Environmental Impact of Solar Panel Manufacturing and End-of-Life Management: Technology and Policy Options

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Executive Summary

Because of the growth in the global solar industry, end of life management of PV cells is an emerging issue. In 2016, the International Renewable Energy Agency (IRENA) published a report entitled *End-of-Life Management: Solar Photovoltaic Panels.* The report identified three ways that industry, government, and other stakeholders can prepare for these increased volumes.

The first of these is to adopt PV-specific waste regulations. The European Union has already added PV panels to its WEEE Directive. The core of the directive is extended producer responsibility. The IRENA report also outlines PV panel waste management approaches taken by Germany, Japan, the United States, India, and China. The United States is characterized as having an established, growing market with our PV-specific regulations. Because there are no federal regulations specifically governing disposal of PV panels, they are treated under RCRA's general framework for waste management. Because PV panels are not specifically listed wastes under RCRA, they must be evaluated using the characteristic hazardous waste method (U.S. EPA Method 1311: Toxicity Characteristic Leaching Procedure). TCLP determines whether extract from a representative sample of the waste contains contaminants that exceed regulatory levels. Some states require testing with alterative leaching procedure methodology (e.g. California's Total Threshold Limit Concentration and Soluble Threshold Limit Concentration).

In 2015, California enacted SB 489, which authorized the state's Department of Toxic Substances Control to adopt regulations to designate end-of-life PV modules identified as hazardous waste as a universal waste and subject those modules to universal waste management. In July 2016, DTSC held a workshop on the draft regulations. The regulations have yet to be finalized, but they provide a roadmap for how other states might choose to regulate end-of-life management of PV panels.

The IRENA report's second recommendation is to expand waste management infrastructure. They further recommend coordination between the energy and waste sectors in order to support PV end-of-life management. To this end, the PV industry in Europe created PV Cycle, a non-profit, member based organization that offers waste management and legal compliance services for companies and waste holders around the world.

IRENA's third recommendation is to promote ongoing innovation, both in the design of PV systems and value creation from the components at end-of-life. These fall into the traditional 3 Rs principles: reduce, reuse, and recycle. Reducing the amount of materials in PV panels is the most preferable options. There has already been a significant amount of research into more environmentally sound alternatives to solar manufacturing (Tsuo et al, 1998). For example, researchers at the National Renewable Energy Laboratory are studying ways to make polysilicon with ethanol instead of chlorine based chemicals, which eliminates the creation of silicon tetrachloride (Strebov et al, 2004). Hydrofluoric acid, used to clean the polysilicon wafers, is also a concern. Rohm & Haas developed a process for using NaOH instead of hydrofluoric acid (Dove, et al, 2012). Thin-film solar cells eliminate the need for many hazardous chemicals, but still require cadmium in their manufacture. Manufacturers and government researchers are working to develop alternatives to cadmium (Peplow, 2014). Lead is also a concern in solar cells. Earlier this month, researchers at the University of Cambridge used theoretical and experimental methods to show how bismuth could be used in place of lead in low-cost solar cells (Hoye, et al, 2017).

Reuse is the second most preferred option in the waste management hierarchy. For PV panels, this involves repair. If a panel is defective, it can be repaired, then possibly resold as replacements or as used panels at a reduced market price. Partially repaired panels can be sold on a second-hand market.

Panels that can't be repaired are recycled. Recycling costs vary based on the size of the systems (utility-scale or home single-panel). Recycling of utility sized systems result in many components including panels, cables, electronics, metals, and construction and demolition waste. Decommissioning of systems on this scale results in high quantities of these wastes and can be collected separately at reasonable costs to be sent to specialized recycler, managed as hazardous wastes, or sent to landfills, if allowed by applicable regulations. The process for single panel systems is a little less straightforward because of the logistics costs of takeback and recycling systems. Some installers offer disposal of single panel systems, but these services vary from place to place. Specific technologies for recycling can be found in the For Further Reading section.

There are not currently sufficient economic incentives to create dedicated PV recycling plants. Thus, most end-of-life PV panels are processed in existing general recycling plants. One of the main technical challenges of PV recycling is delamination and removal of ethylene-vinyl-acetate material that encapsulates the solar cells. The IRENA report goes into great detail about the actual recycling process, as well as how the component materials might be recycled.

