Institute of the Environment & Sustainability

Is Solar the "Free Energy Lunch" of a Decarbonized World?

Written by: Alice Blackorby (B.A. '21) and Arushi Sinha (B.S. '20)

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This Green Paper was prepared by undergraduate researchers **Arushi Sinha** (BS '20) and **Alice Blackorby** (BA '21), as part of the UCLA Institute of the Environment and Sustainability's Corporate Partners Program (CPP).

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Imagining Solar Energy After it Has Gone Global And Powers the World

Will there be enough supply and not too much waste?

With a compound annual growth rate of 36.8% between 2010 and 2018[1] and costs declining by more than 70% over the last decade,[2] solar energy is widely viewed as the technology poised to not only reduce greenhouse gas emissions, but bring them to zero. Moreover, when one maps the global solar potential (**Fig. 1**), it is evident that almost every country can participate in the solar revolution, and that solar expansion is not limited by the amount of solar insolation.

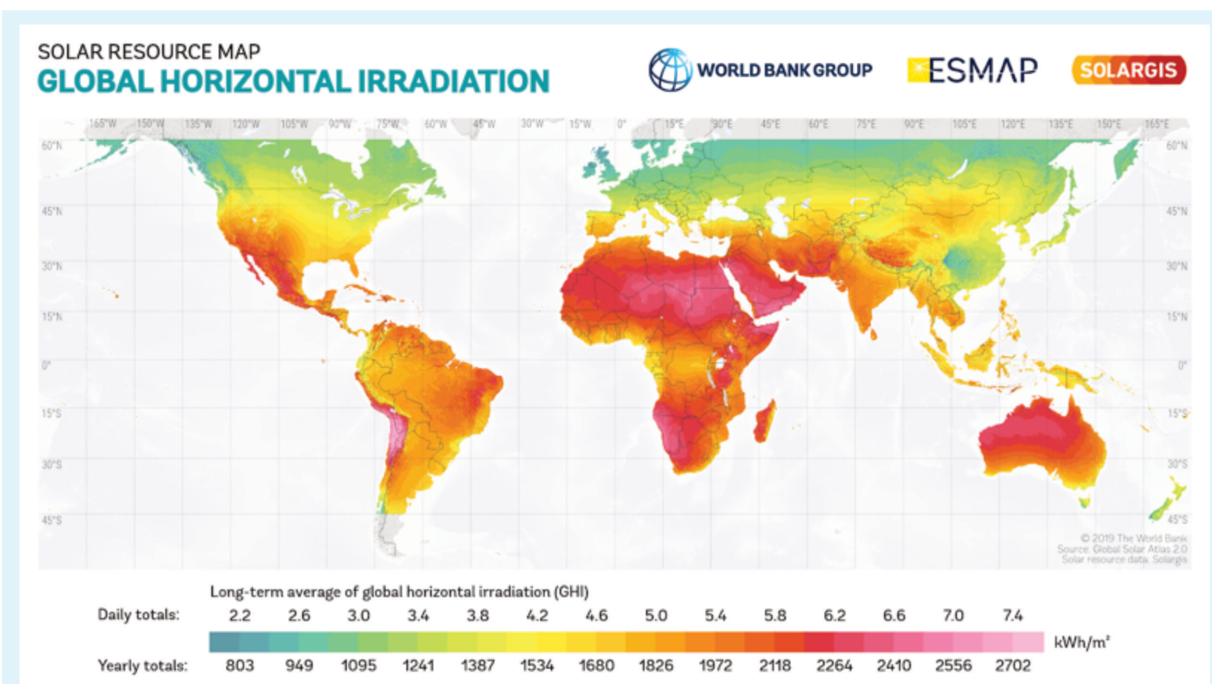


Fig. 1: *A map of daily and yearly global horizontal irradiation or "solar potential"*
SOURCE: Global Solar Atlas

According to the Global Solar Atlas as shown in **Figure 1** above, even India, the second most populous country in the world, with a strikingly less 'red hot' irradiation average than many other countries at its latitude, receives a median of 3.92 kWh/m^2 of solar energy per day[3]. Multiplied by a land area of 3 million km^2 and compared to an annual energy demand of 1,269 TWh[4], India has "in theory" the potential to generate close to 3500 times the energy it needs. This raw potential could never be attained because of energy losses and limits to efficiency. But the point remains: even India likely has enough solar insolation to meet its massive energy demands.

Clearly sunlight is not what is limiting the solar industry. Rather, the solar industry's obstacles are a lack of supporting infrastructure, a shortage of investment capital, and the challenge of sorting through competing variants of the technology in order to identify the best options. These challenges exist today -- when solar energy provides less than 4% of the world's energy supply.[5] What will be the obstacles when solar is scaled up to provide 50% of the world's energy needs? That question motivates our examination of waste streams and recycling for a world run by renewable energy.

A cautionary tale for the imminent global expansion of solar energy is the global expansion of synthetic fertilizer between 1950 and now. The "green revolution" that fertilizer achieved saved the world from famine, but also created over 400 oceanic dead zones spread off the coast of every continent except Antarctica. We are now correcting the fertilizer problem by using technology that promotes precision application of the fertilizer and the selective breeding of crops with lower fertilizer needs. Imagine how many dead zones could have been averted, if, as fertilizer applications exploded by 360% between 1970 and 1990[6], proactive attention was given to the environmental repercussions that we witness today.

"What will be the obstacles when solar is scaled up to provide 50% of the world's energy needs?"

For solar energy, concerns center not just around waste but also the security and public health impacts of supply chains. Energy security for solar means being able to obtain rare earth elements and minerals in sufficient abundance to support massive infrastructures of panels and batteries. Extraction of these minerals involves byproducts of hazardous chemicals that can harm humans.

There is already evidence of significant health hazards surrounding the polysilicon refineries upon which solar panels depend. For example, silicon tetrachloride, a byproduct produced at four times the rate of polysilicon during production, was dumped into the Yellow River in China, rendering neighboring croplands infertile and inflaming the eyes and throats of the local residents.[7] The leading thin-film alternatives to polysilicon, cadmium-telluride (CdTe) and copper-indium-gallium-diselenide (CIGS), use cadmium, which is a heavy metal that is both a carcinogen and a genotoxin.

It is not just the production of solar panels that can create hazardous waste problems as solar expands -- solar power requires batteries to store energy for the times when the sun is not available. Currently, expensive lithium-ion batteries dominate the market. However, not only do they contaminate groundwater from cobalt leaching, they share some responsibility for the armed conflict and illegal mining taking place in the cobalt-rich Democratic Republic of Congo.[8]

Therefore, it is important to critically and systematically think about the complete supply chain and the embedded externalities at play in the solar industry's development. To do this, we adopt a SEEP (social, economic, environmental and political) framework. This allows for a more holistic picture of the solar industry and its future development. Instead of doing a SEEP analysis on a particular technology or a specific company, we use it to frame the choices and challenges facing the industry as a whole.

This then sets the stage for an exploration of recycling and how it can be implemented to proactively mitigate many of the externalities that are exposed in the SEEP analysis. Our goal is to show how recycling might reduce the strain on extraction-based production of solar panels and reduce unintended environmental consequences of an otherwise beneficial technology. Learning from the "green revolution", the solar revolution can be smarter and greener if we have the foresight to guide it with a whole earth wisdom.[9]

We begin by describing the technological landscape of the solar industry and its evolution.

Major Solar Photovoltaic Technologies

------- The Conventional Mono- and Polycrystalline Silicon (c-Si) -------

The first generation of PV technology includes mono- and polycrystalline silicon. As of 2019, these crystalline silicon (c-Si) panels comprise 95% of all global PV production.[10] As such, the production of c-Si must be examined when imagining a global scaling-up of solar power, even if new technologies replace it. The c-Si production process first involves mineral extraction, and silicon manufacturing in processing plants. The silicon is then moved into the production of wafers, cells, and modules to create a PV module for consumption.[11]

------- Thin-film Photovoltaic Systems -------

It is anticipated that new thin-film photovoltaic systems may replace conventional silicon panels. They are being developed with the focus of achieving low marginal costs in mass production. "The key to the idea is the use of pennies worth of active materials".[12] The low dependence of thin-film technologies on silicon, copper, and silver makes their production significantly more feasible to scale up (see **Fig. 2**).

Cadmium-telluride (CdTe) and copper-indium-gallium-diselenide (CIGS) are the most prominent non-silicon based thin-film technologies. CdTe has a bandgap of 1.45 eV which makes it well matched with the solar spectrum.[13] High absorption coefficients have resulted in laboratory efficiencies of 22.1% using only a thin absorber layer.[14] In comparison, commercial c-Si cells that are produced today can achieve an efficiency of 18-22%.[15]

CIGS is perhaps the most promising of the thin-film technologies on the market today. CIGS is currently operating at 22.9% efficiency as of 2019, the highest total-area conversion efficiency of any thin-film technology.[16]

Emerging thin-film technologies comprise only 5% of the market share cumulatively, but their share is expected to grow as the technologies evolve with improved efficiency and better low cost options. As a result, c-Si technologies are losing their monopoly as their market share has fallen from 92% in 2014 to 82% in 2020, and is expected to decrease further to 70.4% in 2030.[17]

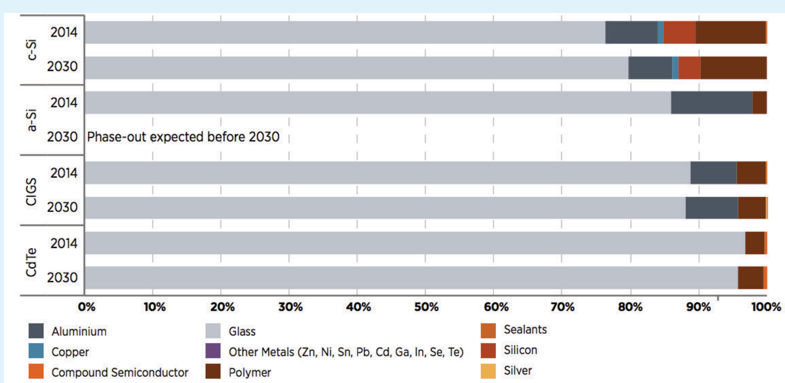


Fig. 2: *Current and projected material compositions of solar technologies. SOURCE: IRENA, 2016*

------- Third Generation in the Works -------

There are a series of PV technologies currently in the research and development or early market penetration phase. Given the lack of commercialization or market penetration, projections of these technologies are less precise. This category includes organic PV cells, perovskite, concentrating PV, as well as nano-enabled cells that vary across development stages.

