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Eco designe: new encapsulant for high recyclability end of life (EoL) PV modules

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The shift towards a renewable energy economy necessitates robust technological support that prioritizes sustainability. Presently, the photovoltaic (PV) industry is characterized by linear economy models, energy-intensive production, downcycling, and limited environmental sustainability. An avenue towards sustainable technologies is through embracing circular economy principles, particularly circular design concepts. Within the design of crystalline PV modules, encapsulation poses a challenge. Specifically, the encapsulation process currently in use hinders high-value recycling or module remanufacturing, thus limiting the potential to extend product lifespans and close material loops. This study investigates new encapsulant materials suitable for the eco-design of PV modules, aiming to assess their physical and optical characteristics. The objective is to support a more effective future recycling scheme and enhance the circularity of the PV value chain. The existing encapsulation technique, which relies on ethylene vinyl acetate (EVA), presents performance limitations and demands an alternative solution. Emerging encapsulation technologies such as thermoplastics (TPO) and elastomers (POE) are explored and compared in terms of their performance, sustainability, and recyclability. The NEST project focuses on addressing end-of-life (EoL) module issues and advancing eco-design practices.

Keywords—EoL, Circular conomy, TPO, POE.

I. INTRODUCTION (*HEADING 1*)

The efficiency of PV modules primarily relies on PV cell technology, and concerns about PV cell lifespans during operation hinder the widespread commercialization of this technology. Over time, PV cells undergoing extended outdoor operation experience significant structural changes, optical absorption decay, and diminished optoelectronic properties, negatively impacting PV module performance. Encapsulation serves as a widely accepted means to enhance the operational stability of PV cells by shielding them from weather-induced degradation and bolstering mechanical resilience against external impacts. While EVA has been dominant as the encapsulating material, it is susceptible to environmental degradation, leading to reduced power production efficiency in PV modules. Various degradation modes in PV modules can be attributed to EVA, including corrosion effects due to acetic acid, which affects metallization and cell connectors, as well as delamination and potential induced degradation (PID). Interest has grown in new encapsulant materials, such as Thermoplastic Polyolefins (TPO) and Polyolefin Elastomers (POE), aiming to overcome EVA-related issues by offering alternatives for PV applications. Unlike EVA, TPO and POE lack vinyl acetate moieties, reducing the risk of acetic acid production during degradation. While POEs undergo chemical crosslinking similar to EVA, TPOs, being thermoplastic, do not require additional crosslinking agents. These materials share similarities with EVA in terms of costs and processing conditions while limiting corrosion and PID risks. Despite extensive studies on the degradation of polyethylene-based polymers, ongoing research focuses on formulations tailored for PV applications and explores the influence of additives on encapsulant degradation during long-term exposure.

This paper evaluates two newly developed PV encapsulant materials, a TPO and a POE, through artificial ageing tests, comparing their performance to the widely used EVA. These tests scrutinize the effects of exposure to UV radiation, temperature, and humidity on additive composition, chemical degradation, and thermal stability. The study utilizes bare polymer films, thermally pre-treated but not encapsulated within the typical PV module stack configuration, to understand how environmental factors influence polymer degradation when directly exposed. This approach offers insights into potential material behavior in scenarios involving additional degradation modes, such as backsheet cracks and extensive delamination. The study aims to advance understanding and comparison of the newly developed materials with respect to state-of-the-art EVA through a comprehensive analysis utilizing DSC, TGA, F-TIR, and UV-NIR techniques.

II. METHODS AND EXPERIMENTALS

Preliminary characterization activities focused on assessing the physical and optical parameters of new encapsulant materials suitable for PV modules' eco-design. Differential Scanning Calorimetry (DSC) involved measuring thermograms of encapsulant materials before and after exposure, providing insights into their thermal behavior. The study analyzed nine commercial encapsulant materials from four different companies to detail results comprehensively.

The samples underwent pretreatment in a vacuum laminator before being subjected to artificial ageing tests. This pretreatment simulated the thermal treatment experienced during the lamination process, facilitating the crosslinking reaction for EVA and POE encapsulants to prevent polymer melting and flow during exposure.

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 (ΔHm0 = 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.

Differential Scanning Calorimetry (DSC) analysis revealed significant changes in thermal behavior among samples aged under different accelerated ageing conditions. These changes stemmed from both physical and chemical ageing processes. Chemical processes, like chain scission occurring during UV ageing due to photo-oxidation, led to chemo-crystallization, influencing melting enthalpy and temperature in the second heating curve. Physical processes, akin to annealing at high temperatures, resulted in changes visible in the first heating curve but lacked reversible effects observed in the second heating curve. No reversible effects of physical ageing can be seen in the second heating curve. Analysis indicated TPO withstanding higher operating temperatures than EVA and POE. Additionally, EVA and POE exhibited positive reactions in crosslinking compared to TPO, impacting cost and lamination cycle time for TPO module production.

