International journal of Inventive Research in Science and Technology ISSN: 2583-5637 (Online)

Volume 4 Issue 11 November 2025

THERMAL DELAMINATION OF END-OF-LIFE (EOL) PHOTOVOLTAIC SOLAR (PV) MODULE TO FACILITATE RECYCLING

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ABSTRACT :- Solar Photovoltaic (PV) module technology is the most prominent, well-established, and mature source of producing renewable energy. A detailed analysis of the gases evolved during pyrolysis of the End-of-Life (EOL) crystalline silicon photovoltaic (c-Si PV) solar module, focusing on recycling strategies has been reported herein. PV modules encapsulated with Ethylene-vinyl acetate (EVA) – with and without Poly-vinylidene fluoride (PVDF) polymer backsheet were pyrolyzed at 500°C and evolve gases was collected in the gas cell.

The current installed capacity in India is approximately 67 GW. As per a report by a European agency, in April 2022, globally cumulative installed PV capacity has crossed 1TW. PV module installations in india are expected to rise further to 20 TW by 2050. But over the next decade, the problem will magnify exponentially. Such end-of-life (EOL) PV installations are treated as solar waste and they need to undergo a carefully strategized waste recycling route in order to keep the overall carbon and pollution footprints to a bare minimum and to propel the circular economy in the PV sector.

Keywords: Photovoltaic solar module, Recycling, Pyrolysis, End-of-Life module, Thermal delamination, Solar cell.

1.Introduction

1.1 Background and Motivation

The establishment of recycling and reuse technologies appropriate and applicable to all photovoltaics (PV) modules is a key issue to be addressed as part of corporate social responsibility to safeguard the environment and to implement a fully material-circulated society without any waste. The life of the solar module is to be expected up to 20-30yearsr depending upon environmental factors of field operation [1,2]. Yellowness/browning, discoloration, delamination, cracks, etc. are the main factors associated with the degradation of solar panels.

So, the PV module must be recycled for the benefit of the environment and also the economy [2-6]. To save the environment from PV waste, the European Union (EU) has pioneered the solar PV module panel's waste sanctions and regulations disposal including recycling and reuse of solar panels. In Europe, where Germany and a few other countries have adopted the EU Waste of Electrical and Electronics Equipment (WEEE) guidelines and enacted appropriate legislation. But most of the country including China and India have not made any significant progress in this direction [7].

As a result of the tetrahydrofuran-based chemical delamination (THF). The materials from a damaged PV module could be separated. The effectiveness of the chemical treatment approach used was insufficient. Because of the lengthy time required to get satisfactory results, as well as the relatively expensive cost of the solvent utilized, this process is not suitable for commercial PV cell and module recycling. As a result, the thermal way was proposed and researched.

As a result, technologies for recycling solar modules are being developed around the world to lessen the environmental impact of end-of-life modules while also recovering some of their value. Current recycling systems, on the other hand, are largely focused on downcycling processes, which recover just a part of the materials and value, so there is still lots of space for improvement. Furthermore, only Europe presently has a solid legal structure in place to promote recycling, while other nations are beginning to develop PV waste-specific laws. The PV industry's long-term development should be supported by regulatory frameworks and organizations around the world, which is currently not the case. When photovoltaic modules reach their end-of-life (EoL) or are no longer able to produce power, appropriate management practices are required. In comparison to chemical treatment, the method takes substantially less time, and there is no problem with leftover solvent. The emission of gas during the thermal decomposition of EVA copolymers is, however, a disadvantage of thermal treatment. The PV industry's long-term development should be supported by regulatory frameworks and organizations around the world, which is currently not the case. When photovoltaic modules reach their end-of-life (EoL) or are no longer able to produce power, appropriate management practices are required. In comparison to chemical treatment, the method takes

substantially less time, and there is no problem with leftover solvent. The emission of gas during the thermal decomposition of EVA copolymers is, however, a disadvantage of thermal treatment. Additional costs of waste solution disposal must also be taken into account in case of chemical treatment.

2. LITERATURE REVIEW

In the Photovoltaic (PV) module Silicon is the main and globally used material. In 2010 Global solar PV installations were 19 GW which increases to 24 GW i.e., a 24% increment in one year [1] and according to the latest data, global installations reached 508 GW in 2018. And according to the international technology roadmap for photovoltaic (ITRPV) is predicted to achieve 4500 GW capacity by 2050 [12]. But this causes adverse effects too as significantly E-Waste will increase. PV waste was 250000 metric tons till 2016 and expires expected to reach approx. 6 million tons by 2050 [13].

Nowadays researchers are focusing based on the 3R strategy, R-Reduce the hazardous components from the solar module, R-Reuse (Generate a robust secondary market for second-hand use of panel even lower rate and lower power rating below 80%), and R-Recycle (Major components should be recyclable and it is reusable. Only for encapsulant not clear evidence how to use). For recycling of PV modules generally three different processes namely, physical, thermal and chemical are used [12].

2.1 Crystalline Silicon (c-Si) Technology

Crystalline silicon(c-Si) can be either monocrystalline or multi-crystalline and contains silicon as major material. It dominates the current market. The industry now uses aluminium back surface fields (Al-BSF), although passivated emitters and rear cells (PERC) are gaining traction in the market, and it is supposed that these will eventually replace older technologies [1]. There is also a lot of research going on on heterojunction (HIT) cells, which is projected to achieve some traction by 2027. For c-Si-based PV cells, there are different cell structures. In a photovoltaic module, the majority of the weighted portion is glass because the weight of gas is approx. 70% and around 10% weight of polymer and back sheet, aluminium is approximately 8%, silicon solar cell with 5% weight, copper which is used for interconnections is 1% and less than 0.1% silver is used [1]. It also consists of some other metals which are lead and tin. Encapsulant is generally made of EVA which sandwiches solar cells.

