PV module eco-design: new incapsulant for high sustainablility and reciclablility of photovoltaic value chain.

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***Abstract* — The transition towards renewable energy economy needs a sustainable technology support. Todays the photovoltaic (PV) industry is characterised by linear economy structures, energy-intensive production, downcycling and little sustainability. One starting point for sustainable technologies is offered by the circular economy with its circular design principles. One problematic aspect of the design of crystalline PV modules is the encapsulation. In particular, the encapsulation avoids high-value recycling or the remanufacturing of modules, which could close loops and extend the lifetime of the products. This work provides a study on new encapsulant materials suitable for the PV modules eco-design in order to evaluate their physical and optical parameters and sustain a future better recycling scheme and improve the circularity of PV value chain. The current encapsulation method using ethylene vinyl acetate (EVA) as the encapsulation material in terms of performance is not the optimal solution and requires an alternative. New encapsulation technologies thermoplastics (TPO) and elastomers (POE) are discussed and compared in terms of performance, sustainability and recyclability.**

I. Introduction

The efficiency of a PV module mainly depends on the PV cell technology and the lifetime of a PV cell under operation is a significant concern for the widespread commercialization of this technology [1]. During the long time operation at outdoor conditions, PV cells experience significant morphological and structural changes, optical absorption decay, and impairment of the optoelectronic properties, which adversely affect the performance of the PV module. Encapsulation is an effective and widely accepted tool for enhancing the operation stability of the PV cells, by preventing the weather-related (moisture, UV light, oxygen, and temperature) degradation and strengthening the mechanical toughness against external impacts [9]. Different types of encapsulation methods have been designed so far and ethylene vinyl acetate (EVA) copolymer has dominated as the encapsulating material in the majority of these studies [2]. However, EVA easily prone to environmental-related degradation and results in a drop in the PV module power production efficiency. Degradation mechanisms taking place due to the effect of temperature and irradiation have been extensively studied and reported in literature. Despite relevant effort being made over the years to develop material properties and improve EVA encapsulant reliability, several degradation modes of PV modules can still be attributed to EVA degradation. Acetic acid, in particular, is a major cause of corrosion effects for metallization and cell connectors as well as delamination and potential induced degradation (PID) [2]. Recently, an interest in new encapsulant materials has increased to overcome the issues due to the use of EVA and new formulations have been tested. In particular, Thermoplastic Polyolefines (TPO) and Polyolefin Elastomers (POE) have been introduced as alternatives to EVA as encapsulants for PV applications [3]. TPO and POE are polyethylene based materials, as well as EVA, but do not have vinyl acetate moieties. TPO and POE present in their structure as additional side groups, acrylates, acrylic acids and n-alkanes. The main advantage of TPO and POE is that they cannot produce acetic acid during degradation because they do not have vinyl acetate moieties. POEs undergo chemical crosslinking, as well as EVA, therefore their formulation includes typically peroxides as crosslinking agents that react forming covalent bonds between the polymer chains. TPOs, instead, being thermoplastic materials, do not require peroxides or additional crosslinking agents to crosslink because they physically form hydrogen bonds upon the application of high temperatures. The materials mentioned above do not have particular drawbacks because they are similar to EVA in terms of costs and processing conditions. Additionally, the lack of vinyl acetate units limits the occurrence of corrosion and PID. Even though degradation of polyethylene based polymers has been largely studied and reported in literature], more in detail studies regarding formulations for PV applications are still in progress. Moreover, the influence of the materials formulation in terms of additives and their effects on encapsulant degradation over long term exposure is still an open question.

In this paper, two newly developed PV encapsulant materials, a TPO and a POE, have been subjected to artificial ageing tests and their performances have been compared to the most widely used encapsulant EVA. The influences of the exposure to UV radiation, temperature and humidity have been studied and the effects on additive composition, chemical degradation and thermal stability are discussed. Bare polymer films, thermally pre-treated but not encapsulated within the typical PV module stack configuration have been the object of this study. The choice of using films has been made to better understand how environmental factors influence the degradation behavior of the polymer itself directly exposed and to have an insight of what could happen to the materials in case additional degradation modes, such as backsheet cracks and extensive delamination, might occur. The work aims to make a step forward in understanding and comparing performances of newly

developed material with respect to the state-of-the-art EVA by means of a comprehensive analysis. DSC, TGA, F-TIR, UV-NIR analysis are presented.

II. Methods and Experimentals

Preliminary characterization activity on new encapsulant materials suitable for the PV modules eco-design in order to evaluate their physical and optical parameters has been performed.

