of ore deposits, thus there is benefit to design products for end-of-life recycling.

Introduction

Fossil fuels accounted for approximately 87% of total global energy consumed in 2025, while nuclear and renewable sources contributed approximately 5% and 8%, respectively. Within the EU, fossil fuels accounted for approximately 74% of total energy consumption, compared with 12% from nuclear and 14% from renewable sources [1].

The EU is also highly dependent on imported energy. In 2024, approximately 43% of the total energy consumed within the EU was produced domestically, while the remaining 57% was imported in the form of crude oil (67%), natural gas (24%), solid fossil fuels (4%), electricity (3%) and renewable energy (2%) [2]. However, the 57% energy-imports value is likely an underestimate, as Eurostat reports nuclear energy production as domestic, regardless of the origin of the nuclear fuel [3].

This import reliance reflects, in part, the EU's limited domestic fossil fuel reserves. Figure 1 presents the global estimated reserves for oil, natural gas and uranium, showing that they are largely concentrated in specific regions outside of the EU. Here, 'reserves' refers to the fuel/minerals that are proven to exist and are currently economically viable to extract. This differs to 'resources', which are larger estimates but are neither officially proven to exist nor currently financially feasible to extract. It should be noted that uranium reserves are generally considered to be comparatively underexplored. The U.S. Energy Administration in 2024 estimated exploration and development expenditure for 158 global oil and natural gas companies at approximately USD 335 billion [4]. By comparison, the Nuclear Energy Agency reported uranium exploration and development expenditure of USD 0.964 billion across 37 countries, with

cumulative exploration expenditure prior to 2024 estimated at USD 33.2 billion [5]. Nevertheless, the geographical concentration of these energy resources means that access to them remains dependent on international supply chains.

The EU's energy dependence leaves it vulnerable to supply chain disruptions caused by geopolitical events and severe weather. These disruptions can have a significant impact on the price of oil, gas and, as a result, production in general [10], [11]. Thus, there is benefit to seeking alternative energy sources that reduce the dependence on high-carbon and high-supply risk energy.

Photovoltaic (PV) electricity is a cost-competitive alternative to fossil fuel electricity generation [12], [13], with the added benefits of being renewable and having a low carbon footprint [13], [14]. However, the PV market is currently dominated by silicon-based PV [15], with China's share in manufacturing silicon PV modules exceeding 80% [16], which can still lead to global supply chain disruptions [17], [18], [19]. Perovskite solar cells (PSC) are an emerging branch of PV technology that have shown promising early stage results due to their high power conversion efficiencies (PCE), however, their issue of long-term stability still needs to be resolved [20], [21], [22]. Perovskite solar technology is attractive because of its simple, solution-based and low-temperature manufacturing processes [23], which creates potential for low-cost production. For a 2GW roll-to-roll manufacturing facility in the United States, Martin *et al*. estimated that materials would account for 93% of overall production cost, followed by labour (3.59%), depreciation (2.37%), equipment (0.8%) and utilities (0.21%) [24]. Similar results were reported by Bhati *et al*. across a range of PSC material choices and manufacturing techniques for manufacturing capacities of 10MW to 5000MW [25]. Roose *et al*. further suggest that even low- and lower-middle income countries could benefit from local, decentralised perovskite module manufacturing as it could reduce costs by 20% – 40% in 7MW – 90MW annual production facilities, when compare with modules imported from a 1GW facility. They also estimate that a GW-scale PSC factory could be 2x – 3x cheaper to build than a silicon module factory. [26].

Although PSCs are a promising technology, some of the minerals used in research device architectures are classified by the EU as critical raw minerals (CRMs) because of their economic importance and high supply risk, with similar classification of criticality by the United States Geological Survey [27] [28]. In addition to this, the EU also has relatively limited CRM reserves compared to the rest of the world [29], thus the potential for large-scale PSC deployment must be assessed carefully to prevent the replacing of the EU's dependence on imported fossil fuels with the dependence on other scarce or geopolitically concentrated critical raw mineral reserves.

To determine which PSC device architectures and material choices would have the potential to alleviate some of the reliance on imported energy into the EU, this work estimates the TWh capacity of three perovskite solar module (PSM) designs manufactured using only the EU CRM reserves and current secondary raw material streams. This analysis is extended to China, Africa, and South America to determine whether other regions would also benefit from PSM deployment. This shows whether PSM's potential for decentralised manufacturing can be complemented by a decentralised material supply.

