METHODS TO ATTAIN A SUSTAINABLE FUTURE IN END OF LIFE MANAGEMENT FOR SOLAR PANELS

By

Kyle Joseph McKeown

A Project Presented to

The Faculty of Humboldt State University

In Partial Fulfillment of the Requirements for the Degree

Master of Business Administration

Committee Membership

David Sleeth-Keppler, Committee Chair

Harinder Singh, Committee Member

David Sleeth-Keppler, Graduate Coordinator

July 2014

ABSTRACT

METHODS TO ATTAIN A SUSTAINABLE FUTURE IN END OF LIFE MANAGEMENT FOR SOLAR PANELS

Kyle Joseph McKeown

The United States has in the past 10 years pursued renewable energy to reduce emissions and to diminish our reliance on coal, natural gas, and of course oil. Photovoltaic (PV) solar systems have been leading the way to attain the goals that were set, compiling over 13 gigawatts (13 billion watts) installed since 2006. With the necessary increase in solar energy, a natural alarm is raised regarding the implications that panels present once they have reached their end of life (EOL). This paper identifies main solar panels that are used today and the implications that each has in regards to recycling at EOL. Additional aspects affecting EOL management include consumer expectations and rigorous product take-back regulations that force companies to consider EOLM. Many manufacturers and third-party recyclers have already taken an initiative to introduce state of the art recycling programs, setting the stage for the PV industry. With each panel design comes a different recycling process, material recovery, and ultimately price. By analyzing the different panels and procedures that recyclers and manufacturers have in place, I created a model to recognize the paths available for newcomers. Each path has its own set of implications that will need to be assessed by management to generate the optimal product take-back program for the company.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

INTRODUCTION

In light of the ever-increasing demand for energy renewable sources are becoming progressively more popular among residential, business and government customers. Photovoltaic (PV) systems are the current market leaders in renewable energy due to the relatively low cost of production, allowing for a decreased per watt rate to the consumer. Different types of solar panel systems each have their own advantages and disadvantages, with the most popular type being crystalline silicon solar panels (monocrystalline and polycrystalline). These crystalline solar panels are primarily made from pure silicon. Although crystalline systems have the highest efficiency, thin-film solar panel systems are gaining market share due to simplified manufacturing and flexibility during installation. Solar systems are designed to last 25 years at which the panel will have to be discarded, reused, or recycled. This paper describes different avenues in which solar manufacturing companies are implementing End of Life Management (EOLM) for PVs. A secondary focus is to identify new potential opportunities in EOLM. The ultimate objective is to provide a comprehensive overview of EOLM options to foster a discussion of sustainable best practices.

Solar Panel Types

Solar panels that hold the majority of the current market share include Monocrystalline, Polycrystalline, and Thin Film solar technologies. Appendix C shows different panel types, EOLM options, material shortages, regulations, and efficiencies of each panel design. Thin Film solar panels have become increasingly popular by demand the past few years due to their ability to be elastic, which allows for flexibility during manufacturing and installation. Many buildings, windows, and wind turbines are being encased by Thin Film solar panels. Thin Film technologies use substantially less materials throughout the manufacturing process, reducing production cost, and increasing application areas. Although thin film technology can be used in many different applications, the materials used in the panel are more detrimental to human health and the environment.

How Solar Panels Produce Electricity

The solar industry incorporates diverse materials in each solar panel such as, silicon vs. non-silicon (Cadmium Telluride and Copper Indium Diselenide), glass, aluminum, precious metals, lead, etc (Figure 1). At the top of a panel manufacturers place a blackout material and a UV enhancement film to reduce glare and direct sunlight into the glass structure. A solar panel is mainly composed of a glass structure, accounting for 80% of the material used in a solar panel. The glass works as a protective layer to the actual solar cells beneath, which is coated with a material to absorb the highest amount of sunlight possible. There are many different metals that convert energy into electricity; the more efficient, or conductive, the better. Gold, silver, and copper are by far the most used for electricity components in solar panels because of their conductive properties. The production of energy in a solar system originates with the semi-conductor. Most semi-conductors are comprised of a silicon wafer, absorbing sunlight through the glass that agitates electrons loose allowing them to flow unreservedly, which in turn creates an electric field. The electric field acts like a diode (electricity will pass in one direction only) allowing the loose electrons to flow freely “downhill” but not “uphill”. The flow of these electrons creates current, or the flow of an electrical charge. The current creates voltage, both current and voltage generates power (Toothman & Aldous 2012). Silicon is a very reflective material rebounding some of the photons before they can recoil electrons freely, which is why a reflective coating is applied before the glass is installed to conduct maximum power. The last step in the process of creating a Silicon based panel includes putting a rigid frame around the glass being comprised of lightweight aluminum. Positive and negative terminals are coated with copper or gold to allow for the most conductivity, and highest efficiency. By interlocking solar panels together it creates a solar array, possible of producing thousands of Kwhrs (Kilowatt Hours).

