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Abstract: Energy demand continues to grow with the world's burgeoning population. Meeting energy needs through renewable sources allows for market growth with limited environmental impact, but sourcing constraints can limit production, creating industrial and environmental problems. The exploitation of end-of-use and end-of-life photovoltaic (PV) options that are traditionally treated as waste offers a valuable opportunity to support renewable energy market growth with fewer sourcing constraints and minimal environmental impacts, but this circular investment has not yet been broadly implemented, nor is broad guidance widely available to aid its implementation. From a business perspective, this paper discusses the technical issues, assesses the anticipated market growth issues, and proposes a combination of circular economy, industrial ecology, and process integration principles to contribute a theoretically supported, practical framework to improve the management of end-of-use/life PV products and support renewable energy market growth.

Keywords: photovoltaics; end-of-life; recycling; renewable energies; circular economy

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1. Introduction

Two economists, Malthus and Solow, presented conflicting perspectives on how to balance industrial progress with planetary limitations. Malthus believed overall restraint (of material use, population growth, etc.) was needed, while Solow suggested that human innovation (in the face of emerging planetary constraints) would provide problem solutions, and thus restraint was unnecessary [1]. While the optimal positioning likely lies between the two extremes, all manufacturers and supply chain partners face substantial environmental and economic issues resulting from the natural tension between material supply and market growth. These issues can be diminished with the appropriate exploitation, management, and integration of end-of-use and end-of-life products and processes, but the cost effectiveness and financial impact of different end-of-use strategies remains unclear; hence, producers often find themselves making critical decisions based on subjective factors.

It is well-recognized that energy demand is growing, from all consumer sources and global regions. The overall growth from 2020 to 2021 alone is expected to be almost 5% (surmounting even the use loss resulting from COVID-19), and the portion of the market growth generated from renewable sources is expected to rise from 17.1% to 24% by 2030 [2]. Within these growing energy needs, renewable sources are one of the fastest growing energy generation options for many developing economies, where traditional utility infrastructures may be inadequate but the economic growth is still expected to outpace that of developed economies. These characteristics suggest that the renewable energy market has important implications for developed and developing nations alike. Developed nations may invest in renewable energy options as a way to reduce their environmental footprint and offset their non-renewable energy production methods of the past, while developing nations are eager to benefit from renewable energy options that lessen their dependence on outside sources and provide the fuel needed to drive their growing economic engines [3,4].

As renewables become larger players in energy production, their manufacturing and supply chain partners must ensure that they can sufficiently and sustainably support the consumer demand. Unfortunately, resources to guide this industrial transition are sparse.

The objective of this paper is therefore to provide a theoretically supported and practical framework to guide PV firms and supply chain partners to proactively address end-of-use and end-of-life environmental and economic concerns, improving their ability to develop and sustain a competitive advantage and remain resilient industry players despite market disruptions of all kinds. Theoretically, this paper contributes by extending recycling, remanufacturing, and circular integration perspectives to renewable energy applications, particularly photovoltaics (PV). Practically, it applies sound theory to develop a strategic framework that can help PV firms and supply chain partners improve their management of end-of-use/life PV products and support sustainable renewable energy market growth.

Among the renewable energy options, PV has fewer use constraints than most. Sunlight falls everywhere on the globe, whereas not all locations are suitable for hydropower or geo-thermal generation, and public support for wind power or bio-energy projects can often be felled by NIMBY (not in my backyard) opposition. Notably, PV can be installed at any scale, from a single 100-Watt module to power a remote off-grid village home to hundreds of megawatts to power an entire grid. This enhances its applicability to provide clean energy everywhere. Thus, this paper addresses only PV renewable energy market growth.

Among supply chains, the PV supply chain is distinctive [5]. It is notably driven by and dependent on government policy. In addition, it is extremely sensitive to inventory fluctuations, raw material shortages, and geopolitical tensions related to supply sourcing; thus, this paper will focus on addressing PV sourcing and supply issues.