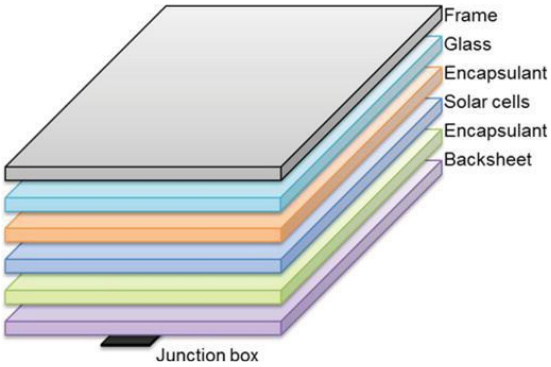

Figure 2.2: Structure of c-Si Solar module [1]

2.2 Thin-Film Technology

Thin films are manufactured by depositing one or more thin layers of a semiconductor on glass, metal, or plastic. It covers 10% of the global photovoltaic market. The cadmium telluride (CdTe) is 65%, Copper Indium Gallium Selenide (CIGS) has approx. 25% of the global market share of thin-film technology. Amorphous silicon is almost 10% of this and they are decreasing because of less efficiency. The target of developing thin-film technology was to produce low cost and have variable geometry. CdTe is widely used but because of the toxic element like cadmium (Cd), it is very dangerous for the environment and mitigates the goal of green energy. Copper Indium Gallium Selenide has a high absorption coefficient. Amorphous silicon has low toxicity but it is also less durable so it is less efficient than others. Current trends show that shortly amorphous silicon technology will be not in use because they are not cost-efficient.

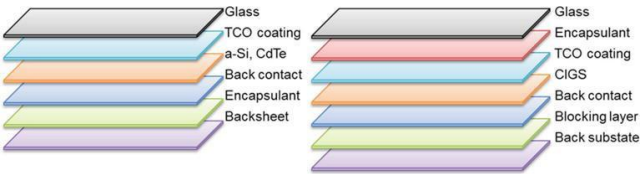

Figure 2.3: Basic structure of thin-film solar module [1]

2.3 Recycling of c-Si PV Modules

The main motive of recycling is to recover maximum material to use for further production and to minimize the amount of remaining waste [9]. A lot of research is going on the recycling of solar modules and considering the situation of collection of e-waste in the coming future. So, the growth of the photovoltaic (PV) industry causes environmental problems considering its end of life (EoL) [14]. Harnessing solar energy through the PV module (Photovoltaic effect) to produce electricity has now become the fastest-growing sector in the renewable energy production industry [1]. A Typical PV module consists of Si solar cells connected in rows and columns by solder and interconnects rails (fig.

2.31). The solar cells are encased in an encapsulant (typically Ethylene Vinyl Acetate, EVA) and fused to glass on the front and with a backsheet. The entire structure is encased in an Aluminum frame. There is a junction box on the backside for making the electrical connections. Photovoltaic modules work for almost 25-30 years before they are no longer usable due to reduced efficiencies. India's annual PV additions achieved a record in 2022 at 18 GW, up 27% from 2021 (Fig. 2.32). Modules installed in the early 2000s are already reaching end-of-life, and the numbers will rapidly increase soon. In India, the PV module waste is expected to reach 200,000 tonnes by 2030 and 1.8 million tonnes by 2050 annually [Figure 2.33]. IEA reported that in 2022, 231 GW of PV was installed globally, bringing cumulative PV installs to 1.2 TW. The worldwide estimated Solar energy target by 2030 is 16 TW (fig. 2.34) and same tonneage estimated Solar Waste will be 78 million tons (fig. 2.35). As the installation of PV modules increases exponentially, the End-Of-Life modules are also expected to rise by the same proportion shortly. Despite the obvious environmental benefits, it is difficult for PV module recycling to be widely accepted due to economic constraints, namely, the low value of recovered material and high recycling cost [2-4]. The lack of PV-specific disposal guidelines, technical know-how, and low industrial involvement further add to this burden. Thus, decommissioned panels are primarily being dumped in landfills or, at best, being sent to glass recyclers [16-18].

Thermal Delamination: EVA has a burnout temperature of Approximately 450°C. The conventional Fluoro polymer-based back sheets burn out at ~ 550 [Figure 2.36]. The reported thermal decomposition involves heating the modules to 200°C. At this temperature, the Back sheet is still intact but can be peeled off. The remaining structure of Si Cell encased in EVA stuck to glass is heated to 480°C at a ramp rate of 15°C /min for 30 minutes to burn off the EVA [4, 7].

Chemical treatment for delamination: There are some reports of chemical approaches being employed for the delamination of PV modules. It has been reported that Toluene or HNO3 gives the best results, but the process takes up to 2 days at 90°C [3, 6]. The disposal of the effluents also needs to be done appropriately. Clearly, this method is not sustainable. Hence it is not being discussed in detail here.

Other delamination methods: Such panels have been delaminated using a wire saw, or even a knife after softening the encapsulant by heating the module on a hot plate at 120°C [5-6]. Another method reported uses a knife heated to 300°C to locally soften the EVA and peel it off from the glass (Figure 6). This method is being used by industry in Japan [5].