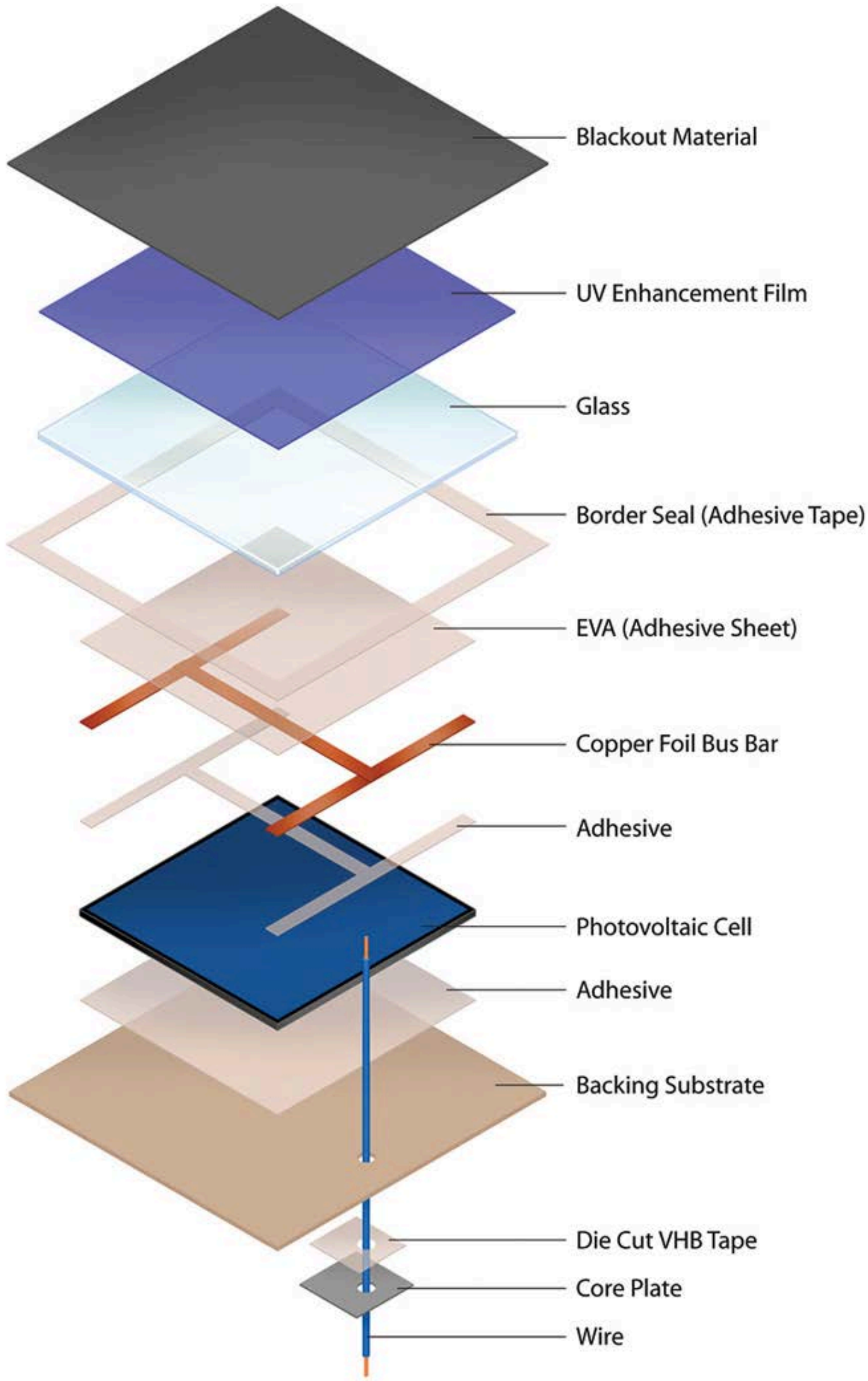


Figure 1: An exploded isometric view of solar panel materials

http://www.techartnc.com/Art_Solar_Panel.html

Market Leaders

Efficiencies, costs, and technological improvements have all contributed to solar panels becoming one of the most used renewable energy sources in the past 10 years. Panels are fetching extreme efficiency because of the materials used, such as cadmium telluride, a common material used in thin film solar panels, achieving upwards of 20% efficiency. In comparison silicon based panels have amplified their efficiency to over 40%, now possible from changes in the manufacturing process. Manufacturing of solar panels has become increasingly efficient, from their designs, to their flexibility, and most of all, using materials that have no short abundance. Panel designs have also become progressively important for manufacturers, installers, and third-party sources due to the demand for adaptable panel applications, while also designing a panel for disassembly and recycling at EOL. Many solar corporations have already initiated a response to the EOLM issue including First Solar, Suntech, and Solar World. These manufacturers produce both silicon based panels and non-silicon based (CdTe) to provide customers with a seamless PV system that will produce the highest energy output for every application. First Solar, one of the leading contributors to solar energy in the US and worldwide has installed over 8 GW (Giga Watts) or 8,000,000,000 watts since opening in 1999. First Solar implemented corporate environmental responsibility initiatives by complying with ISO 14001 (International Organization for Standardization), OHSAS (Occupational Health and Safety), and also introducing the first recycling initiative for solar panels in 2005. First Solar designed and installed state of the art recycling facilities that are operational at all locations, and are capable of accommodating scalable volume as more PV system reach their EOL at 25 years. First Solar's recovery rate for Monocrystalline panels is upwards of 95% of the semiconductor, and 90% of the glass, which can all be used to manufacture a new panel with the same efficiency. Cadmium and Telluride panels are not recycled at First Solar, but are shipped to a third-party recycler. Suntech, another leading manufacturer for PV systems has structured their organization to respond to the rapidly changing environmental shift towards sustainability and introduced global corporate responsibility. Suntech also introduced corporate responsibility initiatives such as ISO 14001 (Environmental Management Standards), OHSAS 18001, committing itself to the highest health and safety management standards. Suntech also introduced SA 8000, a broadly recognized trade union and NGO, as one of the strictest workplace standards worldwide that is used by leading companies to assess, monitor and influence social accountability. The standard focuses on the areas of health and safety, freedom of association, protection against child labor or forced labor, and protection from discrimination and disciplinary practices. In 2008 Suntech joined the Climate Group and Copenhagen Climate Council to collaborate with some of the world's brightest environmental and business minds and develop practical solutions for the reduction of greenhouse gas emissions (Suntech 2014). Suntech, however, does not have a recycling facility, instead they have a relationship with PV Cycle, a major contributor to the recycling of EOL PV systems. PV Cycle, a Europe based company out of Belgium, has designed and implemented procedures to collect and recycle large quantities of PV panels. PV Cycle uses primarily two methods in recycling PV panels, either shredding for silicon based panels, or using chemicals to separate layers in non-silicon based panels

(CdTe and CIG's). Upwards of 95% of materials can be recovered and used for new panel manufacturing. PV Cycle emphasizes reductions in operational costs for corporations by recycling panels for them, rather than a company designing and installing a complete recycling facility. PV Cycle is WEEE (Waste Electrical and Electronic Equipment) compliant to ensure proper EOL recycling minimizing environmental factors. PV Cycle's goal is to execute their commitment to sustainable waste management, by offering the best in class collection and services. Solar World, a US-based company, is the largest manufacturer of solar panels since 1975. Solar World is known for large-scale commercial and governmental installations that require experience and knowledge, which provides customers with reduced energy costs and advances energy independence. Although Solar World does not operate a recycling facility, they are committed to environmental stewardship. Solar World has reduced greenhouse gas emissions, reduced energy consumption by 20%, and has become solely powered by solar energy. The process by which Fist Solar, Suntech, PV Cycle, and Solar World operate their product take-back procedures, are in some ways very similar, and in others very different, which will be discussed in detail later in the case analysis section of the paper.

US Recycling Regulations

In the United States the federal regulations govern the states using the EPA guidelines. States have to abide by the EPA regulations, but have no law regarding recycling procedures or product take-back for solar panels. Disposal of solar panels is based on the Federal Resource Conservation and Recovery Act (RCRA), giving the Environmental Protection Agency (EPA) the authority to control hazardous waste from "cradle-to-grave." This includes the generation, transportation, treatment, storage, and disposal of hazardous waste (EPA 2014). In order to be deemed ‘hazardous’ by regulators, decommissioned or defective solar panels must fail to meet the US EPA Toxicity Characteristic Leaching Procedures (TCLP) standards in accordance with the RCRA (Larsen 2009). “In the US, the generator of waste is liable for the cost of any site remediation that might be needed in the future, even if the waste has been disposed accordingly” (Fthenakis Energy Policy 2000). With little regulation for solar panels at the Federal level, individual states must take the initiative to introduce regulations that enforce product take-back and cradle-to-cradle.

California Health and Safety

With the increasing demand for solar panels, EOLM is becoming increasingly important, and so are many aspects of human and environmental health. The toxic matter within a solar cell that conducts electricity and other components can be extremely harmful to humans and the environment, with prolonged exposure being known to cause cancer, other diseases, and pollution. Looking at the state of California, OSHA (Occupational Safety and Health Administration) completes more meetings and inspections than any other privately owned inspection agency. California OSHA has no record of any new regulation stating how or when a solar panel should be disassembled or recycled. California regulations regard solar panel materials to be E-Waste. E-waste is a popular, informal name for electronic products nearing the end of their "useful life" (CA Gov. 2013). Although California regulates E-Waste, the term can be very broad in what is to be considered E-Waste and the process in which the product is recycled. The State E-Waste recycling program continues to allow California waste to be dumped overseas to poor countries that do not have infrastructure to recycle the waste (SVTC 2013). This type of dumping devastates entire villages and impacts human health (Silicon Valley Toxic Coalition-SVTC 2013). In the same respect California has a policy, Hazardous Waste Control Law (HWCL), which is a stricter policy than E-Waste, but according to SVTC "of the 73 Bills related to the solar PV industry that were introduced in the California Legislature during 2007 and 2008, none addressed the manufacturing or end-of-life hazards discussed in [their white paper]. Most of the Bills focused on installation targets and tax incentives/rebates for photovoltaic adoption". These Bills in turn, could entice corporations to move elsewhere and get away from the "red tape", possibly harming California's renewable sector (Larsen 2009). Other states were not researched, as California is known to be the source and leader in the solar industry.

EU Recycling Regulations

Europe has created regulations to establish recycling initiatives, including Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) directives, established in 2003 to minimize the amount of electronic waste heading for landfills and incineration. RoHS restricts the use of certain substances, while WEEE regulates the collection, treatment and disposal of products, and places restrictions on their design (Larsen 2009). PV Cycle, a relatively new European company established in 2007, has one service in mind: recycling solar panels. This third-party recycling company has designed collection points, certified waste transporters and specialized recycling partners, to offer Europe's photovoltaic (PV) industries convenient collection and waste treatment solutions (PV Cycle 2014). "Most of Europe's solar manufacturing companies support EOL, while only a few in the USA, such as Solar World and First Solar, support total product take-back" (Goodcompany 2013).

In summary, regulations differ across many areas, with some instituting mandatory recycling, while others have very few regulations. Different regulations construct different needs for recyclers and manufacturers. The EU is the only one to influence recycling by including product take-back, fulfilling cradle-to-cradle. For countries that do not force recyclers to apply recycling programs for EOL panels, corporations and third part recyclers will have to design and construct a recycling program to fulfill product take-back and cradle-to-cradle.

