RESEARCH ARTICLE

Extraction and analysis of back-sheet layer from waste silicon solar modules

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Abstract: The back-sheet shields the solar panel from UV rays, moisture, dust, and other environmental factors. With the enormous growth of the solar industry year after year, the demand for recycling is also increasing rapidly. In the present study, the back-sheet layer was extracted from a waste crystalline silicon PV module by thermally heating the module at 130°C temperature. Various characterization techniques, including Raman, FTIR, SEM-EDAX, XRD, and TGA, were used to examine extracted back-sheet layer properties for its reuse. The Raman and FTIR spectra of extracted back-sheet are quite similar to those of reference PET back-sheet, indicating that no significant changes in composition occurred during the extraction process. The extracted back-sheet has a composition of carbon and oxygen as witnessed from EDAX spectroscopy. The extracted back sheet maintained its semicrystalline behavior as that of the reference back sheet, observed by XRD spectroscopy. Thermogravimetric analysis revealed that the thermal stability of extracted back-sheet is up to 252°C in the air environment and up to 315°C in the inert environment. Thermal degradation of extracted back-sheet is a two-step process in an air environment observed by differential thermogravimetry. The observed properties of extracted back-sheet are comparable to those of commercially available back-sheet, and the same may be reused in solar and polymer industries after appropriate processing.

Keywords: solar waste, polymers, back sheet, recycling

1 Introduction

Solar panel installation is rapidly increasing around the world, and according to IRENA 2016, the expected solar installation capacity will reach 4500 GW by 2050 [1]. Although solar energy is a renewable and clean source of energy, the PV module will contribute to hazardous waste due to its limited life span [2, 3]. According to the literature, the solar module has an average life of 25 years, after which they pose a significant threat to humankind [4, 5] because of the release of toxic materials such as lead, cadmium, chromium, and nickel. All of these materials are divided into four categories based on their technology: crystalline solar, thin-film, concentrator photovoltaic (CPV), and emerging technologies [6, 7].

With a 95 percent market share, crystalline silicon-based solar cells are the most efficient and dominant [8–10]. As shown in Figure 1, crystalline silicon solar modules are assembled with various layers such as glass, aluminium frame, encapsulants, solar cells, back sheet, and junction box. Glass is used to give the panel mechanical strength and durability. The solar cells are held together by encapsulant layers, which are attached to the glass and back sheet. The aluminium frame supports and maintains all of the layers, and the junction box is used for electrical connections. Thus, improper dumping of solar modules will result in the depletion of various traditional materials such as glass, aluminium, Si, and Cu, as well as a decrease in valuable metals such as silver, and will pose a health and environmental risk with the release of toxic elements such as lead (used in the soldering along with tin for connections and bus bars) [11–17]. Therefore, solar waste must be managed in an effective, efficient, and environmentally friendly manner. Currently, solar waste is generated from early loss panels, but it is expected that by 2030, massive waste from both early and regular loss scenarios will be available for recycling [1]. As previously stated, the solar module can be a great resource of materials, so research is being conducted in this area to ensure the efficient recovery of involved materials. Mechanical treatment can separate the junction box and aluminium frame, whereas thermal treatment can collect the glass. Metallurgical operations were used to recover the remaining metallic and semiconducting layers [18, 19]. Thermal treatment has been used to recover EVA, and the results have been reported by our group earlier [4]. It is important to note that the materials used as back sheet layers are typically Dupont polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF), and polyethylene terephthalate (PET) alone, and their combination as TPT type structure. TPT (Tedlar/PET/Tedlar)

