The State of Solar Panel Recycling:
Processes and Legislation

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Nicholas Langer

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor

Joshua Earle, Department of Engineering and Society

Introduction

With the climate crisis worsening every day, the adoption of renewable energy shines like a beacon of hope amid the continued use of fossil fuels. Solar energy is one of the fastest growing sectors of renewable energy with a growth rate of 35%-40% per year; in fact, the global power produced by solar in 2019 was six times larger than that of 2012 (Seo et al., 2021). Millions of solar panels have been purchased all while little or no attention is paid to where they end up once they reach their End of Life (EoL). Photovoltaic (PV) solar panels have an estimated lifespan of approximately thirty years, which means the first generations of solar panels are now retiring and the majority end up in landfills.

My goal with this paper is to answer one question: *Why is solar panel recycling ignored by manufacturers and governments?* This paper uses a life-cycle analysis to examine each stage within the life of a solar panel and unearth the unsustainable practices in the background of the solar sector. I also look at existing recycling techniques and why they are currently unviable from a technical standpoint as well as monetary. Finally, I scrutinize existing regulation – or lack thereof – in major solar energy producing nations including Germany and the European Union, India, China, and the United States. Special attention is paid to SolarCycle, an American solar recycling company.

Life-Cycle Analysis

Material Acquisition

The life-cycle of a PV module begins with workers who mine raw materials including silicon, silver, aluminum, and copper. To be used in solar panel production, silicon metal is turned into polysilicon; 45% of the world’s polysilicon is produced in factories in the Chinese region of Xinjiang (Hoffs, 2022). It is worth noting that the high temperatures required for polysilicon production are reached through burning coal. Furthermore, it has been reported “that some Xinjiang polysilicon plants have employed forced labor of Uyghurs, an intensely persecuted Muslim ethnic minority” (Hoffs, 2022).

Other crucial components of PV cells have similar issues with their production. Currently, the solar sector uses ten percent of the world’s silver; if current trends persist, it is estimated that by 2050, more than 50% of the world’s supply of silver could be used in solar panel production (Hoffs, 2022). Current silver mining practices have been shown to cause heavy metal contamination in communities surrounding their operation.

Similarly, mining aluminum and copper are land-intensive processes that often harm and displace indigenous and poor communities such as in Australia and Guinea, where 28% and 22% of raw aluminum is produced respectively (Hoffs, 2022). According to the Institute for Human Rights and Business, 47% “of the top 300 undeveloped copper orebodies globally… are located on, or in close proximity to, Indigenous Peoples’ lands” (Fairbairn, 2022) and 65% are located in protected biodiversity conservation areas. Continuing to mine copper and aluminum in a business-as-usual scenario can only result in harming Indigenous communities and important ecosystems.

Production

Photovoltaic systems emit no greenhouse gasses after production, which makes solar energy a great alternative to burning fossil fuels, but the processes needed to create PV panels can be energy intensive. The high temperatures needed to melt silicon for polycrystalline panels are achieved with coal-burning furnaces. Overall, studies show that the energy payback time –

defined as the time required for the panel to produce the energy it took to create the panel – ranges between six months and two years depending on the type of solar panel in use (de Wild-Scholten, 2013). The expected lifetime of 20-30 years is much longer than this energy payback time, so the decades of green energy production largely outweigh the use of fossil fuels. Ideally, as more PV panels are produced, fossil fuel use in their production can be scaled down and replaced with green energy. Similarly, the carbon footprint of energy produced by PV cells, 20-81 g CO_2-eq/kWh, is far preferable over the carbon footprints of coal, oil, and natural gas, 1079, 885, and 642g CO_2-eq/kWh. In addition to an energy-intensive production process, dangerous materials like sulfuric acid, phosphene gas, and lead are used in manufacturing making factory floors hazardous (Bhandari & Lim, 2018).

Use

Solar cells emit no greenhouse gasses once they are produced, transported, and installed, but solar farms require massive flat areas for their panel arrays. Finding the land for solar farms is often a difficult process without encroaching on indigenous peoples' land. This is nothing new, as coal plants "have supported – and polluted – the Navajo Nation since the early 1960s (Barringer, 2021). Native American tribes like the Navajo have seen their land mined for coal and uranium and could now lose more land to solar.

End of Life

End of life (EoL) disposal of PV panels is the ticking time bomb lurking in the background of the solar industry. The crystalline silicon PV cells rely on have an expected life span of about thirty years; models suggest that 8 million metric tons (t) of PV waste will accumulate by 2030, 80 million t by 2050 (Peplow, 2022). Disposing of solar panels is not particularly easy either. Since the United States has no specific regulations for PV panel disposal, where they ought to end up is left ambiguous. In fact, two solar panels from the same manufacturer, and even the same model, may be classified differently as to whether they are hazardous waste (US EPA, 2021). It is left up to individual homeowners to determine if their panels meet the toxicity requirements for hazardous waste. According to a report from the National Renewable Energy Laboratory, less than 10% of PV modules are being recycled in the United States; instead, the modules are either disposed of in landfills or stored in warehouses until recycling or other management becomes more viable (Curtis et al., 2021).