The search results below include overview information about the problem, research articles about innovative technologies for manufacturing and recycling PV systems, and links legislative and policy information. Each link includes an abstract or summary of the content. The publications included in the "Cited Works" section are not included in the search results. The bibliography in the IRENA report is a good source for information on technology and policy options not included in the results below.

Cited Works

California Department of Toxic Substances Control. *Photovoltaic Modules (PV)-Universal Waste Management Regulations*. Online at https://www.dtsc.ca.gov/HazardousWaste/PVRegs.cfm. Accessed 27 July 2017.

Dove, Curtis, Cindy Dutton, Greg Bauer, Christopher Myers, and Mehdi Balooch. *Methods for Damage Etch and Texturing of Silicon Single Crystal Substrates*. Asia Union Electronic Chemical Corporation, assignee. Patent US8329046. 11 Dec. 2012. Online at https://www.google.com/patents/US8329046. Accessed 27 July 2017.

Environment Directorate-General of the European Commission (2017). *European Union Waste Electrical & Electronic Equipment (WEEE) Directive*. Environment Directorate-General of the European Commission : Brussels, Belgium. Online at http://ec.europa.eu/environment/waste/weee/index_en.htm. Accessed 27 July 2017.

Hoye, R.L.Z.; Lee, L.C.; Kurchin, R.C.; Huq, T.N.; Zhang, K.L.H.; Sponseller, M.; Nienhaus, L.; Brandt, R.E.; Jean, J.; Polizzotti, J.A.; Kursumović, A.; Bawendi, M.G.; Bulović, V.; Stevanović, V.; Buonassisi, T.; MacManus-Driscoll, J. (2017). "Strongly Enhanced Photovoltaic Performance and Defect Physics of Air-Stable Bismuth Oxyiodide (BiOI)." *Advanced Materials,* 1702176. Online at https://doi.org/10.1002/adma.201702176. Accessed 27 July 2017.

International Renewable Energy Agency (IRENA) (2016). *End-of-Life Management: Solar Photovoltaic Panels*. International Renewable Energy Agency (IRENA) : Abu Dhabi, United Arab Emirates. Online at http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=2734. Accessed 27 July 2017.

Peplow, M. (2014). "Thin-film Solar Cells Freed From Toxic Processing." *IEEE Spectrum*, 25 June 2014. Online at http://spectrum.ieee.org/energywise/green-tech/solar/thin-film-solar-cell-freed-from-toxic-processing. Accessed 27 July 2017.

PV Cycle [website]. Online at http://www.pvcycle.org/. Accessed 27 July 2017.

Strebov, D.S.; Pinov, A.; Zadde V.V.; Lebedev, E.N.; Belov, E.P.; Efimov, N.K.; Kleshnikova, S.I.; Touryan, K.; Blake, D. (2004). *Chlorine Free Technology for Solar-Grade Silicon Manufacturing*. National Renewable Energy Laboratory : Golden, CO. Online at http://www.nrel.gov/docs/fy04osti/36750.pdf. Accessed 27 July 2017.

Tsuo, Y.S.; Gee, J.M.; Menna, P.; Strebkov, D.S.; Pinov, A.; Zadde V. (1998). *Environmentally Benign Silicon Solar Cell Manufacturing*. National Renewable Energy Laboratory : Golden, CO. Online at https://pdfs.semanticscholar.org/ac95/f250f064a95a50dcd402cd0134a4e7791515.pdf. Accessed 27 July 2017.

For Further Reading

Overview of the problem

Brouwer, K.A.; Gupta, C.; Honda, S.; Zargarian, M. (2011). *Methods and Concerns for the Disposal of Photovoltaic Solar Panels*. Project Report, San Jose State University. Online at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.456.5648&rep=rep1&type=pdf.

Solar energy plays an essential role in the move towards renewable energy. By generating energy through photovoltaic (PV) solar technology and reducing carbon dioxide emissions to the environment, the solar energy industry is able to present a clean energy source to the market. However, in order to introduce an environmentally safe product to the market, companies need to study the full cycle of the product, from cradle-to-grave. The electronics industry failed to account for their product's end-of-life into consideration in the manufacturing process and created widespread toxic chemical pollution. The solar energy industry can avoid a similar mistake by not only accounting for the materials used during manufacturing, but also the transportation of PV panels, disposal, and reuse of these panels need to be considered. This project attempts to present a safe and sustainable process for the disposal of PV solar panels. A detailed study of current PV solar panel disposal practices is discussed, as well as the feasibility of implementing recycling processes in the solar energy industry.

