Please cite this article in press as: Peters et al., Cradle-to-cradle recycling in terawatt photovoltaics: A vision of perpetual utility, Joule (2024), https://doi.org/10.1016/j.joule.2024.01.025

Joule

CellPress
OPEN ACCESS

Perspective

Cradle-to-cradle recycling in terawatt photovoltaics: A vision of perpetual utility

Ian Marius Peters,[1,*] Jens Hauch,[1,2] and Christoph Brabec[1,2]

SUMMARY

To achieve carbon neutrality, a significant increase in photovoltaic module production is needed, affecting material demand and recycling perspectives. Circular recycling is essential for managing the material flows of a multi-terawatt global photovoltaic fleet. Immediate action is required to prevent the accumulation of millions of tons of low-value waste. Circularity's importance is multi-faceted and varies across materials. Limited silver reserves and competition with other markets necessitate reducing or substituting silver. For polymers, constrained production capacities can also be mitigated through circular recycling. The photovoltaic industry's immense glass demand calls for circular recycling to avoid overwhelming alternative markets. Recycling silicon, aluminum, and copper is vital for the economic feasibility of recycling, especially if silver is replaced. Although prolonging module lifespan reduces yearly material needs and influx into the recycling stream, it might also postpone achieving carbon reduction goals.

INTRODUCTION

Decarbonizing global energy generation demands a rapid transition toward renewable energies, with photovoltaics (PVs) and wind being projected to bear a major part of the load.[1] The year 2022 saw the completion of the first terawatt of cumulative installation, about 60 years after the first module for terrestrial applications entered the market.[2] The second terawatt will not take nearly as long and is expected before 2025,[3]—and before 2030, the industry expects to install more than a terawatt each year.[4] On the basis of these growth projections, as well as on global energy demand and the remaining carbon dioxide budget to stay below two degrees warming, we should see cumulative capacities of between 30 TW_P and 80 TW_P by mid-century.[5–7] Put differently, for every human on the planet, there will be between 10 and 25 solar panels. The rapid growth of PV manufacturing will have massive implications for supply chain and material demand. Recent studies, for example, by Goldschmidt et al.[8] and Hallam et al.,[9] have estimated the amount of feedstock materials and have pointed out supply chain and research challenges associated with the growing demand. Moreover, the scale of the PV supply chain and the embodied materials in the module fleet make dedicated efforts to move toward a circular economy necessary. Corresponding research challenges have notably been discussed by Heath et al.[10]

In this study, we explore the role of a rapidly expanding PV industry vis-à-vis its setting in a market that competes for resources. As a baseline, we use a scenario defined by Verlinden,[11–13] which is characterized by an exponential increase in

CONTEXT & SCALE

As the world races toward carbon neutrality, the photovoltaic (PV) industry is experiencing unprecedented growth, with projections indicating a need for multi-10-terawatt capacity by mid-century. This expansion underscores the critical role of PV in global energy transition while simultaneously emphasizing the need to formulate effective strategies for material demand management and recycling. The study reveals the critical role of circular recycling in supporting the sustained rapid growth of PV production. Circular recycling is particularly relevant, given the finite availability of essential resources such as silver and the constraints in polymer production capacities. We argue that circular recycling is a strategic imperative for the PV industry to sustain its growth while minimizing the strain on global resource pools. For instance, silver, crucial for PV module manufacturing, faces competition from other markets, highlighting the need for its reduction or replacement. Similarly, the vast demand for glass by the PV industry could potentially overwhelm alternative markets, making circular recycling a vital solution. Moreover, the study points out that recycling materials like silicon, aluminum, and copper is essential for installation and manufacturing until a steady-state manufacturing value of about 3.3 TW_P/year is reached in 2033 and a cumulative capacity of 80 TW_P is reached by mid-century. Some more details about this scenario are given in the supporting information. We discuss the development of the PV industry as a consumer of some of the major materials used in PV module production today, including glass, aluminum, silver, copper, ethylene-vinyl-acetate (EVA), and silicon. The discussion focuses on crystalline silicon technology and excludes thin-film technologies. One aspect of this discussion is the availability of alternative markets that could absorb recycled materials from solar panels or that could act as a source. On the basis of these results, we lay out arguments supporting the need for a circular economy with cradle-to-cradle recycling in PVs, and we describe an idealized picture that integrates cradle-to-cradle recycling of solar panels into the context of a general circular economy.

economic viability, especially if silver is replaced. This circular approach aligns with the broader objectives of a circular economy, where cradle-to-cradle recycling integrates with other industries' needs and sustainability goals. Thus, this study not only maps the current landscape of PV material demand and recycling but also charts a course toward a more sustainable and economically viable future for the PV industry.

MATERIAL AND VALUE DISTRIBUTION IN A SILICON PV MODULE

Recycling in the European Union (EU) is driven by regulatory requirements and revenue. The Waste Electrical and Electronic Equipment (WEEE) directive mandates that 85% of panels should be recovered, with 80% prepared for reuse or recycling.[14] These percentages refer to the mass fractions of a module. Silicon PV modules consist of various materials, the mass distribution of which[15–17] is shown in Figure 1 in the left column; 80% of recycling demands the recycling of glass and either aluminum or polymer components, with recycling routes for glass and aluminum being well established. The value in recycled materials, on the other hand, is concentrated in metals, accounting for over 75% of the theoretical recycling value.[18] Notably, silver, despite being a small fraction of the module mass, contributes nearly 50% of the recovered value, making it economically crucial in recycling. It is noteworthy that the commercial value of recycled module materials is significantly below that of the feedstock materials used to make the module. The former was given as 551$/ton in an article in PV magazine[19], and we estimate the latter at around 2,500$/ton.[20,21] The cause for this de-valuation lies in the reduction of material quality after recycling and differs for the various materials (Figure 1, center and right). For example, silicon enters the process as high-grade polysilicon in wafers and exits the recycling process as metallurgical-grade silicon in fragments. Enhancing the commercial appeal of recycling involves reducing the de-valuation at the end of the module's life by facilitating easier separation and sorting of module materials. This analysis focuses on silicon technology, which dominates the market, while circular recycling of CdTe modules is actively pursued by First Solar.[22]

THE CIRCULAR RECYCLING SCENARIO FOR GLASS

Glass makes the largest contribution to solar panel weight. Depending on module architecture and glass thickness, 2/3 to 3/4 of the mass of a solar panel is glass. Glass also has also one of the best-established and documented recycling infrastructures, making it a perfect candidate to explore the implications of circular recycling.