A significant contributor supporting the use of end-of-use/life materials in PV is the limited supply of the resources necessary for their production [6], with shortages forecast particularly for critical metals and polysilicon [7,8]. Even complementary materials that are not geographically constrained are in short supply due to inequitable market distribution and COVID-related supply chain disruptions. In addition, given the anticipated renewable energy market growth, and steady price declines from the improvement of economies of scale and targeted industry support in select countries, many material constraints are expected to continue through to at least 2050 [9]. This scenario provides a unique opportunity to develop alternate sourcing options now, through the circular integration of end-of-use/life products in the PV supply chain. The framework provided in this paper contributes to the literature by elucidating how and when to identify and integrate alternate PV sourcing from end-of-use and end-of-life PV products into the manufacturing cycle, in order to support robust future industry and market growth.

Circular integration is a multi-step and iterative process that applies a combination of circular economy, industrial ecology, and process integration principles [10] to meet the growing consumer demand for PV products, and to modify PV product designs to ease disassembly and broaden end-of-use/life options; all to ensure the adequate supply of the end-of-use/life products to recirculate into meeting consumer demand. An integrated process reduces the need for virgin PV materials, reallocates the end-of-use/life products formerly considered waste to the start of a new manufacturing cycle, and creates new or expanded markets for PV.

The capture and management of end-of-use/life PV products discussion here focuses on the major sources of PV product returns, i.e., consumer returns at the end-of-use or end-of-life. Manufacturer waste is a possible, but distant, source of material. With many PV products in the growth stage of the product life cycle (some types exist in the earlier introductory stage, while others exist in the latter mature stage), the current demand for remanufacturable material is much less than the current supply, yielding a surplus and contributing to literature gaps on how or why to address PV end-of-use/life. Nevertheless, the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS)

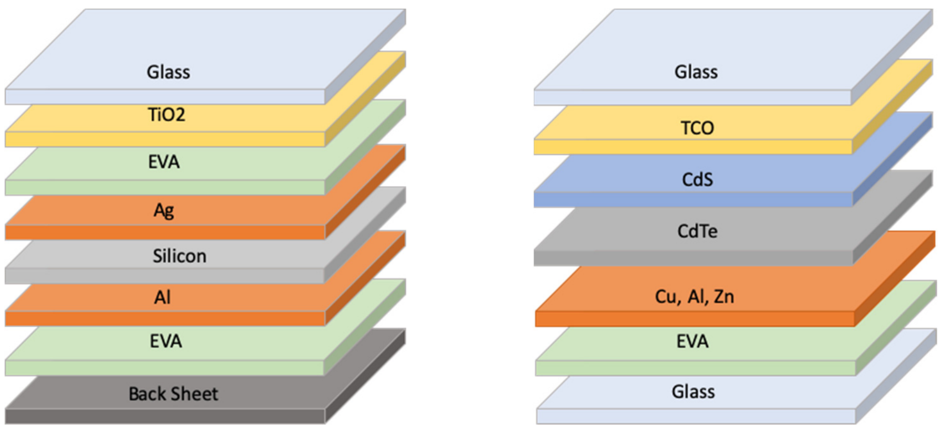
Task 12 and the International Renewable Energy Agency (IRENA) both forecast substantial available end-of-life module waste within 10–20 years [11], providing not only a valuable opportunity to incorporate these materials into the PV supply chain but also an opportunity to fill the literature gap and develop practical solutions in advance of the surge in available remanufacturable PV material.

The critical differences among PV types and between end-of-use and end-of-life PV products are discussed in Section 2, as their value and potential outcomes differ, and thus affect the integration paths which are possible.

2. Technological Issues and Opportunities

The PV market has grown by an average of 30% over the last decade. It continues to grow steadily and globally, in both manufacturing capacity and installation. The market is currently dominated by silicon technology, both monocrystalline and polycrystalline, which comprises 95% of the 2020 market. The second most dominant technology is cadmium telluride, primarily concentrated in the offerings of First Solar, which had a 2020 market share of 4% [12]. A fast-rising technological contender is perovskite modules. Recognizing the distinctions between the three major technologies is critical, as the same end-of-life/use strategies cannot necessarily be applied to all.