It includes combustion/cracking/burning. Solar world performed an experiment by heating a module in a temperature range of 500-550 ˚C in a furnace. During the process of thermal cracking, EVA burns out but the glass plate breaks in the furnace and it becomes very difficult to separate the residual solar cell and glass [5]. And the problem with chemical treatment is that it takes time up to several days. To get rid of the above problem discussed in the thermal approach, two steps heating method was used. The first module was heated at 330 ˚C for 30 minutes and finally at 400 ˚C for 120 minutes [5]. In the first step tedlar which is used on the back sheet, was separated without burning of EVA, and finally, in the second step EVA burn out. This process makes sure removal of encapsulant without breaking glass in the furnace.

The Si recycling technology with high purity by chemical treatment is also under development. It is expected that Si is to be used for PV Cell. Through research Industrial Technology Research Institute, Taiwan (ITRI) found a heating method that involves a single cell module with poly vinyl fluoride (PVF) as a back sheet. At first, a module is heated for 30 mins at 330 ˚C and PVF is separated from the back surface. For thermal burning of PVF and EVA for 2 hours at 400 ˚C a second heating step is carried out. To remove Al electrode, the Si chips are etched with hydrogen peroxide and HCL, to remove the Ag and Si3N4 layer (anti-reflecting coating) HCL is used and to remove the back-surface field BSF layer, P-n junction sodium hydrocode is used. Flue gases evolved during the burning of EVA and PVF is problematic. PADUA University has published a dielectric heating technique to replace combustion and direct heating, as indicated in the previous processes. A single cell module was used in this method, which was de laminated using a radio frequency heating procedure. For recovery, a vacuum-gasification-condensation technique was adopted [15, 23]. However, due to the experiment's limitations, this strategy is not applicable and more research is needed [14]. GC-MS (Gas chromatography-mass spectrometry) was used to analyse distinct components, while SEM was utilised to study the microstructure of the residue and EDS was used to determine the elements contents of the residue.

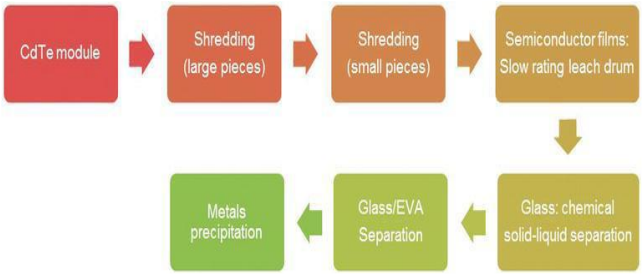

Figure 2.3: First solar recycling process for CdTe Modules

3. Experimental work

According to the literature survey recycling of PV modules can be done by using Physical methods, Chemical methods, Thermal methods, and also by combining two or more methods. So here experimental procedure will be discussed and after that some characterization in order to understand the trace element on solar cell surface and analysis of gas collected in gas jar using FTIR.

One of the key challenges in PV module recycling is delamination, i.e., the removal of the solar cell, solar glass, and backsheet. I have successfully delaminated mini modules and separated the solar glass, solar cells, and backsheet by thermal pyrolysis [findings has been reported and accepted, 8]. Figure 3.00 shows the flow chart of previous work carried out and some findings are reported herein. The recovered Solar glass can either be used to manufacture new modules – possibly for household and distributed power generation or channeled into the glass recycling process. Flow chart of previous work carried out and proof-of-concept shown in below.

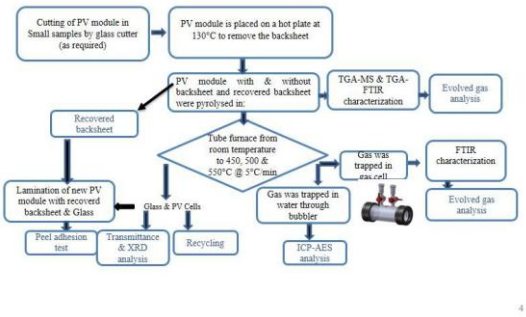

Figure 3.00. Flow chart of previous work carried out and proof-of-concept

3.1 Thermal Approach

The first step in the recycling process of the c-Si PV module is to remove the aluminium frame but, in our case, we have taken a small module and cut it to a size that can be fitted into a tube furnace as we are heating it in a tube furnace. So, we need to remove the back sheet and encapsulant i.e., EVA polymer in our case.

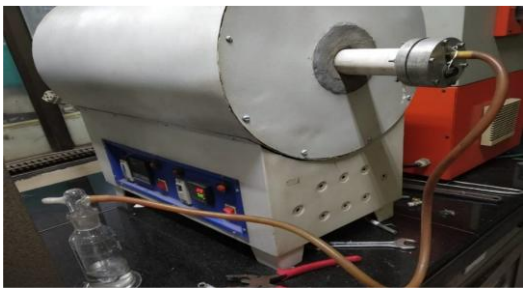

Figure 3.1: Tube Furnace setup with bubbler

Thermal Approach using Tube Furnace

We have taken two samples named 1 and 2. The weight of both samples was measured. Weights of sample1 and sample 2 were 7.9666 gm and 7.8740 gm respectively before performing the experiment. Both modules have EVA as an encapsulant.

3.1.1 Pyrolysis of PV module up to 500 ˚C

We have used a thermal approach here. First of all, we made the setup by connecting a bubbler containing 100 ml of water to the exhaust of the tube furnace so that we can further analyze the particles trap in the water. Compressed air was passed in a tube furnace so that flue gases can be easily passed through the bubbler. We could have used Nitrogen gas but considering the economical point of view, we have used atmospheric air. For sample 1, we passed compressed air at 2.5 Kg/cm^2 and heated the sample in a tube furnace from room temperature to 550 ˚C in 1hour and 20 minutes and hold it here for 30 minutes. As EVA starts burning, flew gases start flowing through the bubbler. Finally, when tube furnace temperature comes to room temperature, we took away our sample 1 which was in a crucible. The products of this experiment are solar cells, glass, residue, and materials inside bubbler water as can flow chart of the procedure can be seen in fig 3.2.