Thermogravimetric Analysis (TGA) measured the thermal stability evolution of encapsulants before and after artificial ageing tests. While EVA exhibited a two-step decomposition process (Fig.3), typical of cleaving vinyl acetate moieties and decomposing main polyethylene chains, TPO and POE showcased a one-step decomposition process, around 428 °C and 424 °C, respectively, emphasizing the absence of deacetylation for TPO and POE.

FT-IR analysis (Fig.4) confirmed the absence of vinyl acetate bands for POEs and TPOs, suggesting no acetic acid formation and consequently no corrosion of metallic components in PV modules. Pronounced photo-oxidation effects during the UV exposure, particularly noticeable for TPO, were also highlighted.

UV-VIS-NIR analysis indicated differences in UV cut-off and transmittance among samples, with implications for outdoor exposure scenarios. 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. 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.

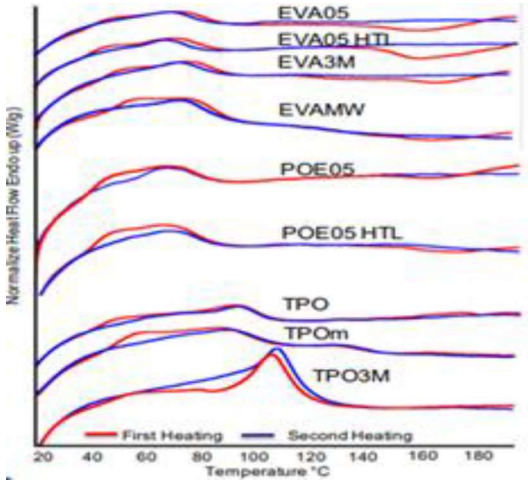


Fig. 1.Example of readable plot using different colors and line styles for clarity.

		$T1_{exp}$ °C	$T2_{exp}$ °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.

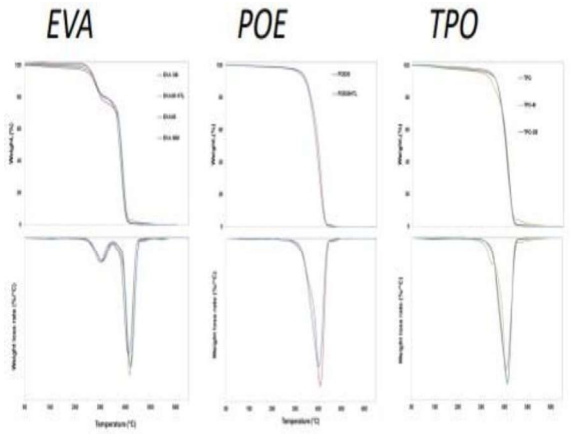


Fig. 3, the decomposition process.

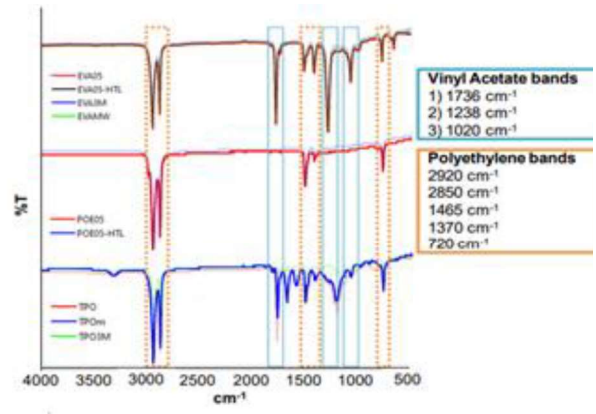
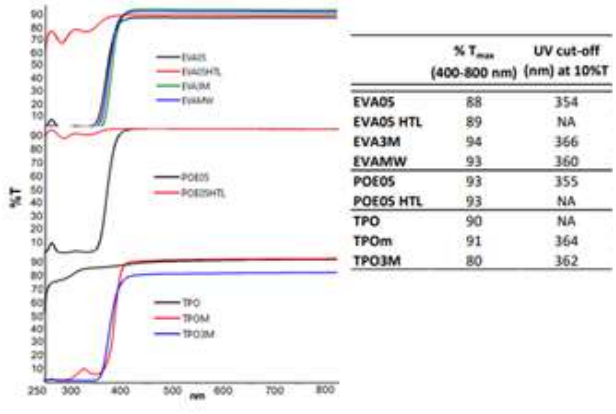


Fig.4. samples FT-IR analysis.



	% 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

IV. Summary of the work

Thermoplastics (TPO) and elastomers (POE) encapapsulants are under test to replace EVA for a new eco-design of PV modules. The assessment of thermoplastics (TPO) and elastomers (POE) as potential EVA replacements in PV module encapsulation aimed to compare stability and degradation behavior under various artificial ageing tests. Additionally, evaluating bare materials highlighted the critical role of PV module components in preventing polymer degradation. The ultimate goal is to enhance the circularity of the PV value chain through improved encapsulation materials and design practices.

V. Aknowledge

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