Organic PV cells are composed of inexpensive organic polymers with low solar conversion efficiencies of 6-8%.[18] However, they are lightweight, flexible, very easily manufactured at a low cost, and can be affixed to almost anything.[19] This makes them ideal for portable applications or building-integrated systems wherein uneven surfaces, size constraints, and additional costs are detriments to the adoption of PV on urban, sunlight-exposed surfaces.

Perovskite as a solar cell technology has rapidly increased in efficiency over the last decade. From a conversion efficiency of 3.8% in 2009 to 24.2% in 2018, perovskite is poised to increase in market share[20] and beat conventional c-Si when it comes to efficiency, since c-Si has a theoretical maximum efficiency that is capped at 29.8%.[21] However, these achievements are yet to be replicated in larger cells. Coupled with its limited longevity in humid conditions, perovskite is yet to challenge conventional technologies for a larger market share despite a lower cost of production and a smaller energy footprint.[22]

Concentrating PV is unique in that it utilizes lenses and mirrors to optically concentrate solar insolation onto a small solar cell. This can increase the effective energy input to be equivalent to that of 1000 suns.[23] Concentrating PV cells are multi-junctional or stacked to take full advantage of this high energy input and can thus reach commercial efficiencies of 20-25% with a theoretical maximum of 59%.[24] While their relatively small area helps to reduce much of the cost of production, concentrating PV is heavily dependent on expensive and additional moving parts such as sun-tracking systems.

Nanotechnologies such as quantum dots, quantum wells, super lattices, and nanocrystals are increasingly gaining traction in the realm of PV R&D. One notable development is the use of photo-electrochemistry in dye-sensitized solar cells. The unique cells mimic natural photosynthesis by using dye molecules to separate charges. While efficiency is currently limited to 5% in commercial cells,[25] dye-sensitized solar cells can greatly benefit from nano-enabled materials such as virus hybrids, which are a low-cost method of boosting electron mobiliy.[26]

A SEEP Analysis of Solar Energy Technologies

There are myriad of PV technologies that are in various stages of development and commercialization. Existing life cycle analyses are thorough in analyzing the environmental impacts of these different PV technologies. From them, we have learned that silicon tetrachloride disposal is an issue unique to silicon-based panels, but that thin-film technologies introduce the health risks of cadmium leaching during both the manufacturing and the post-consumer phases of the supply chain.[27] However, the existing literature on solar panel life cycle analyses fails to employ an integrated perspective across multiple dimensions of impact. The objective of this section is to discuss externalities and factors, positive and negative, in these other fields while grounding our evaluation in current and projected trends of technological innovation.

We utilize a SEEP lens to holistically investigate the solar industry's supply chains as well as complications and expectations for scaling up across social, economic, environmental and political dimensions. We have added depth for specific conventional vs emerging technologies where appropriate and link the analysis to various phases of the solar PV value chain (**Fig. 3**). Overall, this analysis hones on the various push and pull factors at play in the solar industry's development.

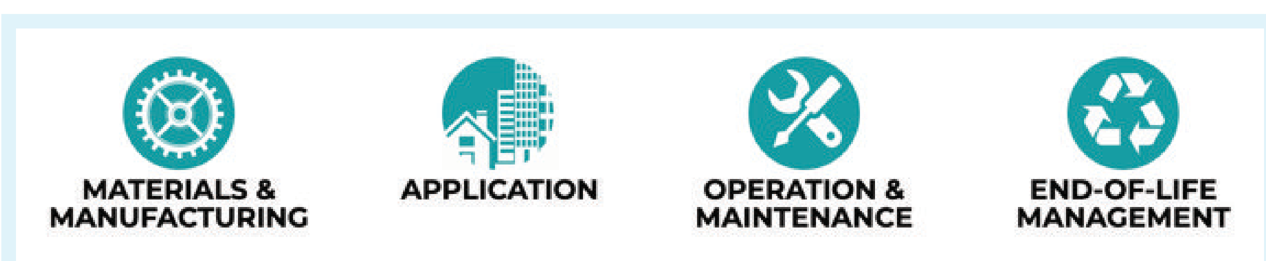


Fig. 3: *The Solar PV Value Chain*

SEEP - Social Implications

The development and expansion of solar energy worldwide has improved energy accessibility, equity measures, and global job markets. Solar investment increases employment opportunities, and can accelerate the process of electrification in rural areas for countries across the global south. A transition to solar from fossil fuel energy sources allows capital intensive services to be supplanted by labor intensive ones that provide large quantities of new jobs in installation and assembly.[28] Further, the jobs across PV supply chains are varied in type and range from sales and design, to manufacturing and quality control.[29] In just one year, from 2007 to 2008, the amount of U.S. companies involved in the solar industry increased by over 50%, and this trend is increasing as the solar sector continues to grow and expand.[30] Job creation measures are consistently positively aligned with the expansion of the solar industry; however, as expanded upon later, there are worker health concerns to account for regarding mineral extraction and toxic inputs to PV technology production.

> "The development and expansion of solar energy worldwide has improved energy accessibility, equity measures, and global job markets."

Additionally, this scale-up of sustainable and accessible energy sources is expected to enhance energy access for millions in the developing world.[31] Lack of rural electrification is a pressing global issue that is typically approached with conventional grid extension. However, renewable technologies provide an enticing alternative as costs drop, and renewables can reach more remote areas that the grid is not able to reach.[32] Solar does face technical, practical, and financial challenges to widespread deployment in remote regions. However, in Bangladesh and Sri Lanka, it was found that the employment of a subsidy framework, customer centric market development, and private incentives to enter new markets enhanced affordability, institutional support, and scale up efficacy.[33] With the proper political, and economic tools, solar energy is a valuable resource to improve widespread energy access in a lower cost and lower impact manner than traditional sources.

Transitioning away from fossil fuel combustion in the global energy supply will have long lasting impacts on not only environmental health, but human health as well. Currently around 300 million children breathe air that exceeds international air pollution guidelines sixfold.[34] These pollutants are associated with increased risk of cognitive or behavioral development issues, respiratory illnesses, and other chronic conditions.[35] The social benefits of expanding PV production and consumption globally are widespread and far reaching.

A transition towards solar energy can reduce dependence on imported fossil fuels. As discovered in Finland, despite demand for heat and electricity projected to increase by 7% over the next several years, import dependency for oil is expected to fall by around 4%.[36] These reductions in import dependency and improvements in energy diversification are beneficial for measures of national security. However, while the energy supply chain becomes less import dependent, the inherently intermittent nature of solar energy introduces additional concerns given its reliance on unpredictable weather conditions.[37] So despite expanded energy access and diversification, there are concerns about the periodic nature of solar energy and the need to have back-up systems in place to meet predictable energy demand levels.

------- Conventional Technologies -------

Looking specifically at impacts of mono- and polycrystalline silicon PV production processes, the emissions associated with natural resource extraction for these PV systems warrant serious social concern over working conditions and related hazardous health consequences. With c-Si production in particular, there are additional questions over resource depletion as demand and consumption continue to rise in the coming decades.

The processing and purification of the raw materials for c-Si PVs is a complex procedure given the need for high purity silicon for the solar cells. Silica is first reduced using a furnace to metallurgical grade silicon. The purification continues until the silicon is solar-grade. Toxic chemicals are employed in this process to dope the silicon, (chemicals such as diborane and phosphine) which can have negative health impacts.[38] At the present level, the small quantities of these chemicals warrant little alarm; however, with increasing scale up in the coming decades, such a process could have significant implications for workers and the environmental impact of the production process. The production processes of materials like aluminum and copper involved in the balance of system (BOS) components have “standard industrial hazards” and are utilized in a vast array of products and materials.[39] Overall, the c-Si production process is intensive, and more intensive relative to newer technologies emerging on the scene, which makes a transition to newer technologies likely and suggests a potential reorganization of the market make-up, unless c-Si production processes themselves evolve to address these concerns.

------- Emerging Technologies -------

Pivoting to emerging technologies, CdTe is dependent on cadmium and telluride, which are by-products of zinc mining and copper processing respectively.[40] Thus, the availability of this technology in the future is implicitly dependent on the optimization of zinc and copper extraction, refining, and recycling. In addition, the carcinogenic and genotoxic properties of cadmium are a primary source of heavy debate when considering the scaling-up of CdTe panel production. Further, the issue of CdTe's potential to draw market share from c-Si and improve aggregate social impact depends on the success of recycling to protect communities from its toxic properties.