Differential Scanning Calorimetry (DSC) was carried out using a DSC 6000 from PerkinElmer Inc. to measure thermograms of encapsulant materials before and after exposure. For each material, around 10 mg were placed in an aluminum pan and subjected to a first heating run from 20 °C to 180 °C, followed by a cooling run from 180 °C to 20 °C and a second heating run from 20 °C to 180 °C. During each step, heating (and cooling) rates were set to 10 K min−1 and a nitrogen flow of 50 mL min−1 was imposed.

Two heating steps were necessary to distinguish reversible changes due to physical processes, such as post crystallization, from irreversible chemical processes with effect on molecular structure. Melting enthalpies and temperatures were calculated by evaluating the area between the melting/crystallization peaks and the baseline. At least three measurements were performed for each sample at each ageing step. Crystallinity was calculated as the ratio between measured heat of fusion and the literature value for the 100% crystalline polyethylene (ΔHm^0 = 293 J g−1) [27,28].

Tested nine commercial encapsulant materials from four different companies: the detailed results are reported respectively for:

- Two EVA and two POEs by Company 1;
- Two TPOs by Company 2;
- One EVA and one TPO by Company 3;
- One EVA by Company 4.

The samples were pre-treated in a vacuum laminator between two non-adhesive sheets at maximum temperature of 150 °C for a total duration of 20 min and were cut into stripes before being subjected to artificial ageing tests. The pre-treatment had the purpose of simulating the thermal treatment that the encapsulant experiences during the lamination process and to allow the crosslinking reaction to take place for the EVA and the POE encapsulant. If not crosslinked, the polymers would melt and flow at the exposure temperature.

III. Results and Discussion

The Differential Scanning Calorimetry (DSC): Samples aged under different accelerated ageing procedures showed significant changes in thermal behavior. In general, thermal properties can be influenced by both physical and chemical ageing processes. Chemical processes such as chain scission that might occur during UV ageing due to photo-oxidation are responsible for chemo-crystallization, namely secondary crystallization. The effects of chemical ageing are irreversible and can be detected by observing changes in melting enthalpy and temperature in the second heating curve. The first heating curve might show the same signs of degradation, but they are the results of a combination of chemical and physical ageing. Physical processes have similar effects to the ones due to annealing at high temperatures, changes in melting temperature and enthalpy might occur and are visible in the first heating curve. No reversible effects of physical ageing can be seen in the second heating curve

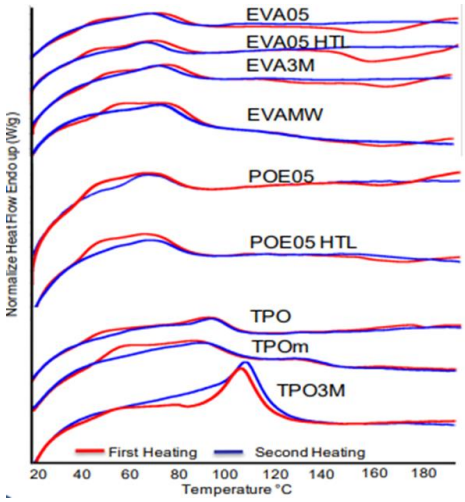


Fig. 1. Example of readable plot using different colors and line styles for clarity.

		$T1_{mp}$ °C	$T2_{mp}$ °C	T_{Cr} °C	X_c %	X_{Cr} %	E_{VA} %
EVA05	***First heating***	47	75	161			
	Second heating	-	69	-	7	100	27
EVA05 HTL	***First heating***	46	72	160			
	Second heating	-	67	-	6	100	27
EVA3M	***First heating***	51	78	166			
	Second heating	-	72	-	8	100	32
EVAMW	***First heating***	55	78	164			
	Second heating	-	74	-	9	100	28
POE05	***First heating***	46	71	165			
	Second heating	-	66	-	6	100	-
POE05 HTL	***First heating***	46	71	171			
	Second heating	-	67	-	7	100	-
TPO	***First heating***	51	94	-			
	Second heating	-	93	-	9	-	-
TPOm	***First heating***	56	89	-			
	Second heating	-	88	-	8	-	-
TPO3M	***First heating***	56	106	-			
	Second heating	-	107	-	22	-	-

Melting Point T_m, Crosslinking T. T_{Cr}, Crystallinity X_c, Degree of crosslinking X_{Cr}, Vinyl Acetate Content E_{VA}

Fig.2. samples melting temperature and crosslink reaction.

Looking at Fig.2, regarding the melting temperature we have TPO higher than EVA and POE, than TPO can withstand higher operating temperatures than EVA and POE; regarding the crosslinking reaction we have a positive reaction for EVA and POE, instead no one on TPO, then it turns in reeduction in cost and lamination cycle time for TPO module production.

