

An Examination of Solar Waste Utilization and Reuse

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ABSTRACT:

Solar energy is widely regarded as a clean, green, and renewable power source. While energy generation from sunlight is inherently renewable, the production and disposal of solar panels introduce sustainability challenges comparable to those of other manufacturing industries. Photovoltaic (PV) panels typically have a lifespan of 25-30 years, after which they enter the end-of-life (EoL) phase and contribute to an increasing volume of waste that is frequently landfilled or otherwise insufficiently managed. This paper examines current and emerging strategies for the reuse, recycling, and repurposing of solar panel waste. Viable approaches include repurposing certain materials for battery applications and reprocessing p-type silicon from decommissioned cells into new ingots as well as recycling aluminum frames and glass using established and cost-effective methods. However, not all materials are equally recyclable. For example, perovskite-doped silicon- an emerging technology that enhances PV efficiency- poses significant environmental and technical challenges due to the presence of toxic lead and the current lack of scalable recycling solutions. By analyzing different PV technologies and their associated waste streams, this study highlights both the opportunities and limitations of existing recovery methods. The findings underscore the need for improved recycling infrastructure, material innovation, and sustainable design practices to mitigate the long-term environmental impact of solar energy systems.

Keywords: End of life, PV, silicon recycling, solar panel waste

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I. Introduction

Solar power adoption has expanded steadily worldwide, driven by its reputation as a clean, green, and renewable energy source. However, comparatively less attention has been paid to the growing challenge of end-of-life solar panel waste, which may pose significant environmental risks depending on the materials used in their

manufacture [1-11]. Despite these concerns, solar energy continues to enjoy substantially higher public approval than nuclear, coal, or oil-based power generation. As far as expense goes, many solar investments pay themselves off in a few years and can achieve net-zero carbon emissions if left operating long enough. Solar panels can be efficiently placed in residential and industrial areas.

Popular installation locations include commercial and domestic building roofs, parking garages, and even vehicles. This local power generation results in electricity that is easily accessible and reduces reliance on long transmission lines, thereby minimizing transmission losses.

Solar power is also generated in large solar farms located far from major load centers. One example is the Elektron Solar Project in Tooele, Utah, which supplies approximately 92% of the electricity required by Utah Valley University. This relatively large installation produces about 80 MW across 550 acres [9]. While such projects benefit from abundant space and lower land costs, they require transmission infrastructure to deliver electricity to distant consumers. In many cases, these solar facilities are sited in remote, high-resource areas, which can necessitate transmission lines that can be comparable in length and cost to those used in conventional centralized power systems. Although modern grid technologies and the modern smart grids can improve efficiency and integration, transmission losses and infrastructure costs remain persistent challenges for power delivery regardless of the generation source.

As more companies and countries incentivize the use of solar, more solar panels are created and eventually discarded. The lifespan of an average solar panel is 25-30 years [4]. Studies have predicted that 1.7-8 million tons of solar waste will be generated by 2030 and 60-78 million tons is expected to be produced by 2050 [6]. As a benchmark for that number, the United States' total municipal solid waste (MSW) was 292.4 million tons in 2018 [7]. The amount of solar waste will continue to rise as more consumers begin using solar power and older panels are phased out.

As the current state stands, the vast majority of the defunct solar material will be placed in landfills and not reused. The United States alone is expected to have over 10 million tons of defunct solar panels abandoned or in landfills by 2050. This is the second largest number of end-of-life solar panels in the world [7]. The predicted demand for solar panels is expected to grow beyond simple rate of replacement. Specifically, demand for monocrystalline silicon (generally n-type [3]) and polycrystalline silicon [1] will continue to rise.



Figure 1: A solar panel with cells made from silicon [11].

