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The Influence of UV Light Exposure on the Reliability of Various Front Materials for Lightweight PV Module

Muhammad Aleem Zahid [1,2], Sungheon Kim [3], In-Sung Jung [4], Seong-Hwan Kang [4], Young-Hyun Cho [1], Eun-Chel Cho [1,*] and Junsin Yi [1,*]

[1] Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon 16419, Korea
[2] Department of Electrical Engineering, University of Engineering & Technology, Taxila 47050, Pakistan
[3] Interdisciplinary Program, Photovoltaic System Engineering Sungkyunkwan University, Suwon 16419, Korea
[4] New and Renewable Energy Material Development Center (NewREC), Chonbuk National University, Chonbuk 54896, Korea
* Correspondence: echo0211@skku.edu (E.-C.C.); junsin@skku.edu (J.Y.)

Abstract: The need for innovative design and materials is increasing for various types of photovoltaic (PV) installations in building integrated PV, agricultural, and floating systems. It is crucial to reduce the weight of the PV module to maximize its use in such applications. For this purpose, the front surface must be made of a polymer-based material instead of tempered glass. This study focuses on the analysis of the optical and ultraviolet (UV) reliability properties of various lightweight polymer front sheets. The results show that the transmittance and UV properties of the front material are good. Moreover, a PV module with a polymer front sheet rather than glass was constructed, and a characteristic investigation as well as UV reliability test were performed. The transmittance of the polycarbonate (PC) front sheet decreased by only <3% and the module fabricated with PC exhibited only an approximately 6% power drop after the UV reliability test; hence, the PC is suitable for use in the PV module industry.

Keywords: photovoltaics; polymer material; transmittance; ultraviolet test; stability

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1. Introduction

Photovoltaic (PV) energy production has gained considerable interest because it is environmentally friendly and does not contribute much to air pollution [1]. PV systems have been installed on land and in a variety of forms including building integrated PV (BIPV) systems [2], floating PV systems [3], and agro-PV systems [4]. Of these, BIPV systems are currently predominant [5]. Currently, the majority of BIPV systems in the market are based on a standard module architecture and exhibit various drawbacks including being heavy weight because of the presence of one or more layers of glass [6]. Acrylic and other polymers are employed as glass replacements in lightweight crystalline-silicon PV modules [6–8]. The weight of the PV module can be significantly lowered if the front sheet is made of a polymer rather than glass, because glass constitutes approximately 70% of the module's weight [9]. In terms of the cost (for the system itself, as well as for the construction and the maintenance and transportation), polymers offer cost-effective solutions in comparison with conventional structures (based on conventional materials, e.g., glass). Lightweight PV modules are beneficial in terms of being easy set up on weak ground or in older buildings and in applications wherein the light weight of the PV module is necessary. In addition, they may be fabricated in almost any size and shape, providing the building with an effective and low-maintenance framework. Furthermore, in recent years, a number of studies have been conducted to increase the supply of lightweight PV modules and systems [10–12]. When a polymer material is used instead of glass as the front-surface material of the PV module, its properties differ from those of low-iron tempered glass; therefore, an assessment of the PV module's output and reliability is required.

Various lightweight materials can be used as front sheets for PV modules. Ethylene tetra fluoro-ethylene (ETFE) films offer excellent corrosion and temperature resistance as well as relatively high melting temperatures. They are light, flexible, and exhibit high transmittance [13]. They show high transparency (95% for the visible light and 85% for UV light). Additionally, polyethylene terephthalate (PET) exhibits high transparency, good mechanical properties, and good chemical resistance [14]. It has been used in a variety of applications ranging from food and drink containers to the manufacture of electronic components. Polycarbonate (PC) is a thermoplastic polymer that is lightweight, exhibits high shock resistance, and has good mechanical properties and transparency [15,16]. Research on lightweight PV modules with PC films as the front material has been conducted in recent years [17]. It is widely used in optical, electronics, medical, and spatial applications and for the preparation of nanowires and nanotubes. Its high impact resistance makes it an important component in many devices such as tablets, smart phones, and so on. Because of its transparency, it is also used in windshields, SED technology, and security screens. Polymethyl methacrylate (PMMA), also known as acrylic glass, is a transparent polymer with enhanced mechanical and scratch resistance properties [18]. The environmental stability of PMMA is superior to those of most other plastics. It can be use in several applications such as transparent panels, contact lenses, and industrial parts, as well as areas of medicine, ballistic protection, and the automobile industry. Hence, it is necessary to analyze the light transmittance and ultraviolet (UV) properties of a material along with the corresponding weight reduction of the PV module. In a joint meeting with module producers and SERI, it was indicated that bursts of sunlight can penetrate the atmosphere at wavelengths of 220 nm [19]. Therefore, even materials with a high initial light transmittance cannot be utilized as the front sheet of the PV module if the transmittance is considerably lowered after the UV test.