Mulvaney, D. (2014). "Solar Energy Isn't Always as Green as You Think." *IEEE Spectrum*, 12 November 2014. Online at http://spectrum.ieee.org/green-tech/solar/solar-energy-isnt-always-as-green-as-you-think.

Provides a good overview of the solar PV manufacturing process, its associated environmental hazards, and some technological innovations to prevent those hazards.

Nath, I. (2010). "Cleaning Up After Clean Energy: Hazardous Waste in the Solar Industry." *Stanford Journal of International Relations* 11(2), 6-15. Online at https://web.stanford.edu/group/sjir/pdf/Solar_11.2.pdf.

In the rising wave of solar energy, some have begun to sound the alarm on the possibility of hazardous waste escaping into the environment. In response, solar firms have begun planning and forming coalitions to recycle used panels before their materials can leach out, trumpeting their efforts to guarantee life-cycle sustainability. But the focus on dealing with used panels threatens to obscure a more pressing concern from waste in the manufacturing process. With the production of silicon base materials exploding in China – where anecdotal evidence shows a lack of safety regulations – solar firms and regulators must shift their focus to ensuring safe production processes, even if the international situation can be difficult. Until these issues are properly addressed, a shadow of doubt will hang over the true environmental impacts of solar energy.

Technology options

Design and Manufacturing

Peplow, M. (2014). "Two Labs Get the Lead Out of Promising Perovskite Solar Cells." ***IEEE Spectrum*****, 5 May 2014. Online at http://spectrum.ieee.org/energywise/green-tech/solar/two-labs-get-the-lead-out-of-promising-perovskite-solar-cells.**

Photovoltaic cells made from perovskite materials have rapidly become one of the hottest areas in energy research over the past few years. But most of these materials have included the toxic metal lead, raising concerns about their environmental impact. Now, two teams have independently developed perovskite cells that swap lead for tin, which could help to convince investors and regulators that the cells have a commercial future.

Recycling

Choi JK. (2017) "A Case Study of Sustainable Manufacturing Practice: End-of-Life Photovoltaic Recycling." In: Campana G., Howlett R., Setchi R., Cimatti B. (eds) ***Sustainable Design and Manufacturing 2017. SDM 2017. Smart Innovation, Systems and Technologies*****, vol 68. Springer, Cham, pp. 277-279. DOI: https://doi.org/10.1007/978-3-319-57078-5_27**

The usage of valuable resources and the potential for waste generation at the end of the life cycle of photovoltaic (PV) technologies necessitate a proactive planning for a PV recycling infrastructure. To ensure the sustainability of PV in large scales of deployment, it is vital to develop and institute low-cost recycling technologies and infrastructure for the emerging PV industry in parallel with the rapid commercialization of these new technologies. There are various issues involved in the economics of PV recycling and this research examine those at macro and micro levels, developing a holistic interpretation of the economic viability of the PV recycling systems. This study will present mathematical models developed to analyze the profitability of recycling technologies and to guide tactical decisions for allocating optimal location of PV take-back centers (PVTBC), necessary for the collection of end of life products. The economic decision is usually based on the level of the marginal capital cost of each PVTBC, cost of reverse logistics, distance traveled, and the amount of PV waste collected from various locations. Results illustrated that the reverse logistics costs comprise a major portion of the cost of PVTBC; PV recycling centers can be constructed in the optimally selected locations to minimize the total reverse logistics cost for transporting the PV wastes from various collection facilities to the recycling center. In the micro- process level, automated recycling processes should be developed to handle the large amount of growing PV wastes economically. The market price of the reclaimed materials are important factors for deciding the profitability of the recycling process and this illustrates the importance of the recovering the glass and expensive metals from PV modules.

Corcelli, F.; Ripa, M.; Ulgiati, S. (2017). "End-of-life treatment of crystalline silicon photovoltaic panels: An emergy-based case study." Journal of Cleaner Production 161(9), 1129-1142. Online at https://doi.org/10.1016/j.jclepro.2017.05.031.