has a thickness ranging from 100 to 450 microns. The back sheet is exposed to the environment and is placed on the backside of the solar panel. The primary function of the back sheet is to prevent water vapor transmission, to protect the solar cell from UV rays, and to provide oxygen barrier properties to protect the solar cell from degradation. It is also considered the most important layer for protecting solar cells and electrical connections from the environment. After considering the various functions of the back sheet, its extraction is required to facilitate the recycling of solar panels, and they can be reused. The reported method for recycling waste solar modules includes physical treatment, thermal decomposition at high temperature, chemical treatment, and a combination of these methods [20–25]. In physical treatments, solar panels were crushed and milled in an eco-friendly manner but resulted in less efficiency for Si recovery due to a reduction in thickness of Si wafer, no back sheet recovery was reported. In thermal treatments, the polymer layers (back sheet and EVA) decomposed at high temperatures (500-600°C) leading to loss of back sheet and EVA and environmental pollution. Chemical methods were also reported to recover various materials from the waste solar panel, but the recovery of the back sheet and its analysis was not mentioned. The motive of all the above-mentioned methods was to recover the solar cell and metals, not the polymeric layers [9, 26, 27]. The recovery of EVA and back-sheet did not get much attention due to its low cost compared to other involved materials in solar panels. But, the recovery of polymeric layers is important to ease the recycling process and avoid polymeric pollution. Therefore, In the present study, efforts are made to extract the back-sheet layer from waste solar modules. The reported method for extraction of the back sheet included thermal treatment at 130C followed by application of mechanical force. The extracted back sheet was analyzed by various characterizations and the same was compared with the commercially available back sheet. The extracted back sheet showed quite similar properties as that of the commercial back sheet layer and the same may be reused again in solar modules or the polymer industry. Also, the reported method for extraction of the back sheet from waste solar modules is environmentally friendly and will ease the recycling of solar modules as well.
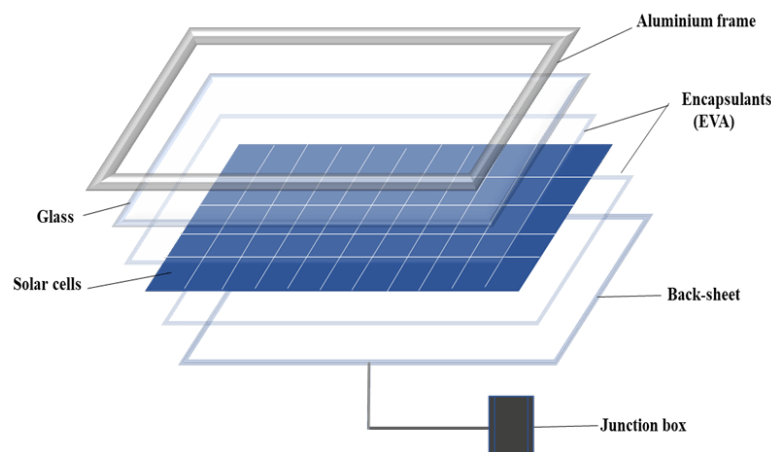

Figure 1   Schematic of crystalline silicon solar panel defining different layers involved

2   Materials and methods

In the present study, an old waste mono-crystalline silicon solar module (0.98 m 1.64 m) was used. The sample (solar module) contained different layers such as an aluminium frame, a glass layer, an EVA layer as a binder, silicon wafer, a back-sheet, and a junction box. Out of all layers, the back sheet layer is thoroughly discussed in the present investigation. The collective weight of the sample weighed 17.18 kg including 0.62 kg of aluminium frame's weight. The junction box aluminum frame was removed mechanically (Figure 2), and the remaining crystalline silicon solar module was cut into small pieces of sizes (0.07 m × 0.08 m) with a diamond wheel cutter with 8000 rpm for further treatment. The small pieces of the solar module were thermally heated on the hot plate (at different temperatures) which was also linked to the thermocouple and temperature controller for sensing and displaying the temperature respectively. Various samples were tried with different temperatures and out of which three samples observation are shown in Table 1. After careful observation, the optimized temperature for extraction of the back sheet was 130°C, where the bonding between the encapsulant EVA and the back-sheet layer become weak. At that temperature, the back-sheet was extracted from the solar module with ease by applying mechanical force and collected for further investigation as shown in Figure 2f. It was observed that no fume was produced during the process, indicating that extracted back-sheet layer material may not be degraded.