Figure 3.2: Solar cells, Glass, and residual obtained from tube furnace after the experiment

3.1.2 Pyrolysis of PV module up to 550 ˚C

Considering the same setup, we put sample 2 in a crucible. The initial weight of the sample was 7.8740 gm and operated tube furnace from room temperature to 550 ˚C in

1 hour and 10 minutes and kept at this temperature for 30 minutes. When the furnace cool down, we took away the crucible in which the sample was placed.
EVA completely burned in both cases and we successfully separated solar cells, glass and residue. Weight loss in both cases was nearly 12%.

Experimental Work:

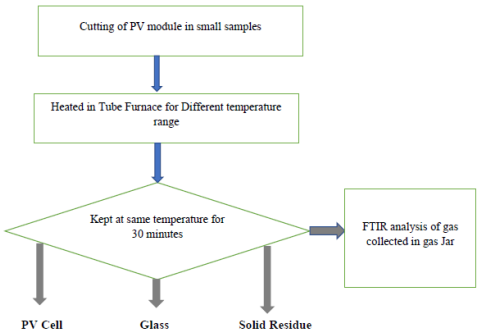

Figure 3.3: Flow chart of Experimental Work

3.1.3 FTIR analysis of PV module

For FTIR analysis of evolved gases during pyrolysis we need to store gases for which we have used gas jar. At first, we cut PV module into small pieces so that it can be pyrolyzed in a tube furnace. We carried out the experiment from room temperature to 450, 500 and 550 ˚C in a time duration of 1 hr 10 minutes and once the respective temperature achieved, compressed air was passed into the tube furnace which causes the movement of evolved gases outside and then we collected that in a gas jar.

3.1.4 FTIR analysis of PV module without backsheet

Similar experiment was done for PV module sample without back sheet (PVDF) from room temperature to 450, 500, and 550 ˚C. But in order to remove the back sheet, we heated the sample on a hot plate to 100 ˚C and peeled off the PVDF layer mechanically, and then heated it in a tube furnace and collected the evolved gases in a gas jar. Finally, FTIR analysis was done in order to compare it with the spectrum in the case of module and back sheet.

Figure 3.4: Hot plate used during the experiment.

Similar experiment was done for back sheet at 500 ˚C. Once we collected evolved gases in gas jar, we can observe the spectrum using FTIR and can compare with the result obtained in the case of module and module without back sheet.

3.2 Characterisation

3.2.1 Transmittance measurement

We need to know about the transmittance of glass in order to understand the re-usability of glass. Transmittance of glass before and after pyrolysis was done by UV Visible Spectroscopy. The working principle of UV-visible spectroscopy is based on the absorption and reflection of Ultraviolet light or visible light or both by chemical compounds. When any material absorbs wavelengths of light, it will undergo excitation or de-excitation which results in the production of spectrum.

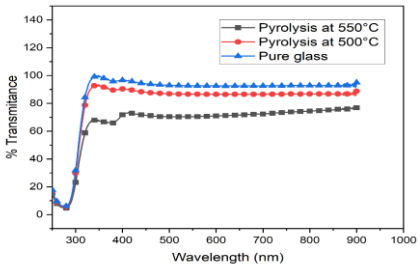

Figure 3.5: Transmittance of glass plate before and after pyrolysis at 500°C and 550°C

From UV-vis spectroscopy experiment graph it can be stated as the transmittance of glass obtained after pyrolysis till 500˚C is around 90% whereas transmittance of glass pyrolyzed till 550 ˚C is around 70%. So, glass having transmittance 90% can be reused. This explain that pyrolysis done at 500 ˚C is better than 550˚C.

3.2.2 ICP AES analysis of trapped gas

ICP-AES stands for Inductive coupled plasma -atomic emission spectroscopy. It is a method of detecting chemical components using analytical techniques. It's a type of emission spectroscopy that makes use of an inductively coupled plasma to create excited atoms and ions that emit electromagnetic radiation at wavelengths specific to a given element. Plasma is an ionised source gas with a high temperature. Inductive coupling from cooled electrical coils at megahertz frequencies sustains and maintains the plasma. The temperature of the source is between 6000 and 10,000 K. The intensity of light emissions at different wavelengths is proportional to the element concentrations in the sample.

We have done the experiment of the trapped gas in the bubbler at 500 ˚C and 550 ˚C. Result obtained from ICP-AES states that Ag, Pb and Sn have less than 0.01 ppm amount whereas Al and Si have some considerable amount. As the temperature increases the trapped elements are more

(table3) in that so it causes less recovery of element if we do leaching of the solid residual left after pyrolysis. So, experiment suggests that the pyrolysis is more favourable at 500 ˚C with respect to 550 ˚C.