INTRODUCTION TO EOLM MODEL

With the first solar systems coming to their terms, the emergence of EOL modules in 2040 is estimated to rise to 33,500 tons, from 290 tons in 2010, creating a sizable environmental issue if not properly dealt with (Muller, Wambach, Alsema 2007). Solar panel systems have dramatically increased since the early 2000's from 170 Mega watts installed, to 50 Giga watts in 2011, illustrating a 51% annual growth rate seen every year (Wesoff 2010). Panel design has also changed over the years, from the large silicon based panels to the light flexible thin film panels. EOLM has become a topic and issue for many of the large solar corporations. Many of the companies have already designed systems to complete product take-back and recycle the used panels that are either damaged or at the end of their terms. Designs of recycling for solar panels actually came about in the early 2000's when solar started to generate attention in the renewable sector. Vasilis M. Fthenakis, a member of the Environmental & Waste Technology group, designed a recycling procedure to allow manufacturers to reuse a majority of the old panel while remanufacturing at a low cost (Vasilis 2000). Vasilis developed two strategies: De-centralized and Centralized. De-Centralized recycling programs, involve more procedures, usually disassembling panels to separate materials and recover as much of the panel possible, but tends to increase costs and time. Whereas centralized recycling retains everything together, normally not disassembling the panel and using a smelter to melt the panel and later will separate materials. De-centralized treatment allows for the separation of hazardous metals from the glass and the metal frame. Within the De-centralized treatment, three distinct options are available. A recycler could melt the solar panel and send the materials to a refinery to extract pure metals that can be used for a new solar panel. The next option for a recycler would be to concentrate the solar materials by disassembling and sorting them to expedite the recycling process. The sorted materials can be then be put through a recycling process like ion exchange and solvent extraction, ensuring a high purity rating. The last process for the De-Centralized option is to recover materials directly, using electricity to separate different materials (electrochemically), which could then be refined and used to manufacture a new product. In 2000, companies such as Solar Cells Inc. used such a procedure to separate the panel components and recover the lead wires, glass, and precious metals. The components were then sent into a hammer mill and separated by glass and metal. At the end of the recycling process the company was able to recover roughly 80% of Tellurium and other metals at commercial grade purity 99.7%.

The Centralized method relies on the use of a large smelter, or a system that melts everything together, before separating the material (involving the same process used for computers monitors and consumer electronics). These recycling methods, although useful, appear dated compared to the latest recycling procedures that corporations such as First Solar and PV Cycle have introduced to recover the majority of the panel with the smallest impact on the environment. Many of these efficient and high tech procedures will be discussed later in the section about main manufacturer. In the same respect, different solar panel designs, by extension, require different EOL management strategies.

EOL Management Model

By researching and understanding all the different angles that are involved within EOLM for solar systems, I generated a model (Appendix A) that displays and identifies all relevant procedures created and currently used by multiple leaders in solar recycling, thus allowing for an overview of the options available, identifying of any potential bottlenecks in the process, and recommendations to improve any of the recycling procedures. The model covers two main categories of panel types: silicon-based and non-silicon-based solar panels. The silicon subcategory is comprised of both Monocrystalline and Polycrystalline, which are two different types of silicon panels. Monocrystalline is based on having one cell or ingot, while polycrystalline is comprised of multiple cells or ingots. The non-silicon subcategory includes cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), which are the main materials in these types of panels. Each categorized panel type has two options for product take-back. Companies can recycle the panel using infrastructure they have installed or ship the panels to a third-party recycler, such as PV Cycle. They can have the panel deemed E-Waste, or re-use the outdated panel. Recycling generates the least amount of pollution, and reduces the cost to manufacture a new panel, because materials recovered in the recycling process can be re-used to make a new panel. A disadvantage of recycling is the high upfront costs to design and install such infrastructure in-house, causing many companies to use third-party recycling agencies. Third party recycling companies simply charge a fee to recycler customer's panels, and will then ship the panels back after the recycling process. Third party recyclers also generate revenue when panels are dropped off with no intent of receiving the panels back. Companies like PV Cycle can recycle the panels and then either resell the raw materials, or manufacturer new panels. The costs for recycling through third-party is unknown, as well as the cost of the recycled materials compared to raw materials. Considering the panel as E-Waste, as described in the regulations section, results in the treatment of a solar panel the same as a TV or a computer. E-waste is usually shipped out of country for recycling, according to Silicon Valley Toxics Coalition (SVTC). Reusing the panel will still create renewable electricity, but as time goes on, the panel loses efficiency dramatically until the cell has no electrons left. The panel could then be recycled, reclaiming a majority of the usable materials, however a new cell would have to be manufactured instead of growing the dated 25-year cell to full capacity.

Recycling Process For A Silicon Panel

To recycle Silicon-based panels most companies, including First Solar and PV Cycle disassemble the panel into four components: aluminum frame, conductors, cell recovery, and the glass structure. The aluminum frame and the conductors (precious metals that transfer electricity) are placed in a shredding mill, then sorted and refined to a certain purity level. The raw metals that have been refined can then be used in the production for a new panel. The cell and the glass structure are put through a process to separate other materials while recycling the glass and sending the cell to the wafer production area. The cell goes through a growth process to increase the amount of electrons and size needed for a solar panel. All materials that have been recycled are then re-assembled to produce a new solar panel that has the same output as a panel built with raw materials.

Recycling Process For A Non-Silicon Panel

CdTe and CIGS (Non-Silicon Based Panels) require a far more advanced recycling procedure that the majority of current solar companies tend to avoid. PV Cycle is one of the few companies that accepts and recycles non silicon based panels, an option used by leading manufacturers such as First Solar. The recycling process begins with a shredding mill, same as the silicon panel, separating all glass from all other materials. The glass is then recycled using a similar procedure for the silicon-based program. All of the other materials like cadmium telluride, indium gallium selenide, and precious metals are put into a chemical bath to separate them. The metals are then refined and used together with the recycled glass to produce a new recycled solar panel. Although the process is much shorter than a silicon-recycling program, the chemical bath that is used to separate materials imposes health and environmental concerns. As for recycling solar panels today, many of the procedures and programs have not been tested on panels at EOL, but instead have only been tested on broken and malfunctioning panels. The solar industry has not received the first wave of solar panels due to the 25-year life span.

FACTORS AFFECTING PV EOLM OPTIONS

Product Take-Back

In light of regulations and increased consumer expectations for the responsible EOLM of panels, the majority of solar corporations have identified the need to implement any EOLM program to guarantee a competitive advantage within the market. In the United States, there is no law regulating the need for solar manufacturers to design and implement a product take-back program, whereas European regulations force companies to not only recycle solar panels, but also to have a product take-back system in place. PV Cycle, a European based company, prides itself for being the only recycler of solar panels for both small and large scale applications. PV Cycle has many collection points, mainly focused in Europe and newly expanding to the US, with a delivery request form for orders less than 40 modules, and more than 40 modules. Recently PV Cycle has discussed requiring manufacturers to clearly label their products so owners know how to handle their solar panels when they reach the end of their natural lives. This will provide further information for those receiving and treating the EOL panels, such as PV Cycle (Larsen 2009). One proposed idea is to have manufacturers and third-party recyclers like PV Cycle put a date, telephone number, and address for when the panel expires. Currently, consumers have to take the initiative to recycle the panels at EOL, but there seems to be forward-thinking discussion of changing that process and involving the manufacturers and third-party recyclers more directly. First Solar, a major manufacturer and recycler of solar panels does not initiate the process for EOL panels, but prides itself on providing a greater return on capital for power plant owners (First Solar 2014). The company has online forms to initiate the recycling process that is comprised of a pay-as-you-go system on a per unit basis, rather than a large upfront cost. Although in the United States there are no regulations for recycling solar panels, First Solar, and now PV Cycle, has generated a competitive advantage that will motivate other manufacturers and third part recyclers to follow. PV Cycle, being the leader in third-party recycling, would be able to use both recycling of silicon based panels and non-silicon identified in the model that was developed. PV Cycle, being capable of recycling all types of panels, currently has the competitive edge in the recycling market, and also the experience to innovate and establish new recycling programs that reduce emissions, producing a higher quality product once recycled. First Solar, and other companies that have invested in infrastructure to do in-house recycling, do not have the ability to recycle all types of panels. First Solar, for example, would only be able to follow the silicon-based path, as they have been doing since 2005. Product take-back does generate an initiative for in-house and third party recyclers to design and implement a take-back program, but at a high cost due to logistics. For E-Waste option, there is no sense of pressure to infuse a product take-back system because of the cost E-Waste has. Reusing the panel generates some response for recyclers to take-back, by replanting solar panels in other locations low efficiency or not, the supply chain is increased at a low to no cost. By visualizing the paths taken by each corporation, one is able to examine what other factors affect each recycler and to identify any gaps in the EOLM process.