The extracted back-sheet layer was evaluated by different characterization techniques to check their structural composition, elemental composition, surface morphology, and thermal stability, and the same was compared with the commercial PET back sheet of M/s Prashant Solar, used as a reference back-sheet.
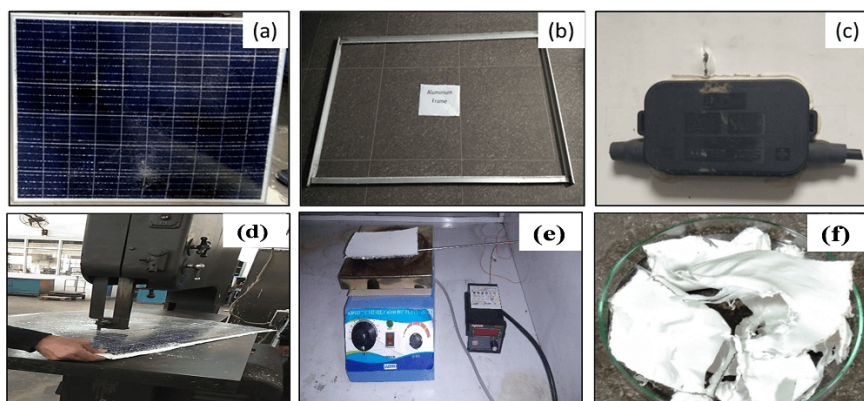

Figure 2   (a) The damaged/discarded crystalline silicon solar module; (b) extracted aluminium frame; (c) dismantled junction box; (d) cutting of PV module with diamond wheel cutter; (e) Experimental setup for thermal treatment on the sample; (f) Extracted back-sheet from the waste solar module.

Table 1   Observation

S.No	Temperature	Remark
1	100°C	Back-sheet was not able to extract, due to strong bonding with EVA.
2	110°C	Back-sheet was not able to extract, due to strong bonding with EVA.
3	120°C	Bonding between EVA and back-sheet starts becoming weak, but the back-sheet was not able to extract with ease.
4	130°C*	Extraction of the back sheet with ease as bonding between EVA and back sheet becomes weak due to softening of EVA.
5	140°C	EVA started melting and some parts of EVA were attached to the back sheet during extraction.

Note: * Optimized temperature

3   Characterization

In order to check the properties of extracted sample for their reuse, the sample was characterized through various characterization techniques and compared with commercially available PET back-sheet. The findings are discussed in detail in the following subsections. M/s Prashant Solar company India provided the reference PET back-sheet for comparison.

3.1   Raman spectroscopy

To check the chemical composition of the back-sheet, two samples each of extracted back-sheet and reference back-sheet were characterized by Renishaw In via micro - Raman spectrometer in the range 4000-400 cm^{-1}. The wave length of laser used is 785 nm. (see Figure 3)
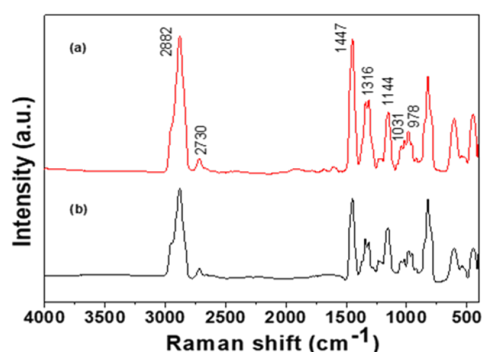

Figure 3   Raman spectra of (a) reference PET back-sheet (b) extracted PET back-sheet

3.2   Fourier Transform Infrared Spectroscopy (FTIR)

To identify the involved functional group in the extracted back sheet, the sample was characterized using Fourier transform infrared spectroscopy in the 4000-400 cm^{-1} range. FTIR spectra provide information for intermolecular interaction regardless of bond bending and stretching. (see Figure 4 and Table 2)

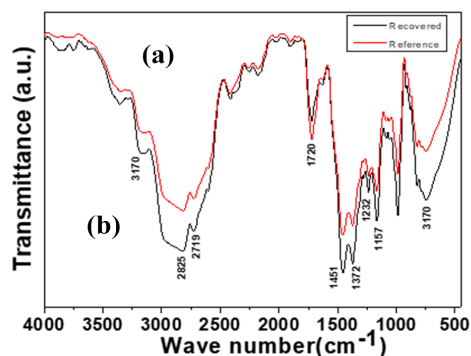**Figure 4** FTIR spectra. (a) Reference back-sheet (PET); (b) extracted back-sheet from discarded silicon solar module.