Results and discussion

Figure 2a shows what proportion of the EU's total energy consumption could be produced using the three PSM designs. These designs are named 'M-Sol', M-UF', and 'M-HIERN' and are described in the Methods section. The grey box of Fig. 2a represents the total annual energy consumption of the EU – 20,353TWh [30]. Assuming all the EU reserves are put aside for PSM production, the orange colour scale of Fig. 2 shows which of the minerals used by each PSM design have EU reserve quantities that would produce less than the total energy consumed each year. The green colour scale box shows which of the minerals used by each PSM design have EU reserve quantities that would produce more than the total energy consumption requirement each year, demonstrating the highest energy values possible for each mineral. The red, blue and yellow lines are the oil, natural gas, and uranium reserves of the EU (with the ± 40% conversion from fuel to electricity factor included), provided for comparison.

Figure 2a shows that the TWh deployment using the EU reserves would be most constrained by the titanium dioxide, indium, caesium, aluminium, graphite and silver with restrictions in annual energy production of 0 TWh – 12,300 TWh. By contrast, the reported reserves of fluorine, zirconium, lead, phosphorus and nickel reserves would theoretically be able to produce 35,000 TWh – 217,300,000 TWh per year, which is significantly higher than current energy demands. Tin energy limit would depend on whether the module uses a fluorine-doped tin oxide substrate (FTO – 8,780 TWh) or indium tin oxide substrate (ITO – 108,000 TWh). By means of comparison, the upper bound of energy production material limit using EU reserves is also high enough to satisfy the world energy consumption of 164,000TWh [1]. Given the nature of PV energy, once the modules are installed, they could produce that electricity annually throughout their operational lifetime.

Figure 2b, c, and d show a similar outcome for China, as well as the countries of Africa and South America. China's deployment potential would be limited by its tin, titanium, silver, caesium, aluminium and indium supply. However, it would be able to produce between 48,000 TWh and 825,700,000 TWh of electricity using its own tin (ITO), fluorine, zirconium, lead, phosphorus and nickel reserves. Africa and South America are abundant in some of their PSC materials, but also have limiting materials. Most of the minerals fall above the annual energy demand, with the capacity to build between 81,000TWh and 12,840,000,000TWh. For Africa, deployment-limiting materials would be indium, caesium, titanium and silver. South America would have deployment limits due to their smaller titanium, graphite, indium and caesium reserves.

Some of the constrained materials have alternatives – for example, indium-tin oxide substrates can be replaced with fluorine-doped tin oxide substrates. For other materials, substitution is less straightforward. Caesium, for example, has no reported reserves in the EU and limited known global reserves. It has been shown to be important in improving PSC stability when incorporated into the perovskite precursor layer [31], however, more recent work has suggested that caesium free PSC can be stable in EC 61215 damp heat tests [32]. This suggests that caesium may be beneficial, but not necessarily indispensable in PSC.

These reserve-based estimates represent a theoretical upper bound, as they do not fully account for competing material uses and extraction rates. They also do not consider energy consumption changes as reported by integrated assessment models, such as those considered in the Intergovernmental Panel on Climate Change AR6 [33]. Lastly, this work does not consider full-system components such as module framing, mounting structures, or batteries. Nevertheless, they do indicate which materials in each region could be more readily available, and which may impose severe supply constraints on large-scale deployment.

The analysis was then extended to estimate the potential contribution of secondary raw material streams to PSM production in the EU. Figure 3 shows that reported annual waste quantities of PSM related materials range from < 20,000 tonnes/year for several materials to 4,600,000 tonnes/year for aluminium [34]. Magnesium is the second largest waste stream at 1,700,000 tonnes/year, followed by titanium, copper, phosphorus, zinc, chromium and nickel.

Despite the large quantities of material contained in these waste streams, only a small proportion of them are recycled and returned to production. Figure 3 also shows the end-of-life recycling-input-rate (EOL-RIR) of PSC relevant CRMs. The EOL-RIR is the proportion of scrap/recycled material that is returned to production, and in the EU it ranges from 0% for lithium, gallium and phosphorous, up to 80% for lead.

The data from Fig. 3 was used to estimate how many TWh of energy could be produced under two recycling scenarios. The first scenario assumes that 100% of the target material contained in the annual waste stream can be recovered and reused in PSC production. The second scenario applies the EOL-RIR to the waste stream to approximate the deployment of the module designs under current recycling conditions.