3.2.3 SEM-EDX analysis of Solar cell

Scanning Electron Microscopy Coupled with Energy Dispersive X-ray:

EDX technique is used to identify the chemical elemental compositions of materials. EDX system is attachment to Electron microscope (SEM/FE-SEM/TEM) instrument where imaging capability of microscope is identified. In Scanning Electron Microscopy, the front surface of solar cell after pyrolysis of PV solar module at 500°C and 550°C was showing in Figure (3.6). As the temperature of the PV solar module pyrolysis increases from 500°C to 550°C the grain size of silicon is reducing and increasing the void space. The reduction of grain size of silicon solar cells may influence the semiconducting properties which most influence the effect for photovoltaic solar module. In some places, the corrosion region was also observed in surface morphology. The degradation of c-Si solar cells was accelerated with high temperatures and other humid environments. Furthermore, the energy dispersive X-ray is used to identify the chemical elements present over the surface of solar cell after pyrolysis at different temperatures. Figure (3.8 & 3.9) shows the EDX spectra of major elements present over the front surface of the solar cell. The results imply that the percentage composition of silicon is slightly less for the higher temperature (550°C) pyrolysis sample. Simultaneously the composition of carbon slightly increases and the rest of the compositions are relatively negligible.

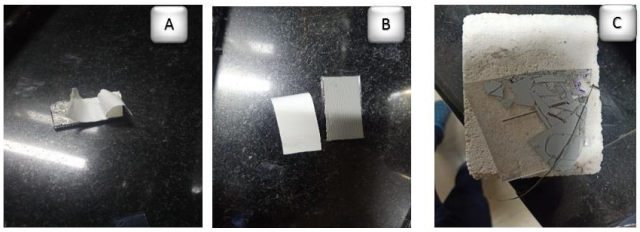

Figure 3.6: Manual separation of intact back sheet/glass, a) Unsuccessful separation of back sheet in hot plate at 45°C, b) Successful separation of back sheet in hot plate at 100°C, c) Separation of glass after pyrolysis at 500°C.

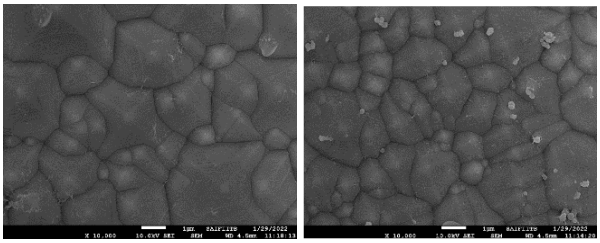

Figure 3.7: SEM image of front surface of solar cell after pyrolysis at A) 500°C & B) 550°C

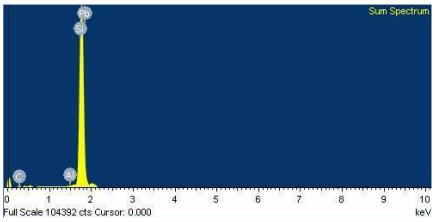

Figure 3.8: Elemental mapping of front surface of solar cell after pyrolysis at 500°C

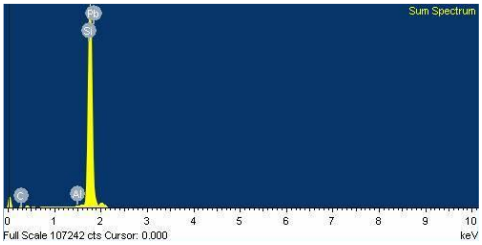

Figure 3.9 Elemental mapping of front surface of solar cell after pyrolysis at 550°C

3.2.4 FTIR Analysis of trapped gases

FTIR stands for Fourier transform infrared spectroscopy. It is most useful to identify the functional group present in a material. The frequency of molecular bonding varies depending on the elements and the type of bond. There are several different frequencies at which every particular bond can vibrate. These frequencies correspond to the ground state (lowest frequency) and various excited states, according to quantum physics (higher frequencies). Exciting the bonding by absorbing light energy is one approach to raise the frequency of molecular vibration. So, when infrared is passed through the sample it is absorbed by the molecule and others are transmitted to the detector.

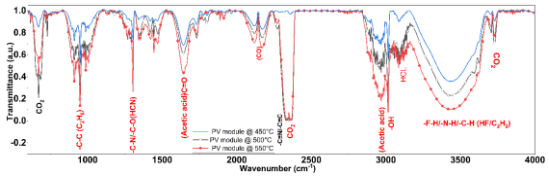

Figure 3.10: FTIR of PV module at 450,500 & 550°C

Matching the peak obtained from FTIR experiment to standard IR library, major elements and fuctional group present are CO2, -C-C(C2H6),-C-N/-C-O(HCN),(Acetic acid)C=O,C-O,HCL, -F-H/-N-H/-C-H(HF/C2H2).

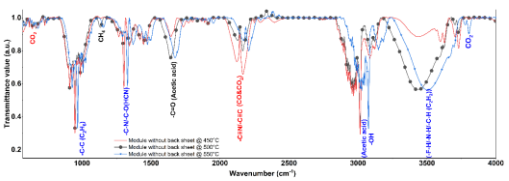

Figure 3.11: FTIR of PV module without back sheet at 450,500 & 550°C

FTIR data of gas collected in gas jar at temperature 450,500 & 550°C of module without back sheet confirm the availability of various gas and functional group like CO2,NO2 ,-C-C(C2H6),CH4,-C-N/-C-O(HCN),(Acetic acid)C=O,C-O,HCL, -F-H/-N-H/-C-H(HF/C2H2).

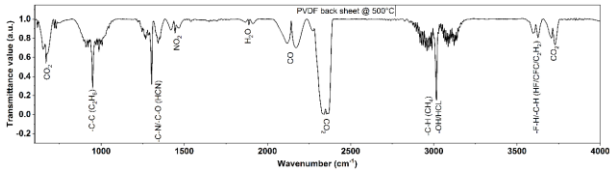

Figure 3.12: FTIR of PVDF back sheet at 450,500 & 550°C

3.2.5 TGA-MS of module, module without backsheet

In present research, the analysis of evolved gases while burning of c-Si PV solar module having Ethylene vinyl acetate (EVA) as encapsulant material and PVDF back sheet, PV module without back sheet and, only PVDF back sheet in TGA coupled with MS setup were done. Before pyrolysis of the PV module in TGA-MS, the back sheet of the module was successfully manually removed by heating the module at 100°C in a hot plate and the back sheet peeled off. The complete spectra of evolved gas during pyrolysis of photovoltaic solar module are characterized with the help of TGA-MS.