Table 2 Different vibration modes and involved functional groups in the composition of the sample observed in the FTIR spectra

Wavenumber (cm^{-1})	Functional group and types of vibration involved in sample
3170	C-H stretching of the phenyl ring
2825, 2719	C-H (symmetric and antisymmetric stretching bands),
1720	C=O (related to carbonyl stretching bands)
1232, 1157	C-O (ester group shows two stretching bands)
1451	C-H2 (stretching)
1372	C-C (phenyl ring stretching band)
736	C-H (bending)

3.3 XRD

A Rigaku Mini Flex II X-ray diffractometer with Cu-Ka radiation in the range 10-60° on a 2θ scale was used to analyze the crystalline behavior of the sample (extracted back-sheet) and reference (virgin back-sheet). The d value corresponding to all of the observed peaks were calculated using Bragg's law equation $2d\sin\theta = n\lambda$, where λ =0.154 nm (X-ray wavelength of Cu-Kα) and n=1. The crystal size was calculated using the Scherrer formula B= $k\lambda/\cos\theta$, where k is a constant assumed to be 1, λ is the X-Ray wavelength of Cu-K as mentioned above, and θ is the diffraction angle. (see Table 3 and and Figure 5)

Table 3 Diffraction angle (2θ), planes, d-spacing, FWHM, and crystal size for the recovered back-sheet.

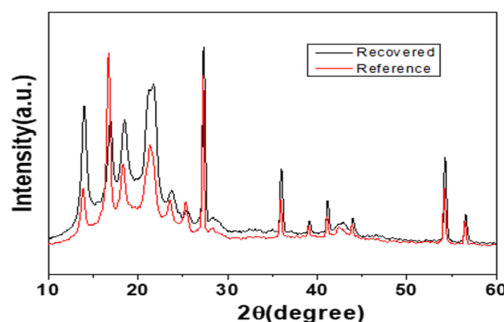| Reference back sheet					Extracted back sheet				
2θ	h k l (plane)	FWHM (°)	Crystal size (Å)	d(nm)	2θ	h k l (plane)	FWHM (°)	Crystal size (Å)	d(nm)
16.78	0-11	0.67	119.84	0.53	16.90	0-11	1.31	61.30	0.52
18.41	010	2.32	34.68	0.48	18.50	010	2.04	39.45	0.48
21.41	-11 1	1.64	49.9	0.42	21.64	-11 1	1.71	47.29	0.41
23.62	0 1 1	1.72	47.18	0.38	23.76	0 1 1	2.82	28.78	0.37
27.17	1 0 0	0.47	173.87	0.33	27.36	1 0 0	0.52	157.22	0.33
35.96	0 2 0	0.58	143.98	0.25	36.04	0 2 0	0.54	154.69	0.25
41.14	0 2 1	1.09	77.83	0.22	41.02	0 2 1	0.65	130.48	0.22
54.19	1 -2 4	0.49	182.09	0.17	54.28	1 -2 4	0.49	182.71	0.17
56.47	-1 -2 6	0.52	173.39	0.16	56.60	-1 -2 6	0.52	173.50	0.16

Figure 5 X-ray diffraction spectra. (red) Reference back-sheet PET; (black) Recovered back-sheet from the discarded solar module.