SEEP - Economic Implications

Solar energy is a sector experiencing massive growth as many countries are seeking to diversify their energy supply, and their economies more broadly. Renewable technologies require higher initial investments in terms of infrastructure than fossil fuels, but the paywall is continuing to come down, and the payback time for solar investments is shrinking on the whole. From 2010-2011, PV installation prices fell by 14% for systems larger than 10kW on average, and declines were even greater in California compared to national averages.[41] Solar PVs have been continuously dropping in price, alongside the rapid increase in solar installations facilitated by China's solar PVs flooding global markets.[42]

IRENA finds that since 2014, the average PV electricity costs have fallen into the fossil-fuel cost range.[43] As of 2012, thin film module prices fell below $1/W with variance between $0.8/W to $0.9/W, whereas c-Si module prices varied from around $1/W to $1.24/W.[44] Costs are continuing to fall, and the speed with which thin film emerging technologies can lower costs and increase efficiency will substantially reorganize PV market composition. While falling system costs are cause for excitement, IRENA posits that the levelized cost of electricity (LCOE) is still high, which impedes PV scale up since up front costs do not paint a complete cost picture. LCOE shows the cost of solar power production over a time frame.

For solar PV development companies, there is an important trade-off to be considered when selecting a PV technology. Currently, thin-film cells have lower efficiency rates compared to mono and poly-crystalline and require more land to produce an equivalent amount of power.[45] The lower efficiency rates are compensated by lower costs and thus, companies must consider the cost differential between technology and land when weighing options. The subsequent decision depends on cost, lifespan, and efficiency, all of which are factors that are changing in response to technological innovations in PV production processes.

For communities considering implementing solar, there are concerns over the intermittent nature of solar energy. Further, the question arises of how to deploy a large scale expansion of an unpredictable energy form in a system with a large and predictable energy demand. To be specific, the intermittent nature of renewable sources poses some problems for the electrical grid. When the sun moves behind the clouds throughout the day, generation capabilities are impacted; this raises concerns of generation potential in direct conflict with the consistent energy needs of communities.[46]

However, a transition to greater use of renewable energy sources like solar would limit some of the devastating consequences of energy crises in the short run, and potentially prevent them in the long run. In 2008, the energy crisis increased oil prices to an all time high of $147 dollars per barrel[47], which is three times the average price in 2004. These fluctuations continue across varying economic and political circumstances, which has calamitous effects for importing countries given the geographically constrained nature of oil reserves.

For solar in the private sector, corporations are increasingly investing in renewables as a method of achieving clean energy targets, and securing strong long-term profit margins. These investments are highly dependent on government incentive programs that are crucial to widespread deployment and adoption. Companies can elect to passively or actively invest in renewables. A passive approach involves sourcing from existing renewable electricity in the grid.[48] This can work through corporate power purchase agreements (PPAs) that contract a supplier to produce a specific amount of renewable energy for the company.[49] A more hands-off approach involves the purchase of unbundled energy attribute certificates (EACs). This means companies pay for renewable energy credits of sorts, but these contributions and payments are entirely distinct from the company's actual energy use, supply, and sources.[50] These passive approaches push the burden off the corporation, and EACs specifically involve paying for their use of less clean energy sources. More active investment includes when a corporation invests in its own renewable electricity production site, to internalize its production and consumption.[51] While EACs are currently the most commonly employed investment method, more active investment is crucial to achieving global renewable energy targets.

SEEP - Environmental Implications

There are several environmental benefits and drawbacks to be considered when analyzing the production process of solar panels. Most prominent is the reduction in greenhouse gas emissions, and prevention of toxic gas emissions from fossil fuel production. The majority of global air pollution comes from fossil fuel combustion, which is responsible for nearly all of the atmospheric sulfur dioxide and nitrogen oxide along with CO_2.[52] The emissions have been linked with adverse health effects in the population including respiratory illnesses, and physical and cognitive development impacts.[53] It is predicted that by 2050, outdoor air pollution will be the leading cause of child mortality.[54] Despite the importance of the pollution reduction, the rise of PV production levels raises toxicity concerns given the hazardous chemicals present in the supply chain. For instance, disposal of silicon tetrachloride, which is a by-product in the production of polysilicon, raises significant toxicity and public health issues especially considering improper waste disposal concerns.

Solar is often seen as the energy savior given that in its use phase, it produces no CO_2 emissions and is a renewable rather than a depleting resource, which works to significantly reduce greenhouse gas emissions.[55] However, the installation and ongoing use of PV systems accrues environmental costs over time. In terms of scale-up, there is alarm over the high land use associated with PV expansion. More specifically, the threats to wildlife from large developments of solar PV farms.[56] Expanding land use for PV installation also reduces cultivable land. The costs associated with large land demands could be reduced by co-locating solar infrastructure with agricultural crops[57], and by placing solar installations on already severely degraded land.

> "...the installation and ongoing use of PV systems accrues environmental costs over time."

Beyond land-use, there are concerns regarding the lack of well-established recycling and waste management processes. Given the lifespan of solar panels hovering around 30 years, without a responsible and comprehensive recycling program, the solar industry will generate a massive amount of waste, some of which is hazardous.[58] We have developed a mathematical model to investigate how differing recycling rates and approaches reduce or exacerbate the strain on extraction-based solar panel production. The results and discussion of this work are explained in the *Recycling as a Necessary Solution* section. Continuing improvement in solar PV technology suggests that increasing efficiency as well as material reuse and recycling will transform the PV market landscape.[59] However, there are limits to these improvements and innovations that as planners, researchers, and scientists, we can reasonably expect.

------- Conventional Technologies -------

Many of the same chemicals found in e-waste like lead, flame retardants, cadmium and chromium are found in solar PVs.[60] Thus, concerns around the electronic industry's waste are often mirrored in PV production life cycle analyses. Additionally, polysilicon's byproduct, silicon tetrachloride, poses public health concerns as previously noted.

------- Emerging Technologies -------

The production of thin-film PVs is a more energy efficient and less resource intensive process than that of silicon-based technologies. The removal of melting, purifying, and slicing processes required to prepare silicon for panels makes thin-film manufacturing much less energy intensive relative to c-Si.

Looking at another emerging technology on the solar scene, the CIGS production process generates hazardous lead, cadmium, and selenium waste. To expand, the selenium concentration raises additional concerns over resource depletion.[61]

SEEP - Political Implications

The political implications of solar energy production and expansion differ significantly from those associated with fossil fuel based power systems. Solar energy is readily available and accessible across the globe; it doesn't require import, but instead can be provided locally. It can be accessed by any country, though some have advantages in terms of generation potential. These factors imply that national investment into renewables can improve energy security through a reduced reliance on fossil fuel imports.[62]

Political systems play a significant role in the deployment and scale up of renewable energy industries. State actors have been vitally important in the solar industry's growth through the employ of feed-in-tariffs (FITs) and Local Content Requirements (LCRs).[63] Feed-in-tariffs offer renewable energy producers long term contracts to accelerate investment and industry expansion. Local content requirements designate a specific portion of intermediate materials to be domestically sourced to bolster the domestic industry. FITs have significantly contributed to the added generation capacity across Europe. Additionally, China has ambitious renewables targets and employs a standardized FIT as one tool in the process of achieving their goals.[64] In the U.S., tax incentives alongside stimulus funding sources have worked to support the PV market's development.[65]

The renewable energy industry in the U.S. especially faces significant challenges in terms of competition with the powerful lobbying interests of the fossil fuels industry. The U.S. political system is fraught with big industries exerting disproportionate influence on political outcomes and decision making processes. Renewables face a strong and established opponent in the lobbying powers of fossil fuels. For instance, in the 2018 U.S. midterm elections, the fossil fuel industry outpaid renewables in political contributions by thirteen to one.[66]

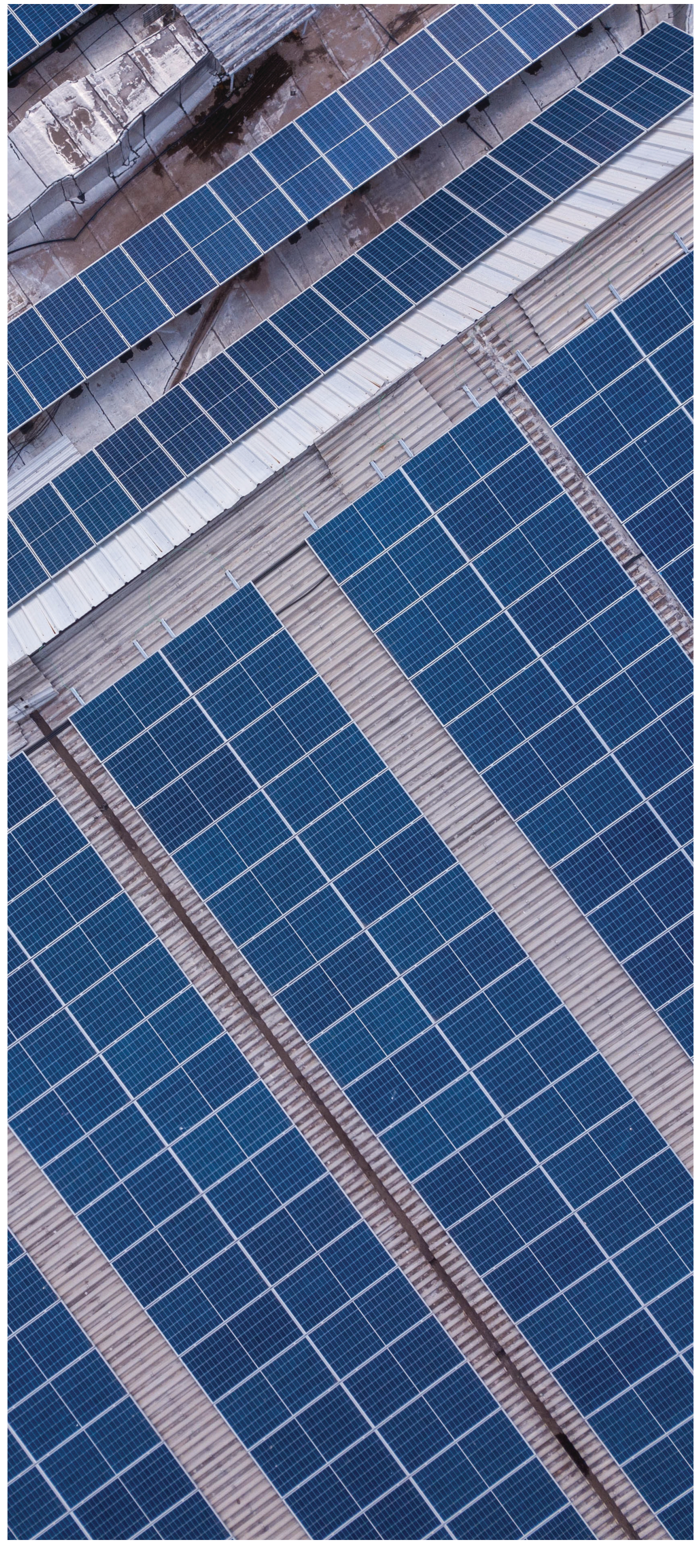
Additionally, some of the biggest fossil fuel companies operating in the U.S. like Exxon have spent billions of dollars to stall renewable energy policy and to thwart climate science research.[67] Such actions emphasize the influence of big industry in U.S. politics, which can prevent competing players from gaining a foothold.