How glass demand for PV develops was explored by Goldschmidt et al.[8] Here, we use similar assumptions as in that study, with a few alterations: (1) we use the Verlinden scenario for capacity expansion, which projects faster growth and a higher cumulative installation than that used by Goldschmidt at al; (2) we use more conservative efficiency improvements, taken from Peters et al.[23], as shown in Figure 2; and (3) we assume an average glass thickness that is greater than the one in Goldschmidt et al.[8] In this study, a glass thickness of 2 mm was used for every glass panel. We assume an average thickness of 3 mm (which is slightly below the current industry

[1]Helmholtz-Institut Erlangen-Nürnberg for Renewable Energies, Forschungszentrum Jülich, Immerwahrstraße 2, 91058 Erlangen, Germany

[2]Institute of Materials for Electronics and Energy Technology (i-MEET), Department of Materials Science and Engineering, Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany

*Correspondence: im.peters@fz-juelich.de

https://doi.org/10.1016/j.joule.2024.01.025

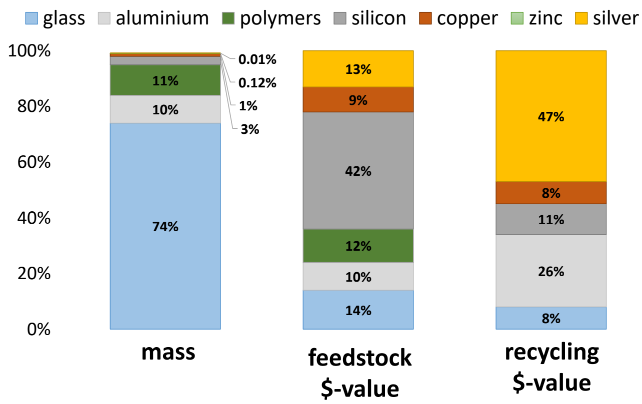

Figure 1. Mass and value of materials in a solar panel

Distribution of mass and values in a silicon solar panel using the initial material feedstock (middle) and the recycling value (right).

standard of 3.2 mm for single-glass modules) and a learning rate corresponding to ITRPV[24] projections of about 1%, reaching 2.5 mm in 2060 (see Figure 2). Note that we make no assumptions about single-glass or double-glass modules and that this number should be interpreted as the average amount of glass used per module. The resulting glass demand over time is shown in Figure 2 and peaks at about 100 million tons by the mid-2030s. This is consistent with that observed by Goldschmidt et al.[8] Subsequently, demand is declining due to a constant capacity paired with technological learning. This decline should, however, not be over-interpreted.

This development will have significant implications for the role of the PV industry in glass manufacturing. The compound annual growth rate (CAGR) of the PV industry in the past decades has consistently been above 20%. This rate far exceeds the projected growth of the glass industry as a whole, which lies, according to publicly available market projections, somewhere around 3.5%.[25] Consequently, the market share of glass produced for PV modules in relation to total glass produced is increasing. Following the Verlinden scenario, the share could grow from 1.5% in 2015 (this year was used because of data availability for sector-specific glass production) to almost 38% in 2034 and would be the by far the biggest single market for glass (see Figure 3). For flat glass alone, the market share would even be above 55%. Regardless of the exact growth scenario, the role of the PV industry as a consumer of glass will grow, and with it the socio-economic relevance. In 2023, more than 100,000 people were employed in the glass industry in the US[26] and more than 180,000[27] in Europe. With the increasing role of glass in the industry, a closer alignment between the PV industry and flat glass production is to be expected. The first examples can already be observed, such as First Solar locating solar panel manufacturing to an area with significant glass production.[28]

Growing glass consumption also has impacts on recycling. In January of 2023, the amount of glass coming from end-of-life (EOL) modules was a negligible fraction of total glass manufacturing, and recycled glass from solar panels can be absorbed by markets that do not require high glass quality, such as road construction[29] or other construction material markets.[30] This situation starts to change drastically as modules installed in the last 10 years reach EOL. At this point, which we will likely reach in the mid- to late-2030s, the amount of glass coming from EOL panels will be in the tens of millions of tons, and no alternative market will be able to absorb it. Moreover, even for the glass that could be absorbed, it is not without challenge

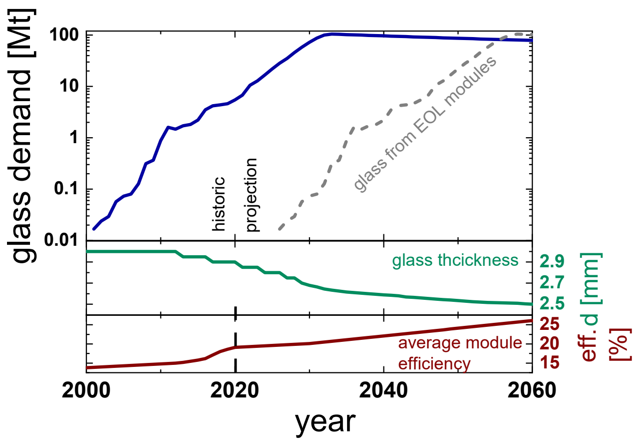

Figure 2. Projected glass use

Detailed scenario for annual glass demand according to the Verlinden scenario and making assumptions about the development of average module efficiency in production and required glass thickness.

for today's solar panel recycling processes to provide glass of sufficient quality. Flat glass manufacturers typically permit impurities of earthenware, stones, and porcelain (ESP) of less than 5g per ton.[31] This requirement is a major exclusion criterion and—for example—prevents glass from demolished buildings from being used for recycled flat glass. Although this criterion is not immediately relevant to the PV industry, the shredding and incineration processes of solar panels in recycling today[32] result in a mixture of materials and components that, at a minimum, would make a thorough sorting unavoidable. Yet, given the small amount of solar panel glass available for recycling today, impurity requirements and recycling efficiency are issues that are currently not addressed—at least, we could find no studies quoting numbers. And even that is not all—recycling processes for white glass are far from perfectly circular. According to Harder,[33] white glass productions only permits a recycling rate of about 60%.

The need for circular recycling for glass stems from a lack of an alternative market that could absorbed sufficient materials from EOL modules. Vice versa, it would be difficult to satisfy the massively growing demand of the PV industry with recycled glass from other markets.