In this study, the main aim of the research is to explore potential lightweight polymer materials and to develop a lightweight PV module that can withstand the consequences of UV light. For this purpose, the effect of UV irradiation on ETFE, PET, PC, and PMMA materials, each of which can be used as a front sheet for lightweight PV modules, was investigated. Additionally, the optical transmittance and yellowing index (YI) difference of the materials before and after UV testing were analyzed. Moreover, a PV module was fabricated using lightweight materials and its electrical properties were measured before and after the UV reliability test. The findings provide insight into the performance of lightweight materials in real environments.

2. Materials and Methods

N-type crystalline silicon solar cells were used to fabricate a single cell module with lightweight material as a front cover sheet. The encapsulants used in the fabrication were ethylene-vinyl acetate (EVA) copolymer, which provides adhesion of the solar cell to the top cover sheet and rear side of the PV module. Conventionally, the front surface of a PV module comprises low-iron glass. The iron content in such glass is as low as 100 ppm in order to allow the maximum amount of light to easily pass through the glass and reach the solar cell [20]. For alternative lightweight materials, optical characteristics such as those of glass should be fulfilled so that the maximum amount of light can be trapped inside the module, which affects the short circuit current density. The possible lightweight front sheet materials for the analysis were ETFE (100 µm), PET (100 µm), PC (2 mm), and PMMA (2 mm). To utilize a lightweight material as a front cover sheet of the PV module, it is important to analyze the optical properties and conduct UV reliability tests for each sample.

All layers including solar cell, EVA, and back sheet for fabricating the PV module were laminated using a solar module laminator (ZEUS, BSL182296). The optimized temperature of 140 °C was applied throughout the lamination process and the complete PV module was fabricated with the total lamination time of 1060 s. Transmittance was measured using a spectrophotometer (Shimadzu, UV-3600) with high sensitivity, low scattered light, and an extendable wavelength range of 185–3300 nm. Its wavelength accuracy for the UV/VIS region is ±0.2 nm and for NIR is ±0.8 nm. UV tests were conducted in a customized closed chamber (CT1205) at 30 kWh for 150 h. The high-resolution surface morphology of the EVA film was observed via field emission scanning electron microscopy (FE-SEM, JEOL JSM-7600F). The energy dispersive X-ray (EDX) analysis was also performed to obtain information about the chemical composition of EVA before and after UV test on the module fabricated using various front cover sheets. Fourier transforms infrared (FTIR) spectra were analyzed using IRPrestige-21 (Shimadzu Corporation, Tokyo, Japan). Flash I–V tests of the PV module were performed using a solar module tester (GSolar Power, XJCM-13A2414) under standard test conditions of ~25 °C at 1000 W/m^2 (AM 1.5 G), which are commonly used to test solar panels on an industrial scale.

3. Results and Discussions

3.1. UV Test Analysis of Lightweight Front Materials

PV modules are assured for a working period of a minimum of 20 years [21]. As lightweight PV modules are exposed to sunlight and severe outdoor environments, it is possible that UV alters the properties of the inherent material. The purpose of the UV test was to verify the reliability and discoloration of each material. The transmittance effect after exposure to UV test is an important parameter to consider because UV light causes severe discoloration of the material, which deteriorates the transmittance and light trapping inside the module, thereby lowering the efficiency of the PV module [22–24]. The test was conducted in the presence of 30 kWh irradiance and a temperature of 46 °C. The transmittance of the front material was measured in the wavelength range of 300–1200 nm. Figure 1 illustrates the discoloration of lightweight materials before and after UV testing. As a result of UV light irradiation, it was observed that PC, PMMA, and PET became yellow. The yellowing effect of PC after UV aging test has also been observed by Redjala, S., et al. [25], whereas ETFE showed no discoloration, as could be seen through the naked eye. This similar observation was also noticed by another research group [26].