------- Conventional Technologies -------

The raw material extraction process within c-Si production involves intensive mining, specifically for the quartz sand that becomes silicon. This production process involves emissions of hazardous materials such as silica dust, silanes, and solvents, among others, which can cause respiratory issues for miners.[68] Hazardous emissions are an externality with implications beyond just environmental concerns. Mined rare earth minerals are often imported and part of a global trade system, which makes it difficult to trace their full impacts. Additionally, this creates global equity questions around natural resource extraction and exploitation. Studies have found that the majority of foreign direct investment going into African countries is connected to the extraction of natural resources.[69] Simultaneously, the accessible nature of solar energy could serve to electrify new regions and promote investment and growth in developing countries. As is the case with many of these dimensions, there are a plethora of considerations to make, and implications to weigh out.

No clear winners

As shown, the solar energy revolution has important and robust social, environmental, and economic benefits. Conversely, there are still drawbacks as with most any technological innovation. But as is abundantly clear, the deployment of renewables reduces fossil fuel combustion and greenhouse gas emissions all while creating jobs, cleaner air, and greater energy accessibility. Though the conventional c-Si technologies comprise almost the entire PV market, this is set to change in the future. As time goes on, the emerging technologies that currently comprise a very small portion of the PV market will compete more aggressively with the conventional c-Si technologies. Those with the highest conversion efficiency rates and the most promising energy payback schemes will receive investment and likely success. No matter the winning technology or production process, recycling to achieve as close to a circular economy as possible is a vital development in the solar industry's future.



Recycling as a Necessary Solution

IRENA projects our global production of solar energy will reach 2840 GW in 2030 and 8519 GW in 2050.[70] However, analyses of the availability of critical elements suggest that we may never reach these sunny targets because of shortages in the supply chain. If the solar revolution is to avoid the missteps of the green revolution, in its earliest stages, recycling should be a key factor in the design of solar energy systems.

> "...recycling should be a key factor in the design of solar energy systems."

Critical Materials

The fundamental ingredients required to produce a successful solar panel are glass, aluminium, polymers, and other metals or semiconductors. In conventional c-Si solar cells, the key semiconductor is silicon and is accompanied by copper and silver. In MIT's Study on the Future of Solar Energy, silicon and silver are two of six PV-critical elements identified. The other four elements, tellurium, gallium, indium, and selenium, are used in thin-film solar cells, namely CdTe and CIGS.[71] Each of these six elements potentially constrain our global solar energy production, and we will reach a point past which recovering them will be economically unfeasible. In other words, "the use of scarce elements does not benefit from economies of scale."[72]

The graphs below show us what to expect as we scale up our production of solar energy in the future. Shown here are the critical material requirements for each technology, in terms of raw amount, based on the current annual production for the solar technology (vertical axis) and the corresponding material extraction rate needed to support that production (horizontal axis). The material requirements vary depending on the fraction of projected demand for energy in 2050 that is met by different PV technologies. For instance, the red bars show the range of quantities of silicon (Si) and silver (Ag) that are required if we need to satisfy anywhere from 5% to 100% of global energy demand in 2050 with the use of conventional (c-Si) or amorphous (a-Si) silicon-based solar cells.

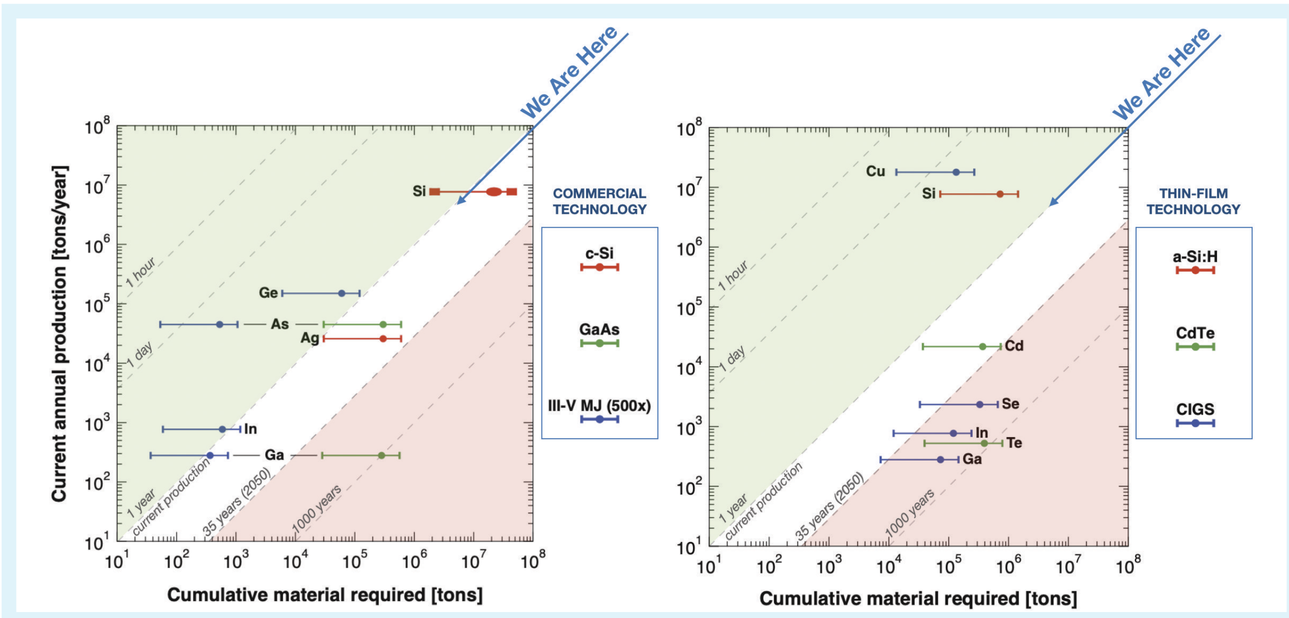


Fig. 4: *Spectrum of critical material requirements for each solar technology based on proportion of total global demand for energy a technology will be required to satisfy in 2050*
SOURCE: MIT, 2015

To put this into perspective, we have added a green, white, and red zone. The green zone, or the upper left triangle denotes the production rates that we are able to satisfy even without using our current extraction and production technology to its full capacity. Conversely, the red zone shows requirements that are currently unattainable.

Looking at c-Si on the left half of **Fig. 4**, we see that we are able to achieve our material requirements at our current rate of extraction of the critical elements, silicon and silver. This means that, by 2050, we have just enough resources needed to transition to 100% solar using conventional silicon-based technology. That is, if all the silver and silicon extracted and processed were used solely for this purpose -- which it is not. Given that our demand for silver from other industries will remain, we cannot reasonably divert 100% of silver extraction to the production of c-Si solar panels.