Monocrystalline silicon is very difficult to source or create because it is made of a single continuous molecule of silicon. This molecular structure is highly uniform when used in thin sheets to form

solar panels. However, the uniform nature of silicon also makes it difficult to source, produce, and replace. If the material for building photovoltaic panels continues to be used without reuse,

eventually the well of available materials will run dry. While significant attention has been devoted to the deployment and maintenance of solar panels, comparatively less focus has been placed on end-of-life considerations. A less frequently addressed question is what happens to solar panels once they degrade or lose efficiency over time. Solar energy has a reputation for being clean and renewable. To maintain that reputation, many solutions will need to be found for reducing or recycling the materials used in the PV process.

II. Definitions

Before discussing solutions for repurposing, reuse, and recycling of photovoltaic (PV) materials at end-of-life (EoL), several key terms must be defined.

The EoL is a common acronym used to describe when a material or piece of equipment is no longer able to be used in its original capacity. After a material or equipment reaches these points in its lifecycle, it is retired. Solar panels, once they reach EoL, become solar waste. Solar Waste is defined in law as “end-of-life solar PV modules, panels, or cells

discarded from use or manufacturing” [8]. More specifically, solar waste can generally be broken up into three categories: semiconductors, framing, and batteries. The many variations of semiconductors used are the most valuable resource that is currently going largely unused [10], while the glass and aluminum supports are the largest by weight and volume [11].

III. Types of Solar Panels Produced

There are numerous variations of solar panels currently available on the market, each distinguished by material composition and structural characteristics. The key ingredient in most solar panels is a semiconductive metalloid called silicon. There are three molecular form of silicon that are useful for the creation of solar panels: monocrystalline, polycrystalline, and amorphous. Solar cells are most often made from monocrystalline silicon (mono-Si) and multi-crystalline silicon (multi-Si). However, amorphous silicon is currently being researched for its use in thin-film technology [1].

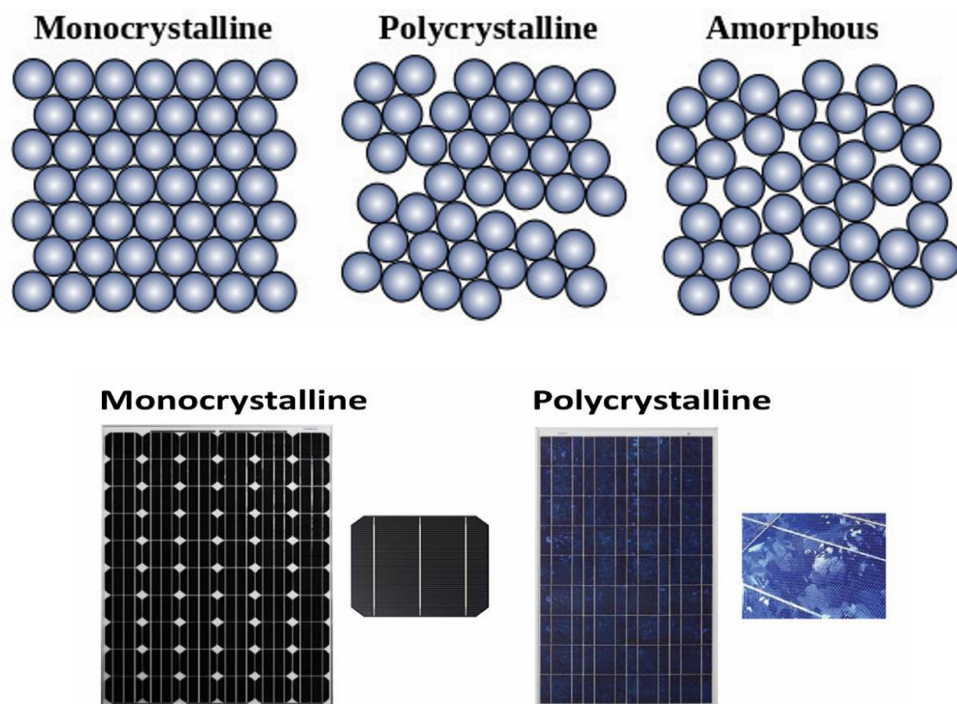


Figure 2: A representative image of three useful Silicon arrangements and the physical difference that is prominent to the naked eye [1].