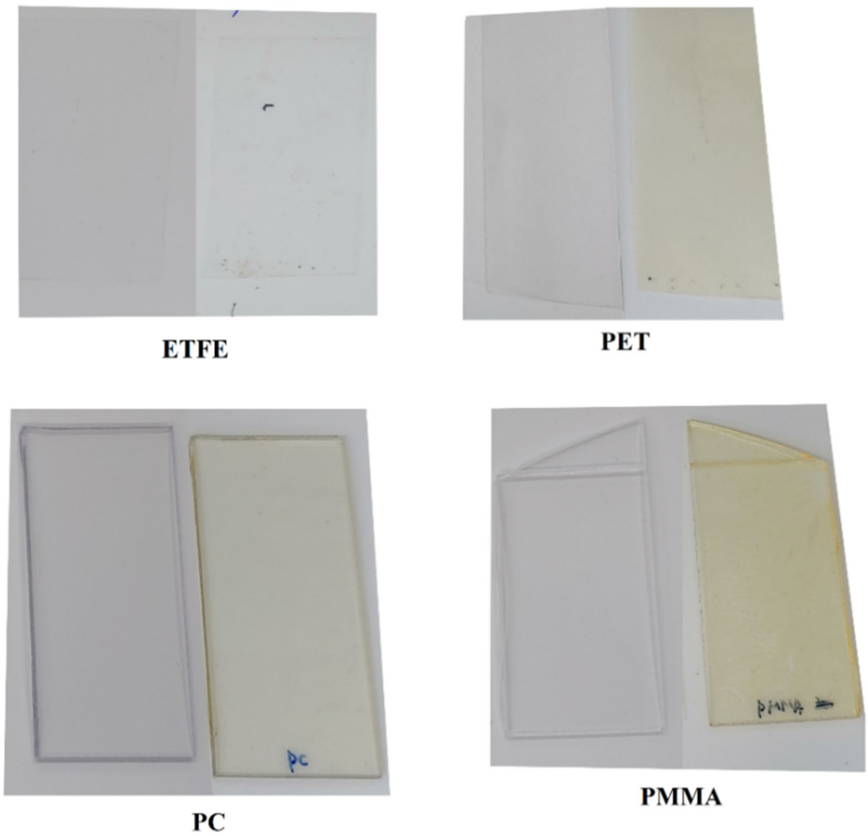

Figure 1. Sample of lightweight front sheets before (**left**) and after (**right**) UV irradiation testing.

The yellowness index (YI) is an important factor that describes the change in color of a sample from white to yellow [27]. This usually occurs because of over exposure to damaging environmental conditions, such as dust, UV radiation, and temperature. The causes of yellowing of polymer materials due to alteration in their properties have already been presented in the literature [25,28–33]. In the case of ETFE, the discoloration of the films hardly changed after the UV test, as indicated by the YI values. Figure 2 shows the changes in the YI of the various front materials.

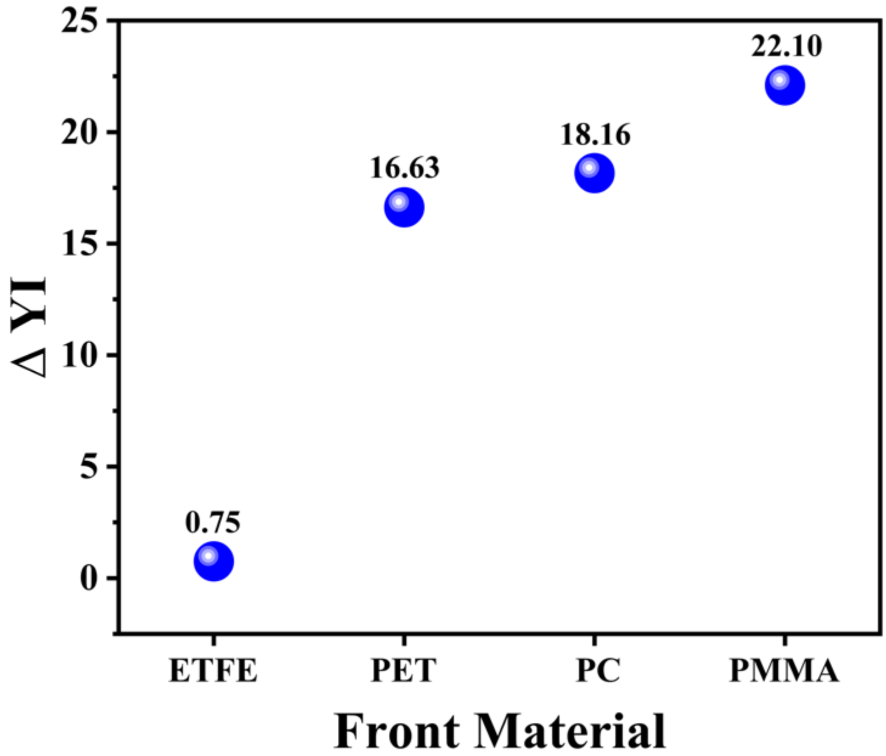

Figure 2. Change in the yellowing index of various lightweight front materials after UV testing.

The change in the YI affected the transmittance of the material. This was confirmed by the change in the transmittance. Figure 3 depicts the transmittance analysis of the front material before and after UV testing in the wavelength spectrum of 300–1200 nm. Table 1 lists the average transmittances of the various lightweight materials before and after the UV test in the wavelength spectrum of 300–1200 nm. It is apparent that the transmittances of ETFE, PET, PC, and PMMA decreased to approximately 2.65%, 15.01%, 2.98%, and 4.16%, respectively, after the UV reliability test. The decrease in transmittance for PC (2 mm) in our work was 4.16% after 150 h of UV exposure, but Redjala, S., et al. showed a 20% drop in transmittance of PC (4.5 mm) after 72 h of UV exposure [25]. Another study showed a decrease in transmittance in PMMA of about 5% after UV exposure of 360 h [28]. The negligible decrease in transmittance of ETFE after UV exposure was already seen [26]. This shows that ETFE has superior UV characteristics as compared with other materials. Our results also showed that the ETFE showed very little effect in transmittance of ETFE after exposure to UV light.