Figure 4a shows that, under the 100% waste recycling scenario, the annual waste streams of titanium, aluminium, nickel and lead are sufficient to manufacture PSM capacity that could generate annually between 31,000 TWh and 209,100,000 TWh - exceeding current EU electricity demand. For tin usage in the M-Sol design, approximately four years of waste would need to accumulate and be fully recovered to manufacture sufficient module capacity to meet the EUs current energy demands. Even under a 100% waste recycling scenario, however, caesium, indium, and silver would still remain a material bottleneck for large-scale PSC deployment.

Applying the EOL-RIR values show a more representative view of the PSM capacity that could be manufactured using EU waste. Figure 4b shows that recycled lead, aluminium and nickel could produce between 67,000 TWh and 801,000 TWh annually and thus be sufficient to support the EU’s energy demands. Tin, however, would remain more restrictive as it would require a 1 to 20 years of cumulative waste generation, depending on the choice of substrate.

A more detailed assessment would also have to account for the proportion of recovered material that can be refined to the purity required for PSC manufacturing [35], [36]. The data for current industrial

purification yields, however, are not currently available for the relevant waste streams.

Although metals are highly recyclable, in practice there are several limits to their recovery. These include, but are not limited to, dissipative use and thermodynamic constraints [37], product design with increasing complexity of material mixes that are not designed to be disassembled and recycled, unclear material flows due to high product mobility, unused or 'hibernating' products not brought to recycling facilities [38], consumer behaviour [39], and insufficient modern recycling infrastructure. Together, these factors reduce recovery yields and increase the cost of recycling, often resulting in recycling that becomes economically unfeasible [40].

Nevertheless, there is agreement that there is significant room for improvement of recycling rates with increased data collection on material flows, increased collection rates of discarded products, improved design of products with EOL-recycling in mind and increased deployment of modern recycling methods [39]. This is of particular interest given that the concentration of some metals in waste from electrical and electronic equipment (WEEE) can equal or exceed their concentrations in primary ores – as demonstrated in Fig. 5.

Designing PSM for EOL-recovery and recycling is therefore beneficial if secondary raw materials are to be incorporated into future module production to reduce the quantity of CRMs wasted each year and to reduce the burden on domestic and global CRM reserves. When combined with improved material tracking, collection and recycling infrastructure, these design principals could enable a larger proportion of metals contained in WEEE to be recovered and reused in PSC devices. This would then strengthen the potential for recyclable technologies to contribute to a lower-carbon and less import-dependent energy system.

Methods

The annual electricity-generation potential of three PSM designs manufactured using only CRM reserves located within the EU was estimated. The data for annual total energy consumption was from the International Energy Agency (IAE) [41], while data for country and region specific mineral reserves were taken from the Raw Mineral Information Systems platform [42]. Equivalent estimates were also produced for China, Africa, and South America. These regional comparisons provide insight into whether other regions could similarly benefit from the deployment of these three PSM designs.

The analysis of module manufacturability within the EU was extended to include secondary sources – i.e., from waste. Recycling rates for each element were also obtained from the RMIS platform. Waste quantities per year for each element were obtained from the Urban Mine Platform, which includes waste from electronic and electrical equipment (WEEE), wind turbines, vehicles, slags and ashes, batteries, and buildings [34]. These values can be found in the supplementary information.

Lastly, a comparison of WEEE elemental concentration was compared to that of ore deposits and the earth's crust to assess the potential value of improved product recyclability as a secondary mineral

source. WEEE concentrations were compiled from ten published studies covering 79 devices and the ore concentrations were also obtained from numerous literature – details of both are provided in the supplementary information. Elemental concentration in the Earth's crust were taken from the CRC Handbook of Chemistry and Physics [43]. Lastly, ore concentrations were largely taken from reports published by the United States Geologic Survey and the British Geologic Survey. Because ore grades vary substantially according to deposit type and location, a single representative average is difficult to define. Thus, multiple reported values were considered for each ore, and the maximum and minimum values were used to define a range.