3.4   SEM-EDAX

In order to study the surface morphology and elemental composition of the back-sheet, the sample (extracted back-sheet) was analyzed with Field emission scanning electron microscopy (FE-SEM) and Energy Dispersive X-ray (EDX) spectroscopy respectively. A thin layer of gold metal was coated on the sample for 60s and 10 mA current by using the SC7620 mini sputter coater. The sample was inserted into the FE-SEM instrument after gold coating. (see Table 4, Figure 6 and 7)

Table 4   Composition of elements involved in Extracted back-sheet observed by EDS spectroscopy

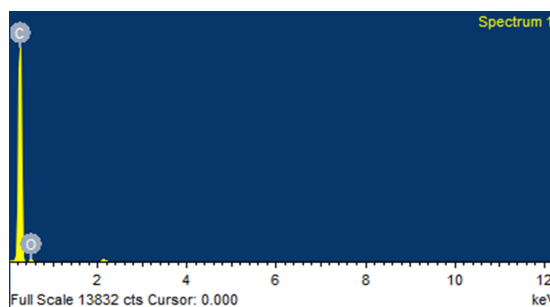| Element	Weight (%)	Atomic (%)
Carbon	95.53	96.61
Oxygen	4.47	3.39

Figure 6   EDAX spectra of Extracted back-sheet from the waste solar module
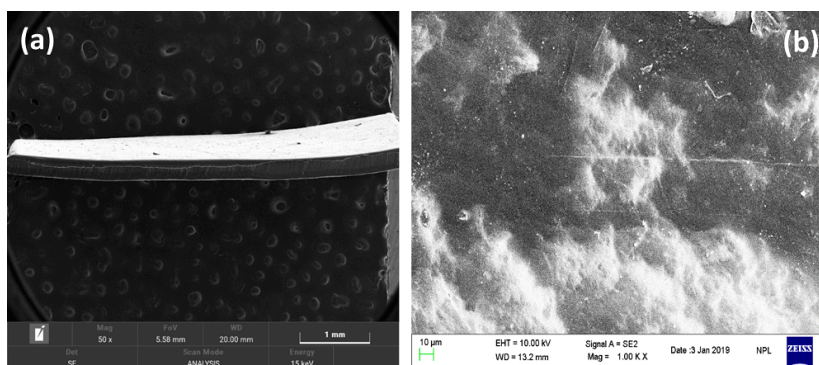

Figure 7   SEM images of extracted polymer sheet. (a) cross-section; (b) surface image.

3.5   Thermogravimetric Analysis (TGA)

The sample (extracted layer) was characterized using thermogravimetric analysis to examine the thermal stability of the extracted back sheet. TGA is a material characterization technique that measures weight loss as a function of time and temperature. The measurements were taken in both air and an inert environment (N_2 gas). The extracted sample ($\sim$7 mg) was placed in an aluminium pan of a TGA instrument and heated for 45 minutes at a rate of $10°C$/minute in a temperature range of 35-500$°C$. (see Figure 8)
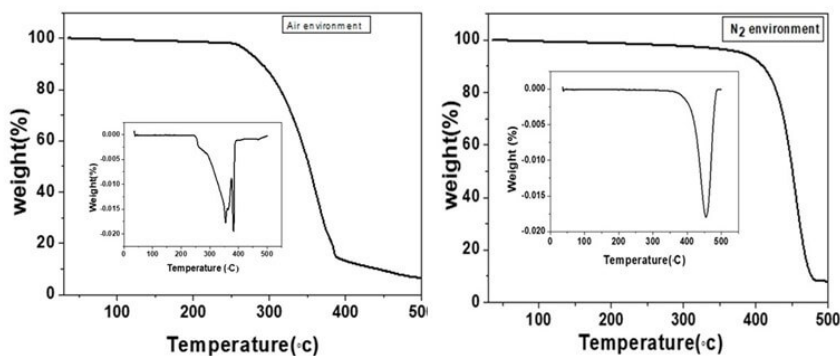

Figure 8   Thermogravimetric measurements of Extracted back-sheet in (a) air environment (b) N_2 environment.