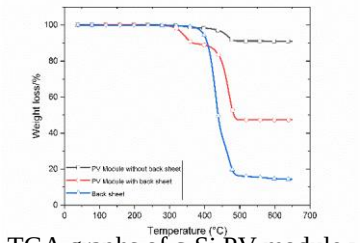

Figure 3.13: TGA graphs of c-Si PV module with, without back sheet and Back sheet

Table 4. Showing elements/compounds of gases with molecular weight (m/e)

Gas	Molecular weight (m/e)
Hydrogen	2
carbon	12
Oxygen/methane CH4	16
Water vapour	18
fluorine	19
Carbon mono-oxide	28
Ethane C2H6/nitric acid NO	30
Carbon dioxide/propene	44
Acetic acid	60

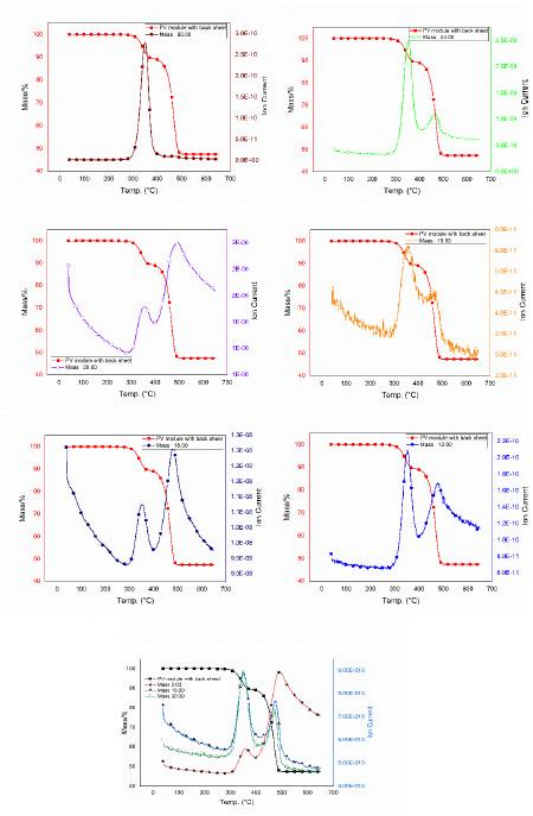

Figure 3.14: TGA-MS graphs of PV c-Si solar cell module having various molecular electron signal spectrum (m/e) having 60, 44, 30, 28, 19, 18, 16, 12, and 2.

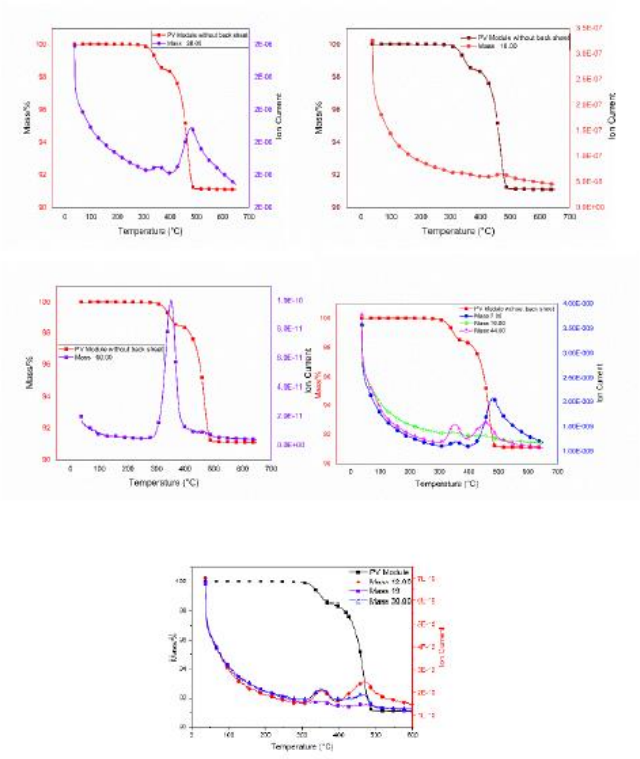

Figure 3.15: TGA-MS graphs of PV c-Si solar cell module without back sheet having various molecular electron signal spectrum (m/e) having 60, 44, 30, 28, 19, 18, 16, 12, and 2.