The PSM designs were developed by the University of Freiburg (M-UF) [44], Solaronix SA (M-Sol) [45], and the Helmholtz Institute Erlangen-Nürnberg for Renewable Energy (M-HIERN) [46]. Each cell/mini-module is being designed for end-of-life (EOL) recycling to recover the glass substrate with the transparent-coating oxide (TCO) layer, as well as for recycling the perovskite layer. The M-UF and M-Sol are 100cm^2 mini-modules that and are undergoing continued development to improve stability, recyclability and sustainability. The M-UF architecture is rear-glass/acrylic-resin-mixture-encapsulant/aluminium-contacts/BCP/PCBM /$FA_{0.83}Cs_{0.17}PbI_3$/Me-2PACz/ITO/front-glass. The M-Sol architecture is rear-glass/tPO-encapsulant/silver-contacts/$MAPbI_3$ /Carbon/ZrO_2/TiO_2/FTO/front-glass. The M-HIERN cell was 6.25cm^2 with an architecture of silver-contacts/BCP/PCBM /$FA_{0.877}MA_{0.146}Cs_{0.054}PbI_{2.838}Br_{0.138}Cl_{0.1}$/Me-4PACz/$NiO_x$/ITO. The material requirements to scale each design up to a 1m^2 module were estimated [29] – the details of which can be found in the supplementary information. The corresponding annual electricity generation of each design was estimated assuming a 16% capacity factor (1400 sunlight hours per year) and a module power production of 240W/m^2, corresponding to 24% PCE under 1 sun illumination. This 24% PCE was chosen under the assumption that PSC would have to be similar to typical commercial silicon module efficiencies [47].

Conclusion

With the increasing interest in perovskite solar cells, their suitability for large-scale, terawatt deployment must be assessed not only in terms of device efficiency and environmental impact, but also from a material availability, supply risk and end of life recovery potential standpoint.

This work indicates that several materials – silver, fluorine, zirconium, lead, tin, phosphorus, and nickel - available from EU reserves could support between 10,200 TWh to 217,300,000 TWh of annual electricity production, depending on the perovskite module design. Indium and caesium impose significant constraints, however, research has shown that there are alternative material choices – including fluorine and caesium-free perovskite layers. Aluminium EU reserves are also a constraint for perovskite module development. A similar conclusion can be drawn for China, Africa and South America, with each region having a different set of abundant and hotspot CRMs.

Secondary material streams could theoretically support substantial PSM deployment in the EU if assuming 100% material recovery from waste – between 31,000 TWh and 23,590,000 TWh for titanium

dioxide, aluminium, nickel, and lead. However, this drops substantially when considering current end-of-life recycling input rates.

Although the reserves-based estimate represents an upper bound for perovskite module deployment as it does not account for competing material usage and extraction rates, they do indicate the potential for the EU and other regions to support a PSM deployment using their own mineral reserves, thus reducing dependence on imported energy and raw materials. Similarly, the elemental concentration in waste from electronic and electrical equipment demonstrate the value in developing products for end-of-life recycling, as well as the potential to manufacture a significant PSM capacity using secondary material streams. However, significant improvements to recycling infrastructure are needed to take advantage of the minerals in electronic waste, especially in the design of products and the collection system.

Despite these limitations, the design of a recyclable perovskite solar module that uses domestic reserves and secondary raw materials show promise in being able to contribute to reducing the EUs dependence on imported energy.

Declarations

Conflicts of interest

There are no conflicts to declare.

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Author Contribution

Author contribution statement as per above method:SB: wrote the main manuscript text. ZW: provided cell manufacturing data. MK: reviewed and edited the manuscript. Ian-Marius Peters: supervised, reviewed and edited the manuscript.Author contribution using the CRediT system:Savannah Bennett: conceptualisation, data curation, investigation, methods, formal analysis, visualisation, writing. Zhenni Wu: investigation, writing – review & editing. Markus Kohlstädt: writing – review & editing. Ian-Marius Peters: conceptualisation, writing – review & editing.

Data availability

The data supporting this article have been included as part of the Supplementary Information.