On the right half of **Fig. 4**, we have our commercial thin-film technologies, CdTe and CIGS, which are limited by cadmium (Cd) and tellurium (Te), and indium (In), gallium (Ga), and selenium (Se) respectively. As can be seen, by 2050, we will be mostly in the red zone. Only slightly over 5% of our demand for energy in 2050 could be satisfied by CIGS thin-film technology given the current annual extraction rates for gallium. For CdTe thin-film technology, tellurium is so limiting that for this technology to satisfy 5% of the expected 2050 energy demand, it would take one hundred years of extraction at current rates to have mined enough tellurium. This suggests that our aspirations for solar energy cannot be met if we restrict ourselves to

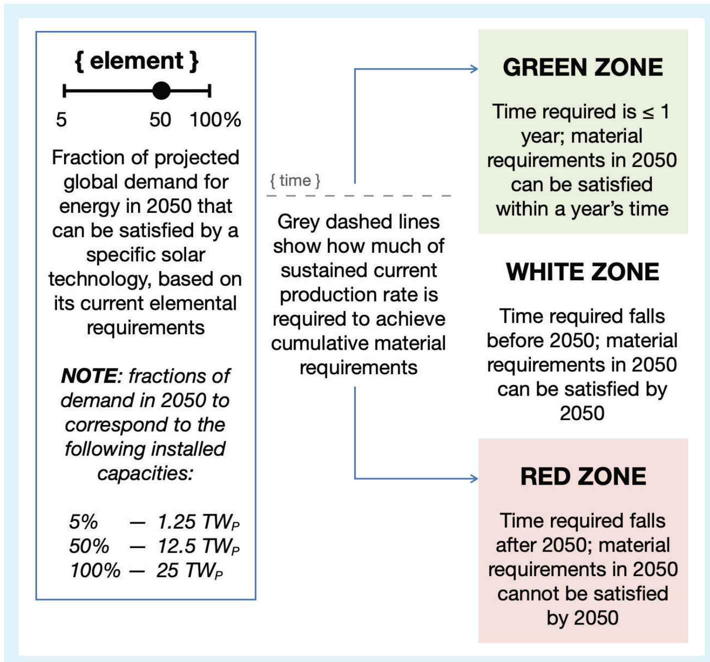


Fig. 5: *Schematic of how to interpret Fig. 4*

mining and extraction of the needed critical materials.

As we near the production ceilings for each of our elements, we are likely to expect an increase in the cost of these PV technologies with an ever-increasing fraction of the cost attributed to the critical materials that are needed. Already, silver accounts for 47% of the material cost of a c-Si solar panel while accounting for less than 0.10% by mass of the panel.[73] While breakthroughs in extraction technology can increase our productive potential and R&D can help decrease our dependence on critical metals, we cannot rely on these hopes in the long run. Research and development in PVs shows us that, even in our most favorable scenario, we still require 7 tons of silver per GW of solar power potential.[74] With a demand for silver across multiple industries, the solar industry is left quite vulnerable to the future availability of critical metals. One solution is a viable market for recycling, so that some material needs are met by recycling as opposed to mining.

Modeling the Benefits of a Circular Economy for Solar Panels

As solar energy grows in popularity and becomes a significant source of energy globally, naysayers caution that the solar boom is over-hyped.[75] While these attacks on the solar industry are filled with misinformation, the challenges posed by a massive scaling up of the solar industry cannot be ignored. Notably, as more and more solar panels are built, the demand for rare earth elements and critical metals may outstrip their supply. When those same panels are "retired" the volume of waste could become an environmental liability. Both of these concerns could be addressed if a circular economy were built around solar panels.

The essence of a "circular economy" is the development of a closed-loop system, in which the waste generated in the manufacture of and disposal of goods at the end of their lifetime does not go into a waste stream, such as a landfill, but instead is looped back to production. Here, we introduce a model that tracks the growth of solar energy through time under different assumptions of recycling. Rather than taking a conventional approach in terms of tracking "mass", our model is framed in units of solar energy potential or **SP**. The units of **SP** are GW/year. At its infancy, all **SP** is in the form of $\mathbf{SP_{NR}}$: the energy production capacity of solar panels produced from non-recycled raw materials. As solar panels age and have to be retired, total **SP** also includes $\mathbf{SP_{W}}$: the theoretical energy production potential of solar waste if that waste had been recycled as opposed to put in a landfill, and $\mathbf{SP_{R}}$: the actual energy production capacity of solar panels produced from these recycled raw materials.

The reason we frame the model in this manner is that we want to examine it as an economic question -- what is the feasibility and value (where value is GW/year) of building a "circular economy" around solar panels -- whereby they are recycled back to produce new solar panels ($\mathbf{SP_{R}}$) as opposed to shunted to a landfill. And when they are shunted to a landfill, we represent them not as waste but as $\mathbf{SP_{W}}$, to remind ourselves that this is a loss in energy production potential.

Our model, which is described in detail in the *Appendix*, examines the consequences of different rates and efficiencies of recycling. As a given, we accept IRENA's projections for the growth of solar energy supply. We then use the assumption that the future demand for solar energy in a given year is satisfied by the cumulative installed capacity of solar panels, as projected by IRENA's model. Our goal is to examine how various recycling rates can reduce the strain on extraction-based production of solar panels and help satisfy our demand for solar energy in the future.

In **Fig. 6**, as a simple theoretical benchmark, we first model how SPW grows through time under the assumption of a 30 year average lifespan for solar panels. We show two different curves for $\mathbf{SP_{W}}$: the solid orange depicts $\mathbf{SP_{W}}$ where the efficiency of recycling is 100% (which of course it never is), and the dashed orange depicts $\mathbf{SP_{W}}$ when the efficiency of the recycling is 81% (which is currently feasible--

see below). If immediately, starting in 2020, every solar panel were recycled, then the orange curves in **Fig. 6** represent the energy production value of recycled panels. Clearly, even if we instituted mandatory recycling immediately, the amount of solar energy potential from recycling does not become substantial until well beyond 2030. Put another way, under the most optimistic possible assumptions, recycling is not expected to contribute much to total solar energy production for at least another decade or two.

The model also makes clear the importance of another key variable: the efficiency of recycling. The difference between the solid orange curve and dashed orange curve is marked by 2050. In reality, the recycling process of solar panels is imperfect. As such, not all of the projected 4595 GW of productive potential in solar waste by 2050 can be harnessed. Experiments suggest that while recycling efficiencies are relatively high, they vary depending on the solar technology. For instance, 90% of the glass, 100% of the metal, and 85% of the silicon in c-Si panels can be recovered.[76] On the other hand, 90% of the glass and 95% of the semiconductors in thin-film panels can be recovered.[77] A reasonable range for recycling efficiencies might be between 70% and 90% with existing technologies. By 2050, this would translate into reducing the strain on extraction-based production by between 37.8% and 48.5%.

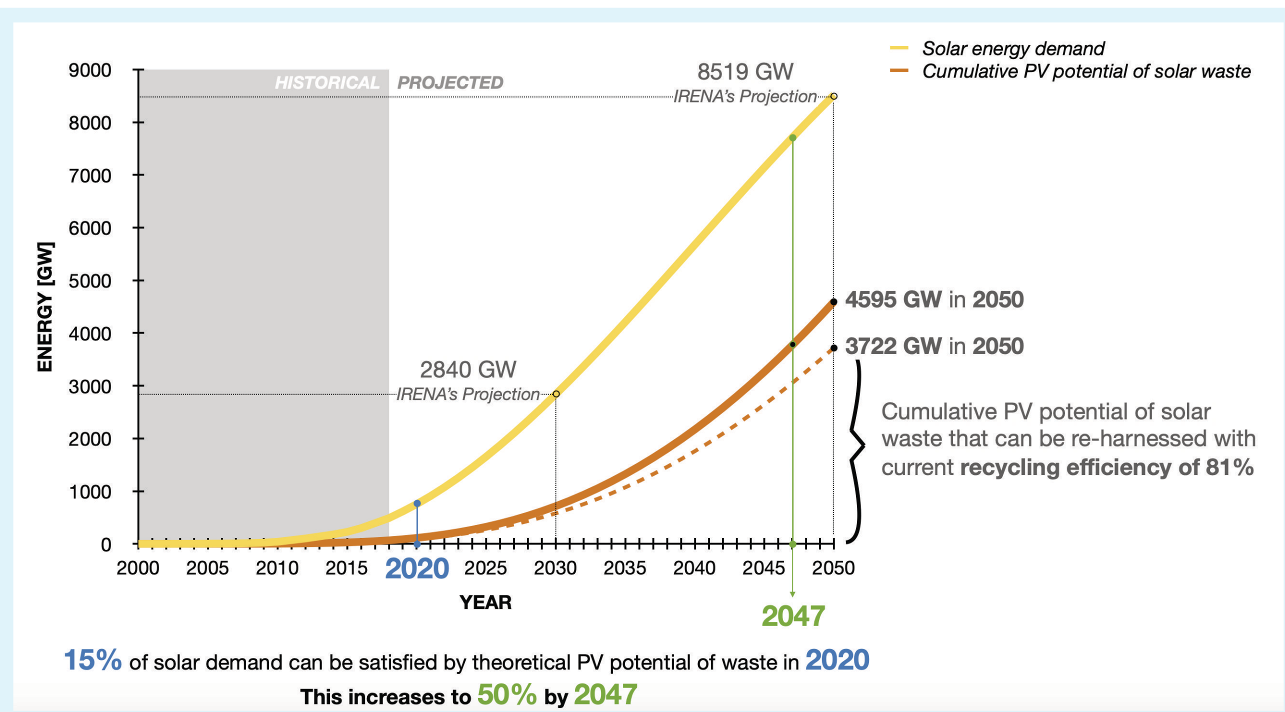


Fig. 6: *A business-as-usual case, showing how demand for solar energy compares with the cumulative maximum energy production potential of solar waste until 2050*

Modeling what happens under the assumption of immediate and mandatory recycling with total compliance (**Fig. 6**) is a useful thought-experiment; however, it does not illuminate more realistic scenarios. Since there is not yet a major waste stream from solar panels, it is not clear what a realistic scenario would look like. As a proxy, we decided to use the history of plastic recycling. In particular, we emulated the global trajectory of plastic recycling from 1980 to 2010. When translated to the case of solar panels, this means that if recycling begins in 2020, we should be able to recycle 23% of our solar panels in 30 years.