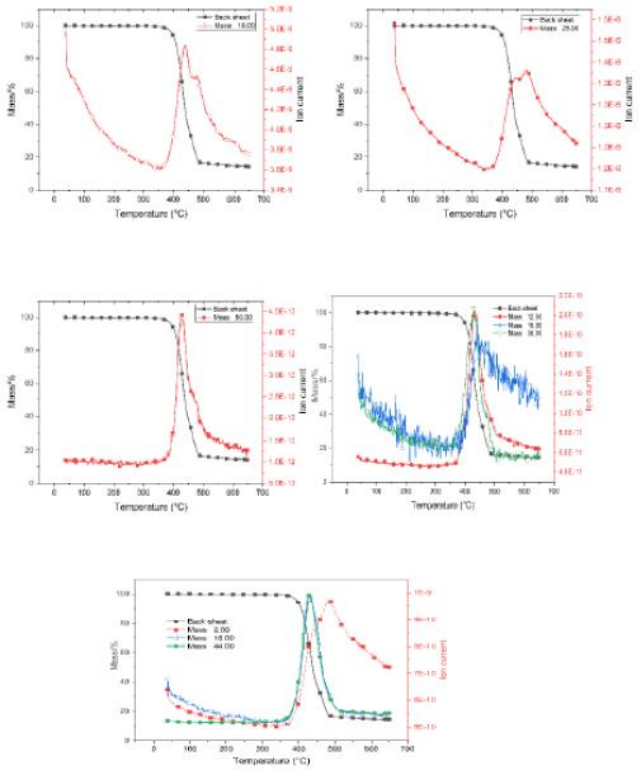

Figure 3.16: TGA-MS curves of back sheet having various molecular electron signal spectrum (m/e) having 60, 44, 30, 28, 19, 18, 16, 12, and 2.

4. Result and Discussions

The pyrolysis analysis of evolved gas during thermal degradation of EVA was quantified by the Thermo-gravimetric Analysis (TGA) coupled with mass spectroscopy (MS) technique. Thermal degradation of Ethylene co-vinyl acetate (EVA) polymer with 29-32% vinyl acetate monomer of semi- crystalline silicon solar PV module undergoes for two steps degradation. Upon heating, the acetic acetate is first eliminated (deacetalization) in temperature range of 300-400°C and leaving unsaturated polyene. Acetic acid trace is seen at molecular weight (m/e) 60. On Further heating, the polyene undergoes the chain scission reactions and EVA fully degrades at temperatures ranging from 400-500°C [21].

Pyrolysis analysis of waste materials and biomass wastes are analyzed by TGA-MS and TGA-FTIR techniques to understand the complete spectra to identify the volatile species of evolved gas at the time of thermal degradation. Both TGA-MS and TGA coupled with FTIR are valuable techniques for corroborating the thermograph as well as spectrograph of volatile species gas evolved during thermal heating. The mass-loss rate of waste materials shows almost similar trends with the same pyrolysis conditions for both setups. The major evolved gas appeared at temperatures ranging from 230-470°C. In the first stage (300-400°C) major gases were characterized as CO2, CO, NH3, HCN, H2. And in the second phase (400-500°C) CO and CO2 gases are dominants. The emission of CO2 causes increases in global warming and CO emission is toxic in nature [22].

During thermal treatment (pyrolysis) of solar panels containing hazardous materials like Pb, Cd, and Cr could be released into the environment. For pyrolysis, the PV module is placed inside the closed furnace and heated at 500°C and complete degradation of encapsulant (EVA) was obtained. Further, the trapped gases were analysed to quantify the release of the metal in the gas phase. The results verified that a small number of hazardous metals were also present during the thermal degradation process of the PV module [23].

After that, the removal/delamination of the back sheet and encapsulant from the solar cell and glass plate is a challenging task. Several routes have been employed for the removal of encapsulants by organic solvent, nitric acid, shockwave recycling, and thermal decomposition. The well-established c-Si solar module back sheet and encapsulant polymers account for 3.6 wt.% and 6.55wt.% respectively and with the majority of aluminium (10.5wt.%) and glass (74.2wt%) of PV module. In-situ pyrolysis was performed in a vacuum atmosphere for c-Si solar PV module having EVA and PVDF back sheet was tested by using TGA-MS and TGA-FTIR with selected molecular fragments ion intensity spectral signals such as m/z= 43, 44, 2, 13, 18 to identified evolved gas during decomposition [24-25].

Module contains two steps of mass loss, one is at 300-400°C and another is 400-500°C, depending on the degradation mechanics involved during the exothermic/heating process. The acetic acid is released in the first decomposition stage where approximately 11.11% and 3.10% weight loss for PV module samples and PV module without back sheet respectively were observed. Not only deacetylation, but it also decomposes in the gas phase into smaller fragments like H2, C, CH4, H2O, CHN, NO, CO2. After deacetylation, β-scission started to start second step mass loss and hydrolytic depolymerisation at 400-500°C. The major weight loss occurs in this phase, where 46% and 7.10% weight loss for PV module samples and PV module without back sheet respectively were observed. The mass loss of PVDF back sheet is only 90% at temperature 500°C. From the TGA graph, it was concluded that the EVA was completely burnt and the mass of the back sheet stuck with

the PV module. PVDF membrane exhibited excellent thermal stability up to 440°C, above which it started to decompose to around 15 wt%. This pyrolysis was further analysed by MS spectrograph to complete the picture of evolved gas.

5.Challenges in Recycling of Si-based PV module

1. **Market for recovered Si**: Recovered Si may have different levels of purity like Ferro-Si, metallurgical-grade (MG) Si, or solar-grade (SG) Si. These all have a different level of purity like 75% for Ferro-Si, 99% for MG-Si, and 99.9999% for SG-Si. Purer Si recovery, on the other hand, necessitated additional processes and will be more expensive [2]. With the help of the current recycling technique, we get ferro-Si which is having minimum Si content i.e., 75% [8]. So, because of the process variation, quality issue, and various types of panels in the market, it is very difficult to convert it into Solar grade (SG) and thus restricted to 75% i.e., metallurgical grade (MG).

2. **Cell efficiency standardization:** Cell efficiencies are changing because of the research going on in this field and the life cycle of a solar module is about 25 years so efficiency in this duration changes a lot and recyclers need to wait a lot to get a particular type of panel [2].