Beyond the crystalline arrangement of silicon molecules, the impurities introduced into the silicon plays a critical role in determining its electrical

properties. Silicon wafers are commonly doped with boron or phosphorus to produce p-type or n-type material, respectively, and these tailored properties

are what make silicon an effective semiconductor. In some emerging designs, silicon is paired with perovskite-based materials to enhance performance [3, 5], although research in this area is still ongoing. Another advanced configuration includes n-type heterojunction (HJT) cells [3], which are not the focus of this paper. Importantly, each type of doped silicon used in solar panels presents distinct advantages and challenges, particularly with respect to reusing and recycling.

IV. Repurposed Uses of Retired Solar Panel Materials

A. Creation of New Si Ingots

While solar panels degrade overtime, the silicon that makes up the solar cells maintains its properties as a semiconductor. Old slices of silicon can be ground up and reused to grow new silicon ingots composed of a single, pure silicon molecule. This process is known as re-seeding. Figure 3 shows a picture of an

ingot of silicon that has been sliced extremely thin. Silicon ingots are ideally made of a single monocrystal of silicon that is uniform throughout the entire block. Doped silicon is ideally consistently doped throughout the whole ingot, leading to symmetry in every slice. Because of the monocrystalline structure, dopants must be incredibly controlled during their incorporation. The value of a monocrystal is the uniformity it provides. If a defect is shown on a slice, it is not viable for use. This leads to solar waste during manufacturing that may or may not be reused. One of the drawbacks of the uniformity within an ingot of silicon is the difficulty to find replacement wafers. In a monocrystalline board, every wafer is identical to every other wafer. This property results in higher efficiency. If a solar panel is damaged, the wafer will be replaced with an undamaged wafer from a different ingot. If both ingots are not exactly similar, the efficiency will decrease.



Figure 3: A silicon ingot with thin silicon wafer sliced off.

A research group in the Netherlands recently published findings on the recycling of end-of-life silicon wafers for reuse in new solar panels [3]. The study showed that three distinct types of silicon can be effectively recovered from retired solar cells. As the lead author explained: “This scheme would result in three material flows... n-type doped cells, p-type boron-doped cells, and a flow of monocrystalline PERC cells that could be either boron-doped or gallium-doped” [3]. These silicon streams can be recycled separately but must not be mixed, as combining incompatible dopant types

degrades their electrical performance. In p-type silicon, boron doping creates electron “holes” that facilitate charge transport, while in n-type silicon, dopants such as phosphorus or arsenic introduce free electrons that enable conductivity. However, if silicon contains comparable concentrations of both boron and phosphorus, the dopants can electrically compensate for one another, effectively canceling out their semiconducting behavior [18]. As a result, the material loses the functional advantages of doping and becomes significantly less useful for photovoltaic applications.