An important distinction between the three major technologies is their differing fabrication methods. Silicon technology uses modules based on 150–200 µm thick wafers that are specifically diced to size and sandwiched between two layers of encapsulant, after being interconnected with tabbing ribbons. The silicon modules have a protective pane of glass on the sun-directed side, a composite plastic back sheet on the opposing side (a junction box resides externally), and a frame (generally aluminum) finishing the structure [13,14]; see Figure 1 for details. The two other technologies, cadmium telluride and perovskites, are called thin-film technologies, because ultra-thin layers (or films of around 1 micrometer or less) of metals, dielectric and semiconductors are deposited directly onto a substrate (glass or flexible), and a circuit is created via mechanical or laser scribing to yield a working module [13,14]; see Figure 1 for details. Thin-film components, particularly if they are encapsulated, are more difficult to separate compared to the more modularly assembled silicon wafer-based technologies. This distinction affects end-of-use/life disassembly and reuse or recycling options, because the ease of separation/disassembly contributes to the speed and fiscal benefits of the system reintegration.



(**a**) (**b**)

Figure 1. Left (**a**): structure of a standard PV silicon module. Right (**b**): structure of a standard CdTe module.

Another important distinction is between the complete PV system and the PV module which provides the power for that system. A simple PV system, connected to the electric grid, consists of the PV module and the balance of systems (BOS), which consists of a mounting system (fixed or tracking (of the sun)), an inverter (or several micro-inverters), electrical connecters and the electric panel. In terms of reliability and functionality, the chances of significant degradation for an entire PV system are small during the first 10 years of service. Most early issues appear in the inverters due to complex electronic circuits, rather that the module itself. The other BOS components are passive (wiring, metal racking, manual isolation switches), and are thus very unlikely to experience degradation or failure. Total module failure is uncommon; rather, their performance habitually decreases or degrades over time, and thus PV modules tend to be longer-lived and in fact more reliable than the other system components. Steady module degradation is well characterized and largely predictable. All manufacturers provide a guaranteed power output over time, typically retaining 80% of the original power rating after 25 years. Random module degradation can be caused by localized extreme weather conditions (e.g., hailstorms) or various production or assembly flaws (e.g., hot-spots, potential induced degradation, delamination, glass breakage, quick connector failure or moisture ingress), which are specific to a certain technology or are more preeminent in certain technologies.

Identifying the likely type and origin of a PV module failure and separating that failure from the failure of other system issues is technology dependent, and is a significant issue in the determination of whether a product is end-of-use (it is still working but the consumer no longer wants it, or it is not working but is repairable), or end-of-life (it is neither working nor repairable, but can be cannibalized for parts or recycled). Some recycling initiatives currently exist for PV system components, such as steel racking or copper wiring. Some recycling initiatives currently exist for PV modules, using a variety of processes (delamination, material separation or purification) to separate the high-value materials [15–20]. For Si modules, the highest value components are the Si wafer and the Ag contact metal. The Si wafer must be removed without breakage for the maximum reuse value. For the CdTe modules, the Cd and Te are the most valuable to recycle. Note that these components—Si wafers and Ag and CdTe thin-film layers—represent a very small portion of the module by weight or volume. The single or double layers of glass represent by far the bulk of the weight and volume for both Si and thin-film modules. Most of the current recycling initiatives involve thermal, chemical or mechanically based separation methods, and all have various economic and environmental benefits or consequences. Preferably, PV materials would be able to be separated for recycling usage for an economic benefit and without a negative environmental consequence, but the current product designs were not initially created with these goals in mind; thus, an optimal process for end-of-life PV recycling is not currently available. A discussion on the re-design of PV products to integrate these goals and support market growth is included in Section 3.

3. Market Growth Issues

The underlying issues that must be evaluated with regard to PV market growth are demand changes, product design issues, and supply constraints. Each issue impacts potential end-of-use/life PV options, and thus must be considered as critical components of the eventual management framework. Brief discussions on the essential points for each issue follow.