SILVER AND COPPER

Silver poses the greatest resource challenge in PV panel production. Detailed discussions about silver demand in the PV industry were given by Hallam et al.[9] and Goldschmidt et al.[8] The PV industry's silver demand in 2020 was approximately 12.7% of annual silver production (23,500 t) and is projected to surpass annual production before 2030 in the Verlinden scenario. Known global reserves would be depleted at a cumulative installation of approximately 70 TW_P[9]. Silver is widely used in various applications, including soldering and brazing alloys, batteries, dentistry, glass coatings, LED chips, medicine, nuclear reactors, photography, radio-frequency identification (RFID) chips, semiconductors, touch screens, and water purification.[34] In today's market, the PV industry faces increasing difficulties in extending its market share for silver production, as price pressure favors other markets with higher margins. The development in silver usage across different markets is shown in Figure 4. Urgent action is needed to reduce and replace silver in PV panels.[35] Recycling does not reduce silver demand to install the necessary module

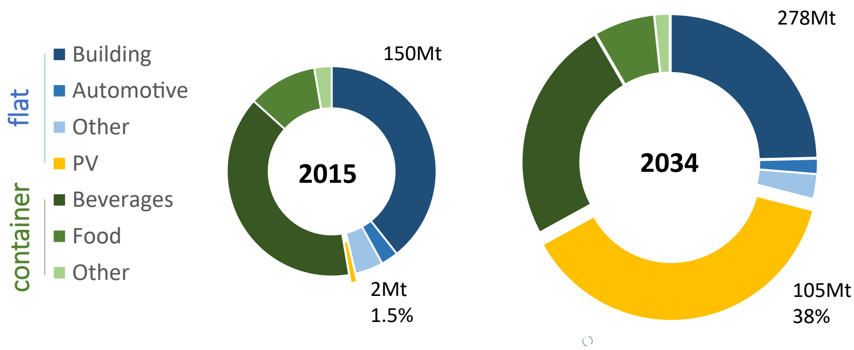

Figure 3. Glass
The glass market and the PV industry's role in it in 2015 and 2034.

capacity initially, but it can help maintain a certain amount of silver in coming module generations and reduce future demand.

Replacing silver would significantly impact recycling economies, as silver recovery currently generates substantial revenue (see Figure 1). New module concepts are required to enhance the value of recovered materials in the absence of silver. Copper is a promising candidate for silver replacement, with significantly larger reserves—2 billion tons estimated[36] compared with 550,000 for silver[37]—and higher annual mining—26 million tons compared with 26,000. The price of copper in February 2023 was about a factor 60 below that of silver. Technological challenges remain, but successful examples of copper usage as a partial silver replacement exist.[38–40] Copper recycling is well established, with the US alone having recycled 800,000 tons of copper in 2018.[41] In addition, large alternative markets in construction, electronics, and transportation[42] exist that could serve as sources of recycled copper for PV manufacturing.

Another resource-limited material used in the PV industry is indium, which is especially relevant for low-temperature passivating contacts used in heterojunction-type solar cells and tandems. World indium reserves are undetermined with just about 900 tons being mined per year.[43] Indium is most commonly recycled from scrap indium tin oxide (ITO), to which the PV industry could become a major contributor. The finite nature of indium deposits has long been recognized, and alternative materials are the subject of active research.[44]

Silver is resource limited, which is an immediate challenge for scaling module manufacturing. Circular recycling cannot resolve this issue but is necessary to alleviate it by making silver from old solar panels available. Replacing silver with copper reduces the economic appeal of existing recycling processes, and efficient copper recycling will be important to compensate for this loss.

ALUMINUM, EVA, AND SILICON

Aluminum

Apart from iron, aluminum is the most produced metal by mass globally. The World Economic Forum quotes the annual production in 2021 at 68 million tons.[45] United States Geological Survey (USGS) estimates global resources at between 55 and 75 billion tons.[46] The major markets for aluminum are the car industry, construction, and packaging. In PV module production, by far the largest amount of aluminum is used for the frames. We estimate that 300,000 tons of aluminum was used for

Please cite this article in press as: Peters et al., Cradle-to-cradle recycling in terawatt photovoltaics: A vision of perpetual utility, Joule (2024), https://doi.org/10.1016/j.joule.2024.01.025

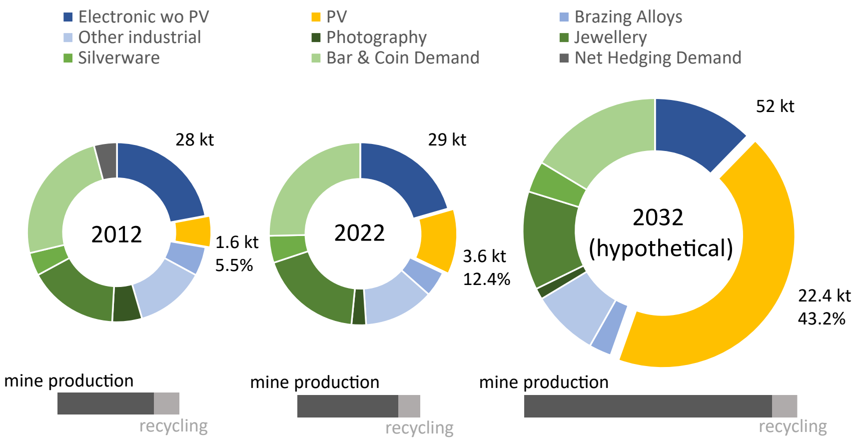

Figure 4. Silver

The silver market and the PV industry's role in it in 2012, 2022, and, hypothetically, 2032 if the transition away from silver was not accelerated and enough silver could be mined. In this hypothetical scenario, silver mining would have to increase by almost 80% compared with 2022 to accommodate the additional demand of the PV industry. Given the small growth in silver mining in the past years, such an expansion seems unlikely.

this purpose in 2014. Following the Verlinden scenario, this number would increase to 16 million tons in 2032 and constitute a 17% share of the aluminum market, assuming a 2.5% CAGR for all markets other than PV[47] (Figure 5 [Aluminium]). We made no assumptions about learnings in aluminium consumption. Lighter frames, larger modules, and frameless modules would all contribute to reducing the aluminum demand of the PV industry. Under these assumptions, the PV industry would become the fourth-largest market for aluminum. It is worth noting that recycling of aluminum is already well established and global consumption contains an estimated 75% of secondary aluminum.

The argument for circular recycling of aluminum is an economical one and is similar to that for copper. Currently, aluminum is the second-most valuable recycling product of a PV module, and its role will likely increase as silver is replaced. Recycling processes that retain the value of recycled components are indispensable.

EVA

We are using EVA as an example for the polymer demand in PV production. EVA is the main material used as an encapsulant and is expected to maintain its dominant role over the next decade, though with a reduction in its market share.[24] The PV market is already a major consumer of EVA, with a demand of 1 million tons per year or 26% of today's production. The largest market currently is the footwear industry (EVA is the main material in the sole of sneakers), which is about twice the size of the PV market. A projection to 2030—according to the Verlinden scenario and assuming that EVA's share in solar panels reduces from 95% to 70%—results in a demand of 6 million tons per year and a market share in excess of 50% of total production (Figure 5 [EVA]). The growing demand for EVA in solar panels has several consequences: one is that footwear producers and solar panel producers become even fiercer competitors if EVA production is not scaled fast enough. This could be an issue for the PV industry because the profit margins and markup for footwear are typically greater than for solar panels.[48,49] A second consequence is that, similar to glass, we expect an increase in EVA manufacturing specifically for and collocated with solar panel manufacturing. A third consequence is that the footwear industry will not be able to function as a potential alternative market for recycled EVA from solar panels.