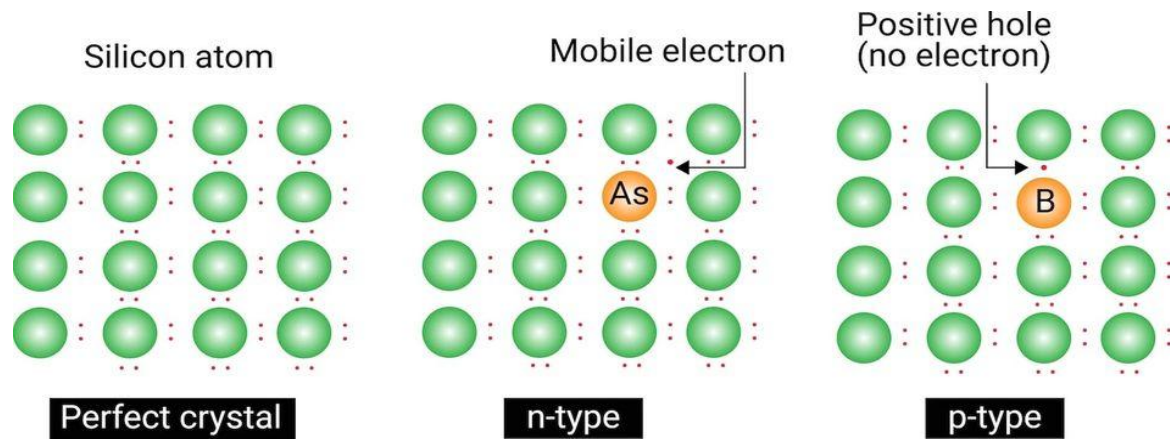


Figure 4: An example of chemical different between P-type and N-type silicon [12].

To avoid mixing dopants, the researcher group is developing a new methodology of sorting and classifying doped silicon recovered from EoL PV. One of the notable discovery was that, if the solar cell was polycrystalline, it will always be made from p-type Boron-doped silicon. However, it anticipated that large amounts of p-type silicon can be recovered from former panels and reused [3]. One of the limitations of the ingot recycling method is the required harsh divide between p-type and n-type silicon. Many solar companies do not label their panels by dopant. As such, any material recycling must be preceded by lab testing to discover the type of dopant.

In order to facilitate effective reuse, the researchers are developing a secondary objective: a new methodology of sorting and classifying doped silicon. As a result of doping, p-type material is incredibly difficult to recycle into new n-type material or vice-versa. Even other types of p-type cannot be combined. For example, boron-doped silicon and gallium-doped silicon cannot be mixed together into new, effective p-type silicon. The chemical properties of the two elements, although similar due to a shared column of the periodic table, are not similar enough to mix in new ingots. Mixing two different kinds of p-type doped silicon is undesirable. Mixing a p-type and n-type silicon is eminently worse. When mixed, the properties of n-type and p-type silicon cancel out the desired special effect of the other, thus rendering an unusable product.

Another limitation of the proposed recycling approach is the distribution of available doped silicon types. A large proportion of currently

decommissioned solar panels are based on p-type silicon, typically split between boron- and gallium-doped variants. Consequently, existing recycling methods predominantly recover p-type material [3]. In contrast, most newly manufactured solar panels are shifting toward n-type doped silicon, which is in significantly higher market demand. This mismatch between recovered material and industry demand reduces the immediate economic viability of large-scale recycling under current conditions. However, given the ongoing evolution of photovoltaic technologies, recovered p-type silicon may become more valuable in future applications as material requirements and cell architecture continue to change.

B. Reuse of Recycled Silicon in Battery Storage Systems

Lithium-ion batteries are widely used for storing excess solar energy, helping to address one of the key limitations of photovoltaic systems: their intermittency. Because solar panels only generate electricity when sunlight is available, they cannot produce power during nighttime or periods of poor weather and shading. Energy storage systems such as batteries represent a solution by capturing surplus electricity during peak solar generation and releasing it when needed. In addition to improving reliability, battery integration can enhance the overall output and economic value of solar farms. However, batteries remain one of the most expensive components of solar energy systems. If they could be partially constructed using recycled materials, such as waste silicon from end-of-life solar panels, the overall cost and resource demand of energy storage could be significantly reduced.

In 2025, a study conducted at the University of Virginia investigated the potential use of recycled silicon wafers from decommissioned solar cells in battery applications [2]. In this work, polycrystalline silicon wafers were treated using laser ablation to increase their surface area. The objective was to evaluate their performance as electrode materials in lithium-ion batteries, potentially eliminating the need for some costly conventional electrode components. The preliminary results demonstrated that laser ablation significantly enhanced the surface area of the silicon wafers, particularly when applied to one or both sides of the material. Electron microscopy images (Figure 5) confirmed the development of a more textured surface morphology. This increased surface area was associated with improved electrochemical

performance, including higher capacity retention and enhanced rate capability, especially under high current density conditions.