Regulatory Differences

As discussed in the earlier section, regulations differ vastly from the federal level and state level, as well as in different countries. Due to the toxic content of electronics products, regulations have been passed to provide environmentally sound EOLM solutions for short life-cycle products (Pagnell 2007). The problem with currently existing regulations is that they are based on short life-cycle products, such as computer monitors, whereas solar panels tend to last 25 years. In Europe, producers and recyclers must abide by WEEE, which demands that all electronic waste be recycled to keep toxic chemicals and materials from entering landfills. For its part, Japan has passed similar legislation for mandating EOL take-back of washers and dryers, television monitors, video recorders, and refrigerators, among others. Japan and China are now becoming the largest manufacturers of solar panels, and need to follow regulations to keep this renewable “Green” energy actually green. In the United States, California has enacted several laws in recent years placing the responsibility for the recycling and disposal on the manufacturers, retailers and consumers (Pagnell 2007). At the Federal level there is very little regulation that ensures product take-back, ultimately leaving it up to the states and manufacturers to take the initiative. Identifying the regulatory differences that affect each country and state, pinpoints where each company will be within the model created. Each manufacturer and recycler are affected by the regulations, but the determining factor for each is to take cost, supply chain and material costs into account to realize the right path to ensure EOLM.

Cost Factors

Companies that were either affected by regulations, like PV Cycle, or decided to venture into installing a recycling program, had to consider the substantial cost they would incur and the types of panels they would recycle. Although I have no current data about the cost involved in designing and installing recycling infrastructure, Vasilis M. Fthenakis completed a study in 2000 to study the cost savings of recycling a solar panel. The projected cost of recycling Cadmium Indium (thin film) panels was estimated to be about $0.08/ Watt, and with shipping and other recycling costs the total ended up at $0.11/ Watt. In comparison, the current cost for landfill disposal was $0.01/ Watt for large quantities of non-hazardous waste, and $0.23/ Watt for hazardous waste. Vasilis recognizes that designing the panel for easy disassembly and separating the materials will generate a lower cost, instead of smelting (centralized method) all the materials and later sorting. The current study showed that such recycling is technologically and economically feasible, but not without careful forethought. He did state that recycling designs might change in the future, as more economic incentives may be given to developing clean technologies and reducing carbon dioxide emissions. As for the costs, although outdated, the research completed by Vasilis indicated that recycling was not only better for the environment by reducing carbon emissions, but also financially viable for firms to invest. Considering the paths taken by today's recycling corporations many, if not all, use a system that disassembles panels in some kind of way, rather than using the non-disassembly path, which uses a large smelter to melt the materials. By designing the panel for easy disassembly, Vasilis believed costs would be reduced dramatically by condensing the amount of processes in the recycling procedure. Recycling in-house as Vasilis researched, incurs extremely high up front costs to design and install recycling infrastructure. Although the high costs do generate some concerns, the benefits include a lower manufacturing cost for solar panels as descried above. This option will also generate the greatest return through control over the supply chain and design efficiencies. While some companies can identify and incur the optional benefits of an in-house program, a midway cost for recycling would be to outsourcing the recycling to agencies like PV Cycle. Third-party recyclers tend to have extremely high fixed costs, but also reap the benefits due to having the industry rely on them to recycle products that ultimately are not financially feasible for them (Pagell 2007). The high fixed costs can be offset with the income generated from third-party recycler's fee that is charged to recycle the panel. At the time of completing the recycling process, companies like PV Cycle then ship the recycled panels back to the customer or manufacturer. Another revenue source for third-party recyclers is when customers drop off panels they do not want returned. Companies can then recycle the panel and either sell the raw materials or completely recycle the solar panel, to be installed once again. Other options to consider when calculating cost factors are the benefits of reusing the panel. By reusing the panel there are no large costs incurred, and it will create an incentive to design the panel to last longer than 25 years. Panel design could be updated to allow for easy refurbishment or life extension through minimal part replacements, since panels that are not recycled at 25 years realistically have no recycled value. When management looks at options to either invest in infrastructure and promote a closed loop system, outsource and use third-party recyclers, or re-use the panels and promote design efficiencies, low cost options usually prevail. Although the low cost option always sounds appealing, the decision has long term implications: companies that outsource recycling effectively forego the opportunity to gain competitive advantage from the unique knowledge that is developed through managing recycling processes in-house. In-house recycling also becomes beneficial when it comes to keeping product out of other competitive channels; the supply chain effectively keeps solar cores or materials away from the competition (Pagell 2007). Recycling in-house also produces another supply chain issue; if a majority of solar manufacturers are either recycling in-house or using a third-party recycler, suppliers of raw materials will ultimately disappear. Distorting the supply chain will create a competitive market and will force supplier prices down, creating a problem for third-party recyclers, but not in-house recyclers, who use the materials in a closed-loop. By understanding the cost factors for recycling and the procedures that recyclers use, companies can find the best option based on where the company wants to go.

Design Efficiencies

With solar panels now being designed to wrap buildings instead of using paint, designing panels to be used as a roofing tile and encasing wind turbine blades with solar, the sky is the limit for the applications and designs solar can be used for. Looking at the dissimilar factors for designating a path for solar manufacturers, third-party recyclers, and consumers, design is one, if not the most important, factor that is sometimes overlooked. Having a recycling program in-house will generate a greater incentive to design panels for easier disassembly. Many of the panels today are becoming harder to disassemble, identifying these trends will allow in-house recycling to become more efficient and more productive. For third-party recyclers, panel design does not affect them in the manufacturing sense as much as the recycling programs. By pushing manufacturers to consider new designs that focus on disassembly for recycling, it will ultimately reduce costs and provide more incentives for consumers and manufacturers to use third-party recycling. As discussed in earlier sections, reusing the panel has design implications in that if more panels are reused it will generate a response to design panels to last longer and be updated to allow for easy refurbishment or parts replacement. With the reusing path, I do believe the design implications would not be realized until the panels do not produce any electricity, which could be a total of 40 years. This path would take the longest but would have the greatest design impact and benefit if ever considered.

Supply Chain Implications

Recycling solar panels has several implications with respect to the supply chain that includes conflict between manufacturers and suppliers. Reusing solar panels will also reduce demand for new panels. To reuse the panel extends the availability of already operational panels and minimizes the use of new materials, which is a sustainable option for manufacturers and third-party recyclers. With both in-house and third-party recycling, possible conflicts arise with raw material suppliers, who will see a decreasing demand for their products. In-house manufacturers using an in-house recycling program might see higher prices for raw materials that they still rely on, due to the impact of recycling on raw material prices.

Panel Materials

Materials used in solar panels are either conductive (produce electricity) or hazardous in some manner. For identifying the optimal EOLM path, manufacturers and recyclers need to understand the implications that each panel design has and the infrastructure that is needed to recycle, or re use each panel. In house recycling will have the toughest decision due to the extremely high costs involved for recycling all panel types. The majority of manufacturers that recycle in-house rely on third-party recyclers for non-silicon based panels. This creates an advantage for third-party recyclers in that if they design and implement a recycling program that accepts all panel types, they increase their revenue stream by at least double. Using the E-Waste path, the material each panel design has determines the path for where it will be recycled. The majority of panels are considered the same material and composition as a TV or computer monitors. Reusing the panel is not affected directly by the material type, although, as discussed earlier, new designs could prolong the life of each panel, and therefore, produce energy for a longer period of time.

Pros and Cons Defining Paths

By analyzing the different factors involved in determining a path from the model created (Appendix A), corporations can identify any implications that arise from the given channels. The channels provide two specific paths of either recycling panels at EOL, or reusing the panel with a certain decrease in efficiency rating at an average rate of 2-3% per year. At year 25 the majority of panels are 81% efficient, and will continue to degrade to a point where the solar cell cannot be remanufactured. Manufacturers and third-party recyclers need to understand the costs involved in waiting to recycle a panel or simply reusing it. Supply chain and material implications also play a large role in determining the path, and its ultimately up to the managers to be aware of these options and paths available, both to understand their choices and to understand the strategic implications of the choices of their competitors (Pagnell 2007).