Although photovoltaic (PV) technology has been projected as one of the most promising candidates to replace conventional fossil based power generation, claims about the potential disadvantages of the PV panels end-of-life (EoL) deserve careful attention in order to fully establish a feasibility and viability baseline and support technological and implementation policies. The current challenge concerning PV technology resides in making them efficient and competitive in comparison with traditional power generation systems, without disregarding the appraisal of EoL impacts. The emergy analysis method proved to be a reliable approach for the evaluation of the efficiency, effectiveness and environmental friendliness of technological processes under a global scale perspective and may likely be applied to the EoL PV investigation as a complement of conventional energy and economic assessments. Therefore, this method was used in this study to evaluate the sustainability of a PV panel recycling process. In addition, this paper aims to explore the implications of methodological assumptions when Emergy Accounting (EMA) tackles waste management systems, in order to address the shortcomings in this field.

Results show that the PV panel treatment can generate large environmental benefits not only at the local scale of the process, but also at the larger scale of the industrial manufacture and material recovery, as well as at the even larger scale of the biosphere where resources come from and pollution is released. The comparison between the emergy invested for electricity production via PV and fossil energy sources also including EoL resource and environmental costs, highlights that PV technology is competitive under both energy and environmental points of view. This comparison reveals that the solar technologies imply remarkable emergy savings (1.45E+12 sej/kWh for fossil sources versus 3.57E+11 sej/kWh for crystalline silicon photovoltaic down to 2.31E+11 sej/kWh for cadmium telluride photovoltaic). Results clearly show that PV solar power can be considered a mature technology and can favorably compete with other renewable and non-renewable options for electricity generation. However, efficiency improvements of PV panels thermal recovery are still possible and may lead to further decrease of still too large emergy costs of the treatment process, not to talk of potential recovery alternatives such as chemical treatment for silicon cells and better upstream industrial design.

Idiano D'Adamo, Michela Miliacca, and Paolo Rosa (2017). "Economic Feasibility for Recycling of Waste Crystalline Silicon Photovoltaic Modules," ***International Journal of Photoenergy*****, Article ID 4184676. Online at https://doi.org/10.1155/2017/4184676.**

Cumulative photovoltaic (PV) power installed in 2016 was equal to 305 GW. Five countries (China, Japan, Germany, the USA, and Italy) shared about 70% of the global power. End-of-life (EoL) management of waste PV modules requires alternative strategies than landfill, and recycling is a valid option. Technological solutions are already available in the market and environmental benefits are highlighted by the literature, while economic advantages are not well defined. The aim of this paper is investigating the financial feasibility of crystalline silicon (Si) PV module-recycling processes. Two well-known indicators are proposed for a reference 2000 tons plant: net present value (NPV) and discounted payback period (DPBT). NPV/size is equal to −0.84 €/kg in a baseline scenario. Furthermore, a sensitivity analysis is conducted, in order to improve the solidity of the obtained results. NPV/size varies from −1.19 €/kg to −0.50 €/kg. The absence of valuable materials plays a key role, and process costs are the main critical variables.

Dias, P.; Javimczik, S.; Benevit, M.; Viet, H.; Bernardes, M. (2016). "Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules." ***Waste Management*** **57, 220-225. Online at https://doi.org/10.1016/j.wasman.2016.03.016.**

Photovoltaic modules (or panels) are important power generators with limited lifespans. The modules contain known pollutants and valuable materials such as silicon, silver, copper, aluminum and glass. Thus, recycling such waste is of great importance. To date, there have been few published studies on recycling silver from silicon photovoltaic panels, even though silicon technology represents the majority of the photovoltaic market. In this study, the extraction of silver from waste modules is justified and evaluated. It is shown that the silver content in crystalline silicon photovoltaic modules reaches 600 g/t. Moreover, two methods to concentrate silver from waste modules were studied, and the use of pyrolysis was evaluated. In the first method, the modules were milled, sieved and leached in 64% nitric acid solution with 99% sodium chloride; the silver concentration yield was 94%. In the second method, photovoltaic modules were milled, sieved, subjected to pyrolysis at 500 °C and leached in 64% nitric acid solution with 99% sodium chloride; the silver concentration yield was 92%. The first method is preferred as it consumes less energy and presents a higher yield of silver. This study shows that the use of pyrolysis does not assist in the extraction of silver, as the yield was similar for both methods with and without pyrolysis.