The laser-ablation method resulted in improved electrochemical properties, especially when linked with all-active material LiCoO₂ cathodes. The research is still ongoing on the best use of the ablated wafer; this study proves that solar waste can be reused in adjacent fields. Using new silicon wafers as anodes for a rechargeable battery application would be a costly endeavor. The reuse of wafers from alternative sources, such as PV panels that have reached their EoL, would significantly decrease the cost of the anodes. Because silicon is so costly to refine, recycling the material is a positive move for efficiency.

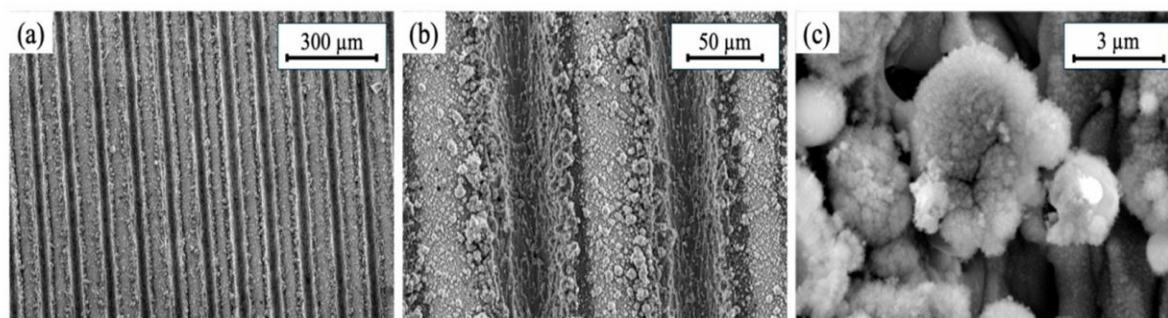


Figure 5: Electron microscopy images for a laser-ablated Si electrode at relatively variable magnifications.

Research at the University of Virginia has contributed to the emergence of solar recycling companies [17]. One example is “We Recycle Solar,” which processes end-of-life solar panels by recovering and recycling components for reuse in new panels. The company provides limited technical details, but the process likely involves separating silicon, identifying dopants, and refining the material for reuse. It has also expressed interest in incorporating recycled silicon into lithium-ion batteries, suggesting potential economic value in this recycling pathway. Early indications suggest that recycled silicon does not significantly reduce battery storage performance.

V. Repurposing Frames and Mounts of Retired Solar Panel Materials

Silicon is an important component of any PV module, but it is not the only one. Figure 6 shows

the multiple layers that exist on any given photovoltaic module.

A solar panel is composed of many layers, of which silicon slices only account for one. As shown in Figure 6, some of the other materials endemic to a panel are glass and framing, typically made of aluminum. Glass as a substance is very easy to reuse or recycle. The old or broken material can easily be crushed and remelted to form new glass panes. Recycling is a much cheaper alternative to the fabrication of new glass. By reusing the material, profit margins increase. Aluminum is a material that conventional recycling facilities are already well equipped to process. The aluminum frames and mounting structures used in PV modules can be efficiently recycled at relatively low cost using established commercial methods [4]. Although these components represent a substantial portion of discarded solar panel mass, they are among the

easiest to recover and resell as scrap. In fact, prioritizing the recovery and recycling of just aluminum and glass from PV modules could divert approximately 90% of solar panel waste by weight from landfills [13].

The framing and casing of solar cells are often neglected when discussing solar waste. When discussing theory and only interacting with the material through images, it is easy to over-focus on the silicon based components. Many images of solar

panels show the product head on—focusing on a black rectangle with lines. It is often overlooked that solar panels are three-dimensional systems requiring structural support and mounting infrastructure that require framing and mounting. In order to facilitate this shift in thinking, a picture of a solar panel taken from a non-traditional angle is shown below in Figure 7. The picture shows a mounted solar array supported by an aluminum frame and mounted on small cinderblocks.