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Figures

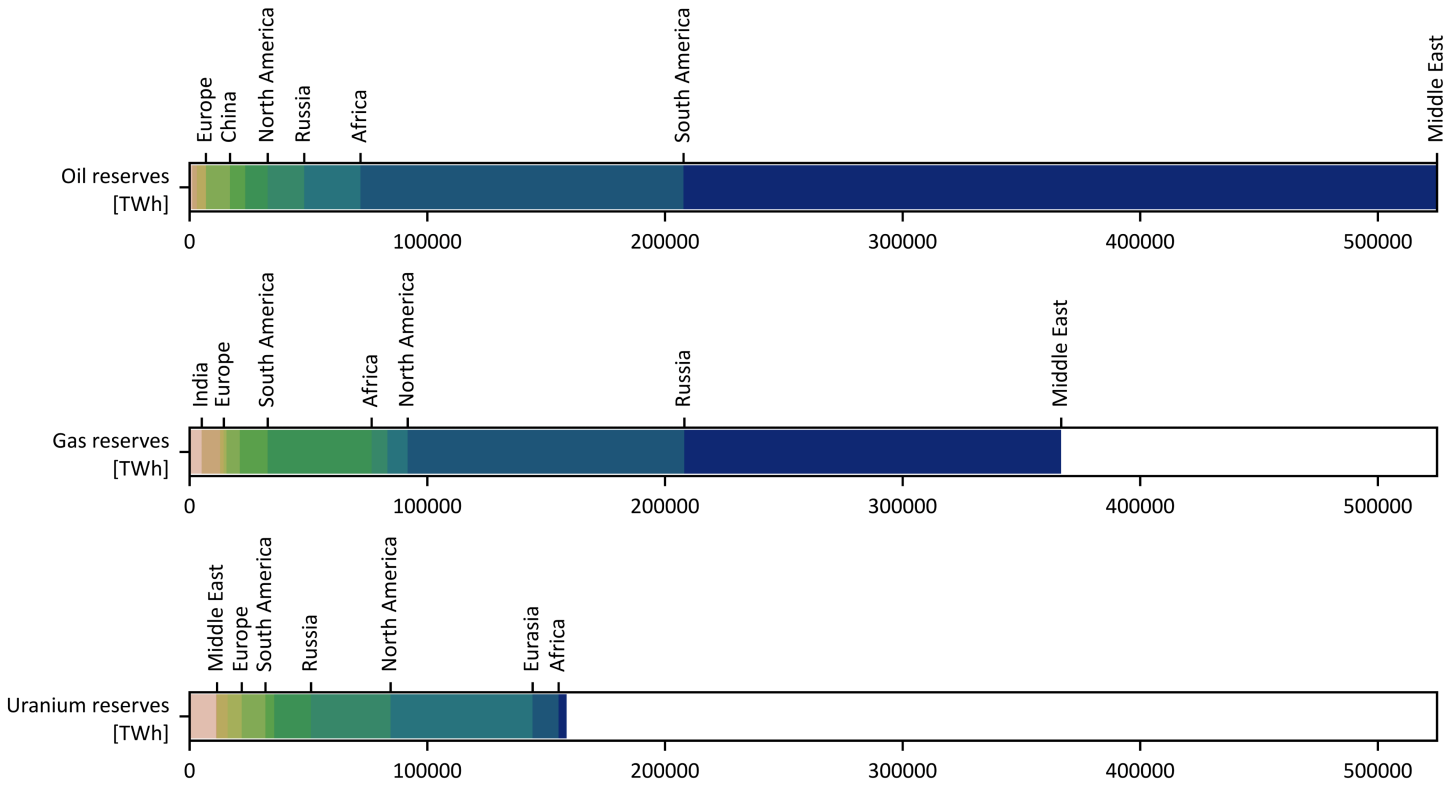


Figure 1

Estimated world reserves for oil, natural gas and uranium, expressed as potential energy production. Oil and natural gas data are from the Organization of the Petroleum Exporting Countries [6]. Uranium data are from the Nuclear Energy Agency [7]. Oil is converted from million barrels to TWh using a factor of 1:1.63 and natural gas is converted from million standard cubic metres to TWh using a factor of 1:11.1 [8]. Oil and natural gas and further reduced by fuel to electricity conversion losses of 37% and 40%, respectively. Tonnes uranium are converted to TWh using a factor of 1:0.044TWh [9].