Dias, P.; Javimczik, S.; Benevit, M.; Viet, H. (2017). "Recycling WEEE: Polymer characterization and pyrolysis study for waste of crystalline silicon photovoltaic modules." ***Waste Management*** **60, 716-722. Online at https://doi.org/10.1016/j.wasman.2016.08.036.**

Photovoltaic (PV) modules contain both valuable and hazardous materials, which makes its recycling meaningful economically and environmentally. In general, the recycling of PV modules starts with the removal of the polymeric ethylene-vinyl acetate (EVA) resin using pyrolysis, which assists in the recovery of materials such as silicon, copper and silver. The pyrolysis implementation, however, needs improvement given its importance. In this study, the polymers in the PV modules were characterized by Fourier transform infrared spectroscopy (FTIR) and the removal of the EVA resin using pyrolysis has been studied and optimized. The results revealed that 30 min pyrolysis at 500 °C removes >99% of the polymers present in photovoltaic modules. Moreover, the behavior of different particle size milled modules during the pyrolysis process was evaluated. It is shown that polymeric materials tend to remain at a larger particle size and thus, this fraction has the greatest mass loss during pyrolysis. A thermo gravimetric analysis (TGA) performed in all polymeric matter revealed the optimum pyrolysis temperature is around 500 °C. Temperatures above 500 °C continue to degrade matter, but mass loss rate is 6.25 times smaller. This study demonstrates the use of pyrolysis can remove >99% of the polymeric matter from PV modules, which assists the recycling of this hazardous waste and avoids its disposal.

Jung, B., Park, J., Seo, D., Park, N. (2016). "Sustainable System for Raw-Metal Recovery from Crystalline Silicon Solar Panels: From Noble-Metal Extraction to Lead Removal." ***ACS Sustainable Chemistry and Engineering*** **4 (8), 4079-4083. Online at http://dx.doi.org/10.1021/acssuschemeng.6b00894.**

Methods for recovering raw materials from end-of-life solar panels were studied. A process for removing the hazardous element lead (Pb) in solar panels was also investigated. We achieved recovery rates of 80%, 79%, and 90% for Si, Cu, and Ag. We also achieved a removal rate of 93% for Pb. We immersed the cells in 5 M nitric acid solution under agitation at 200 rpm to dissolve the metals. We sequentially recovered Si, Cu, Ag, Al, and Pb. To recover Si, a process for removing the Al electrode and SiNx layer was required. LIX84-I and 150 g/L H2SO4 solution were used to respectively extract and strip Cu. The purity of Ag powder after reduction Ag2O was 99.7%. An electrolytic refining process increased the Ag purity to 99.99%. We were able to achieve a removal rate of 93% for Pb through neutralization and sulfurization. © 2016 American Chemical Society.

Latunussa, C.E.L.; Ardente, F.; Blengini, G.A.; Mancini, L. (2016). "Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels." ***Solar Energy Materials and Solar Cells*** **156, 101-111. https://doi.org/10.1016/j.solmat.2016.03.020.**

Lifecycle impacts of photovoltaic (PV) plants have been largely explored in several studies. However, the end-of-life phase has been generally excluded or neglected from these analyses, mainly because of the low amount of panels that reached the disposal yet and the lack of data about their end of life. It is expected that the disposal of PV panels will become a relevant environmental issue in the next decades. This article illustrates and analyses an innovative process for the recycling of silicon PV panel. The process is based on a sequence of physical (mechanical and thermal) treatments followed by acid leaching and electrolysis. The Life Cycle Assessment methodology has been applied to account for the environmental impacts of the process. Environmental benefits (i.e. credits) due to the potential productions of secondary raw materials have been intentionally excluded, as the focus is on the recycling process. The article provides transparent and disaggregated information on the end-of-life stage of silicon PV panel, which could be useful for other LCA practitioners for future assessment of PV technologies. The study highlights that the impacts are concentrated on the incineration of the panel's encapsulation layers, followed by the treatments to recover silicon metal, silver, copper, aluminium. For example around 20% of the global warming potential impact is due to the incineration of the sandwich layer and 30% to the post-incineration treatments. Transport is also relevant for several impact categories, ranging from a minimum of about 10% (for the freshwater eutrophication) up to 80% (for the Abiotic Depletion Potential – minerals).