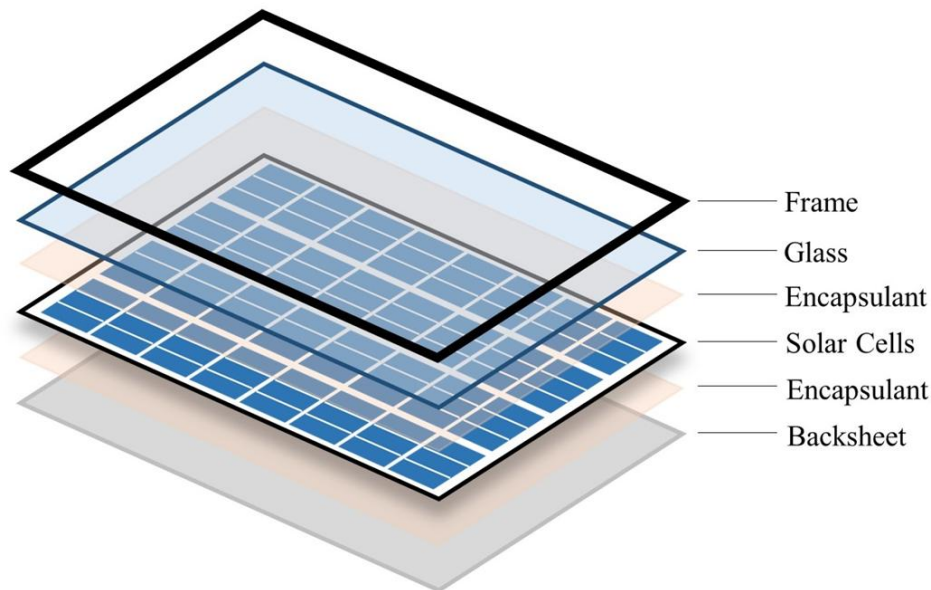


Figure 6: A graphical representation of multiple key components in a solar panel beyond silicon [4].



Figure 7: A mounted solar array. The aluminum grid and bars that secure the PV module are prominent [14].

Most solar panels are mounted to prevent water from collecting and damaging components, even in regions with low rainfall. Mounting structures also help address uneven terrain, ensuring panels remain securely positioned. In large installations, such as the Elektron Solar Project [9], every panel is supported by frames that allow for tilting or sun-tracking while protecting sensitive components from environmental exposure. The widespread use of mounting systems means that significant amounts of aluminum are incorporated into PV installations. Because aluminum is a finite resource, its recovery and reuse are both economically and environmentally important. A team of engineering students from the University of Mauritius developed a prototype system to separate glass and aluminum from end-of-life solar panels [4]. Their mechanical approach crushes the panel so that the glass fractures while the aluminum deforms, enabling effective separation. This design addresses a growing recycling challenge and shows promise for scalable application in dedicated PV recycling facilities. While recovering silicon often receives the most attention, focusing solely on high-value

materials usually overlook a substantial portion of solar waste. Aluminum constitutes a large share of discarded PV components and is already widely recyclable across multiple industries. Effective solar waste management should therefore consider practical, high-impact recovery pathways alongside more advanced material reclamation approaches.

VI. Future Development in Reuse of Solar Waste

Some solar waste materials currently have limited or no viable pathways for reuse. Perovskite, for example, has been studied since 2009 as a potential alternative to silicon in photovoltaic cells, yet practical methods for its recycling or reuse have not been established. Unlike silicon, which is a relatively pure element modified through controlled doping, perovskites consist of multiple elements arranged in a specific crystalline structure. One of the most common compositions is methylammonium lead triiodide (MAPbI₃), which includes carbon, nitrogen, hydrogen, lead, and iodine organized in a precise molecular configuration [15]. Figure 8 illustrates the structure of MAPbI₃.