Table 1: Factors Affecting PV EOLM Options

Options	In House	Third Party	E-Waste	Re-Use
Product Take Back	Having in house recycling programs initiates a response to implement product take back into the recycling program to generate the largest response in logistics	Manufacturers still have to implement a produce take back program to ship the panels to a third party recycler	E-waste does not provide pressure for manufacturers/customers to instill a product take back program. Ultimately, manufacturers will have to pay to dispose the panels	Re-using EOL panels will increase the supply for renewable energy, but also decrease the panels that can be recycled. This option allocates the EOL panels to places that can generate renewable energy at a very low cost
Design Efficiencies	Having recycling in house will generate more incentives to design a panel for easy disassembling	Panel design will only be realized if the third party decides it will reduce costs and provide other incentives	Does not have any implications for design efficiencies	Design benefits could be to design the panel to last longer than 25 years. Panel design could be updated to allow for easy refurbishment, or life extension through minimal parts replacement
Cost Factors	The largest investment, although, should generate the greatest return through control	Midway cost investment: Cost incurred by paying a fee to a third party recycler	Relatively lowest cost, only cost incurred is disposal fee. Manufacturers	No cost incurred although panel loses efficiency to a point where recycling is not a

	over the supply chain and design efficiencies		implementing a recycling program or customers will be affected by this cost	viable option
Supply Chain Implications	Closes the supply chain loop that creates value for a company long term. Channel Conflict will be here if manufacturers still need to rely on suppliers	Materials are controlled by recycler and can pose a chance of conflict for suppliers of raw materials	Supply chain neither controls or generates incentives for manufactures who decide to use this option	Adding another realized path that EOL panels could be used for, generates a greater resource and larger supply chain. Also extends the supply of already operational panels and minimizes use of new materials, which is a sustainable option
Materials	Certain types of materials generally are hazardous and may cause manufacturer's or third part recyclers to only recycle one specific panel type	Third party recyclers could take advantage of other manufacturers not recycling all types of panels	Materials determine the path for where the panel will be recycled, either E-Waste or deemed hazardous materials. Majority of the panels are E-Waste and are recycled the same way as TV and Computer monitors	The panel materials do not affect re-using the panel, although at a certain point the panel can no longer be recycled and has no intrinsic value

MAIN INDUSTRY PLAYERS AND APPLICATIONS

First Solar

First Solar, est. 1999, is the main contributor in the manufacturing sector for creating a product take-back system. Based on First Solar's statistics in 2013, they are able to recycle 95% of the semi-conductor and 90% of the glass from their main product, silicon based panels. First Solar has been recycling since 2005 and has created a sustainable business model that will lead new companies into the right direction. The recycling program was funded through the revenue from solar panel sales, and went to the extent of designing a logistics department to provide customers with packaging and transportation to a recycling center. The process for First Solar starts with a shredder and moves through a hammer mill to reduce the size of material and to break the lamination bond. First Solar then uses a chemical bath to remove the semi conductor films, which are also etched from the glass during the procedure. The materials are then separated and moved to a screen to separate the glass and the blackout material that allows the maximum amount of sunlight into the panel. The glass is then sent to a wash station to clean the chemicals remaining, and the chemical will be put through a metal recovery system to extract all metals in the chemicals. Metal such as Cadmium Telluride are sent to a third-party refinery to process the material to become raw metals that can be used to manufacture new solar panels. First Solar stands behind the state of the art procedure stating they have a success rate of 90% glass and 95% semiconductor recovery to be used in new panels.

Solar World

Solar World organizes recycling of their panels through a “Bring In” for all customers, where other companies are initiating the take-back. Solar World has operated a pilot structure for PV Cycle since 2003, where some of the components are recycled in-house and others are shipped to PV Cycle. The process for Solar World starts with an incinerator where the plastic is burned in a semiconductor at a little over 1100 degrees Fahrenheit. Any of the remaining materials, metals, glass, etc., are separated manually. Glass and metals are sent for recycling, while the solar cells are re-etched to the wafer to then be installed in new solar panels. Through PV Cycle’s recycling system they claim that both recycled wafer and a newly manufactured have equal electrical production even after going through a re-etching process. Solar World tries to keep the wafer as thick as possible, due to the lower the thickness the lower the electricity yield a panel will give. Dr. Karsten Wambach, Manager at Sunicon, the silicon subsidiary of Solar World, told Renewable Energy Focus that the financial viability of recycling is a question of supply: “The waste streams are very small … therefore recycling is hardly viable today. In the future, with larger waste streams, it will be a must (Kari Larsen 2009).

PV Cycle

Europe has implemented regulations and life cycle assessments (LCA) to grade products on the ecological impacts during all life phases (Muller, Wambach, Alsema 2007). Jennifer Woolwich creator and owner of PV Cycle based out of Belgium designed the corporation to be a collection point for all EOL panels at any quantity. PV Cycle, a third party recycling corporation, designed two recycling programs to accommodate different panel types, silicon based and non-silicon panels. The non-silicon panels are first delaminated using a chemical bath. The components of a CIG or CdTe panel come apart and are either put into a shredder or solubilizing chemical bath (chemical bath that separates and attracts different metals using electronic fields). PV cycle then has separate facilities to recycle the glass and semiconductor, which later will become new parts for a solar panel. The process for silicon based solar panel is somewhat similar in that both procedures shred the panel for separation later. The glass is then put through a processing line that is mixed with standard glass pieces, and partly reintroduced in glass fiber, insulation products, or used in glass packaging products. The metals and plastics will be used in the production of new solar panels. PV Cycle has introduced various disposal sites for <40 modules and >40 modules. Many solar companies can actually become a disposal site for PV Cycle as long as they deal with recycling of PV panels. The main focus is to enable customers to appropriately dispose of their photovoltaic (PV) modules, thereby creating additional value for them and show your commitment to sustainable product management (PV Cycle 2014). PV Cycle also took an initiative to label panels when they need to be removed at EOL and sent to the manufacturer for recycling.

OPTIONS AND GAPS

By analyzing the options consumers, manufacturers, and third party recyclers can take based on the factors discussed, there are many options available and gaps that can be identified. Solar panels have not been designed to facilitate easy recycling nor do they have the ability to be used for an extended period of time, beyond the currently accepted 25-year lifespan. Product take-back needs to include labeling of products that includes the date the panels will need to be returned, and the costs for the manufacturer or third-party to recycle. Logistics for transporting the panels is a major concern and needs to be addressed to ensure proper efficiency within the recycling program. The United States does not have any set regulations for product take-back and recycling, which does not promote sustainable handling of panels at EOL. By identifying the supply chain implications and the possible gaps that can be filled, the PV industry will continue to move towards recycling and fulfilling cradle-to-cradle.

Leasing Options

A currently underutilized option for manufacturers and third-party recyclers is leasing solar panel systems. By leasing a PV system the manufacturer or recycler retains the responsibility for product take-back at EOL and will then recycle the system to be leased again to consumers. Solar energy is still a relatively high-cost investment, and takes a considerable amount of time to pay back, but by reducing the upfront cost and leasing the PV system it benefits both the consumer and the manufacturer/recycler. Integrating such a system would be a promising revenue source and would assist the recycler or manufacturer by knowing when systems would be deemed EOL. Keeping track of solar systems leased would allow the company to schedule recycling accordingly and become more efficient.

ASSESSMENT OF EOLM

Measuring and tracking success for manufacturers and third-party recyclers is key to identifying strengths and weaknesses and strengths that can be used to better the future for PVs. Many recyclers have their own set of guidelines they abide by, such as ISO standards, WEEE compliance, and many other corporate responsibility agencies. If recyclers are not assessed, other than by their own standards, then there will be no incentive other than competition to better their recycling facilities. Questions arise regarding who is evaluating the recyclers from a third-party seat. One organization providing nongovernmental oversight is the Silicon Valley Toxics Coalition (SVTC), who is forcing solar companies to stay on track towards a more sustainable future, and to avoid "the road many electronic companies went down when it comes to recycling" (Craig 2012 Earthtechling). A very promising aspect of SVTC's initiatives is the balance scorecard (See Appendix E Pg. 24), which was created to identify what companies are incorporating into their recycling programs to move towards a sustainable future. The balanced scorecard in 2013 proved to be very noteworthy on the basis of respondents, and to me uninspiring. "Issued to 40 of the top solar industries, representing 82.8% of the total market share only 49.5% responded to at least one card" (SVTC 2013). The surprisingly low response rate, SVTC believed, was due to the economic hard times, even though alternative energy sources are increasing, many businesses could not survive. The scorecard was based on 3 keys: Sunny the best, Partly Cloudy, and Rainy being the worst. The card rated companies on 12 aspects of a sustainable systems including cradle-to-cradle. The surprising fact from the table below is that only a handful of the 40 companies actually accounted for cradle-to-cradle, while no one company, including First Solar, received anything higher than partly cloudy. The hard truth is that third-party assessments lead to the conclusion that the majority of manufacturers have recycling systems that are not fulfilling cradle-to-cradle, module toxicity levels, and consuming too much water during their processes. Although some major recyclers are not present in this evaluation, including PV Cycle, this scorecard creates awareness to consumers and suppliers. Many people buy products based on a company's visions to be responsible, looking for ISO and WBCSD valuations to validate the company's behavior and overall attitude towards the environment. With SVTC digging deeper into the procedures each recycler uses, it generates a response for manufacturers and third-party recyclers to become greener. For future recyclers this scorecard will be the benchmark of quality and environmental stewardship.