3.1. Intensifying Sustainable Market Demand

As energy demands grow globally, world leaders are increasingly recognizing that citizens must be protected from the negative environmental repercussions that can accompany economic growth. One approach applied to address this environmental/economic conundrum is legislation that supports, subsidizes, and advocates for renewable energy generation options. Even before the COVID-19 pandemic disruptions, economic policies prioritized the development of and investment in PV energy generation, particularly in the European Union and other economic blocks. During and after COVID-19 production disruptions, much of the planet's population experienced clearer skies and reduced secondary pollution. This refreshing experience strengthened citizen and leadership support for renewable energy investments, and has resulted in economic recovery packages that combine pandemic and renewable energy investments. For example, the Biden Administration (US) is advocating for 80% of U.S. electricity generation to come from renewable or clean sources by 2030 [21], adding to the pre-COVID renewable energy demand that was already projected to be unmet prior to Biden's advocacy.

The IEA predicts the post-COVID energy use surge will generate higher CO_2 emissions than ever before [22], and those emissions can only be minimized by using and expanding renewable energy generation. Economies that have already invested in renewable energy options to drive down their emission contributions have already helped lower the global projected emission levels. As these results proliferate, more investment opportunities will become attractive, and more consumers will desire renewable energy options, thus intensifying the sustainable demand for the PV market.

3.2. Product Design Issues

The PV product design is crucial, as it drives virtually all possible integration options. First and foremost, the product design (or redesign) must support the use of non-virgin materials while still meeting quality standards. Past products were often designed to meet quality standards with few material constraints, under the assumption that virgin materials at the right price, quality, and volume requirements would both be available and the most effective. With many virgin material sources gone or depleted today, alternate sources must be considered and incorporated into the design. A particular challenge for the creation or modification of an integrative PV product design is that PV products are typically designed and manufactured decades prior to their potential return. Their lengthy life cycle has allowed them to avoid many of the current advanced design principles, such as design for reuse/recycling or design for disassembly, etc. Their prolonged return lead time also covers vast changes in technology, regulation, and material advances, creating uncertainty and more complex PV design requirements, in addition to their high quality, efficiency and durability needs.

For example, the modification of a PV product design to provide multiple disposition options (e.g., remanufacturing or refurbishment, cannibalization for component parts, recycling of the whole or parts, or full disposal) requires capturing and addressing all of the routine PV design requirements, plus a determination of the future responsibility scope, strategies, activities, and environmental and economic returns [20]. Multiple interdependent decisions must be made. The more modular design of silicon PV products could be leveraged to allow for easier component disassembly, testing, and reassembly than the encapsulated design of thin-film PV products, but would enhancing the modularity negatively impact the product quality? Should the manufacturer take vertical responsibility for the collection of end-of-use/life products, or contract that step to third parties? Which collection option is expected to yield the highest return? Are there intellectual property or safety issues that would discourage product reuse in other applications or in other markets? These evaluation decisions influence the disposition options for both the previously produced PV products we hope to integrate at their end-of-use/life, and the PV product designs we hope to modify moving forward.

Product design modification decisions based on predictions must allow that actual business or regulatory decisions and technological developments may not materialize, and thus there is significant inherent risk. However, suitable design methodologies that provide benefits regardless of the materials at hand or contextual predictions include the use of standardized parts; limiting hazardous, toxic, or fused materials; aspiring for flexible, modular designs (to allow components to be swapped out in order to extend life or for them to be dismantled to repair others); damage resistant designs that can be easily inspected, tested and disassembled; and the use of clearly indicated and durable component part identification [23].

3.3. Ensuring Adequate Supply

Ensuring an adequate supply of end-of-use/life PV materials is very dependent on the condition of the PV product and the PV product design itself. The value of the recovered product often determines which supply acquisition strategies are applied, and through which supply chain channels. Higher value goods, whether of fiscal or intellectual property value, are more likely to be directly acquired through vertical company strategies, with choices requiring various cost assessments, such as the development and maintenance of the collection infrastructure, transportation and storage, etc. With many of the necessary PV production materials now being in limited supply, PV producers are more likely to accelerate their own acquisition strategies. Complementing this, government entities are increasingly enforcing extended producer responsibility (EPR) policies that hold PV producers responsible for the entire life cycle of their products. In order to meet these needs, for example, the majority of European PV manufacturers are partners in PV Cycle, a non-profit organization addressing global PV waste and compliance issues [24]. Because PV producers will be held responsible for end-of-use/life products anyway, why not invest in reallocating that former waste cost to a potential future asset while simultaneously addressing supply constraints?