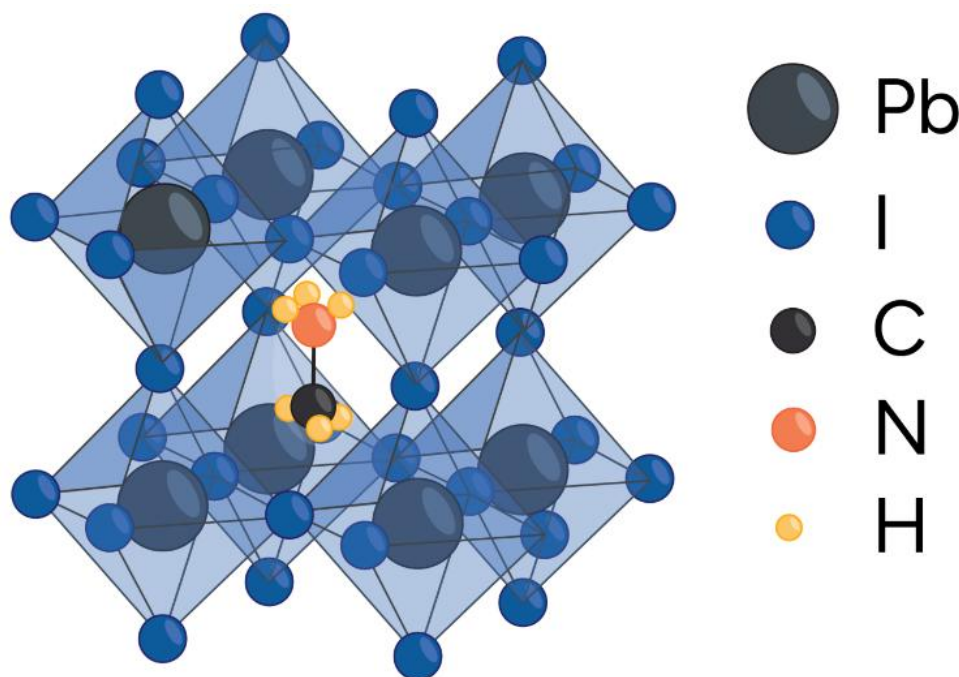


Figure 8: Chemical composition of methylammonium lead triiodide (MAPbI₃), a widely studied perovskite material [15].

Perovskite is the name of a family of materials that may be part of the next generation of solar power development. Perovskite has a higher efficiency rating along with a lower expense than the

traditional boron or gallium doped silicon [15]. Perovskite materials are also more tolerant of defects than monocrystalline silicon. Individual regions do not need to be perfectly uniform for a

photovoltaic panel to maintain high efficiency. In fact, perovskite cells do not need to be made from slices or segments. PV perovskite cells can be printed on backing material with a similar process as a common laser printer used at your home or work. Figure 9 shows a fully usable printed perovskite solar cell.

Perovskite-doped silicon solar panels are expected to enter the commercial market in the coming years after extensive development. While their performance and fabrication have been widely studied, end-of-life management has received far less attention. At present, there are no well-established methods for safely recycling or disposing of perovskite-based materials. This is

particularly concerning because their degradation can release lead, a component of their chemical structure (see Figure 8). Lead is a potent neurotoxin and poses serious health risks to humans and other mammals, underscoring the need for dedicated disposal and recycling strategies. Lead release from photovoltaic cells typically occurs as the materials degrade near the end of their service life. Consequently, regions that adopt perovskite solar technologies may not experience the impacts of lead leaching into surrounding soil and waste streams until approximately 20-30 years after installation. However, as demonstrated by the Flint water crisis [16], lead can pose serious environmental and public health risks when it is not properly contained.