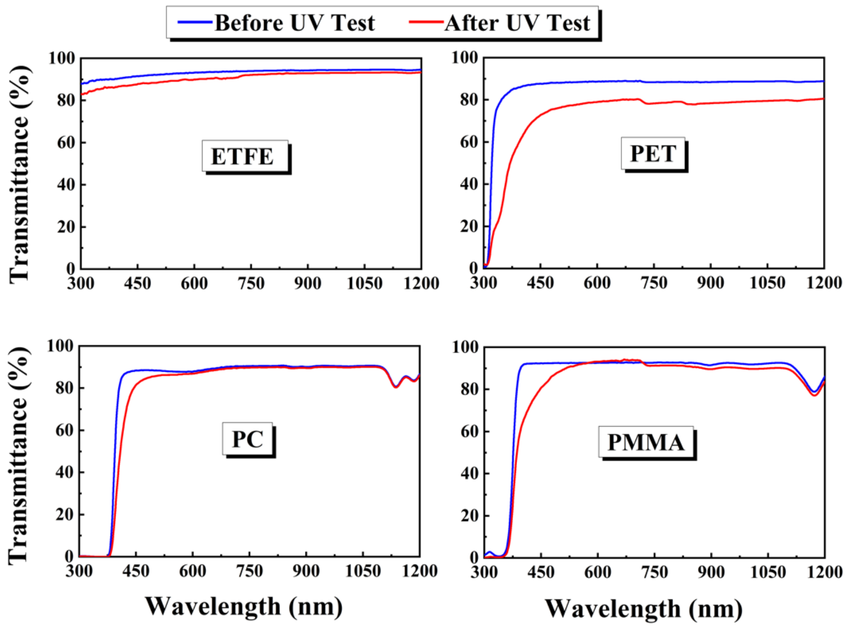

Figure 3. Transmittance patterns of light weight front materials before and after the UV test.

Table 1. Average transmittances of lightweight materials before and after the UV test in the wavelength spectrum of 300–1200 nm.

Material	Transmittance before UV Test [%]	Transmittance after UV Test [%]
ETFE	93.17	90.70
PET	85.86	72.97
PC	79.62	77.25
PMMA	83.87	80.38

3.2. Fabrication of PV Module Using Front Materials

In the previous section, the experimental film was found to be lightweight, with good transmittance and UV properties. The previously examined film was used to manufacture a PV module (ETFE and PC), and its electrical properties and UV reliability were investigated. Figure 4 shows the structure of the PV module based on various front sheet materials. The purpose of the EVA/glass attached to the bottom of the module is to support the PV module during lamination.

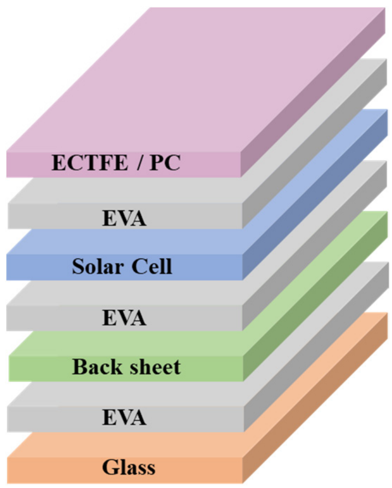

Figure 4. Structure of the PV module according to various front sheet materials.

3.3. Surface Characterization

To study the surface morphology and elemental composition of EVA before and after the UV test, the EVA samples were characterized via FE-SEM and EDX. The corresponding results are presented in Figure 5 after the EVA was extracted from the module, wherein the ETFE and PC sheet were used as the front material. Figure 5a shows the analysis results for the EVA extracted from the PV module with the ETFE as the front sheet before undergoing the UV test. Figure 5b shows the extracted EVA of the PV module with the EFTE front sheet after UV illumination. The UV light on the ETFE covering module caused browning of EVA, which is related to photo-oxidation [34], as the atomic % of oxygen increased to some extent. Brown EVA absorbed a substantial amount of sunlight in the UV and visible regions of the solar spectrum, which limited the photon availability required for current production [35]. Figure 5c shows the extracted EVA of the PV module with a PC as the front sheet before the UV test. Figure 5d shows the EVA extracted from the PV module with a PC as the front sheet after illumination by UV in the test chamber. Thus, UV light on the PC covering module did not affect the properties of EVA, which remained unchanged. The absorption peaks at 1740 cm^{-1} as shown in Figure 5e correspond to the acetic acid, which is the UV degraded product of EVA, which forms as a result of ester elimination [35].