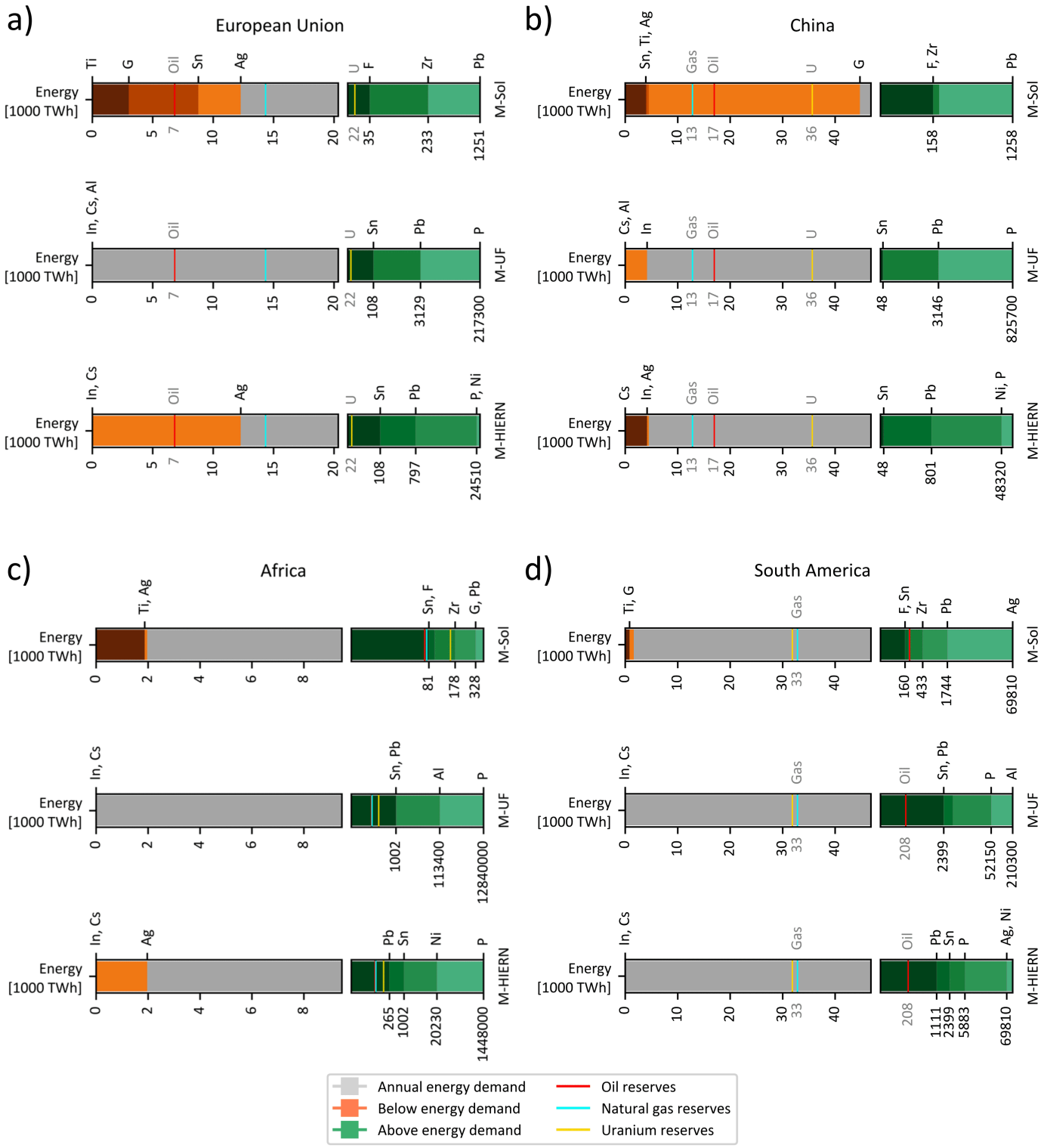


Figure 2

2a: The estimated energy generation (TWh/year) that could be produced by each of the perovskite solar module designs manufactured using EU mineral reserves alone. Grey is the total annual energy demand of the region provided by the IEA. Orange values are for reserves that would manufacture less than total annual energy demand. Green values are for reserves that could manufacture more than annual total energy demand. Red, blue and yellow lines are for the oil, gas, and uranium reserves of the region. 2b, 2c,

2d) Similarly for China, Africa and South America. The total energy supply excludes the energy embedded in products. There is little to no clear data on caesium and indium reserves.

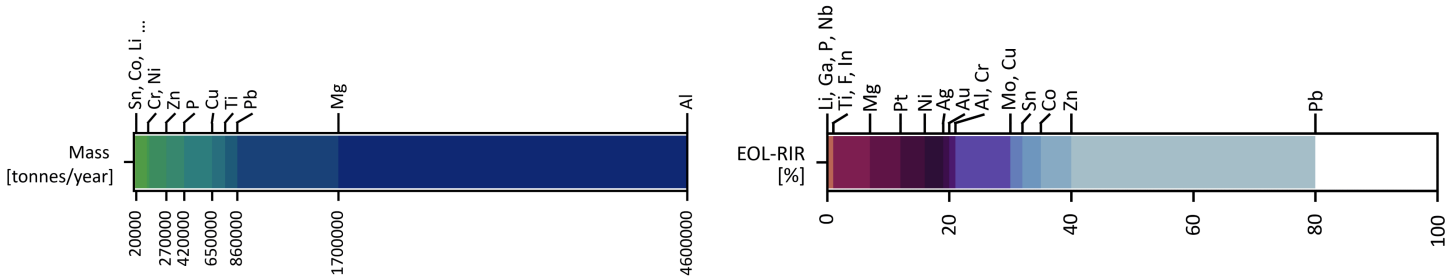


Figure 3

Left: estimated annual generation of waste in the EU of PSC relevant materials. materials with reported quantities of below 20,000 tonnes/year are grouped in the first category and include Sn, Co, Li, Mo, F, Ga, Nb, Ln, Au, Pb, Pt. Right: End-of-Life recycling input rate for minerals in the EU. There is no data for caesium and indium.