SUMMARY

By changing the way a solar panel is designed to incorporate a more sustainable and easily disassembled product, more companies would have an incentive to reduce, recycle, or re-use. Redesigning solar panels for future use can, not only reduce manufacturing costs, but also inspire investors to take part in a more sustainable journey, as BMW has done with their entire product line. BMW has re-engineered all of their products to allow for easy disassembly at EOL to reduce the need to remanufacture new products, ultimately reducing pollutants into the environment and reducing costs at the same time. This, in turn, will also create another revenue source for BMW with products that can be easily disassembled, and then recycled to produce a new and improved part for a new BMW. If solar companies took such an approach in designing a system that would fulfill cradle-to-cradle, I believe the market would respond in a positive way incentivizing other companies and products to follow in their footsteps. Investors and governments would be encouraged to take part in a sustainable journey for renewable energy that will always generate a revenue source from the previous product manufactured.

REFERENCE LIST

Alsema, E. Life Cycle Analysis of Solar Module Recycling Process. *MRS Proceedings*.

Craig, L. (2012, January 19). Recycling Solar Panels A Big Money Maker? EarthTechling.*EarthTechling*. Retrieved June 29, 2014, from http://earthtechling.com/2012/01/recycling-solar-panels-a-big-money-maker/

DTSC's Proposed Solar Recycling Regulations will haunt California for Years to Come. (n.d.). – *Silicon Valley Toxics Coalition*. Retrieved June 29, 2014, from http://svtc.org/blog/solar/dtscs-proposed-solar-recycling-regulations-will-haunt-california-for-years-to-come/

EPA. (n.d.). *Summary of the Resource Conservation and Recovery Act*. Retrieved June 29, 2014, from http://www2.epa.gov/laws-regulations/summary-resource-conservation-and-recovery-act

Erica Gies, . <http://www.thedailygreen.com/environmental-news/latest/solar-panel-recycling-460810>.

"Essential 'green' Metals Are Being Thrown Away." - Environment. N.p., n.d. Web. 01 Oct. 2013. http://www.newscientist.com/article/dn20523-essential-green-metals-are-being-thrown-away.html

Feature. (n.d.). *End-of-life PV: then what?*. Retrieved June 29, 2014, from http://www.renewableenergyfocus.com/view/3005/end-of-life-pv-then-what-recycling-solar-pv-panels/

Fthenakis, V. M. End-of-life management and recycling of PV modules. *Energy Policy*, 1051-1058.

"How Solar Cells Work." HowStuffWorks. N.p., n.d. Web. 01 Oct. 2013. <http://science.howstuffworks.com/environmental/energy/solar-cell1.htm>.

Marshall, M. (2011, May 1). Essential 'green' metals are being thrown away. - *environment*. Retrieved June 29, 2014, from http://www.newscientist.com/article/dn20523-essential-green-metals-are-being-thrown-away

McCabe, J. (2013, August 27). First Solar's Stewardship of Recycled CdTe Modules in Question : Retrieved June 29, 2014, from http://www.greentechmedia.com/articles/read/First-Solars-Stewardship-of-Recycled-CdTe-Modules-in-Question

Muller, Anja, Karsten Wambach, and Erik Alsema. "LIFE CYCLE ANALYSIS OF A SOLAR MODULE RECYCLING PROCESS." (2007): n. page. Print. <http://www.sjsu.edu/people/dustin.mulvaney/courses/envs116/s1/3EADA45D-CAB9-4316-B613-AB16F9CC20D1.pdf>.

Murthy, N. N. The supply chain implications of recycling. *Business Horizons*, 133-143.

N.p.. Web. 1 Oct 2013. <http://www.oregon.gov/odot/hwy/oipp/docs/life-cyclehealthandsafetyconcerns.pdf>.

N.p.. Web. 26 Oct 2013. <http://www.firstsolar.com/About-First-Solar>.

NREL: Energy Analysis -. Retrieved June 29, 2014, from http://www.nrel.gov/analysis/publications.html

Nath, I. Cleaning Up After Clean Energy: Hazardous Waste in the Solar Industry.

"New Thin Film Increases Efficiency of Stacked Solar Cells." New Thin Film Increases Efficiency of Stacked Solar Cells. N.p., n.d. Web. 01 Oct. 2013. <http://www.gizmag.com/stacked-solar-cell-gallium-arsenide-film/29006/>.

"Photovoltaic News and Pv Jobs." Pv Magazine. N.p., n.d. Web. 01 Oct. 2013. http://www.pv-magazine.com/news/details/beitrag/first-solar-invests-in-mexican-tellurium-mine>.

Retrieved June 29, 2014, from http://www.oregon.gov/ODOT/HWY/OIPP/docs/life-cyclehealthandsafetyconcerns.pdf

Retrieved June 29, 2014, from http://www.pvcycle.org/pv-recycling/

Retrieved June 29, 2014, from http://www.solarscorecard.com/2013/2013-SVTC-Solar-Scorecard.pdf

SEIA. (n.d.). *PV Recycling*. Retrieved April 7, 2014, from http://www.seia.org/policy/environment/pv-recycling

Solar Photovoltaic End-of-Life. (n.d.). *Texas Solar Energy Society Welcomes You*. Retrieved June 29, 2014, from http://www.txses.org/solar/content/solar-photovoltaic-end-life

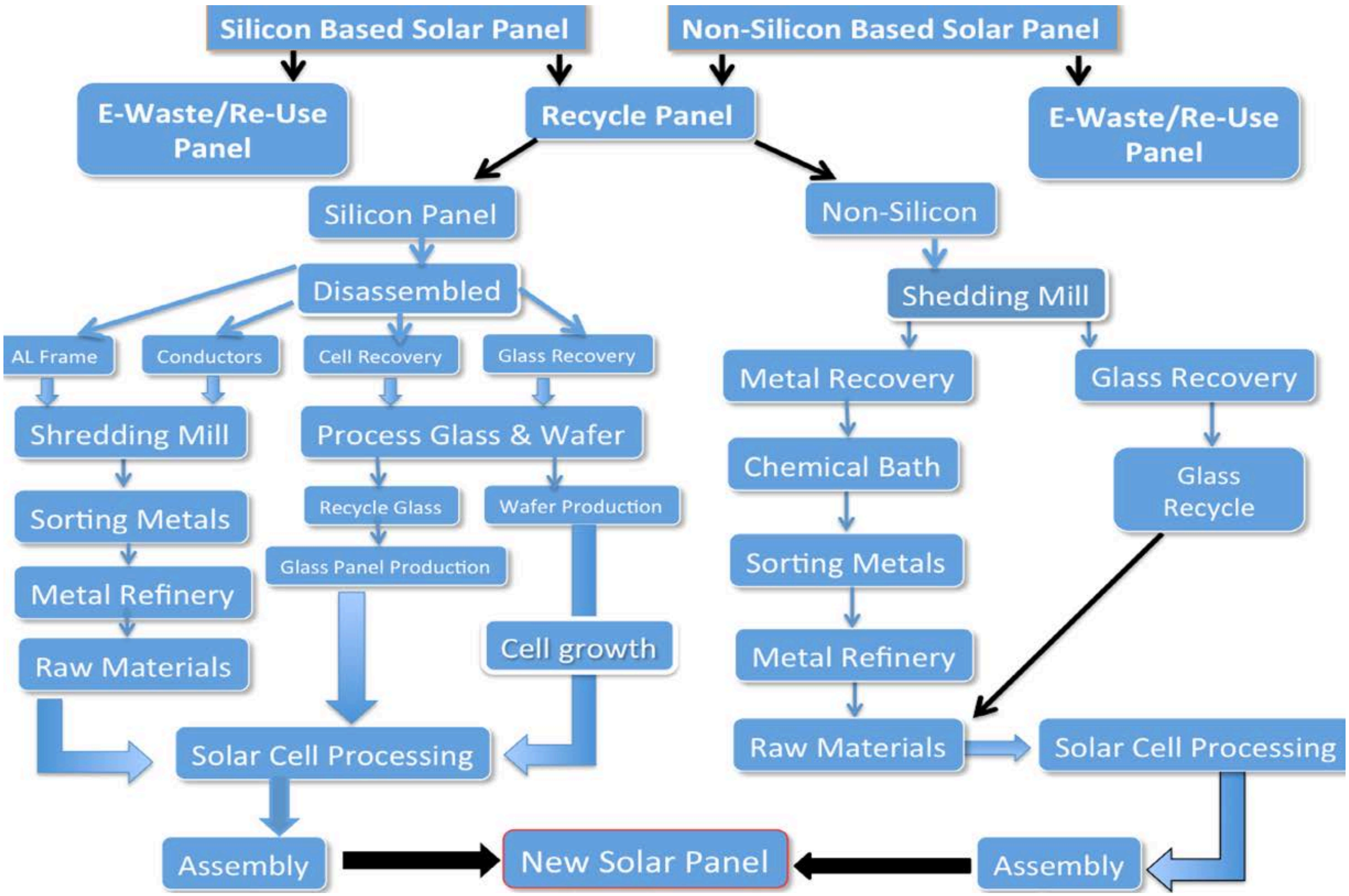
The Recycling Advantage. (n.d.). *Recycling Services*. Retrieved June 29, 2014, from http://www.firstsolar.com/en/technologies-and-capabilities/recycling-services