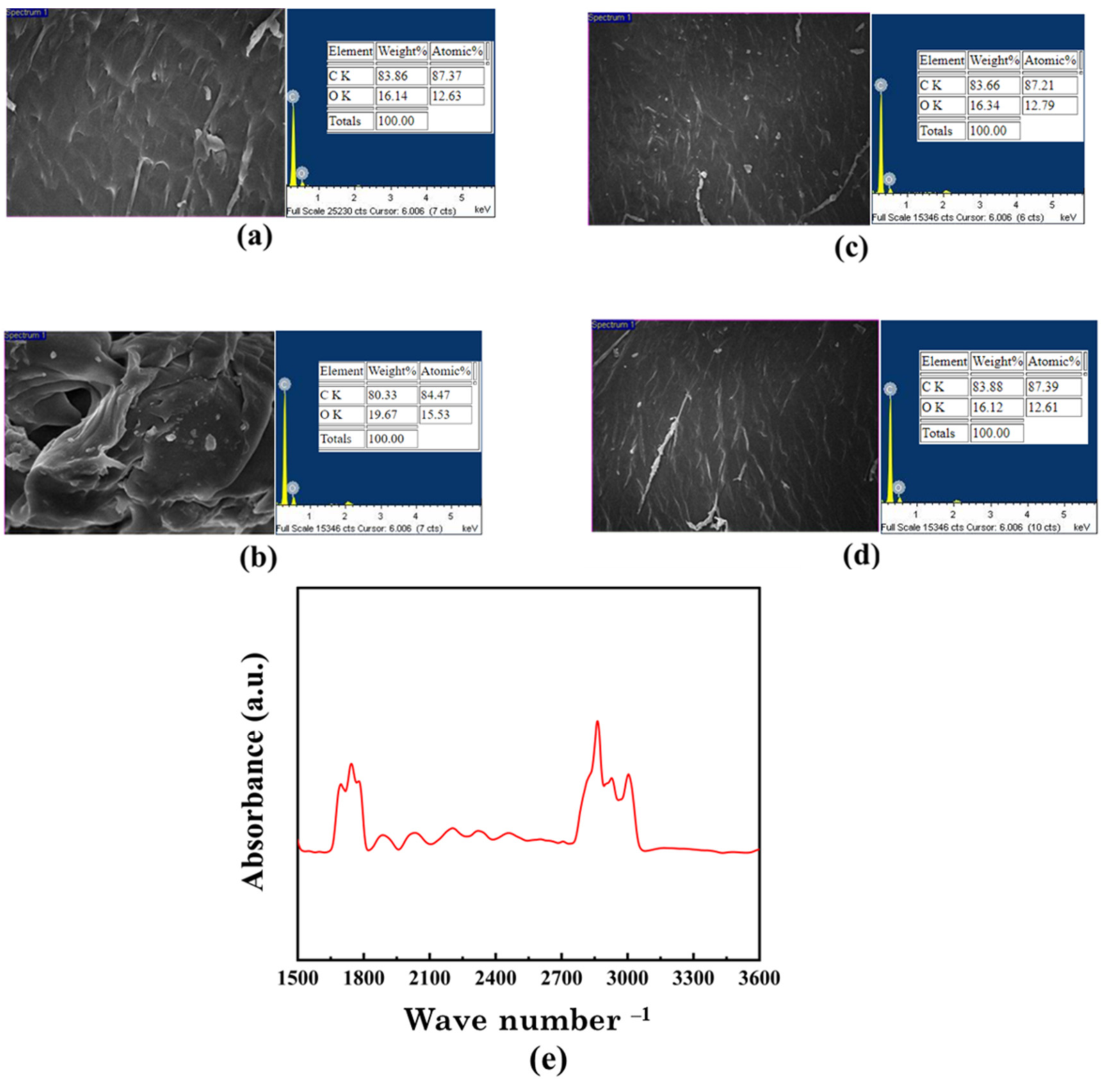

Figure 5. FE-SEM images and EDX analysis of EVA. EVA used in module having ETFE as a front sheet; (**a**) before and (**b**) after UV test. EVA used in a module having PC as a front sheet; (**c**) before and (**d**) after UV test. (**e**) FTIR image of EVA covered by ETFE after UV test.

3.4. I–V Curve Analysis

The current–voltage (I–V) curve exhibits the various current and voltage output combinations of the PV device. Figure 6 shows the I–V characteristics of a single cell module fabricated using ETFE and PC as the front cover sheet before and after the UV test.