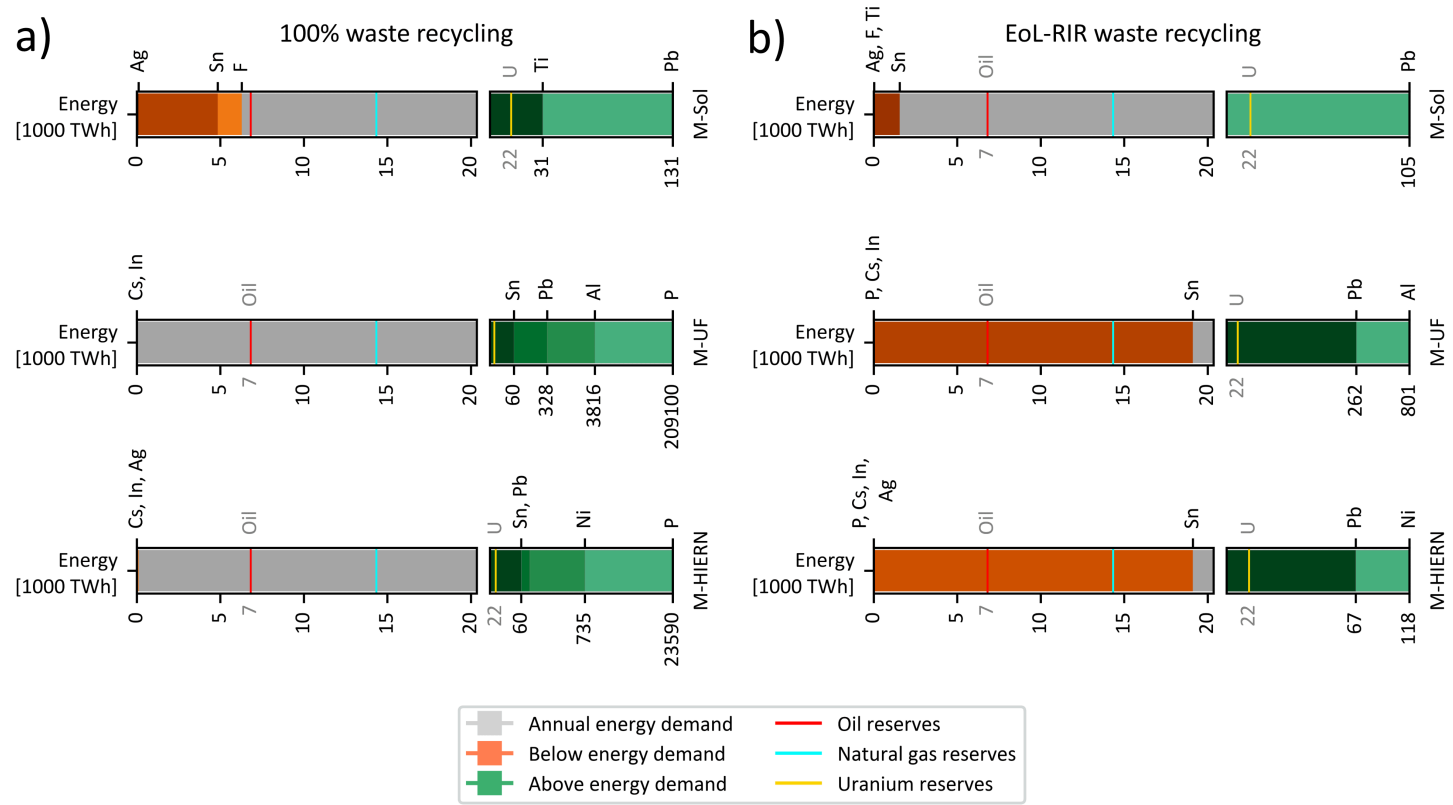


Figure 4

Left - the potential TWh of energy production using 100% of the waste of CRMs in the European Union. Right - the potential TWh of energy production using the EOL-RIR of the waste of CRMs in the EU.