4 Result and discussion

Raman spectra for reference PET back-sheet and extracted PET back-sheet depicted in Figure 3. it has been observed from Figure 3 that the Raman spectra for both back-sheets are quite similar. The bands at 2880 cm^{-1} and 2720 cm^{-1} corresponded to the methylene group adjacent to oxygen atoms and the methylene sequence's C-H bond, respectively. The vibration band at 1447 cm^{-1} is related to the bending of CH_2 and O-CH. The 1316 cm^{-1} band corresponds to C-CH and O-CH bending. PET back-sheets have main characteristics bands at 1144 cm^{-1}, 1031 cm^{-1}, and 978 cm^{-1} due to mixed-mode (glycol C-O stretch + ring CH in-plane bend), mixed-mode (ring CH in-plane bend + COC + glycol C-O stretch, C-C stretch +CCO bending), and mixed-mode (O-CH_2 stretch + glycol C-C stretch +ring torsion), respectively [28]. The Raman spectra show no significant difference in the extracted back-sheet compared to the reference PET back-sheet, which is also confirmed by FTIR. All the bands visible in the Raman spectroscopy were also observed in FTIR spectroscopy along with some extra peaks. However, the carbonyl stretching bond (C=O) is missing in the case of Raman spectroscopy and observed in IR spectra. The FTIR spectra (Figure 4) of the sample (extracted back-sheet) and reference (virgin back-sheet) show various similar vibrational bands. However, some marginal changes were observed in peak bands that may be due to the extracted back sheet being used for a longer time in solar panels. Various absorption bands can be found in the 1500-500 cm^{-1} range, which may be related to bending vibrations in the molecule. The C-H stretching of the phenyl ring shows the peak at 3170 cm^{-1}. The ester group C-O exhibits two stretching bands at wavenumbers 1232 cm^{-1} and 1157 cm^{-1}. At 1739 cm^{-1}, the carbonyl group C=O exhibits a stretching vibration band. Peaks at 2825 cm^{-1} and 2719 cm^{-1} are corresponded to C-H bonds (symmetric and antisymmetric stretching bands), respectively, while the peak at 736 cm^{-1} is related to C-H bending vibration band [29]. The different bands observed in FTIR spectra of the sample (extracted back-sheet) are illustrated in Table 2. PET is a semi-crystalline polymer [30, 31] as evidenced by the XRD spectra shown in Figure 5. The reference back sheet XRD spectra shows peaks at 16.78° 0 -1 1), 18.41°(0 1 0), 21.41°(-1 1 1), 23.62°(0 1 1), 35.96°(1 0 0), 41.14°(0 2 1), 54.19°(1 -2 4), 56.47°(-1 -2 6). The extracted back-sheet shows comparable peaks with small shift in 2θ value 16.90° 0 -1 1), 18.50°(0 1 0), 21.64°(-1 1 1), 23.76°(0 1 1), 36.04°(1 0 0), 41.02°(0 2 1), 54.28°(1 -2 4), 56.6°(-1 -2 6). There is a small shift observed in extracted back-sheet 2θ, FWHM, and crystal size value as compared to the reference back-sheet as shown in Table 3. According to EDAX, the polymer film is composed of carbon and oxygen, as shown in Figure 6. The fluorine atom's peak is missing, indicating a non-fluorinated polymer back-sheet. As shown in Figure 7, the SEM images of the sample's cross-section area revealed that the extracted back-sheet is a single-layer polymer sheet. Furthermore, the thickness of the extracted back-sheet is comparable to the reference back-sheet and was found to be 300 μm. Thermal degradation of the back-sheet layer is a two-step reaction in the air environment, but a one-step reaction in the N_2 environment (Figure 8), according to DTG (inset Figure 8). The extracted sample has a temperature stability of up to 252°C (related to melting of PET) in an air environment and up to 315°C in an inert environment. The TGA graph revealed that degradation occurred until 390°C in an air environment, which corresponds to PET polymer decomposition [30]. The thermal stability temperature *i.e.* 252°C justifies the polymer recovery temperature of 130°C. There was 7% residue left in the air environment and 9% in the N2 environment until the temperature reached 500°C which concluded incomplete decomposition of PET polymer.

5 Conclusion

In the present work, the back-sheet layer was extracted by thermal treatment at 130 °C temperature to ease the recycling process of discarded silicon solar modules. The extracted back sheet was analyzed by various characterizations and found comparable properties to the commercially available back sheet. TGA investigation demonstrated that the extracted back-sheet is thermally stable up to 252°C, indicating extraction temperature (130°C) is justified to maintain the properties of the back sheet. The extracted back-sheet may be reused again in solar PV modules or polymer industry with appropriate processing according to application. During the extraction of the back sheet layer, no pollution was observed as the treatment was done at a much lower temperature 130°C than its stability temperature *i.e.* 252°C. Therefore, the reported method for extraction of the back sheet from waste solar modules will surely help in recycling solar panels and will reduce environmental pollution as well.