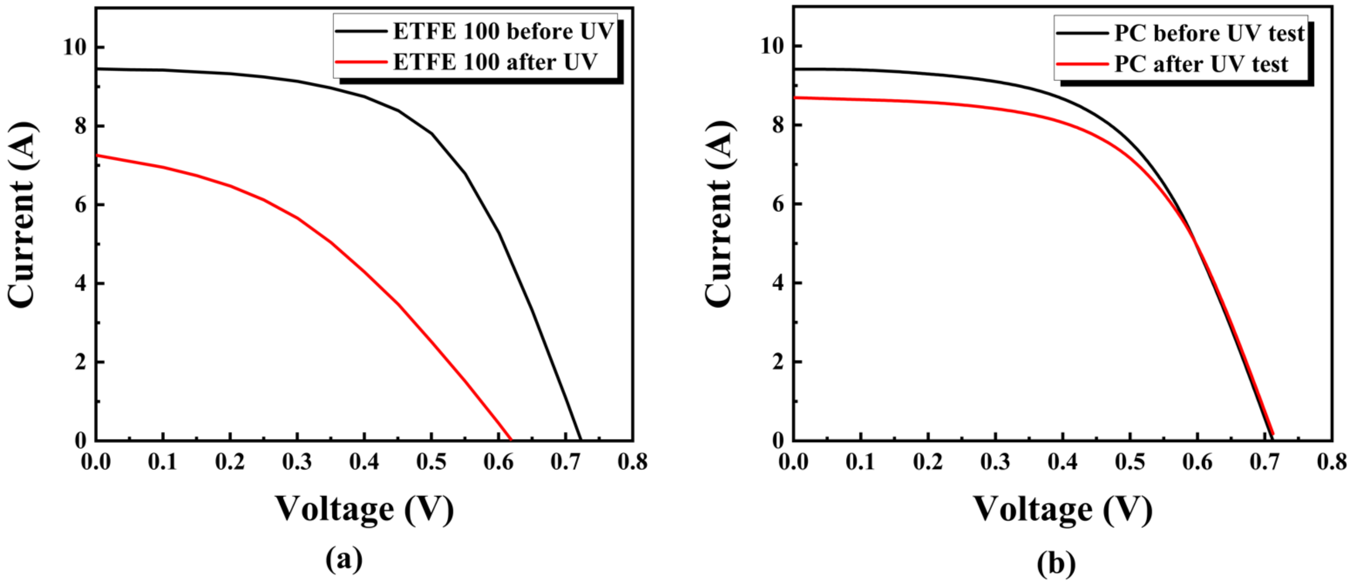

Figure 6. I–V curve of the lightweight one-cell PV module using (**a**) ETFE and (**b**) PC as a front cover sheet before and after the UV test.

Table 2 shows the percentage decrease in the electrical parameters after the UV test of the PV module using the ETFE and PC as the front cover sheet. The degradation of the ETFE based module was due to the browning of the EVA. This browning of EVA could reduce the module performance by up to 50% [36]. Brown EVA absorbed a substantial amount of sunlight in the UV and visible regions of the solar spectrum, thereby limiting the photon availability required for current production, which resulted in a decrease in the I_{sc} of the module. From the transmittance spectra, it can be observed that ETFE could not block all UV light, which directly interacted with EVA and caused damage in the form of power loss in the PV module. Moreover, the stabilizer concentration in EVA decreased progressively at high temperatures and when exposed to UV light [37]. Acetic acid formation resulting from the browning of EVA [38–40] caused a reduction in the FF of the PV module. The reduction in V_{oc} was related to the decrease in shunt resistance [35]. Further, the lowering of I_{sc} in the PC based PV module was due to the yellowing of the PC itself, which reduced the transmittance of light. As the PC itself blocked UV light, the EVA was unaffected, as its color remained the same.

Table 2. Percentage decrease in the electrical parameters after the UV test of the PV module.

Sample	ΔVoc (V) (%)	ΔIsc (A) (%)	ΔFF (%)	ΔPmax (%)
ETFE Module	14.40 ↓	23.26 ↓	31.27 ↓	54.85 ↓
PC Module	~same	7.64 ↓	~same	6.11 ↓

↓ means decrease.

4. Conclusions

The front surface of a PV module must be made of a polymer-based material instead of glass to maximize its use in applications where weight is a serious concern. This study focused on the analysis of the optical and UV reliability properties of various lightweight polymer front sheets. It was shown that the transmittance of ETFE, PET, PC, and PMMA decreased to approximately 2.65%, 15.01%, 2.98%, and 4.16%, respectively, after the UV reliability test. Moreover, a PV module was fabricated using ETFE and a PC as the front cover sheet and its electrical properties and UV reliability were investigated. Decreases in P_{max} for the ETFE and PC-based modules were 54.85% and 6.11%, respectively. This suggested that PC material is a suitable candidate for use in lightweight PV module applications.