Please cite this article in press as: Peters et al., Cradle-to-cradle recycling in terawatt photovoltaics: A vision of perpetual utility, Joule (2024), https://doi.org/10.1016/j.joule.2024.01.025

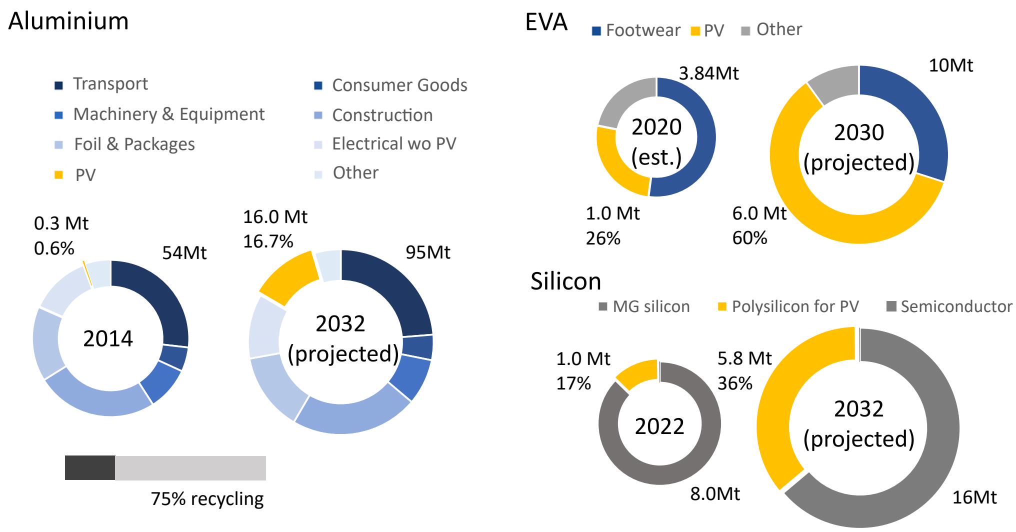

Figure 5. Aluminum, EVA, and silicon

Markets and the PV industry's role in them for aluminum (a) in 2014 and 2032, EVA in 2020 and 2030, and silicon in 2022 and 2032.

It is important to note that EVA comes in various forms and that the PV and footwear industries use different ones. Still, basic materials and processes are similar, and with growing demand, the PV and footwear industries become even stronger competitors.

Additional polymers are used in modules as edge sealants and backsheets, yet the large variety of available materials and the dynamics in their development make the market situation difficult to analyze. In general, we expect the role of the PV industry as a consumer for these polymers to also grow, though the transition to bifacial modules will reduce the demand for backsheets.

EVA is not a fundamentally resource-limited material like silver, but there is a threat of a bottleneck in production capacity. Circular recycling of EVA cannot remove the need to expand production, but it would give us more time and it will reduce the number of factories we need.

Silicon

Silicon is the second-most common element in the Earth's crust. Global production of metallurgical-grade silicon in 2020 was about 8 million tons,[50] which includes feedstock for polysilicon production—projected to surpass 1 million tons (or 17%) in 2023.[51,52] Polysilicon production, in turn, includes about 15,000 tons of semiconductor-grade silicon.[53] We project silicon demand using a 4% CAGR[54] for metal-grade silicon demand, excluding PV applications, and for the demand of semiconductor-grade silicon. Demand for PVs is scaled assuming that 1 million tons is sufficient for producing 400 GW worth of panels (2.5g/W) and a 10% learning rate in demand per capacity doubling. The resulting numbers for 2032 suggest a doubling of overall silicon demand and a growth of polysilicon demand to 5.8 million tons (36% share) (see Figure 5 – Silicon). Although the significance of the PV market for silicon production will grow, it is unlikely to become dominant. The majority of silicon will still be used in metallurgical processes in ferrous foundries, the steel industry, and aluminum production. The limited demand for material purity and the high demand make these applications potential consumers of recovered silicon from PV panels. The availability of an alternative market to absorb downgraded silicon reduces the risk of waste creation. Still, material flows between these industries need to be established.

Remarkably, the USGS report on silicon characterizes recycling as "insignificant."[50] Yet, while the downgrading of PV silicon is an option, there are clear benefits to its recycling. The study by Heath et al. argues that silicon should be recovered at high purity to increase its economic benefit to recyclers and decrease the energy footprint of polysilicon production.[10] Our analysis supports this conclusion. Silicon production requires between 160 and 375 kWh of electrical energy to generate 1 kg of silicon wafers from newly mined material.[55] In our opinion, the greatest benefit of silicon recycling is to reduce this energy demand and consequently shorten the energy payback time of modules made from recycled silicon. In the process of contact and junction formation, silicon wafers are admixed with small amounts of other elements. Using this silicon, the energy demand for creating solar grade silicon would already reduce to 60 kWh/kg. A research task to improve silicon quality and reduce the energy demand even further while boosting commercial value would be to develop concepts that avoid the mixture of impurities into solar grade silicon altogether or concepts that facilitate their removal.

Circular recycling of silicon has the potential to become the main economic driver for module recycling. Today, silicon is the most de-valued material that is recovered from modules. Recovering silicon with higher quality will require innovation in solar cell and module architectures.

BEYOND THE MODULE

The preceding sections focused on the PV module, while circular recycling also encompasses other PV system elements. This includes materials like mounting structures, cables, and inverters. Mounting structures, typically made from steel, aluminum, and concrete, have a varied selection based on installation type and location. Their combined mass is difficult to estimate, but will likely also be tens of millions of tons. Iron constitutes over 90% of mined metals, with 2.6 billion tons mined globally in 2021,[56] while 4.2 billion tons of concrete was produced in 2020.[57] Iron and concrete are essential in manufacturing and civil engineering,[58] and only a small fraction of these materials will be used for PV installations. Recycling concepts are developed in the context of urban mining.[59] Use as a mounting structure will increase the relevance of the PV market for this material. Copper, vital for the power grid, sees approximately 45% usage in that sector.[60] An expanded power grid supporting renewable energies[61] is expected to increase copper demand. Recycling paths for copper wire are discussed, e.g., in Li et al.[62] Inverters, which are intricate electronic devices, consist of numerous materials and components. Although delving into inverter recycling exceeds the article's scope, it is crucial due to the substantial quantities required. With tens of millions needed, inverter recycling deserves heightened attention from research and industry.