Pa, P.-S. (2017). "Environmentally friendly electrochemical recycling of indium from scrap ITO glass and PET." ***International Journal of Advanced Manufacturing Technology*****, 89 (5-8), 1295-1306. Online at http://dx.doi.org/10.1007/s00170-016-9174-3.**

Indium, the key raw material used in liquid crystal displays (LCDs), light-emitting diodes (LEDs), and solar cells, is a rare metal. The demand for devices that use touch panels has grown enormously, and Indium has become a vital and indispensible material. However, the worldwide depletion of indium resources has made it necessary to recycle as much indium as possible. This is done not only for commercial purposes but also to protect the environment. Although direct electrochemical methods can be used to remove the indium-tin oxide (ITO) layer from intact discarded or defective thin-film transistor (TFT)-LCDs or from flexible polyethylene terephthalate (PET) touch panels, it is not possible to do this with broken or cracked panels, large numbers of glass fragments, or deformed PET material because the necessary electrical connections cannot be made. Therefore, in this study, an indirect electric discharge process was used. Tests were made using DC straight polarity and DC reverse polarity, and a multicylinder electrode was used to conduct carrying out of positive (or negative) electrical discharge in the electrode assembly without the need for electrical connection to the workpiece. An electric field is created by electrical discharge between the cathode and anode through the electrolyte to create an electrical field between the electrode and the ITO surfaces. There is no likelihood of the electrodes making direct contact with the ITO glass fragments, and so, the danger of short circuits is avoided. This method facilitates the smooth and highly efficient recycling of indium avoiding methods that use strong acids and other chemicals that are harmful to the environment. The higher the current used, the faster the feed rate of the workpiece can be, and removal will also be more efficient. A small gap between the electrodes (1 mm) will also speed up the removal rate. Pulsed DC current is conducive to the rapid removal of deposits of electrochemical by-product and also allows a higher feed rate. However, this raises the total electrical power input. The use of ultrasonics speeds up ITO removal as does an increase in electrolyte temperature. A small-diameter anode and a small gap between the electrodes also speed up the removal rate.

Pagnanelli, F., Moscardini, E., Abo Atia, T., Toro, L. (2016). "Photovoltaic panel recycling: from type-selective processes to flexible apparatus for simultaneous treatment of different types." ***Transactions of the Institutions of Mining and Metallurgy, Section C: Mineral Processing and Extractive Metallurgy*****, 125 (4), 221-227. Online at http://dx.doi.org/10.1080/03719553.2016.1200764.**

Photovoltaic (PV) technology for renewable energy utilisation is constantly growing throughout the world. Many recent efforts were devoted to the treatment of end-of-life panels, but only two full-scale processes were developed for crystalline silicon modules (Deutsche Solar) and CdTe panels (First Solar). Furthermore, recent developments concerned with new technologies designed for treating together more kinds of PV panels by automated processes. In this work, a picture of the PV world in terms of market, typology, waste dynamics and recoverable materials was given. A description of full-scale processes will be reported evidencing products and yields of recovery. A case study of process development for the simultaneous treatment of different kinds of PV panels was presented. In particular, experimental results in lab and pilot scale were described regarding the development and optimisation of a process including both physical pre-treatment and hydrometallurgical treatment for the recovery of target metal.

Savvilotidou, V.; Antoniou, A.; Gidarakos, E. (2017) "Toxicity assessment and feasible recycling process for amorphous silicon and CIS waste photovoltaic panels." Waste Management 59(1), 394-402. Online at https://doi.org/10.1016/j.wasman.2016.10.003.

End-of-Life (EoL) photovoltaic (P/V) modules, which are recently included in the 2012/19/EU recast, require sound and sustainable treatment. Under this perspective, this paper deals with 2nd generation P/V waste modules, known as thin-film, via applying chemical treatment techniques. Two different types of modules are examined: (i) tandem a-Si:H/μc-Si:H panel and, (ii) Copper-Indium-Selenide (CIS) panel. Panels' pretreatment includes collection, manual dismantling and shredding; pulverization and digestion are further conducted to identify their chemical composition. A variety of elements is determined in the samples leachates' after both microwave-assisted total digestion and Toxicity Characteristic Leaching Procedure (TCLP test) using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) analysis. The analysis reveals that several elements are detected in the two of panels, with no sample exceeds the TCLP test. Concentrations of precious and critical metals are also measured, which generates great incentives for recovery. Then, further experiments, for P/V recycling investigation, are presented using different acids or acid mixtures under a variety of temperatures and a stable S/L ratio, with or without agitation, in order to determine the optimal recycling conditions. The results verify that chemical treatment in P/V shredded samples is efficient since driving to ethylene-vinyl acetate (EVA) resin's dissolution, as well as valuable structural materials recovery (P/V glass, ribbons, cells, P/V intermediate layers). Among the solvents used, sulfuric acid and lactic acid demonstrate the most efficient and strongest performance on panels' treatment at gentle temperatures providing favorably low energy requirements.