By 2050, it is estimated that most PV waste will come from China, Europe, and North America [25]. Many PV materials can be recaptured from end-of-use/life PV products, and either reused immediately or recycled into "new to you" materials for production processes. First Solar reports a recovery rate of up to 90% for end-of-use/life semiconductor material and glass for use in new modules [26], and their capacity is scalable to adapt to the coming surge of PV product returns. Sourcing valuable components and elements (usually from waste electrical and electronic equipment (WEEE)) has been labeled "urban mining" [27], and can be more cost-effective than traditional mining options, as those investments have lagged behind demand projections. Indeed, the constraint here is less that the materials are not suitable or are of inappropriate quality, but that (with the exception of First Solar) the return and collection infrastructure has not yet been suitably developed to support such ventures. Given the anticipated PV market growth, and the expected arrival of significant volumes of end-of-use/life PV products, now is the time to invest broadly in the development of the needed collection infrastructure and integration capacity so that PV firms can both gather the materials needed to support future production demands and develop a sustainable competitive advantage.

The current PV supply is more centralized than the future available supply. For example, the current customer PV end-of-use/life product returns are predominantly located with their customers in more developed economic regions, such that the logical entry gate for returns would be there, with possible fiscal incentives being applied to encourage a higher quality and more homogenous returned product, if needed. The development of the remaining infrastructure following collection—e.g., PV product grading, disposition, and material reintegration—will be contingent on each PV manufacturer's unique product and supply chain, although it is anticipated that aligning geographic and/or skill specializations will also influence decision-making. Depending on the ability of the company to influence the end-of-use/life product quality levels, companies will need to inspect and make disposition decisions on PV modules reflecting a wide range of acceptability. For example, returned PV modules could be representative of any point on a continuum from poorly selected but functioning perfectly, and thus capable of an immediate return to the market, to completely end-of-life, unable to be reused at all and being suitable only for disposal. In addition, due to environmental policy changes regarding PV product or processing materials (particularly metals or chemicals), some returned PV modules may now be banned, or may require processing steps that are too hazardous, and thus cannot be integrated into the PV energy market. Ideally, if the grading step is managed correctly, the company can optimize the output of the process in both economic and environmental terms.

4. A Framework for Improved Management

Improving the integration process for the PV market and PV products will require iterative decision making to create balanced and system-wide benefits.

The main starting point is product design or redesign so as to include the end-of-use/life PV products that will become available in volume in the near future, and to begin integrating the current low volume levels of those same products. Part of the redesign evaluation should be an assessment of which of the PV system components are more or less likely to fail or need replacement, when that is likely to occur, and which of those components can be reused more frequently. For example, with a PV module reliability greater than that of the inverters, the end-of-use/life protocols will differ between those two PV components, even though they are both contained in the same PV system.

The processing methods to manufacture the redesigned PV products must then also be redesigned to support those new product varieties, and supply chain connections must be adapted to possible new partners and stakeholders. Greater results and progress speed can be achieved if PV manufacturers are willing to collaborate on product and process system redesigns, as combining expertise would likely produce higher quality outcomes. Those collaborations are likely to be technologically distinct, given the differences in module types, but do not have to be. There is a risk to sharing information, and the cross-pollination of expertise across technology types could lessen the perceived risks of the individual firms. Some examples of this cross-pollination have already been offered through PV Cycle.org, through its role as a member-based non-profit which focuses on industry-wide versus individual-member improvement initiatives.

Concurrent with the PV product and processing modifications, infrastructure development needs should focus first on identifying and implementing appropriate collection strategies for end-of-use/life products. For example, collection methods will most likely require decentralized pick up, because returning modules would be unwieldy for the typical consumer, and thus logistics optimization would be emphasized. Developing this infrastructure capacity is timely and costly. Various methods (decentralized versus centralized) and routes (intermodal, etc.) could be tested with the current low levels of returned materials, and then expanded to scale as material volumes increase. First Solar's methods already meet these criteria, but address only 4% of the world's PV. PV Cycle works with all PV types and has global outreach, but a majority of its partnerships are via the European Union. Full circular integration will require a global footprint and connections.