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References

1. Baharwani, V.; Meena, N.; Dubey, A.; Brighu, U.; Mathur, J. Life cycle analysis of solar PV system: A review. *Int. J. Environ. Res. Dev.* **2014**, *4*, 183–190.
2. Shukla, A.K.; Sudhakar, K.; Baredar, P.; Mamat, R. BIPV based sustainable building in South Asian countries. *Sol. Energy* **2018**, *170*, 1162–1170. [CrossRef]
3. El Hammoumi, A.; Chalh, A.; Allouhi, A.; Motahhir, S.; El Ghzizal, A.; Derouich, A. Design and construction of a test bench to investigate the potential of floating PV systems. *J. Clean. Prod.* **2021**, *278*, 123917. [CrossRef]
4. Elborg, M. Reducing land competition for agriculture and photovoltaic energy generation–A comparison of two agro-photovoltaic plants in Japan. In Proceedings of the International Conference on Sustainable and Renewable Energy Development and Design (SREDD2017), Royal University of Bhutan (RUB), Mohithang Thimphu, Bhutan, 3–5 April 2017; Volume 3, p. 5.
5. Shaikh, P.H.; Nor, N.B.M.; Sahito, A.A.; Nallagownden, P.; Elamvazuthi, I.; Shaikh, M.S. Building energy for sustainable development in Malaysia: A review. *Renew. Sustain. Energy Rev.* **2017**, *75*, 1392–1403. [CrossRef]
6. Martins, A.C.; Chapuis, V.; Virtuani, A.; Ballif, C. Ultra-lightweight PV module design for building integrated photovoltaics. In Proceedings of the 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Washington, DC, USA, 25–30 June 2017; pp. 2104–2108.
7. Kajisa, T.; Miyauchi, H.; Mizuhara, K.; Hayashi, K.; Tokimitsu, T.; Inoue, M.; Hara, K.; Masuda, A. Novel lighter weight crystalline silicon photovoltaic module using acrylic-film as a cover sheet. *Jpn. J. Appl. Phys.* **2014**, *53*, 92302. [CrossRef]
8. Martins, A.C.; Chapuis, V.; Sculati-Meillaud, F.; Virtuani, A.; Ballif, C. Light and durable: Composite structures for building-integrated photovoltaic modules. *Prog. Photovolt. Res. Appl.* **2018**, *26*, 718–729. [CrossRef]
9. Zahid, M.A.; Hussain, S.Q.; Cho, Y.H.; Yi, J. Optical properties of CaF2 thin film deposited on borosilicate glass and its electrical performance in PV module applications. *Appl. Sci.* **2020**, *10*, 5647. [CrossRef]
10. Halbe, A.; Novak, J.; Sharpe, K.; Housser, G.; Haldars, P. Evaluation of mounting mechanisms for the installation of lightweight PV systems on commercial rooftops. In Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, CO, USA, 8–13 June 2014; pp. 3539–3542.
11. Honeker, C.; Fuller, E.; Watts, A.; Booth, D.; Flaherty, B.; Mao, E. Reducing installed costs of residential solar by the use of adhesive mounted lightweight solar modules. In Proceedings of the 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 5–10 June 2016; pp. 3135–3140.
12. Metacarpa, D.; Fobare, D.; Garney, A.; Yan, F.; Dwyer, D.; Holton, E.; Haldar, P. Reduced balance of system costs using lightweight photovoltaics integrated with roofing material membranes. In Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC), New Orleans, LO, USA, 14–19 June 2015; pp. 1–4.
13. Lamnatou, C.; Moreno, A.; Chemisana, D.; Reitsma, F.; Clariá, F. Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis on buildings. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2186–2201. [CrossRef]
14. Sulyman, M.; Haponiuk, J.; Formela, K. Utilization of recycled polyethylene terephthalate (PET) in engineering materials: A review. *Int. J. Environ. Sci. Dev.* **2016**, *7*, 100. [CrossRef]
15. Liu, Y.; Li, Q.; Shao, H. Properties of ZnO: Al films deposited on polycarbonate substrate. *Vacuum* **2009**, *83*, 1435–1437. [CrossRef]
16. Le Bail, N.; Benayoun, S.; Toury, B. Mechanical properties of sol–gel coatings on polycarbonate: A review. *J. Sol Gel Sci. Technol.* **2015**, *75*, 710–719. [CrossRef]