Fig. 7 is a plot of the derivative or the rate of change of two key variables: $\mathbf{SP_R}$ and $\mathbf{SP_W}$. The blue curve in **Fig. 7** is the rate of change of $\mathbf{SP_R}$ over time and delineates the increase in recycling rates that we can expect to achieve following the trajectory set by plastic recycling in the past. As a result of the blue curve lifting above zero after 2020, we note that the solar waste accumulation rate, the dotted grey line, shifts downward. This indicates that the rate of change of $\mathbf{SP_W}$ is smaller than that which was calculated in **Fig. 6**. In particular, waste accumulation rates which were 284 GW/year by 2050 in the **Fig. 6** benchmark scenario, are expected to fall by 23% to 218 GW/year in **Fig. 7**. This is a step towards a more circular economy; however, one could argue that even in this case, we may already be late to the game.

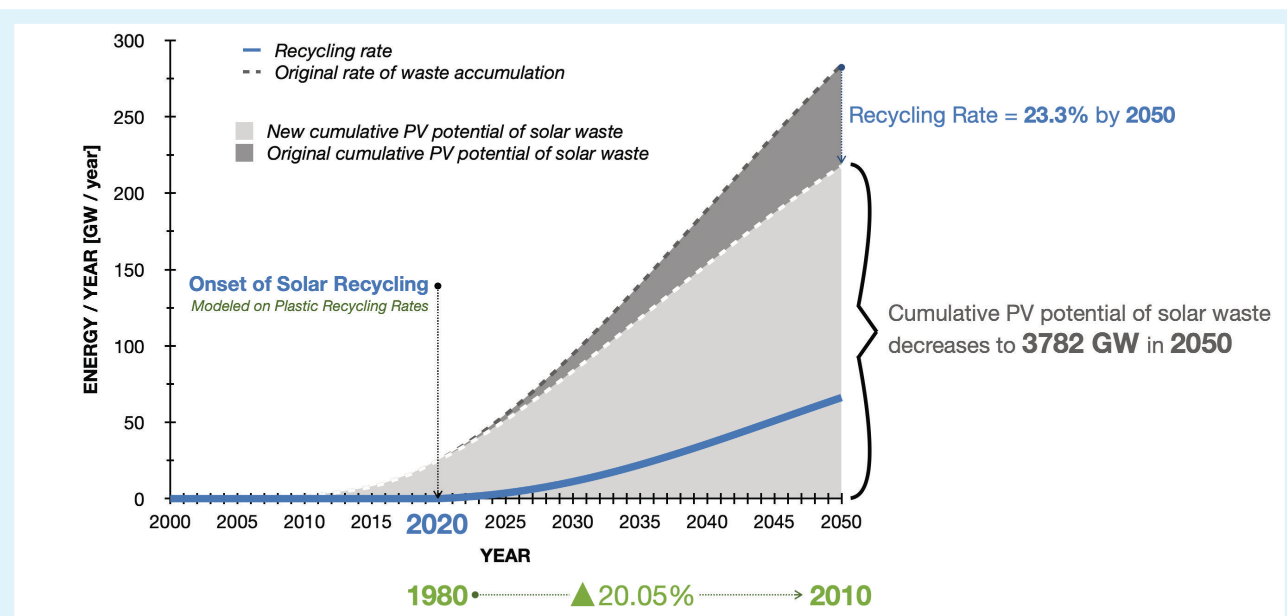


Fig. 7: *A proxy for a realistic recycling case, showing how recycling rates similar to that of plastic in its earliest stages influence the rate of solar waste accumulation until 2050*

We used the information in **Fig. 7** to recreate a plot resembling **Fig. 6** but for the aforementioned case where plastic recycling is used as a proxy for a realistic solar panel recycling scenario. For simplicity, we assumed that the recycled solar panels are of the same quality and have the same lifetime as non-recycled solar panels.

Historically, the onset of plastic recycling was brought about by changes in consumer consciousness, government intervention, and producer responsibility. If similar influences are activated in the solar supply chain, we note that solar waste accumulation rates, $\mathbf{SP_W}$, can fall by 2050. However, the slow rate at which $\mathbf{SP_R}$ increases does little to limit the total volume of global solar waste, which is what accumulates when we integrate over the years. As shown in **Fig. 8**, even in the best case of 100% recycling efficiency, as denoted by the solid orange line, we are only able to decrease the energy production potential of solar panels in the landfill by 17.7%. In other words, even with this adoption of solar recycling, we would have succeeded in setting back our waste growth curve, $\mathbf{SP_W}$, by only 3 years. By 2050, the raw materials in our waste stream could be scavenged to satisfy 45% of our total demand for solar energy, or 36% after accounting for losses that can occur during the recycling process.

Significant efforts at solar panel recycling are still nascent. A big challenge is that implementing recycling of solar panels requires taking steps to ensure minimal damage to panels during their post-consumer phase. Introducing durable labelling to identify eligible products, matching each panel to the relevant recycling and recovery streams, building the supporting processing infrastructure,

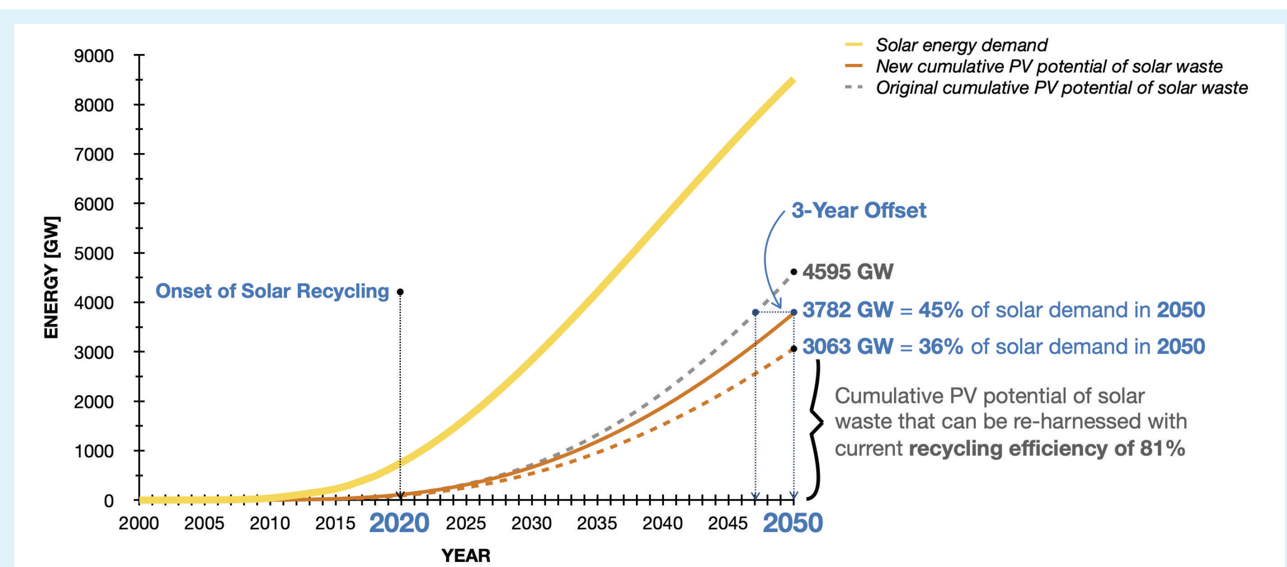


Fig. 8: *A proxy for a realistic recycling case, showing how recycling rates similar to that of plastic influence cumulative maximum energy production potential of solar waste until 2050*

and creating more recycle-friendly panel designs for the future are all needed to build a robust recycling system.[78] Steps that we take today can only have a tangible effect 30 years down the road, when the solar panels that we are putting onto the market now reach the end of their lifetime.

Learning from Plastics and Aiming for Lead-acid Batteries

Our solar industry is young. As IRENA predicts (**Fig. 8**), the solar industry's capacity is expected to increase more than six-fold in the next 30 years. Now, not 30 years from now, is the time to vigorously initiate the research and development processes needed to develop economically viable recycling systems.

In Germany and the UK, solar waste management frameworks have been put into place by the EU's PV CYCLE initiative wherein the extended producer responsibility program mandates that solar producers facilitate the collection of used solar panels.[79] While the primary goal of this was to eliminate the health burdens associated with irresponsible toxic waste disposal, the new foundation for the EU's Waste Electrical & Electronic Equipment (WEEE) Directive is high-value recycling and now focuses on the recovery of rare materials as well as other components of solar panels.[80]

With initiatives such as these taking place on a more global scale, it is not too difficult to imagine a more circular solar supply chain. Knowing that extraction-based production will face a great stress in the future, a quality-regulated feedback loop could be highly profitable when those supply-chain stresses emerge in 30 years.

Lead-acid batteries are the epitome of success when it comes to developing a circular supply chain. Lead-acid batteries are the most efficiently recycled product in the world -- they are recycled at a rate of 99.3%.[81] Supported by reclamation mandates across battery-dependent industries, the battery standard itself has evolved to create more recycle-friendly guidelines and has thus encouraged the development of specialized recycling companies.[82] This is a story that the solar industry can learn from.

As discussed, the solar panel recycling process is currently 81% efficient. Even if we aim to achieve a consumer recycling rate of 70% instead of the 99.3% benchmark set by lead-acid batteries, the solar supply chain can evolve into one that is more circular and sustainable by 2050. Our goal here is to show what is needed to asymptotically flatten the growth of solar waste by 2050.