3. Burning of EVA and Tedlar produces heavy smokes: Thermal way of recycling is more prominent but gases produced on burning of PVA and Tedlar are harmful to the environment and thus mitigate the target of using the solar module. So, research in the area of treatment of gases must be done.

6. Conclusion

Pyrolysis of PV solar module was employed to examine the evolving gases emission. During heating, degradation mechanisms such as; deacetylation, β-scission, and hydrolytic depolymerisation started. TGA-MS is used to characterize the Molecular electron signal spectrum (m/e) having 60, 44, 30, 28, 19, 18, 16, 12, and 2. Emission CO2 causes the increase of global warming and CO emission is toxic in nature. The major evolved gas appeared at temperatures ranging 230-470°C. The qualitative study shows that the toxic and hazardous gases of pyrolysis of PV module after removal of back sheet is quite less as compared to pyrolysis of whole PV solar module as some of the peak of harmful gases like NOx, C=O are small or absent in MS graph in case of module without back sheet, so removal of back sheet before pyrolysis results in less harmful gases.

Transmittance of glass plate after pyrolysis decreases which leads to the performance of the photovoltaic solar module. Pyrolysis at higher temperature is not recommended for higher transmittance value of glass in photovoltaic module lifetime operation. Intact back sheet was successfully mechanically removed at 550°C and intact glass was also obtained after pyrolysis of the module at 500°C and 550°C. The recycled intact back sheet and glass plate may be used for the lamination of new solar cells. FTIR spectral peaks strongly support the TGA-MS results. The emission of evolved gases and fumes during the burning of PV module is much higher as compared to PV module without the back sheet.

REFERENCES

1. Lunardi, Marina Monteiro, et al. "A review of recycling processes for photovoltaic modules." Solar Panels and Photovoltaic Materials (2018): 9-27.

2. Metz, A., M. Fischer, and J. Trube. "Recent Results of the International Technology Roadmap for Photovoltaics (ITRPV)." (2017).

3. REN21, Paris Secretariat. "Renewables 2017 global status report." Secretariat Renewable Energy Policy Network for the 21 (2017).

4. Green, Martin A. "Commercial progress and challenges for photovoltaics." Nature Energy 1.1 (2016): 1-4.

5. Weckend, Stephanie, Andreas Wade, and Garvin A. Heath. End of life management: solar photovoltaic panels. No. NREL/TP-6A20-73852. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2016.

6. Klugmann-Radziemska, Ewa & Ostrowski, Piotr & Cenian, Adam & Sawczak, Miroslaw. (2010). Chemical, thermal and laser processes in recycling of photovoltaic silicon solar cells and modules. Ecological Chemistry and Engineering S. 17. 385-391.

7. Strachala, David & Hylský, Josef & Vanek, J. & Fafilek, Guenter & Jandová, K. (2017). Methods for recycling photovoltaic modules and their impact on environment and raw material extraction. Acta Montanistica Slovaca. 22. 257-269.

8. Wang, Teng-Yu, Jui-Chung Hsiao, and Chen-Hsun Du. "Recycling of materials from silicon base solar cell module." 2012 38th IEEE Photovoltaic Specialists Conference. IEEE, 2012.

9. Bohland, J., et al. “Economic Recycling of CdTe Photovoltaic Modules.” Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference - 1997, https://doi.org/10.1109/pvsc.1997.654101

10. Doi, Takuya, et al. “Experimental Study on PV Module Recycling with Organic Solvent Method.” Solar Energy Materials and Solar Cells, vol. 67, no. 1-4, 2001, pp. 397–403., https://doi.org/10.1016/s0927-0248(00)00308-1

11. Komoto, Keiichi, et al. “Recycling of PV Modules and Its Environmental Impacts.” 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), 2018, https://doi.org/10.1109/pvsc.2018.8547691

12. Tammaro, Marco, 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, vol. 81, 2015, pp. 103–112., https://doi.org/10.1016/j.renene.2015.03.014.

13. Qin, Baojia, et al. "Recovering Polyethylene Glycol Terephthalate and Ethylene-Vinyl Acetate Copolymer in Waste Solar Cells via a Novel Vacuum-Gasification-Condensation Process." ACS ES&T Engineering, vol. 1, no. 3, 2020, pp. 357–362., https://doi.org/10.1021/acsestengg.0c00091

16.Tomioka O. Japanese companies work on ways to recycle a mountain of solar panels.
Nikkei Asian Review. 17 Nov. 2016. Available from: https://asia.nikkei.com/magazine/
20161117-INCOMING/Tech-Science/Japanese-companies-work-on-ways-to-recycle-a mountain-of-solar-panels

17.Tao, Meng, et al. "Major Challenges and Opportunities in Silicon Solar Panel Recycling." 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), 2020, https://doi.org/10.1109/pvsc45281.2020.9300650.

18.Rimez, B., Rahier, H., Van Assche, G., Artoos, T., Biesemans, M., & Van Mele, B. (2008). The thermal degradation of poly (vinyl acetate) and poly (ethylene-co-vinyl acetate), Part I: Experimental study of the degradation mechanism. Polymer Degradation and Stability, 93(4), 800-810.

19.Singh, S., Wu, C., & Williams, P. T. (2012). Pyrolysis of waste materials using TGA- MS and TGA-FTIR as complementary characterisation techniques. Journal of Analytical and Applied Pyrolysis, 94, 99-107.

20.Farrell, C., Osman, A. I., Zhang, X., Murphy, A., Doherty, R., Morgan, K., ... & Shen, D. (2019). Assessment of the energy recovery potential of waste Photovoltaic (PV) modules. Scientific reports, 9(1), 1-13.