Toothman, J., & Aldous, S. (2000, April 1). How Solar Cells Work. *HowStuffWorks*. Retrieved March 12, 2014, from http://science.howstuffworks.com/environmental/energy/solar-cell.htm

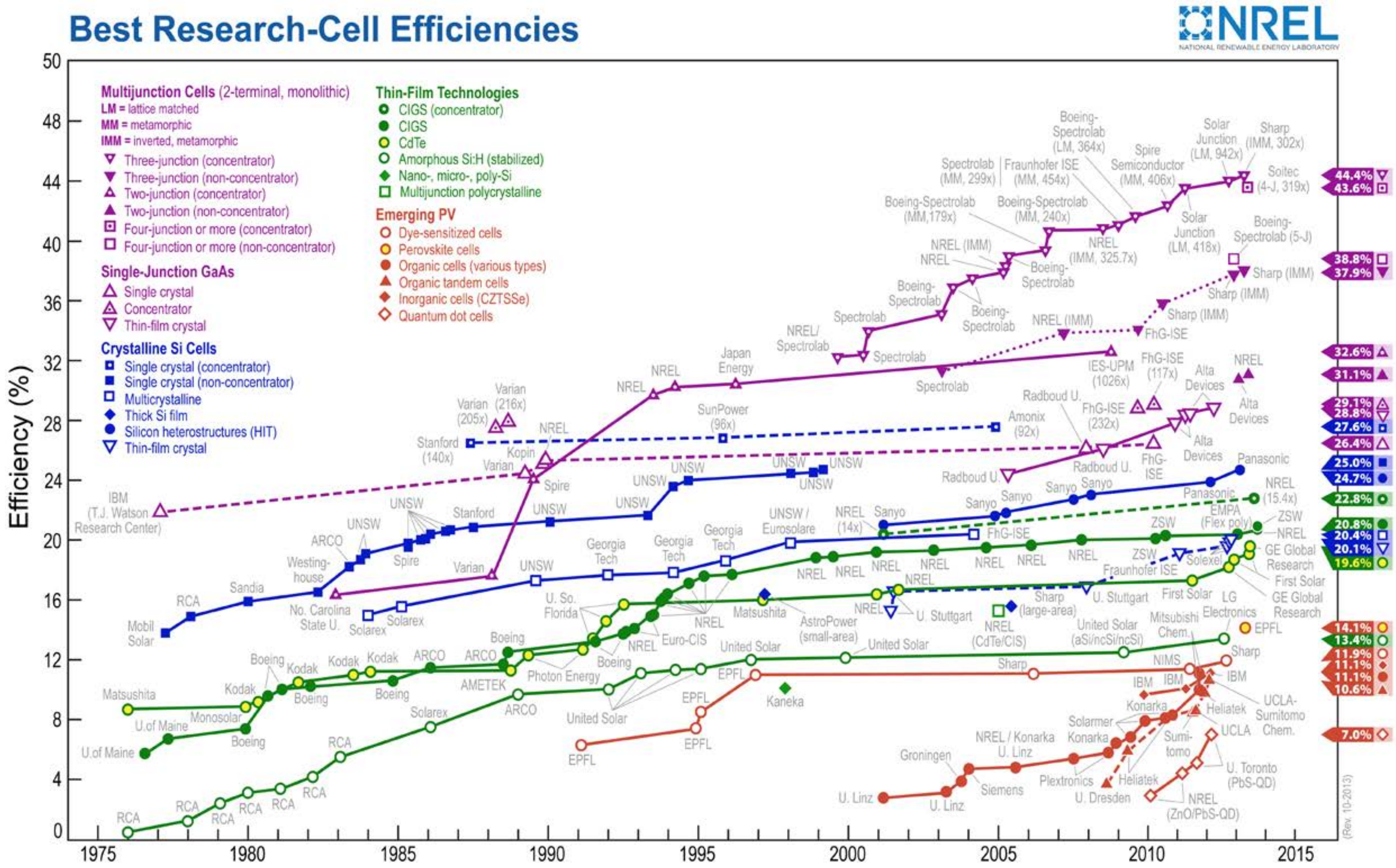
Weadock, Nick. N.p.. Web. 1 Oct 2013. <http://2011.solarteam.org/news/recycling-methods-for-used-photovoltaic-panels>.

"WHY CHOOSE SOLARWORLD." Made in America. N.p., n.d. Web. 01 Oct. 2013. http://www.solarworld-usa.com/why-choose-solarworld/solar-panels-made-in-usa.

Appendix A


Silicon Based Solar Panel
Non-Silicon Based Solar Panel
E-Waste/Re-Use Panel
Recycle Panel
E-Waste/Re-Use Panel
Silicon Panel
Non-Silicon
Disassembled
Shedding Mill
AL Frame
Conductors
Cell Recovery
Glass Recovery
Metal Recovery
Glass Recovery
Shredding Mill
Process Glass & Wafer
Chemical Bath
Glass Recycle
Sorting Metals
Recycle Glass
Wafer Production
Sorting Metals
Glass Panel Production
Metal Refinery
Metal Refinery
Cell growth
Raw Materials
Raw Materials
Solar Cell Processing
Solar Cell Processing
Assembly
New Solar Panel
Assembly