In **Fig. 9**, we see that if 70% of solar panels are diverted to recycling streams rather than directed to landfills by 2050, our rate of change of $\mathbf{SP_R}$, the blue curve, increases a lot more dramatically than in the prior two cases. In turn, this allows the industry to achieve a relatively stable rate of change in $\mathbf{SP_W}$: 85.5 GW of solar waste accumulation per year. This translates to a solar supply chain that is 30% driven by recycled solar panels by 2050, a fraction which is set to increase exponentially thereafter.

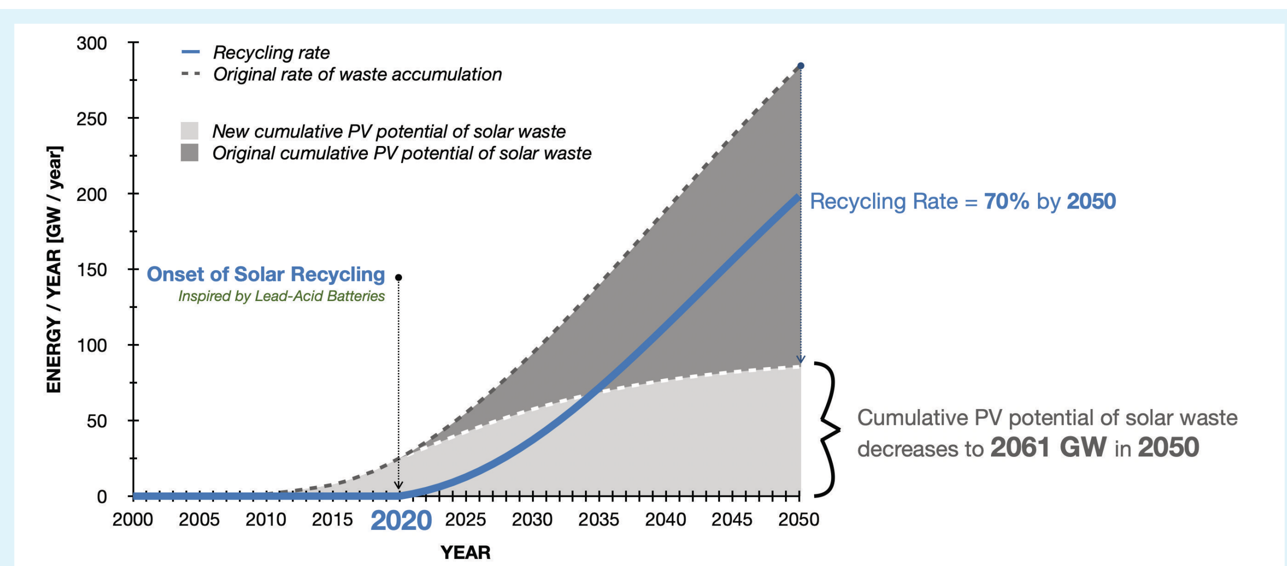


Fig. 9: *An ideal case, showing how a fast growth of recycling rates can result in a stable, plateaued rate of solar waste accumulation by 2050*

In the larger scheme of things, **Fig. 10** shows how the orange $\mathbf{SP_W}$ curves are kept in check in this scenario. We note that, by 2050, the energy production value of solar waste is less than half of what it would have been had we continued along our baseline scenario in **Fig. 6**.

The important takeaway is that recycling cannot be integrated into a supply chain overnight. Conscious decisions need to be made by consumers, producers, and governments alike in order to set the stage for a feedback system that takes advantage of the PV potential of solar waste and arranges for the recovery of its components to fuel the coming generations of technology. This is not easy. With the design of solar panels currently on the market, we may only be able to recover the bulk materials such as glass and external frames and wiring at a cost-effective margin. However, our analyses of critical materials show us that this margin is fluid and that it may serve as a stimulus for renewing the solar industry and encouraging large-scale recycling of solar panels within the next 30 years.

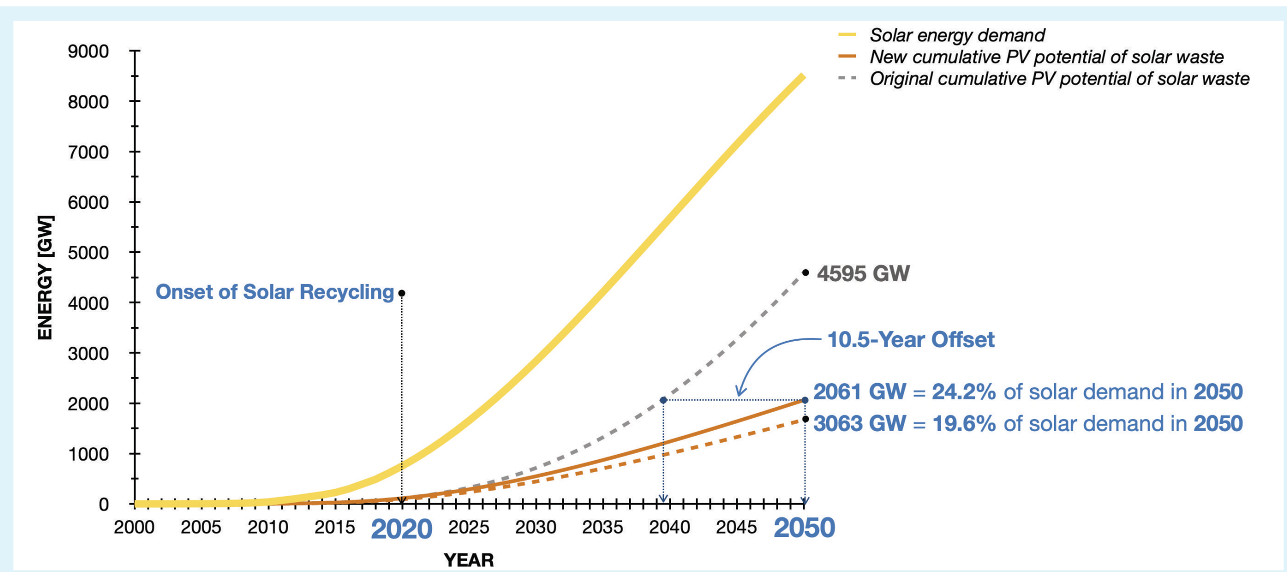


Fig. 10: *An ideal case, showing how a fast growth of recycling rates influences cumulative maximum energy production potential of solar waste until 2050*

Transparency as a Pathway to Accountability

The previous section was a thought experiment. The model served as a tool to explore the economic consequences of being too slow to embrace solar panel recycling. If we truly want to mitigate these issues before they become a pressing concern, we must take active steps to build a circular economy around solar panels that aspires to the benchmark established by the lead-acid battery industry. An ecolabel may be the option best suited to moving the system in this direction.

The Solar Scorecard was created by the Silicon Valley Toxics Coalition as a resource to aid the public in making informed consumer decisions around their PV purchases and the repercussions that they may have on a social and environmental spectrum. Ecolabels such as the Solar Scorecard take our SEEP analysis one step further in that they actively measure and collect data about implications such as the ones we explored and grade PV producers according to how they actively address these externalities. Such scoring systems are instrumental in creating transparency within the industry and revealing how different products stack up across different metrics. The benchmarks analyzed include emissions reporting, workers' health and safety, module toxicity, and extended producer responsibility.[83] As the solar industry is evolving, so too are these metrics.

One of the aspirations for the 2020 update of the Solar Scorecard is to implement a circular economy methodology into the system. Metrics for recycling have traditionally been limited to identifying waste collection and diversion streams; however, the Solar Scorecard will soon start asking producers more uncomfortable questions about how they recycle rather than if they do. This will help illuminate the true fate of an old solar panel and its components.

Resources such as the Solar Scorecard are vital in a market where consumers often feel overwhelmed by choices and are unable to fully understand the distinctions across the market landscape. The role of Solar Scorecard and other ecolabel certification resources are key to moving towards a circular economy. Ultimately, as consumers, we have the purchasing power needed to keep afloat the ethically-minded companies and demand change from the ones that cut corners. Providing unbiased information about a company's policies, externalities, and impacts will help those companies best equipped to reduce long term social and environmental impacts succeed.

Appendix

In this model, we tracked three crucial variables:

- $\mathbf{SP_{NR}}$ **:** the energy production capacity of solar panels produced from non-recycled raw materials (in units of GW / year). For years prior to 2019, this was based on historical data.[84]
- $\mathbf{SP_{R}}$ **:** the energy production capacity of solar panels produced from recycled raw materials (in units of GW / year). Historically, there has been no substantial recycling effort for "inactive" or "retired" solar panels. Thus, 2020 is the earliest year that we can introduce recycling.
- $\mathbf{SP_{W}}$ **:** the theoretical energy production potential of solar waste (in units of GW / year). This is to show the energy that "inactive" or "retired" solar panels in waste streams such as landfills, could potentially generate if their lifetimes were extended either by advancements in research and development or by recycling initiatives that aim to recover their components.