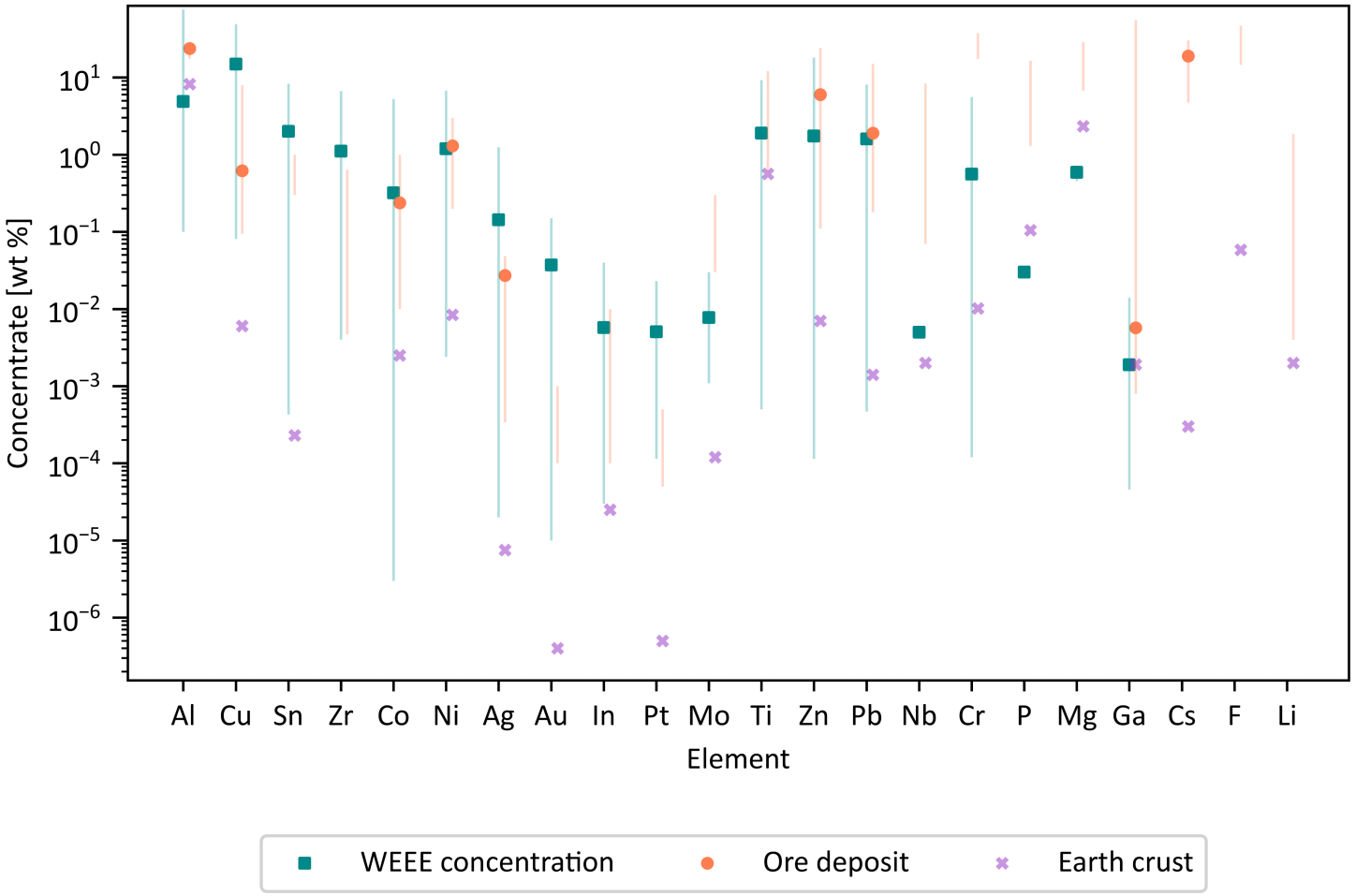


Figure 5

Concentration of metals/minerals from three sources: waste from electronic and electrical equipment (WEEE), in ore deposits, and in the earth's crust. The vertical lines are the minimum and maximum range for all of the elements considered, while squares and circles are the average values. Source of data is provided in the supplementary information. The elements ordered by the largest to the smallest difference between the WEEE and ore concentration ranges.

Supplementary Files

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