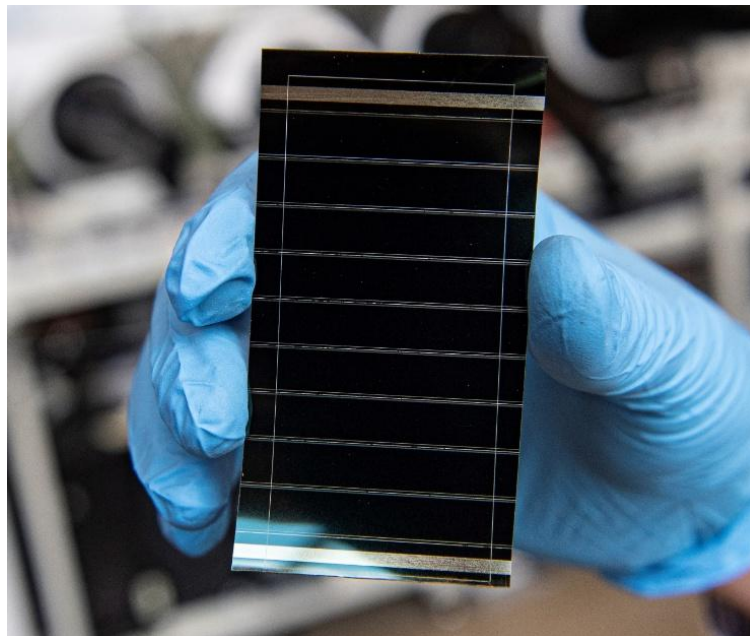


Figure 9: A printed perovskite solar module [17].

Perovskite solar cells are a more controversial form of photovoltaic technology, as they cannot be considered entirely clean or green, even if they may achieve carbon neutrality. Addressing lead leakage during manufacturing and operation is important, but the release of lead at end-of-life presents an even greater challenge for storage and decommissioning. Despite these concerns, research and development of perovskite technologies are unlikely to slow, given their high efficiency and potential for lower production costs. This makes it essential for engineers to evaluate the full lifecycle impacts and associated risks. Like any material, perovskites offer both advantages and drawbacks: while they can improve performance, their composition includes

lead, a potent neurotoxin that may contaminate groundwater and surrounding environments. As such, perovskites represent both a promising advancement and a significant challenge for the future of photovoltaic technology and sustainable energy systems.

VII. Conclusion

waste materials

Solar power is widely regarded as a clean and renewable energy source and enjoys strong public support. However, while sunlight itself is inherently renewable, the full lifecycle sustainability of solar

energy systems depends on what happens after photovoltaic (PV) panels reach the end of their operational life. Solar panels typically have a lifespan of 25-30 years, after which they are often discarded into landfills or left as unmanaged waste. This growing stream of end-of-life (EoL) solar waste highlights a critical gap between renewable energy generation and sustainable material recovery. This paper examined the types of solar panels currently in use and explored how materials and by-products from decommissioned panels can be reused, recycled, or repurposed. Viable pathways include the recycling of aluminum frames and glass, the recovery and reprocessing of p-type silicon into new ingots, and potential reuse of certain materials in energy storage applications such as batteries. However, the analysis also shows that not all PV technologies are equally amenable to recycling. Emerging materials such as perovskite-doped silicon present additional environmental and

technical challenges, particularly due to toxic lead content and the lack of scalable recycling solutions. Similarly, variations in dopant compositions across manufacturers such as differences in p-type boron-doped silicon as well as other technologies like N-type heterojunction (HJT) cells introduce further complexity that was not fully addressed in this study.

Future research should focus on deeper investigation of doped silicon variations across manufacturers, improved classification of different PV technologies, and expanded exploration of material recovery techniques. Further study is needed to develop scalable recycling processes for advanced solar cell materials and to integrate end-of-life considerations more directly into PV design. Addressing these challenges will be essential to ensuring that the growth of solar energy remains aligned with long-term environmental sustainability goals.

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