For years up to and including 2020, $\mathbf{SP_{R}}$ = 0, reflecting the lack of recycling initiatives. For every given year between now and 2050, we will assume that the integrated sum of $\mathbf{SP_{NR}}$ and $\mathbf{SP_{R}}$ is equal to IRENA's projected cumulative solar photovoltaic capacity in GW for that year, as shown in **Fig. A1**. We use IRENA's projections as it takes into consideration resource availability, market potential, and cost competitiveness of solar energy in context of policies and supporting consumer engagement in the clean energy transformation.[85]

As IRENA's raw data was unavailable to us, we decided to create a polynomial fit of their key projections in order to express cumulative solar photovoltaic capacity as a continuous function. In the model, this takes the form of $\mathbf{T_{SP}(t) = at^3 + bt^2 + ct + d}$ where $\mathbf{T_{SP}(t)}$ is the cumulative solar photovoltaic capacity in t years after the year 2000. The coefficients calculated were a = 0.1249, b = 15.0018, c = 304.2233, d = 1836.8. In physical terms, $\mathbf{T_{SP}}$ is the sum of the photovoltaic capacity of solar panels produced using both non-recycled and recycled components. Thus,

$$T_{SP}(x) = \int_0^x SP_{NR}(t) + SP_R(t)\, dt \tag{1}$$

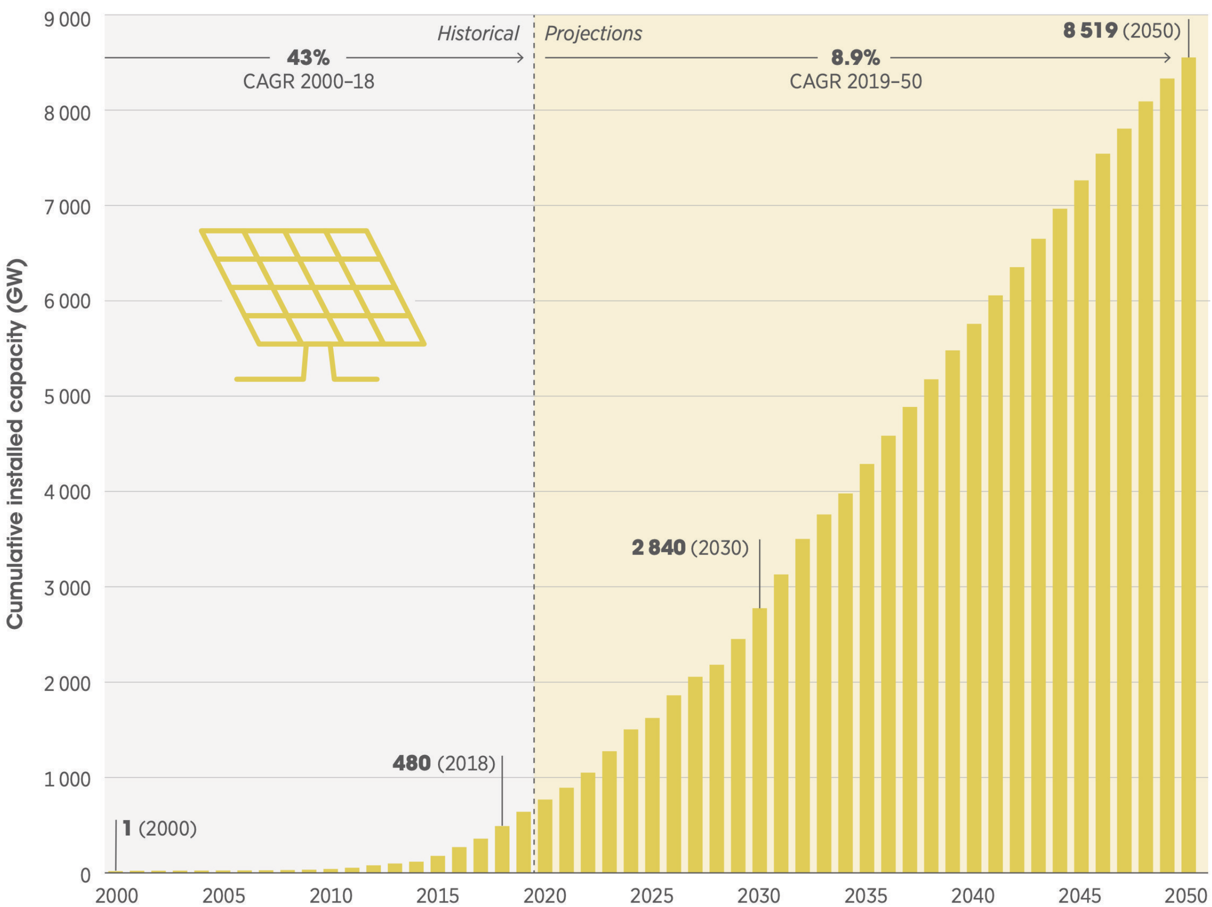


Fig. A1: *IRENA's future projections of cumulative solar photovoltaic capacity*
SOURCE: IRENA, 2019

The residence time or lifetime of solar panels is denoted as $\mathbf{t_{SP}}$ which is set to be 30 years. This is assumed to be uniform for solar panels produced from both non-recycled and recycled raw materials. This allows us to calculate the waste accumulation rate:

$$SP_W(t) = \frac{T_{SP}(t)}{t_{SP}} \tag{2}$$

From here, calculating the cumulative energy production potential of solar waste, $\mathbf{T_W}$, is a matter of integrating over the years such that

$$T_W(x) = \int_0^x SP_W(t)\, dt \tag{3}$$

In the business-as-usual case, wherein recycling is not introduced by the year 2050,

$$T_{SP}(x) = \int_0^x SP_{NR}(t)\, dt \tag{4}$$

because $\mathbf{SP_R(t)} = 0$ for all $\mathbf{t} \leq 50$. Thus,

$$T_W(x) = \int_0^x \frac{T_{SP}(t)}{t_{SP}}\, dt \tag{5}$$

In **Fig. 7**, $\mathbf{T_W}$ was depicted as the solid orange line. The dashed orange line was 81% of $\mathbf{T_W}$, representing the lower bound fraction of cumulative energy production potential of solar waste that can be recovered by recycling methods that have been explored thus far. In the future, we expect this fraction to increase as recycling processes develop and become more efficient.

In the case that is modeled on the trajectory of plastics reuse and recycling from 1980 to 2010, the onset of recycling, $\mathbf{SP_R(t)}$ was to be modeled as a continuous function. The 30-year time period beginning from 1980 was chosen as it marked the most notable and rapid increase in consumer recycling habits following the success of Woodbury, New Jersey, the first city in the US to mandate recycling through a curbside pickup program which soon became a national model.[86] Data from the EPA was used to calculate the increase in plastic diversion rates.[87] The following table summarizes the information gathered and calculated:

Year	Plastics Generation [Tons]	Plastics Landfilled [Tons]	Fraction Diverted [%]
1980	6.83 million	6.67 million	2.34
1990	17.13 million	13.78 million	19.56
2000	25.55 million	19.95 million	21.92
2005	29.38 million	23.27 million	20.80
2010	31.4 million	24.37 million	22.39

SOURCE: EPA, 2020

Note that plastic diversion includes both reuse and recycling. As solar panels cannot be "reused" after disposal due to effects of chemical leaching, loss in efficiency, and damage, the fraction diverted was translated as the fraction of solar panels recycled when applied to the model.

From 1980 to 2010, plastic diversion rates increased by 20.05%. When applied to the model, the goal was to achieve a recycling rate of at least 20.05% by 2050 if the phasing in of solar recycling were to begin in 2020. The following equation was used to model the recycling rate, $\mathbf{SP_R}$ as a continuous function of time:

$$SP_R(t) = x_R \cdot SP_W(t) \cdot (1 - e^{-t/t_P}) \quad (6)$$

where $\mathbf{x_R}$ = 0.30 and $\mathbf{t_P}$ = 20 years.

These values of $\mathbf{x_R}$ and $\mathbf{t_P}$ were chosen as they provided the necessary increase in recycling rates by the end of the 30-year period (i.e when t = 30). Computing $\mathbf{SP_R}$ in this way translated to an increase in recycling from 0% in 2020 to 23% in 2050. Although 23% is greater than the observed 20.05%, this loose fitting was deemed appropriate for two reasons. Firstly, as $\mathbf{t_P}$ is a variable of time and since the model claims to make no arguments with respect to increments of time that are smaller than a whole year, $\mathbf{t_P}$ was rounded to the nearest whole year. As such, the extent to which $\mathbf{t_P}$ could be adjusted for a closer fit was limited and $\mathbf{t_P}$ was chosen such that it provided an increase in $\mathbf{SP_R}$ that seemed appropriate. Secondly, it is important to note that lessons which were learned during the phasing in of plastic recycling can be applied to the solar industry's future as well. This means that recycling of solar waste will likely be more structured and its rate of increase is expected to be higher. As such, this loose fitting that falls within a reasonable range of the threshold set by plastics was used.

By calculating $\mathbf{SP_R}$, we are able to decrease $\mathbf{SP_W}$ by establishing the following relation:

$$SP_{W,new} = SP_{W,old} - SP_R \quad (7)$$

$\mathbf{SP_W}$ can be replaced by $\mathbf{SP_{W,\,new}}$ in equations (2) and (3) to recreate the same analysis as before but for recycling rates that are modelled on historical plastic recycling.

In the case of recycling that is inspired by the rates achieved by lead-acid batteries, $\mathbf{SP_R}$ was defined in the same way as in equation (6); however, $\mathbf{x_R}$ was set to be 0.99 × 0.81 and $\mathbf{t_P}$ was 15 years. Here, the choice of $\mathbf{t_P}$ was similarly limited. $\mathbf{x_R}$, on the other hand, was strategically chosen as 0.99 is the target recycling rate of lead-acid batteries and 0.81 is the recycling efficiency that can be reasonably achieved by current methods and process technologies. Therefore, $\mathbf{x_R}$ denoted the target recycling rate that could be achieved by aspiring for the recycling rate of lead-acid batteries while also taking into account the practical limitations in the efficiency of solar recycling. As was the case for the plastic recycling described above, equation (7) was used to relate $\mathbf{SP_R}$ to the other variables in the model and to analyze the results in a similar fashion.

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