Further aspects that demand attention are transportation and logistics. Today, disassembly and transportation of old modules to a recycling location add costs that may well turn a profit into a loss. Recycling would be aided by short distances and easy—ideally automated—disassembly.[63] The growth in quantity of EOL modules over time, as well as integration with other products, will likely support the local establishment of multi-purpose facilities for circular recycling. Careful positioning of recycling facilities as further infrastructure is installed seems sensible.

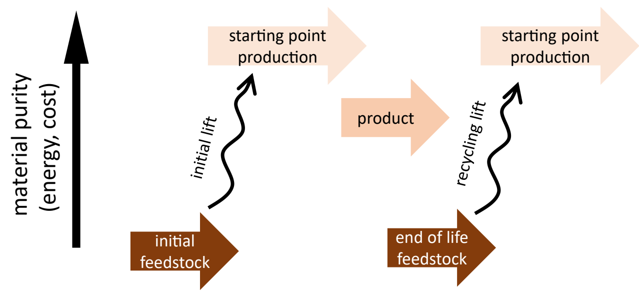

Figure 6. Material quality during a cycle
Sketch of the purity levels materials go through during mining, in production, in a final product, and at the end of life.

THE CASE FOR CIRCULAR RECYCLING

We need to design solar panels for circular recycling

Fundamentally, recycling can be described as a process of restoring the quality of materials obtained from EOL modules to a level needed for the manufacturing of new components. In many regards, quality improvement is identical to refining a given material to an acceptable concentration of impurities. The necessary lift in material quality determines the time-, energy- and capital-intensity of the recycling process, and it decides whether recovered materials from recycling can compete with newly mined ones (see Figure 6). These considerations result in several tasks for research and development. One aspect of improving the usefulness and the competitive advantage of recycled materials is to improve the quality of the EOL feedstock. To realize this improvement, we need to develop concepts for modules in which materials can be separated more easily and cleanly. These concepts require effort in materials development and in interface design. Crucially, enhancing separation methods should not compromise module durability. Any developed concept must adeptly balance the challenges of improving separability while ensuring the longevity and robustness of modules. Another aspect is that we need better sorting of module components according to their exact bill of materials. This need requires improved documentation of bill of materials and improved characterization to enable quick, easy, and accurate material identification. These measures then need to be integrated into novel PV module architectures to transition from a "design for immortality"[64] toward a "design for recycling" paradigm. The required lift in material quality can be reduced complementarily through the utilization of materials that can tolerate higher levels of impurities. Searches for materials with improved tolerance to contamination and improved separability can be supported with high-throughput methods of materials development.[65,66] Overall, these measure will increase the value of recycled materials, close the de-valuation gap shown in Figure 1, and make recycling commercially viable.[67] This is especially important to compensate for lower recycling values in modules with low or no silver.

We need dedicated circular recycling of PV modules to conserve and manage resources

A global module fleet capacity in the tens of TW_Ps involves material flows in the tens of millions of tons per year for PV panels alone. If all the components of the energy infrastructure are considered, these numbers will be even higher. Circular recycling in PVs will be crucial to avoid waste streams on a scale roughly equivalent to today's global e-waste. As shown for the example of glass in Figure 3, EVA in Figure 5 (EVA), and polysilicon in Figure 5 (Silicon), PV manufacturing is already dominating—or has a good chance to dominate—the supply chain to an extent where passing materials to a different sector, and particularly a sector with a lower demand for material quality, will no longer be an option. The most suitable market, and in some cases the only one large enough to absorb the amount of recycled material, will be PV module manufacturing itself. In addition, we need to recover precious metals like silver and copper with very high efficiency to limit the amount of new material required to maintain the module fleet and to support the economic success of recycling. Several open research tasks are connected to these issues that go beyond those outlined in the previous discussion. These tasks include the reduction and replacement of silver in PV modules, the improvement in recycling efficiency of PV glass, and facilitating polymer recycling.

We need a circular economy to boost the economic prospect of recycling

Recycling success will benefit greatly from being economically competitive. Establishing a circular economy for PV panels will help accomplish this in several ways. The most important aspect is simply market size. In 2019, Veolia collected about 5,000 tons of PV modules in total in France.[68] This amount is sufficient for the operation of one exemplary dedicated recycling site. As this market grows, economies of scale will play a part in reducing costs, supported by mechanisms like improved binning of components with different composition, such as, for example, different cover glasses. Such a development can be supported by the development of technologies that allow mono-material sorting. Furthermore, larger production volumes will allow the establishment of reliable supply chains that have the potential to reduce the risks of supply chain disruption. A second important aspect is the technological innovation that anticipates the needs of circular recycling. Ensuring the growth of a circular economy will require market incentives and support for research and development.

A VISION OF PERPETUAL UTILITY

Establishing a full circular economy for PV modules is a process that needs to accompany the energy transition and rapid installation of solar panels. As installations undergo different phases (growth, consolidation, steady state), circular recycling also adopts different roles. A vision of what this development could look like is shown in Figure 7. During the growth phase, recycling can do little to reduce material demand. Module generations constructed during this phase that we are currently in, which has lasted 40 years or more and that will continue for at least another decade, will need to be made predominantly from new materials. The major task for PV module recycling during this phase is preparation. Processes need to be in place to handle vast amounts of EOL modules and recover the buried materials. Although there is a delay equal to the module lifetime, eventually the flow of recycled modules will equal that of produced ones. Hence, recycling will need to be a process with features similar to module production. Recycling needs to be fast, automated, and extremely cost effective. Making sure module technologies are compatible with these requirements, and developing the industrial processes to make this possible at the required scales is the major R&D challenge today. As we enter the consolidation phase, PV module recycling must be implemented, and these materials need to enter the circle to reduce the demand for newly mined ones. The main challenge for PV module recycling during this phase will be one of interconnection. Because PV technologies change over generations, and because recycling will not be perfect, a narrow, closed loop for a single product is not a useful goal. Rather than aiming for a narrow, closed loop, the ideal should be

Please cite this article in press as: Peters et al., Cradle-to-cradle recycling in terawatt photovoltaics: A vision of perpetual utility, Joule (2024), https://doi.org/10.1016/j.joule.2024.01.025