Shin, J., Park, J., Park, N. (2017). "A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers." ***Solar Energy Materials and Solar Cells*****, 162, 1-6.**

This paper details an innovative recycling process to recover silicon (Si) wafer from solar panels. Using these recycled wafers, we fabricated Pb-free solar panels. The first step to recover Si wafer is to dissolve silver (Ag) and aluminium (Al) via nitric acid (HNO_3) and potassium hydroxide (KOH), respectively. The next step is to remove anti-reflection coating (ARC) and emitter on the surface by using an etching paste which contains phosphoric acid (H_3PO_4). Wafers onto which the etching paste was applied were heated for 2 min at 320, 340, 360, 380, and 400 °C. The recycled wafers showed properties with the thickness of over 180 μm, resistivity of 0.5–4 Ω cm, which are almost identical to those of commercial virgin wafers. Furthermore, the solar cells manufactured with the recycled wafers showed an efficiency equivalent to that of the virgin cells. Pb-free solar panels were fabricated with the solar cells by using 60Sn-38Bi-2Ag solder to assemble the solar panels. Thermal cycling test based on the standard IEC 61215 were performed on the solar panels in order to confirm their stability.

Zhang, Z., Sun, B., Yang, J., Wei, Y., He, S. (2017). "Electrostatic separation for recycling silver, silicon and polyethylene terephthalate from waste photovoltaic cells." ***Modern Physics Letters B*****, 31 (11), art. no. 1750087. DOI: 10.1142/S0217984917500877**

Electrostatic separation technology has been proven to be an effective and environmentally friendly way of recycling electronic waste. In this study, this technology was applied to recycle waste solar panels. Mixed particles of silver and polyethylene terephthalate, silicon and polyethylene terephthalate, and silver and silicon were separated with a single-roll-type electrostatic separator. The influence of high voltage level, roll speed, radial position corona electrode and angular position of the corona electrode on the separation efficiency was studied. The experimental data showed that separation of silver/polyethylene terephthalate and silicon/polyethylene terephthalate needed a higher voltage level, while separation of silver and silicon needed a smaller angular position for the corona electrode and a higher roll speed. The change of the high voltage level, roll speed, radial position of the corona electrode, and angular position of the corona electrode has more influence on silicon separation efficiency than silver separation efficiency. An integrated process is proposed using a two-roll-type corona separator for multistage separation of a mixture of these three materials. The separation efficiency for silver and silicon were found to reach 96% and 98%, respectively.

Policy options

Malandrino, O., Sica, D., Testa, M., Supino, S. (2017). "Policies and measures for sustainable management of solar panel end-of-life in Italy." ***Sustainability (Switzerland)*** **9(4), art. no. 481. Online at http://dx.doi.org/10.3390/su9040481.**

The purpose of this work is to carry out a review of the main technical-economic and environmental implications associated with the production of photovoltaic (PV) energy, one of the renewable sources for the production of electricity which currently presents the highest rate of growth worldwide-particularly in Europe and in Italy. The review provides a detailed exploration of the most important initiatives taken at the national level for the end-of-life management of the modules, and highlights issues associated with the disposal and/or recycling of obsolete photovoltaic panels in terms of techno-economic and socio-environmental sustainability. The paper highlights the main critical elements and potential opportunities deriving from the technological, managerial, and organizational options available to enhance recovery and recycling rates of PV panels in Italy. Results point out the importance of a circular economy perspective, through the involvement and awareness of the actors in the process, in order to render an even greener photovoltaic energy life cycle. © 2017 by the authors.

What are the waste disposal requirements for solar PV systems?
https://training.ny-sun.ny.gov/88-resources/faqs/general-faqs/207-is-anything-within-the-arrays-or-associated-materials-such-that-future-disposal-will-require-disposal-as-anything-other-than-simple-garbage-as-in-household-garbage
New York State requirements for recycling solar PV systems.