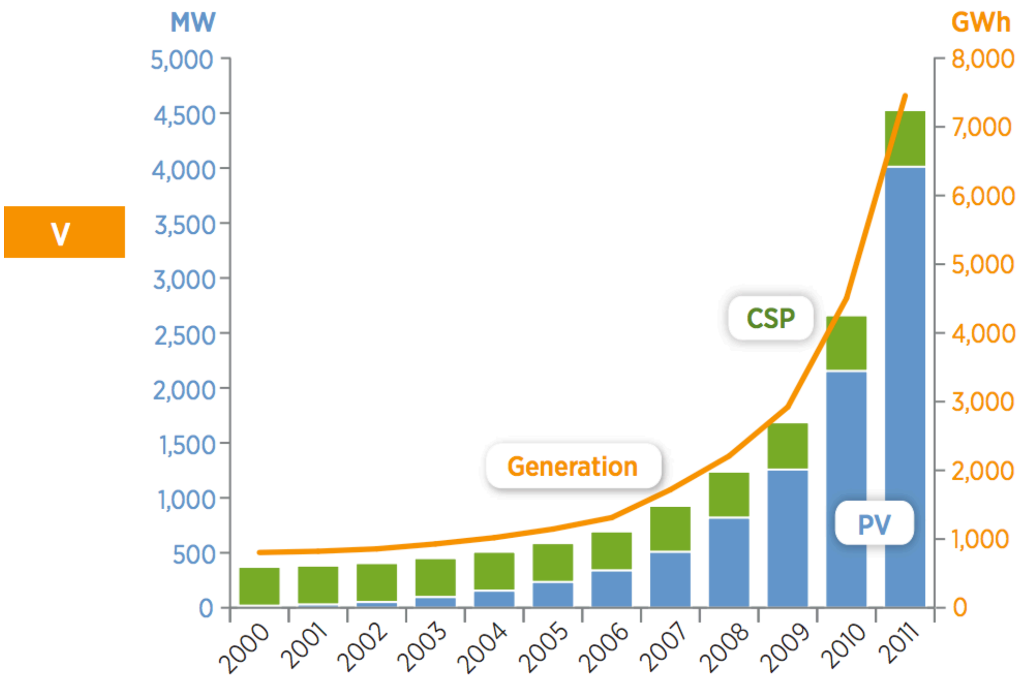
Appendix B


Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Thick Si film
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Perovskite cells
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
44.4%
43.6%
38.8%
37.9%
32.6%
31.1%
29.1%
28.8%
27.6%
26.4%
25.0%
24.7%
22.8%
20.8%
20.4%
20.1%
19.6%
14.1%
13.4%
11.9%
11.1%
11.1%
10.6%
7.0%
(Rev. 10-2013)

Appendix C

Solar Panel Systems						
Cystalline Silicon	**Materials Shortage**	**Efficiency**	**% of Market**	**Recycling Method**	**% Recyclable**	**Hazardous Affects**
Monocrystalline Silicon	NO	15-21%	~85%	YES	Glass ~ 90% Silicon Cells ~ 4%	Pure Silicon Lead
Polycrystalline Silicon	NO	13-16%		YES		Pure Silicon Lead
Amorphous Silicon	Silane	5-10%		YES		Pure Silicon Lead
Recycled Poly-Silicon Panel	NO	12-16%	N/A	N/A	Glass ~ 90% Silicon Cells ~ 4%	Melting Metals into Slag Delamination
Recycled Mono-Silicon Panel	NO	15-21%		N/A	Glass ~ 90% Silicon Cells ~ 4%	Melting Metals into Slag Delamination
Thin-Film Solar Panels		7-13%	14%	?	95%	
Cadmium Telluride (CdTe)	Telluride	9-14%		?		Cadmium Tellurium
Copper Indium Gallium Selenide (CIS/CIGS)	Indium	10-12%		?		Cadmium Selenium
Organic	?	5%	~<1%	?	?	N/A
Recycled Thin-Film Panel	NO	9-14%	?	Delamination & Recovery	95%	Melting Metals into Slag Delamination
Data: Navigant Consulting Graph: PSE AG 2012 First Solar 2013						

Appendix D



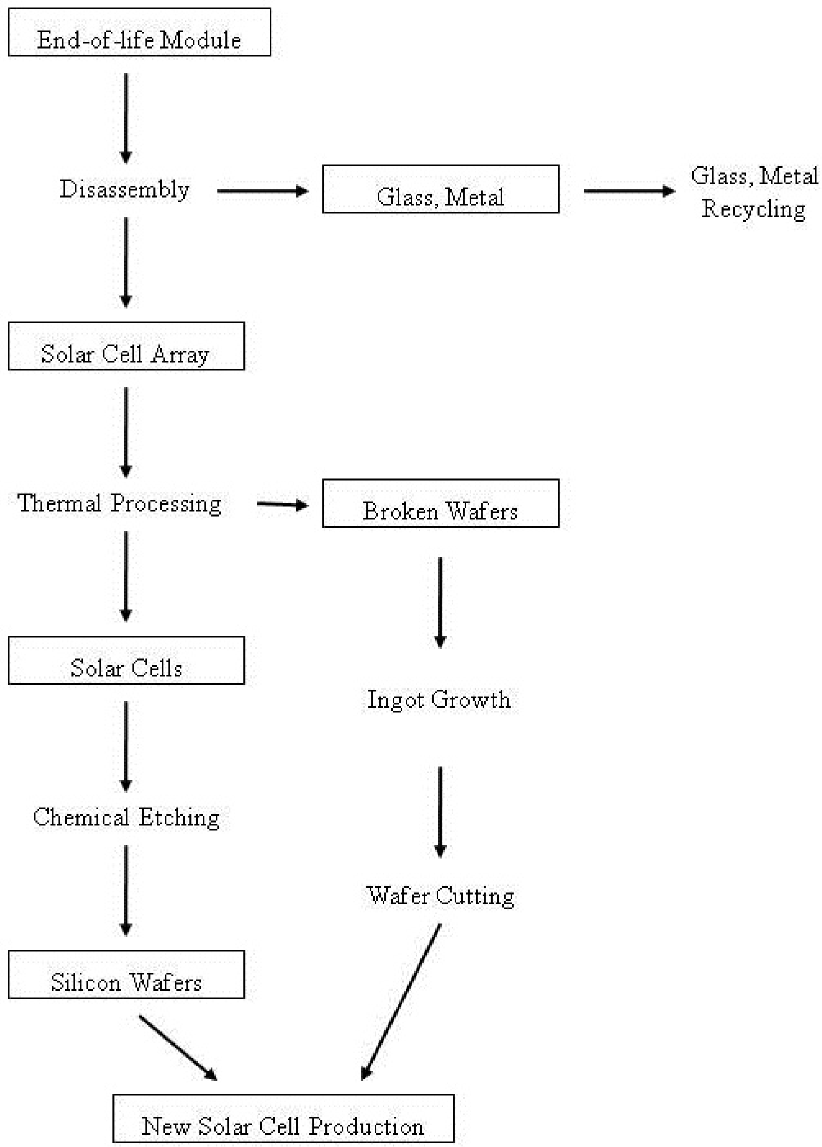
	U.S. Solar Energy Generation (Million kWh)	U.S. Solar Energy Capacity (MW) and % Increase from Previous Year			
		PV*	CSP	Total	Increase
2000	804	18	354	372	4.3%
2001	822	29	354	383	3.0%
2002	857	52	354	406	5.9%
2003	929	97	354	451	11.2%
2004	1,020	155	354	509	12.8%
2005	1,145	234	354	588	15.5%
2006	1,312	339	355	694	18.0%
2007	1,718	508	419	927	33.5%
2008	2,208	819	419	1,237	33.5%
2009	2,922	1,257	430	1,686	36.3%
2010	4,505	2,153	507	2,660	57.7%
2011	7,454	4,011	516	4,527	70.2%

Sources: SEIA/GTM, Larry Sherwood/IREC

Appendix E

	EPR	Emissions Transparency	Chemical Reduction Plan	Worker Rights, Health, Safety	Supply Chains	Conflict Minerals	Module Toxicity	C2C Recycling	Prison Labor	Biodiversity	Water	Energy & GHGs	**Overall Score**
MAXIMUM SCORE	**20**	**10**	**5**	**15**	**10**	**5**	**10**	**5**	**5**	**5**	**5**	**5**	**100**
Trina	14	5	5	15	7	3	10	4	5	2	3	4	77
Yingli	9	4	5	14	8	3	10	4	5	5	3	5	75
SunPower	7	6	5	14	7	3	10	4	5	3	2	4	69
Upsolar	14	4	0	13	8	3	10	2	3	5	0	4	66
SolarWorld	9	10	5	8	7	0	0	3	5	0	5	5	64
REC	10	10	5	8	7	0	0	1	4	5	3	4	57
First Solar	12	6	0	13	7	3	0	4	3	0	2	5	55
Axitec	4	0	0	10	8	3	10	4	3	5	0	0	47
Suntech	9	2	5	10	7	3	0	0	4	5	0	2	47
Mitsubishi	0	4	5	4	7	0	10	0	0	5	5	5	45
Aleo	10	0	0	11	7	0	0	4	3	5	0	3	43
Renesola	2	0	0	12	7	0	10	1	3	5	0	1	41
LDK	4	0	0	12	0	3	10	3	3	5	0	0	40

Appendix F


End-of-life Module
Disassembly
Glass, Metal
Glass, Metal
Recycling
Solar Cell Array
Thermal Processing
Broken Wafers
Solar Cells
Ingot Growth
Chemical Etching
Wafer Cutting
Silicon Wafers
New Solar Cell Production