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Authors contribution

Chitra: Experimental work, Data analysis, and writing the manuscript draft.
Dheeraj Sah: Assisted in experimental work and Data analysis.
Parveen Saini: Analysis and Interpretation of results, Co-supervision.
Sushil Kumar: Conceptualization, review & editing, Supervision.

Conflict of interest

The authors declare no conflict of interest that are directly or indirectly related to the work submitted for publication.

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References

[1] Irena I. End-of-Life Management: Solar Photovoltaic Panels, 2016.
https://www.irena.org

[2] Zhang L and Ciftja A. Recycling of solar cell silicon scraps through filtration, Part I: Experimental investigation. Solar Energy Materials and Solar Cells, 2008, **92**(11): 1450-1461.
https://doi.org/10.1016/j.solmat.2008.06.006

[3] Doi T, Tsuda I, Unagida H, *et al*. Experimental study on PV module recycling with organic solvent method. Solar Energy Materials and Solar Cells, 2001, **67**(1-4): 397-403.
https://doi.org/10.1016/S0927-0248(00)00308-1

[4] Chitra D, Sah K, Lodhi C, *et al*. Structural composition and thermal stability of extracted EVA from silicon solar modules waste. Solar Energy, 2020, **211**: 74-81.
https://doi.org/10.1016/j.solener.2020.09.039

[5] Paiano A. Photovoltaic waste assessment in Italy. Renewable and Sustainable Energy Reviews, 2015, **41**: 99-112.
https://doi.org/10.1016/J.RSER.2014.07.208

[6] Tammaro M, Salluzzo A, Rimauro J, *et al*. Experimental investigation to evaluate the potential environmental hazards of photovoltaic panels. Journal of Hazardous Materials, 2016, **306**(5): 395-405.
https://doi.org/10.1016/J.JHAZMAT.2015.12.018

[7] Harnisch J. Study on photovoltaic panels supplementing the assessment impact in the recast of WEEE directive, Bio-Intelligence Service. European Commission (DG ENV), 2011.

[8] Freiburg. Photovoltaics Report, 2021.
https://www.ise.fraunhofer.de

[9] Jing T and Yu S. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Solar Energy Materials and Solar Cells, 2015, **141**: 108-124.
https://doi.org/10.1016/J.SOLMAT.2015.05.005

[10] Bruton TM. General trends about photovoltaics based on crystalline silicon. Solar Energy Materials and Solar Cells, 2002, **72**: 3-10.
https://doi.org/10.1016/S0927-0248(01)00145-3

[11] Fernández LJ, Ferrer R, Aponte DF, *et al*. Recycling silicon solar cell waste in cement-based systems. Solar Energy Materials & Solar Cells, 2011, **95**(7): 1701-1706.
https://doi.org/10.1016/J.SOLMAT.2011.01.033

[12] Latunussa CEL, Ardente F, Blengini GA, *et al*. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar Energy Materials and Solar Cells, 2016, **156**: 101-111.
https://doi.org/10.1016/j.solmat.2016.03.020

[13] Polanský P, Pinkerová M, Bartůňková M, *et al*. Mechanical behavior and thermal stability of eva encapsulant material used in photovoltaic modules. Journal of Electrical Engineering, 2013, **64**: 361-365.
https://doi.org/10.2478/jee-2013-0054

[14] Park J, Kim AW, Cho BN, *et al*. An eco-friendly method for reclaimed silicon wafers from a photovoltaic module: From separation to cell fabrication. Green Chemistry, 2016, **18**(6): 1706-1714.
https://doi.org/10.1039/c5gc01819f

[15] Padoan FCSM, Altimari P and Pagnanelli F. Recycling of end of life photovoltaic panels: A chemical prospective on process development. Solar Energy, 2019, **177**: 746-761.
https://doi.org/10.1016/j.solener.2018.12.003

[16] Shin J, Park J and Park N. 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, 2017, **162**: 1-6.
https://doi.org/10.1016/J.SOLMAT.2016.12.038

[17] Strachala D, Hylsk J, Vank J, *et al*. Methods for recycling photovoltaic modules and their impact on environment and raw material extraction. Acta Montanistica Slovaca, 2017, **22**(3): 257-269.