Without any specific rules to follow regarding recycling, and since recycling is not considered profitable, hazardous and rare materials are sent to landfills where they can wreak havoc on ecosystems. PV cells can contain dangerous levels of heavy metals like cadmium and lead; a broken cell could leach these harmful metals into the surrounding environment, poisoning the water (Peplow, 2022).

Recycling Techniques

Techniques and Associated Difficulties

Recycling solar panels is particularly difficult due to their composition. PV panels contain several complex polymers, metals, and silicon crystals that are heavily integrated. The recycling process typically consists of “collection, transport, dismantling, incineration, separation of non-compositional materials, and refinement of such materials” (Majewski et al., 2021). Currently, there exist both mechanical and chemical methods of separating materials to be scrapped and/or recycled. Mechanical processes include stripping down the frame and physically dismantling much of the internal electronics.

Unfortunately, the vast majority of recyclers today stop after recovering the aluminum frame, glass cover, and copper wiring (Tao et al., 2020). These materials are the easiest to recover and together account for more than 80% of a panels mass, while only making up about 30% of the panel's value (Peplow, 2022). Current recycling quotas – in countries that have them – are based on mass, which means that recyclers can strip away heavy materials without actually recycling the expensive silver wiring and silicon crystals. These rare, toxic materials left over are disposed of, which does nothing to circumvent adverse effects to the environment, and little value is regained through these methods.

Recycling solar panels further than stripping of aluminum, glass, and copper becomes expensive very quickly. After workers strip the aluminum and glass frame from the solar panel, the result is then crushed into fine particles of low purity that are treated using a combination of several methods that separate elements based on their size, shape, conductivity, and other properties(Papamichael et al., 2022). In order to extract more value from the left-over silicon, silver, and other materials, they must be purified. For example, low purity silicon (ferro-silicon) can be acquired fairly easily and is the primary form in which silicon is salvaged. The value of ferro-silicon, with a purity of >75%, is $0.45/kg; metallurgic silicon, with a purity of 99%, is worth $1.50/kg; and solar-grade silicon, with a purity of 99.9999%, is worth $5.52/kg (Tao et al., 2020). Collecting silicon in higher purities could extract more value during recycling; however, the processes required for collecting metallurgic or solar-grade silicon are energy intensive and expensive.

Other processes like high-voltage crushing, which can separate metals, and pyrolysis, which can optimize the breakdown of polymers could be utilized as well (Papamichael et al., 2022). These methods would use different alkali or acidic solutions to target and dissolve the different components in PV cells. Certain organic solutions have also been found to break down the polymers covering the silicon crystal, making it easier to isolate and recycle (Papamichael et al., 2022). Unfortunately, chemical processes used to break down polymers can also produce hazardous waste as a product of the reactions involved (Peplow, 2022). More research is needed into making these processes cheap, efficient, and safe so that solar panel manufacturers will be more likely to implement them.

Problems with Profitability

The best way to ensure that EoL solar panels are recycled is to make the recycling process is profitable. When recyclers only recover the aluminum frame, glass, and copper wire, they recover a value of about $3/panel; meanwhile, the processes cost upwards of $25/panel. More intensive recovery processes can be used to recover $10-$18.14/panel, but these processes will cost even more (Tao et al., 2020). Clearly, PV recycling cannot sustain itself independently with the processes available today. Granata et al. conduct a profitability simulation of PV recycling with various recycling outputs and silver concentrations in the panels. The amount silver concentration was chosen as a variable in the study because recent trends in solar panel manufacturing have shown a decrease in silver use. They found that profitability is highly dependent on how early the United States invests in recycling capability (Granata et al., 2022). Higher recycling volumes and higher concentrations of silver also make profitability more attainable. In simulations where the US began investing later than 2025, higher recycling volumes were needed to achieve the same profit as scenarios where the US started investing earlier (Granata et al., 2022).

Early investment is clearly important, but the recycling processes cannot be self-sustaining at current rates. Some researchers have noted that PV fees – a price per ton of photovoltaic material to be recycled – could be necessary features of the recycling system in certain scenarios (Granata et al., 2022). Researchers Granata et al. found that profitability was only possible at high recycling volumes of 30,000 tons/year with a $150/ton PV fee based on US investment in 2025. A later investment than 2025 will necessitate higher PV fees to keep the process running (Granata et al., 2022).