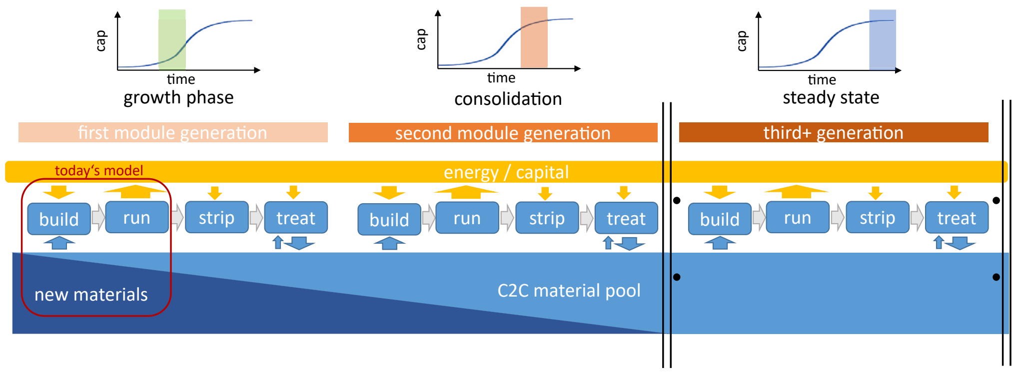

Figure 7. Perpetual utility

Vision for the development of a photovoltaic module over multiple lifecycles. At the beginning of each life, energy, capital, and material are invested to construct a module (in the figure, this phase is indicated with the word ''build''). During its life, the module is operated, generating energy and capital (run). At the end of life (EOL), the module is deconstructed into materials and components (strip), which are treated (treat) and returned to a material pool from which materials for subsequent cycles are taken. Initially, while photovoltaic installations are expanded (first life), the majority of materials have to be newly mined. A second generation of modules can already be made partially of materials mined from old modules. By the time the cumulative installed module capacity (cap) converges toward a steady-state value, all material should come from a material pool. This material pool will be open and include materials from old modules as well as other products.

interconnected loops in which various products provide building blocks for a common material pool from which new products can be created. An analogy for this process is the natural cycle of bio matter nourishing soil for the growth of new plants. A tree at the end of its life is subjected to decomposition through manifold processes. Decomposition reduces the tree to chemicals and compositions that are, in general, simpler and more inert than the original substance. These materials become part of the soil or are used by other life for nourishment and other purposes. In conjunction with other life entering this circle, a substrate is created that is simultaneously compatible and sufficiently complex to support the vast variety of life on earth. In a similar way, we envision components and materials from old products to enter a material pool that will become the substrate for any new product that we may want to build. Constructing the interconnected loops of this great circle will be the main research and development task in this coming phase, which we may enter in about 10 years. In this picture, the subsequent steady-state phase is not only characterized by an equilibrium of module production and retirement but also by an equilibrium of material flows into and out of the common material pool; hence, only a minute fraction of newly mined materials are needed to maintain the established module fleet. Materials do not become waste but enter a stage of perpetual utility, with the sun providing the energy to treat and rejuvenate them. To minimize the environmental impact of our future energy system, this vision should be implemented in the next 25 years.

CONCLUSION

Transitioning to carbon neutrality requires a massive expansion of PV installations and production, which has implications for the PV industry as a consumer of materials needed for module construction. An ambitious expansion scenario formulated by Pierre Verlinden was explored to understand its materials demand and recycling perspectives. As the PV market grows rapidly, its share in global materials consumption increases, particularly for materials essential to silicon PV module production. This growth has consequences for recycling, as alternative markets accepting lower material quality become unavailable. Flat glass is a notable example where the PV industry could reach a 55% market share.

The PV industry will face an increasingly competitive environment for obtaining feedstock materials due to low margins in module manufacturing. This gives alternative markets a competitive advantage as prices rise. Silver is a critical example where PV module manufacturing competes with higher-margin applications, and the demand for PV alone could exceed known reserves. Reducing silver demand is imperative, but eliminating silver has further implications for recycling. Currently, silver contributes about half of the value recovered from a recycled PV module. Alternatives need to be established to make recycling more profitable. Recovering materials at higher purity enhances their value, as seen in the recycling of silicon (see also Heath et al[10]) or aluminum. Although large alternative markets exist for these materials, the market value of low-quality recycled materials is low, estimated at around 20% of the initial purchase value.

Although the Verlinden scenario is ambitious in terms of production scaling speed, the final production capacity needed to maintain a certain cumulative PV capacity depends on the production capacity and module lifetime reached—not the speed of scaling. Hence, less ambitious expansion scenarios would still project similar material demands, albeit at a later stage. Increasing module lifetime from 25 to 50 years is the most effective lever to reduce material demand while reaching the target capacity. However, this approach also extends the time required to reach the target, potentially jeopardizing carbon reduction goals. A potential workaround using intermediate manufacturing of technologies with lower material demand and lower capital expenditure is discussed in the supporting information.

As we move toward a renewable energy infrastructure, supporting innovation is crucial to ensure that renewable energy is also sustainable. Circular recycling is essential for managing the significant material flows required for a global PV module fleet in the multi-terawatt range. Although the mass recycling of PV modules is still years or decades away, it is vital to prepare for circular recycling now to avoid dealing with millions of tons of low-value waste in the future. This perspective presents a vision for approaching circular recycling of PV materials with perpetual utility.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2024.01.025.

ACKNOWLEDGMENTS

This work was supported by the Helmholtz Association in the framework of the innovation platform "Solar TAP" (Az: 714-62150-3/1[28]) and the state of Bavaria via project "PV-Tera – Reliable and cost efficient photovoltaic power generation on the Terawatt scale" (no. 44-6521a/20/5) and co-funded by the European Union (ERC, C2C-PV, project number 101088359). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. ChatGPT was used in the final revision to improve formulations and shorten the text.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Bloomberg NEF (2022). New Energy Outlook. https://about.bnef.com/new-energy-outlook/.

2. Sharp started mass-producing solar cells in 1963 with a first commercial application of the developed modules on buoys. https://global.sharp/corporate/info/his/only_one/lcd_solar/subwin/solar_01.html?TB_iframe=true?height=360&width=630.

3. There are various growth scenarios and industry announcements regarding the growth of photovoltaic production; in the Global Market Outlook For Solar Power 2022–2026, Solar Power Europe predicts global solar to more than double to 2.3 TW in 2025. The report can be downloaded here: https://www.solarpowereurope.org/insights/market-outlooks/global-market-outlook-for-solar-power-2022#downloadForm.

4. Similarly, there are various statements about when 1 TW annual production will be reached. Longi has stated that they anticipate global production of 1 TW annually by 2030, https://www.pv-magazine.com/2022/05/17/global-annual-solar-deployment-to-hit-1-tw-by-2030/.