[18] Larsen K. End-of-life PV: then what? Renewable Energy Focus, 2009, **10**: 48-53.
https://doi.org/10.1016/S1755-0084(09)70154-1

[19] Tammaro M, Rimauro J, Fiandra V, *et al*. Thermal treatment of waste photovoltaic module for recovery and recycling: Experimental assessment of the presence of metals in the gas emissions and in the ashes. Renewable Energy, 2015, **81**: 103-112.
https://doi.org/10.1016/J.RENENE.2015.03.014

[20] Zhang J, Lv F, Ma LY, *et al*. The status and trends of crystalline silicon PV module recycling treatment methods in Europe and China. Advanced Materials Research, 2013, **724**: 200-204.
https://www.scientific.net/AMR.724-725.200

[21] Berger W, Simon FG, Weimann K, *et al*. A novel approach for the recycling of thin film photovoltaic modules, Resources. Conservation and Recycling, 2010, **54**: 711-718.
https://doi.org/10.1016/J.RESCONREC.2009.12.001

[22] Granata G, Pagnanelli F, Moscardini E, *et al*. Recycling of photovoltaic panels by physical operations. Solar Energy Materials and Solar Cells, 2014, **123**: 239-248.
https://doi.org/10.1016/J.SOLMAT.2014.01.012

[23] Marwede M, Berger W, Schlummer M, *et al*. Recycling paths for thin-film chalcogenide photovoltaic waste – Current feasible processes. Renewable Energy, 2013, **55**: 220-229.
https://doi.org/10.1016/J.RENENE.2012.12.038

[24] Pagnanelli F, Moscardini E, Granata G, *et al*. Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies. Waste Management, 2017, **59**: 422-431.
https://doi.org/10.1016/j.wasman.2016.11.011

[25] Huang WH, Shin WJ, Wang L, *et al*. Strategy and technology to recycle wafer-silicon solar modules. Solar Energy, 2017, **144**: 22-31.
https://doi.org/10.1016/j.solener.2017.01.001

[26] Mahmoudi S, Huda N, Alavi Z, *et al*. End-of-life photovoltaic modules: A systematic quantitative literature review, Resources. Conservation and Recycling, 2019, **146**: 1-16.
https://doi.org/10.1016/j.resconrec.2019.03.018

[27] Xu Y, Li J, Tan Q, *et al*. Global status of recycling waste solar panels: A review. Waste Management, 2018, **75**: 450-458.
https://doi.org/10.1016/J.WASMAN.2018.01.036

[28] Lin CC, Krommenhoek PJ, Watson SS, *et al*. Chemical depth profiling of photovoltaic backsheets after accelerated laboratory weathering. Proceedings of SPIE - The International Society for Optical Engineering, 2014, **9179**: 289-299.
https://doi.org/10.1117/12.2066400

[29] Donelli I, Taddei P, Smet PF, *et al*. Enzymatic surface modification and functionalization of PET: A water contact angle, FTIR, and fluorescence spectroscopy study. Biotechnology and Bioengineering, 2009, **103**: 845-856.
https://doi.org/10.1002/bit.22316

[30] Samsaray T and Potiyaraj P. Preparation and properties of graphene / poly (Ethylene terephthalate) composite fibers. Solid State Phenomena, 2020, **304**: 9-14.
https://doi.org/10.4028/www.scientific.net/ssp.304.9

[31] Japu C, Antxon M, Alla A, *et al*. Bio-based poly(ethylene terephthalate) copolyesters made from cyclic monomers derived from tartaric acid. Polymer, 2014, **55**(10): 2294-2304.
https://doi.org/10.1016/j.polymer.2014.03.018