An important step in creating a circular economy for PV systems is establishing the infrastructure required for each step of the recycling process. The infrastructure should be established as soon as possible in order to have a good chance of controlling solar panel waste.

Regulation

Germany and the European Union

Germany generated almost 40 Gigawatts of power from solar panels in 2015, when they were overtaken by China as the largest PV market. That energy was collected by 1.5 million PV power plants across the country and accounted for 6 percent of the nation’s consumption. By 2050, Germany is predicted to accumulate between 4.3 and 4.4 million tons of PV waste (Weckend et al., 2016). Germany adopted the EU regulations regarding electronic waste (e-waste) known as the Waste Electrical and Electronic Waste Directives (WEEE) in 2014. WEEE introduced the concept of extended producer responsibility, which requires that solar panel manufacturers fund their product's recycling at its end of life and that at least 80% of the materials used are recycled (Ferrell, 2022). This legislation has been largely successful at reducing the number of solar cells that end up in landfills and sparking innovation in recycling. An EU-funded company, PV cycle, reported that they were able to recycle nearly 95% of PV contents (Ferrell, 2022). Pressure from European Union nations' governments to recycle End-of-Life solar panels resulted in solar manufacturers investing in their processes and researching their optimization. WEEE should be looked at as a model for the most successful solar waste recycling legislation in place.

India

India has made a huge surge ahead in the installation of PV panels in recent years making it into the top ten producers of solar energy. In 2012, 1 Gigawatt of solar power was installed. By 2019, this number reached 85.9 Gigawatts. In 2022, the Indian government surpassed its goal of installing 100 Gigawatts of solar power capacity ahead of schedule (Rathore & Panwar, 2022). India does not have any specific rules regarding the disposal of solar panels. Solar panel distributers are required to follow the WEEE regulations regarding management and handling of e-waste, but India does not have the infrastructure to support large-scale recycling (Rathore & Panwar, 2022). Currently, India is expected to produce upwards of 200,000 tons of photovoltaic waste by 2030 and has the capacity to recycle about 0.4 tons per year (Rathore & Panwar, 2022). Because of the lack of infrastructure and despite the WEEE regulations India has adopted, only 4 percent of e-waste was recycled between 2015 and 2017 (Suresh et al., 2019).

China

China is the largest market for PV solar panels and also the largest manufacturer of them. The largest solar farm in the world is located in the Qinghai province and is made up of four million solar panels stretching across twenty-seven square kilometers (Bhandari & Lim, 2018). China has pushed solar energy emphatically as it attempts to decrease dangerous air pollution that has become common in large cities. It is predicted that by 2050, China will have between 13 and 20 million tons of solar waste; however, unlike EU countries, China has no policy comparable to WEEE (Majewski et al., 2021). Manufacturers are not responsible for funding collection or recycling of their products and though some companies have spoken about sustainability and recycling initiatives, there is no incentive to follow through or dedicate resources as they are all acting within the established guidelines – none (Bhandari & Lim, 2018).

In early 2022, the "first pilot project for recycling polycrystalline silicon – a key material in solar cells"("New Policy Grapples," 2022) was opened in China. The plant is able to recover silicon from retired solar panels at a lower purity. The recovered silicon is not pure enough to be made into more solar cells, but the plant hopes to utilize cross-sector collaboration so that the reclaimed silicon may be used in making other silicon alloys ("New Policy Grapples," 2022). The same year also saw China pass a new policy that outlines a plan to reuse retired solar panels and turbines, their first response to the growing waste problem. While certainly steps in the right direction, these steps alone are not nearly enough. The silicon recycling plant that opened has a capacity to process 10 MW of solar material each year compared to the 53,000 MW installed in 2021 alone ("New Policy Grapples," 2022). Clearly, China needs to invest more in their recycling infrastructure to increase their capacity, but using reclaimed silicon in other sectors that do not have the purity standards of solar panels is exactly the type of reuse that is needed in other countries.

United States

Currently there is very little legislation regarding solar panel disposal in the United States. In fact, the federal government has no specific regulations that cover solar panel waste. These recycling laws are left up to states, the majority of which have not implemented any laws, leaving proper disposal up to the consumer. Two companies in particular, SolarCycle and First Solar, have started a policy of product recovery once solar panels reach their EoL, but this policy is not widespread.

Washington State has stood out from the rest of the country in that it does have specific regulations for solar panel recovery. A new law now requires that solar panel manufacturers fund the recovery and processing of EoL PV cells; this law will not go into effect until 2025 however. California is attempting progress by changing the classification of solar waste from hazardous waste to universal waste. Universal waste is a subset of the hazardous waste classification that has less stringent rules regarding storage and transportation, yet bears the same penalties for violations (Berger, 2021). The idea is that some solar panels are not being recycled because the regulations for holding and moving them are too expensive to follow. By walking back some of the more onerous standards, the Department of Toxic Substance Control (DTSC) estimates that 15% of solar panel modules will be recycled as a result of these changes in regulation (Berger, 2021).