Thermogravimetric Analysis (TGA) measurements on the encapsulants before and after the exposure to the artificial

ageing tests were carried out to monitor the evolution of the thermal stability of the materials.

For the EVA material, Fig. 3, the decomposition process took

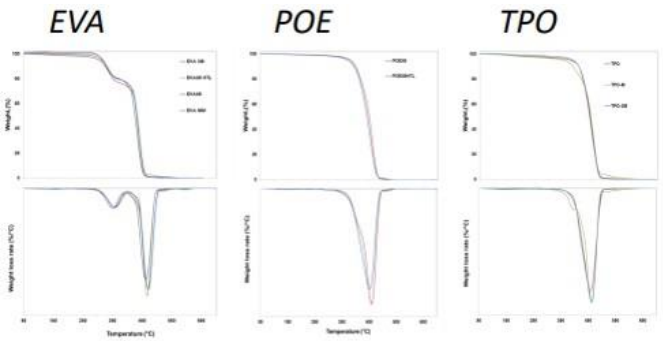


Fig.3. samples TGA analysis.

place in two steps: the first step was typical of the cleavage of vinyl acetate moieties, whereas the second step corresponded to the decomposition of the main polyethylene chains. TPO and POE are characterized by a one-step decomposition process, with a maximum weight loss rate at around 428 °C and 424 °C, respectively, showing absence of deacetylation for TPO and POE.

FT-IR – Analysis, Fig.4, show the absence of vinyl acetate bands for POEs and TPOs then it turns in any formation of

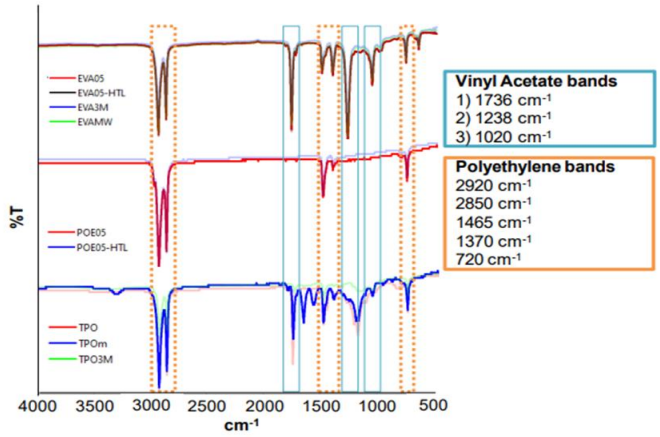
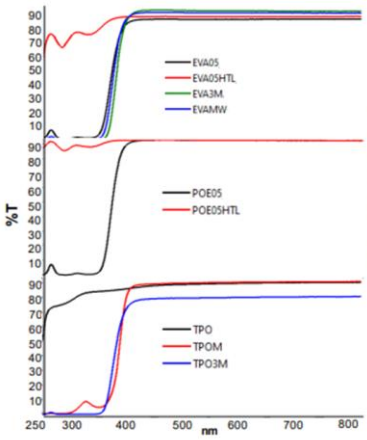


Fig.4. samples FT-IR analysis.

acetic acid and conseguntely no corrosion of metallic components in the PV modules. FT-IR confirmed that photo-oxidation reactions take place during the exposure to UV radiation and that the effects are particularly pronounced for TPO.

UV-VIS-NIR - Analysis , Fig.5, shows the UV cut-off of EVA3M sample highest UV cut-off (366 nm), meanwhile the EVA05HTL, POE05HTL and TPO transparent in UV region (250-400nm); in the Visible region (400-800 nm) the sample EVA3M has highest transmittance followed by EVAMW and the two POEs



	% T_{max} (400-800 nm)	UV cut-off (nm) at 10%T
EVA05	88	354
EVA05 HTL	89	NA
EVA3M	94	366
EVAMW	93	360
POE05	93	355
POE05 HTL	93	NA
TPO	90	NA
TPOm	91	364
TPO3M	80	362

Fig.5 UV-VIS-NIR analysis

UV test reproduces in a more reliable way what actually happens in the field during outdoor exposure, although the damages that the polymers have faced are over estimated and more severe than the damages that the materials might have experienced in the usual PV module stack configuration.IV.

IV. Summary of the Work

Thermoplastics (TPO) and elastomers (POE) encapapsulants are unders test to replace EVA for a new eco-design of PV modules. The aim of the work was to compare the stability and degradation behavior characteristics of two different types of emerging encapsulant materials under the influence of different artificial ageing tests. Additionally, testing bare materials highlights even more the importance of PV module components that prevent polymers from degradation. The aims is to improve the circularity of PV value chain.

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