In conjunction with the development of the return and collection infrastructure, in order to fully integrate the end-of-use/life products and materials into the PV supply chain, the products need not only to be collected and aggregated but also, based on the technology type, protocols must be developed and implemented for disassembly, testing, and remanufacturing for end-of-use products, or recycling for end-of-life products. As indicated above, developing these procedures under the lower volumes of PV material now available would allow for pilot testing and incremental improvements to take place before having to manage significantly larger material volumes. In addition, with Industry 4.0 advances, disassembly, testing, and remanufacturing or recycling protocols should involve automation, in order to speed the return to market of products or materials, reduce the longer-term human process cost (as haphazard recycling efforts are often outsourced to less-developed economies with limited worker protections), and enhance the profit margins of the returns process. In order to provide a related example from mobile phones, Apple's Liam and Daisy robots were developed to aid in the material recovery process of their end-of-use iPhones [28]. While Apple's automated process has some constraints—i.e., it requires more standardized inputs and a relatively high up-front investment—once established, the robots can handle up to 200 phones per hour. Leveraging this vertical integration of their product's life cycle, Apple has also recently reported that it intends to make its phones completely from recycled materials by 2030 [29], reducing its reliance on external material or geo-political partners.

If end-of-use products are determined simply to be working but less desired by primary consumers (e.g., want to upgrade), or working but repairable, secondary markets can be developed for these PV products to gain supplemental revenue for the manufacturer. With the predictable degradation being relatively low (e.g., module efficiency decreases of less than 20% after 25 years), the potential exists to reassign these types of PV products from developed to developing regions (similar to the secondary mobile phone market), or from applications that require higher efficiency to applications that can tolerate lower efficiency (similar to battery reassignments from electric vehicles to home energy storage) to expand or create new markets. Higher efficiency needs are unique to certain PV applications, but are not necessarily needed for all. There is a guaranteed global market to be had for remanufactured—or "new to me"—PV, at a cost reduction from that of new PV, especially if the remanufactured PV comes with manufacturer-sponsored warranties for the expected efficiency and life span.

Less product-specific, and more contextual, PV manufacturers should also work with political leadership to craft supportive policies that can not only subsidize or ease the path toward the needed end-of-use/life infrastructure investments but also generate or reinforce the continued market demand. Although it is not under their immediate control, the political context sets the stage in which PV manufacturers must exist and try to thrive. If they are not already aware, legislators can be educated on the strategic connections between global climate change challenges, PV material shortages, and the geo-political tensions related to energy production and independence. Regardless of individual political parties or priorities, representatives are keen to develop, be associated with, and support initiatives that positively address both environmental and economic needs, as this integration process does.

5. Conclusions

The continued growth of the renewable energy market, particularly the PV sector, combined with significant environmental and economic managerial concerns regarding end-of-use and end-of-life products, provides challenges and opportunities for the entire industry. Despite the immense economic and environmental value of the circular integration of end-of-use and end-of-life photovoltaics, this process has not yet been broadly implemented, nor are guidance frameworks available to aid its implementation. From a business perspective, this paper discussed technical PV issues, assessed anticipated market growth issues, and proposed a combination of circular economy, industrial ecology, and process integration principles to contribute a theoretically supported, practical framework to improve the management of end-of-use/life PV products, and to support renewable energy market growth.

Theoretically, this paper contributes to the literature by extending recycling, remanufacturing, and circular integration perspectives to renewable energy applications, particularly photovoltaics. Practically, it contributes by applying sound theory to develop a strategic framework that elucidates how and when to identify and integrate alternate PV sourcing from end-of-use and end-of-life PV products into the manufacturing cycle, in order to support robust future industry and market growth. The application of the framework to guide managerial decisions will help PV firms and supply chain partners proactively address environmental and economic concerns, and better develop and sustain a competitive advantage so that they can remain resilient industry players despite market disruptions of all kinds.

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