According to the Solar Energy Industries Association (SEIA), SolarCycle is one of only five American companies that are capable of providing recycling services to End of Life solar panels (Hurdle, 2023). A fairly new company, SolarCycle was founded in early 2022 and since then has raised $37 million in fundraising and investments and opened a solar panel recycling plant in Odessa, Texas (Kart, 2023). This recycling facility has partnered with large solar farms across the Southwest United States to collect and recycle their EoL panels at a capacity of 500,000 panels per year. The company is reportedly using their latest round of funding to increase this capacity to 1 million panels per year by the end of 2023 (Kart, 2023). Another innovative sustainability strategy that SolarCycle utilizes is what they call a second-life system. This is a grid of solar panels that still work, but were replaced by consumers who wanted to upgrade their system. By simply reusing old panels to partially power the recycling plant, SolarCycle saves on recycling and electricity costs and when the panel really does reach its end of life, it is on-site to be recycled (Kart, 2023). The recycling initiatives that SolarCycle aims for are similar to the WEEE regulations and should act as a framework for other American companies that follow in their footsteps.

Discussion

Relevant Actors

Based on research of relevant literature, the parties involved in solar panel recycling include consumers, manufacturers, governmental legislation, and the photovoltaic (PV) cells themselves; these groups will be analyzed in an actor-network framework. Many individual consumers who put solar panels on the roofs of their homes did so in the name of green energy and would pay extra to know that their efforts are really sustainable. However, it is unlikely that all the individual consumers will think it is worth paying $20-$30 per panel to recycle when they could pay $1-$2 per panel to send them to a landfill (Kisela, 2022). The chances that large solar farms will pay the recycling fee for each of their hundreds of panels is even lower. Consumers also have little influence over the adoption of recycling processes in the solar industry since they have no influence over the adoption of recycling policies and must work within the infrastructure available.

The goal of the manufacturer is to reduce costs and increase profits for the company. Providing services to collect and recycle EoL solar panels would introduce a multitude of new costs that cut into the profitability of the company, especially since the recycling process has not yet been made profitable. Regardless, these services are available in countries such as Germany, where it is required, and are also provided by a select few American companies such as First Solar, which established one of the industry's first PV recycling program in 2005 (*Recycling*, n.d.). Companies that recycle their PV products are rare in America because the processes are not profitable, and unlike in Germany, there are no regulations requiring sustainable EoL practices.

Government oversight may be a necessary first step to creating a circular economy in the solar industry. Regulations for toxic and electronic waste, such as WEEE in Germany, have seen success in decreasing the number of solar panels that end up in landfills, and should act as a basis for similar legislature in other countries. Extended producer responsibility is especially important in future recycling mandates so that the cost is not placed onto the consumers. Governments should also be responsible for ensuring that regulations are attainable and that the required infrastructure (transportation, storage, recycling plants) is created to ensure that sustainability goals are met and avoid the situation that India is in currently. Governments could also fund research into more cost-effective methods of recycling and optimizing the process. Governments and manufacturers have the most influence over the future of PV waste by setting legislation and company policy.

Finally, solar panels act as a member of the actor-network through their continued iteration. As new solar panels use less silver, the value that is easily extracted in recycling decreases. Consequentially, recycling solar panels that are low in silver is far less profitable. Future solar panel construction should be more focused on being easily disassembled to make recycling easier and cheaper. Continued innovation in recycling processes will also make the process cheaper and yield a higher value.

Conclusion

The solar industry is an important part of the future of green energy and has carved out a demand that is not going away. That said, The End-of-Life disposal of PV cells is unsustainable as waste is harmful to the environment and wasting precious metals in the panel restricts further production. A circular economy, where old panels are recycled and used to create new ones, is preferrable, but the processes required to make a profit are not yet fully understood. Further research into recycling techniques to separate and purify PV components is necessary. Special attention should be paid to recovering the most rare and valuable materials such as silver and silicon rather than bulk materials like aluminum and glass, which are worth much less. Meanwhile, lawmakers need to pave the way for recycling by mandating a certain yield, such as WEEE has done in the European Union, and/or incentivize businesses to invest in recycling technology and research. Many solar panel manufacturers are comfortable in the current wasteful climate and need external motivation from legislators to make progress on PV recycling. Major projects will be needed to create the factory and shipping infrastructure required for large-scale recycling, but these projects are necessary, and an earlier start is the best-case scenario.

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