5. Kurtz, S.R., Leilaeioun, A.M., King, R.R., Peters, I.M., Heben, M.J., Metzger, W.K., and Haegel, N.M. (2020). Revisiting the terawatt challenge. MRS Bull. *45*, 159–164.

6. Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., De Souza, L., et al. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy *227*, 120467.

7. Haegel, N.M., Atwater, H., Barnes, T., Breyer, C., Burrell, A., Chiang, Y.M., De Wolf, S., Dimmler, B., Feldman, D., Glunz, S., et al. (2019). Terawatt-scale photovoltaics: Transform global energy. Science *364*, 836–838.

8. Goldschmidt, J.C., Wagner, L., Pietzcker, R., and Friedrich, L. (2022). Technological learning for resource efficient terawatt scale photovoltaics. Energy Environ. Sci. *14*, 5147–5160.

9. Hallam, B., Kim, M., Zhang, Y., Wang, L., Lennon, A., Verlinden, P., Altermatt, P.P., and Dias, P.R. (2022). The silver learning curve for photovoltaics and projected silver demand for net-zero emissions by 2050. Prog. Photovolt. Res. Appl. *31*, 598–606.

10. Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., et al. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy *5*, 502–510.

11. Pierre Verlinden has devised a scenario to grow to 80 TW that he has used in presentations at least since 2019. The analysis was shown, for example, during his presentation for receiving the Becquerel Price at the 2019 EUPVSEC in Marseille. The slides are available here: http://becquerel-prize.org/pdf/2020_01_31_Pierre_Verlinden_Becquerel_Prize_Challenges_of_PV_Industry_20190909.pdf. The numbers have also been used in Haegel et al.[7] The results were also reported in Verilinden[12] and Haegel[13].

12. Verlinden, P.J. (2020). Future challenges for photovoltaic manufacturing at the terawatt level. J. Renew. Sustain. Energy *12*, 053505.

13. Haegel, N.M., Verlinden, P., Victoria, M., Altermatt, P., Atwater, H., Barnes, T., Breyer, C., Case, C., De Wolf, S., Deline, C., et al. (2023). Photovoltaics at multi-terawatt scale: Waiting is not an option. Science *380*, 39–42.

14. European Commission (2013). DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on waste electrical and electronic equipment (WEEE), Article 11 and Annex V. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:en:PDF.

15. Ilias, A.V., Meletios, R.G., Yiannis, K.A., and Nikolaos, B. (2018). Integration & assessment of recycling into c-Si photovoltaic module's life cycle. Int. J. Sustain. Eng. *11*, 186–195.

16. Dubey, S., Jadhav, N.Y., and Zakirova, B. (2013). Socio-Economic and Environmental Impacts of Silicon Based Photovoltaic (PV) Technologies. Energy Procedia *33*, 322–334.

17. Saraswat, J., Mukherjee, M., and Mall, N. (2020). Prospects for PV recyclability and the associated end-of-life management; an Indian perspective. In Energise 2020. https://www.energiseindia.in/wp-content/uploads/2020/02/Energise-2020-paper-proceedings.pdf.

18. Weckend, S., Wade, A., and Heath, G. (2016). End-of-Life-Management, Solar Photovoltaic Panels. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09.

19. Cecilia, L'Ecluse, and Julia, Attwood (2020). The afterlife of solar panels. PV magazine *11*. https://www.pv-magazine.com/magazine-archive/the-afterlife-of-solar-panels/.

20. Powell, D.M., Winkler, M.T., Choi, H.J., Simmons, C.B., Needleman, D.B., and Buonassisi, T. (2012). Crystalline silicon photovoltaics: a cost analysis framework for determining technology pathways to reach baseload electricity costs. Energy Environ. Sci. *5*, 5874–5883.

21. Sofia, S.E., Wang, H., Bruno, A., Cruz-Campa, J.L., Buonassisi, T., and Peters, I.M. (2020). Roadmap for cost-effective, commercially-viable perovskite silicon tandems for the current and future PV market. Sustainable Energy Fuels *4*, 852–862.

22. First Solar (2022). Sustainability Report. https://www.firstsolar.com/Resources/Sustainability%20Documents.

23. Peters, I.M., Hauch, J.A., and Brabec, C.J. (2022). The role of innovation for economy and sustainability of photovoltaic modules. iScience *25*, 105208.

24. (2022). International Technology Roadmap for Photovoltaic (ITRPV): R&D findings from the 13th Edition, p. 2. https://etip-pv.eu/news/other-news/international-technology-roadmap-for-photovoltaic-itrpv-r-d-findings-from-the-13th-edition/.

25. CAGR rates, assembled from various publicly available sources like Yahoo Finance, MarketWatch, GlobeNewsWire, etc.

26. IBISWorld; Glass Product Manufacturing in the US (2023). Glass Product Manufacturing in the US - Employment Statistics 2004–2029. https://www.ibisworld.com/industry-statistics/employment/glass-product-manufacturing-united-states/.

27. Statista, Number of employees in the European Union's glass manufacturing industry, 1995 to 2020. https://www.statista.com/statistics/1270093/eu-number-of-employees-in-glass-manufacturing-industry/.

28. First Solar. Local production of glass and sourcing of materials for expanded production in Perrysburg. https://www.firstsolar.com/Technology/Manufacturing.

29. Sandanayake, M., Li, L., Zhao, J., and Joseph, P. (2022). Applications of Solar Panel Waste in Pavement Construction—An Overview. Sustainability *14*, 14823.

30. Máčalová, K., Václavík, V., Dvorský, T., Figmig, R., Charvát, J., and Lupták, M. (2021). The Use of Glass from Photovoltaic Panels at the End of Their Life Cycle in Cement Composites. Materials (Basel) *14*, 6655.

31. A summary of recycling requirements and customs (German). https://www.baunetzwissen.de/glas/fachwissen/herstellung-eigenschaften/recycling-von-glas-2445257.

32. Monteiro Lunardi, M., Alvarez-Gaitan, J.P., Bilbao, J.I., and Corkish, R. (2017). A Review of Recycling Processes for Photovoltaic Modules in Solar Panels and Photovoltaic Materials. In Intech Open, B. Zaidi, ed.

33. Harder, J. (2018). Glass recycling – Current market trends, recovery. https://www.recovery-worldwide.com/en/artikel/glass-recycling-current-market-trends-3248774.html.

34. Bullion Vault. What is silver used for in industry? https://www.bullionvault.com/silver-guide/silver-industrial-demand.

35. Zhang, Y., Kim, M., Wang, L., Verlinden, P., and Hallam, B. (2021). Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption. Energy Environ. Sci. *14*, 5587–5610.

36. U.S. Geological Survey (2023). Mineral Commodity Summaries – Copper. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-copper.pdf.