17. Brounne, M.; Heuseveldt, J.W.; Rosca, V.; Okel, L.A.G. Novel light-weight PV module design based on use of polycarbonate. In Proceedings of the International Conference EU PVSEC for Photovoltaic Research, Brussels, Belgium, 24–28 September 2018; p. 1.
18. Pawar, E. A review article on acrylic PMMA. *IOSR J. Mech. Civ. Eng.* **2016**, *13*, 1–4.
19. Holley, W.H. *Semiannual Technical Progress Report: Advanced Development of PV Encapsulants. Annual Subcontract Report, 1 January 1993–30 June 1993*; National Renewable Energy Lab., Springborn Labs: Golden, CO, USA, 1993.
20. Burrows, K.; Fthenakis, V. Glass needs for a growing photovoltaics industry. *Sol. Energy Mater. Sol. Cells* **2015**, *132*, 455–459. [CrossRef]
21. Dunlop, E.D.; Halton, D.; Ossenbrink, H.A. 20 years of life and more: Where is the end of life of a PV module? In Proceedings of the Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, Lake Buena Vista, FL, USA, 3–7 January 2005; pp. 1593–1596.
22. Pern, J. *Module Encapsulation Materials, Processing and Testing (Presentation)*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2008.
23. King, D.L.; Quintana, M.A.; Kratochvil, J.A.; Ellibee, D.E.; Hansen, B.R. Photovoltaic module performance and durability following long-term exposure. In Proceedings of the Photovoltaic Performance and Reliability Workshop, AIP Conference Proceedings, Vail, CO, USA, 18–21 October 1999; Volume 462, pp. 565–571.
24. Parretta, A.; Bombace, M.; Graditi, G.; Schioppo, R. Optical degradation of long-term, field-aged c-Si photovoltaic modules. *Sol. Energy Mater. Sol. Cells* **2005**, *86*, 349–364. [CrossRef]
25. Redjala, S.; Aït Hocine, N.; Ferhoum, R.; Gratton, M.; Poirot, N.; Azem, S. UV Aging Effects on Polycarbonate Properties. *J. Fail. Anal. Prev.* **2020**, *20*, 1907–1916. [CrossRef]
26. Lim, J.R.; Shin, W.G.; Lee, C.G.; Lee, Y.G.; Ju, Y.C.; Ko, S.W.; Kim, J.D.; Kang, G.H.; Hwang, H. A Study of the Electrical Output and Reliability Characteristics of the Crystalline Photovoltaic Module According to the Front Materials. *Energies* **2020**, *14*, 163. [CrossRef]
27. Jang, W.; Shin, D.; Choi, S.; Park, S.; Han, H. Effects of internal linkage groups of fluorinated diamine on the optical and dielectric properties of polyimide thin films. *Polymer* **2007**, *48*, 2130–2143. [CrossRef]
28. De Castro Monsores, K.G.; da Silva, A.O.; de Oliveira, S.S.; Rodrigues, J.G.P.; Weber, R.P. Influence of ultraviolet radiation on polymethylmethacrylate (PMMA). *J. Mater. Res. Technol.* **2019**, *8*, 3713–3718. [CrossRef]
29. Clark, D.T.; Abu-Shbak, M.M. Surface aspects of the heat treatment of polyethylene terephthalate as revealed by ESCA. *Polym. Degrad. Stab.* **1984**, *9*, 225–237. [CrossRef]
30. Factor, A.; Chu, M.L. The role of oxygen in the photo-ageing of bisphenol-A polycarbonate. *Polym. Degrad. Stab.* **1980**, *2*, 203–223. [CrossRef]
31. Buxbaum, L.H. The degradation of poly (ethylene terephthalate). *Angew. Chem. Int. Ed. Engl.* **1968**, *7*, 182–190. [CrossRef]
32. Day, M.; Wiles, D.M. Photochemical degradation of poly (ethylene terephthalate). III. Determination of decomposition products and reaction mechanism. *J. Appl. Polym. Sci.* **1972**, *16*, 203–215. [CrossRef]
33. Sang, T.; Wallis, C.J.; Hill, G.; Britovsek, G.J.P. Polyethylene terephthalate degradation under natural and accelerated weathering conditions. *Eur. Polym. J.* **2020**, *136*, 109873. [CrossRef]
34. Badiee, A.; Wildman, R.; Ashcroft, I. Effect of UV aging on degradation of Ethylene-vinyl Acetate (EVA) as encapsulant in photovoltaic (PV) modules. In Proceedings of the Reliability of Photovoltaic Cells, Modules, Components, and Systems VII, San Diego, CA, USA, 17–21 August 2014; Volume 9179, p. 91790O.
35. Meyer, E.L. On the Reliablity, Degradation and Failure of Photovoltaic Modules. Ph.D. Thesis, University of Port Elizabeth, Port Elizabeth, South Africa, 2002.
36. Pern, F.J.; Czanderna, A.W.; Emery, K.A.; Dhere, R.G. Weathering degradation of EVA encapsulant and the effect of its yellowing on solar cell efficiency. In Proceedings of the Conference Record of the Twenty-Second IEEE Photovoltaic Specialists Conference, Las Vegas, NV, USA, 7–11 October 1991; Volume 1, pp. 557–561.
37. Pern, F.J.; Czanderna, A.W. Characterization of ethylene vinyl acetate (EVA) encapsulant: Effects of thermal processing and weathering degradation on its discoloration. *Sol. Energy Mater. Sol. Cells* **1992**, *25*, 3–23. [CrossRef]
38. Kempe, M.D.; Jorgensen, G.J.; Terwilliger, K.M.; McMahon, T.J.; Kennedy, C.E.; Borek, T.T. Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices. *Sol. Energy Mater. Sol. Cells* **2007**, *91*, 315–329. [CrossRef]
39. Klemchuk, P.; Ezrin, M.; Lavigne, G.; Holley, W.; Galica, J.; Agro, S. Investigation of the degradation and stabilization of EVA-based encapsulant in field-aged solar energy modules. *Polym. Degrad. Stab.* **1997**, *55*, 347–365. [CrossRef]
40. Pern, F.J.; Czanderna, A.W. EVA degradation mechanisms simulating those in PV modules. In Proceedings of the AIP Conference Proceedings, Tucson, AZ, USA, 24–29 May 1992; American Institute of Physics: Washington, DC, USA, 1992; Volume 268, pp. 445–452.