37. U.S. Geological Survey (2023). Mineral Commodity Summaries – Silver. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-silver.pdf.

38. Geissbühler, J., Wolf, S.D., Faes, A., Badel, N., Jeangros, Q., Tomasi, A., Barraud, L., Descoeudres, A., Despeisse, M., and Ballif, C. (2014). Silicon Heterojunction Solar Cells With

Copper-Plated Grid Electrodes: Status and Comparison With Silver Thick-Film Techniques. IEEE J. Photovolt. *4*, 1055–1062.

39. Lennon, A., Colwell, J., and Rodbell, K.P. (2019). Challenges facing copper-plated metallisation for silicon photovoltaics: Insights from integrated circuit technology development. Prog. Photovolt. Res. Appl. *27*, 67–97.

40. Hatt, T., Bartsch, J., Kluska, S., Nold, S., Glunz, S.W., and Glatthaar, M. (2020). Low-cost Cu-plated metallization on TCOs for SHJ Solar Cells - Optimization of PVD Contacting-layer. In 47th IEEE Photovoltaic Specialists Conference (PVSC), *0397–0400* (Calgary, AB, Canada).

41. Sangine, E.S. (2018). Recycling—Metals, U.S. Geological Survey Minerals Yearbook. https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-recycling.pdf.

42. Flanagan, D.M., and Copper, U.S. (2018). Geological Survey Minerals Yearbook. https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-copper.pdf.

43. U.S. Geological Survey (2022). Mineral Commodity Summaries – Indium. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-indium.pdf.

44. Hofmann, A.I., Cloutet, E., and Hadziioannou, G. (2018). Materials for Transparent Electrodes: From Metal Oxides to Organic Alternatives. Adv. Electron. Mater. *4*, 1700412.

45. World Economic Forum. Here's what the world mined in 2021 in one infographic. https://www.weforum.org/agenda/2022/10/all-the-metals-we-mined-in-2021-visualized/.

46. U.S. Geological Survey (2023). Mineral Commodity Summaries – Aluminum. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-aluminum.pdf.

47. Aluminiumleader.com. How the World Aluminium Market Works. https://www.aluminiumleader.com/economics/world_market/.

48. Threadcurve.com (2022). What's the Profit Margin on Shoes?. https://threadcurve.com/whats-the-profit-margin-on-shoes/.

49. Macrotrends.net. First Solar Profit Margin 2010-2022 | FSLR. https://www.macrotrends.net/stocks/charts/FSLR/first-solar/profit-margins#

50. U.S. Geological Survey (2020). Mineral Commodity Summaries. Silicon. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-silicon.pdf.

51. Clean Energy Association (2021). Estimated Polysilicon Production per Year, Distributed by Region of Production. https://www.cea3.com/cea-blog/global-polysilicon-capacity-outside-xinjiang-smip.

52. Taiyang News (2022). Polysilicon Prices To Fall 'Steeply' By 2023-Start, Rethink Energy Expects Global Polysilicon 'Overcapacity' in Coming Decade. https://taiyangnews.info/business/polysilicon-prices-to-fall-steeply-by-2023-start/.

53. SEMI (2023). Silicon Shipment Statistics. https://www.semi.org/en/products-services/market-data/materials/si-shipment-statistics.

54. Globenewswire.com (2022). Metallurgical Grade Silicon Market Growth to Come from Bundled Application Clusters, Opines. Fact.mr. https://www.globenewswire.com/en/news-release/2022/08/25/2504923/0/en/Metallurgical-Grade-Silicon-Market-Growth-to-Come-from-Bundled-Application-Clusters-Opines-Fact-MR.html.

55. Hallam, B., Kim, M., Underwood, R., Drury, S., Wang, L., Dias, P., and Polysilicon, A. (2022). A Polysilicon Learning Curve and the Material Requirements for Broad Electrification with Photovoltaics by 2050. Sol. RRL *6*, 2200458.

56. U.S. Geological Survey (2022). Mineral Commodity Summaries – Iron Ore. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-ore.pdf.

57. Global Cement and Concrete Association (2023). Cement and Concrete Around the World. https://gccassociation.org/concretefuture/cement-concrete-around-the-world/.

58. Royal Society of Chemistry. Periodic Table (Iron Press). https://www.rsc.org/periodic-table/element/26/iron#.

59. Koutamanis, A., van Reijn, B., and van Bueren, E. (2018). Urban mining and buildings: "A review of possibilities and limitations". Resour. Conserv. Recy. *138*, 32–39.

60. International Copper Association (2018). Copper Environmental Profile. https://copperalliance.org/wp-content/uploads/2021/08/ICA-EnvironmentalProfileHESD-201803-FINAL-LOWRES-1.pdf.

61. Child, M., Kemfert, C., Bogdanov, D., and Breyer, C. (2019). Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew. Energy *139*, 80–101.

62. Li, L., Liu, G., Pan, D., Wang, W., Wu, Y., and Zuo, T. (2017). Overview of the recycling technology for copper-containing cables. Resour. Conserv. Recy. *126*, 132–140.

63. Automatic assembly of PV installations is currently developed, one example is the company Terabase. https://www.terabase.energy/products-services/construction.

64. Anastas, P.T., and Zimmermann, J.B. (2003). Through the 12 Principles GREEN Engineering. Environ. Sci. Technol. 95–101. https://pubs.acs.org/doi/pdf/10.1021/es032373g.

65. Sun, S., Hartono, N.T.P., Ren, Z.D., Oviedo, F., Buscemi, A.M., Layurova, M., Chen, D.X., Ogunfunmi, T., Thapa, J., Ramasamy, S., et al. (2019). Accelerated Development of Perovskite-Inspired Materials via High-Throughput Synthesis and Machine-Learning Diagnosis. Joule *3*, 1437–1451.

66. Zhao, Y., Zhang, J., Xu, Z., Sun, S., Langner, S., Hartono, N.T., Heumueller, T., Hou, Y., Elia, J., Li, N., and Matt, G.J. (2017). Discovery of temperature-induced stability reversal in perovskites using high-throughput robotic learning. Nat Commun *12*, 2191. https://doi.org/10.1038/s41467-021-22472-x.

67. D'Adamo, I., Miliacca, M., and Rosa, P. (2017). Economic Feasibility for Recycling of Waste Crystalline Silicon Photovoltaic Modules. Int. J. Photoenergy *2017*, 1–6.

68. Spaes, J. (2020). More than 5,000 tons of modules collected for recycling in France, PV Magazine. https://www.pv-magazine.com/2020/02/04/more-than-5000-tons-of-modules-collected-for-recycling-in-france/.