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Review

Encapsulant Materials and Their Adoption in Photovoltaic Modules: A Brief Review

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Abstract: In the last two decades, the continuous, ever-growing demand for energy has driven significant development in the production of photovoltaic (PV) modules. A critical issue in the module design process is the adoption of suitable encapsulant materials and technologies for cell embedding. Adopted encapsulants have a significant impact on module efficiency, stability, and reliability. In addition, to ensure the unchanged performance of PV modules in time, the encapsulant materials must be selected properly. The selection of encapsulant materials must maintain a good balance between the encapsulant performance in time and costs, related to materials production and technologies for cells embedding. However, the encapsulants must ensure excellent isolation of active photovoltaic elements from the environment, preserving the PV cells against humidity, oxygen, and accidental damage that may compromise the PV module's function. This review provides an overview of different encapsulant materials, their main advantages and disadvantages in adoption for PV production, and, in relation to encapsulant technologies used for cell embedding, additives and the interaction of these materials with other PV components.

Keywords: PV modules; encapsulant materials; cost-performance balance; cells preservation

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1. Introduction

A new energy-consuming society requires more and more energy, and renewable sources become imperative. Therefore, the need to provide green energy is related not only to the growth request for energy but also to growing socio-political concerns and the need for urgent action, on a global scale, to limit climate change. The requests to replace fossil-based resources and to reduce CO_2 emissions could be met through the decarbonization of the energy sector [1–3].

The worldwide capacity in green energy production has increased by up to 650 GW in the last 10 years, leveraging solar energy, which is the cleanest and fastest-growing renewable energy source [4,5]. The capture of solar energy, and its transformations in electricity and heat, required the development of advanced devices and technologies. In all cases, the formulation of innovative and more efficient materials for solar energy capture and conversation is essential [6–8].

In the last two decades, in order to convert efficiently the sun's energy into electrical energy, PV module design and production have been significantly advanced, and the growth trend in this field is mainly oriented towards producing lighter and low-cost PV modules. The key factors for the development and market penetration of PV modules are their conversion efficiency, durability, and stability. The current operating life of a PV module is less than 25 years, while the latest generation of double-sided heterojunction photovoltaic panels, produced by 3SUN (ENEL Green Power, Rome, Italy), can maintain high properties and performance for about 35–40 years [9].

Crystalline silicon (c-Si) PV modules are the most produced and commercially available photovoltaic devices. They consist mainly of glass–encapsulant–cells–encapsulant–backsheet. The encapsulant sheets, based on polymer materials treated to obtain resistant structures, are extremely important components in PV modules. They are able to provide mechanical stability, electrical safety, and protection for the cells and other module components against environmental impacts [10–17].

Although this review mainly addresses encapsulant polymeric materials that are used in making the PV module, it is also relevant to mention the manufacturing sequence for crystalline silicon wafers, which constitutes the substrate of most solar cells today. The manufacturing sequence for crystalline silicon wafers can be divided into three steps: (i) silicon feedstock, (ii) crystallization, and (iii) wafering. However, the refinement processes for the hyper-pure silicon material were developed to enable the semiconductor industry. Although the silicon feedstock comes with more than sufficient purity for solar cells, the morphology of the micrometric-sized silicone crystals must be changed because of their extremely high brittleness. For this reason, the silicon material must be melted and recrystallised under controlled conditions in order to generate larger crystal grains that are bonded, to minimize the crystal defects that could limit and compromise the solar cell's performance. The transformation of silicon ingots to thin layers is carried out using slicing technologies, that are changed overtime, in the presence of some colling media [15].

The crystalline silicon (c-Si) PV modules consist mainly of glass–encapsulant–cells–encapsulant–backsheet, and, currently, the backsheet is substituted by glass or plastic sheeting to increase the solar capture efficiency, as shown in Figure 1. Based on information available everywhere, as summarized in Figure 1, the evolution of Si-PV module technologies and devices develops toward lighter and lower-cost efficient PV modules, through the use of innovative and high-performance materials. Thin-film PV modules are designed similarly to c-Si modules, and thin-film PV modules also use encapsulants, which are imperative to ensuring the efficient isolation of the PV components from exterior impacts [18–34].

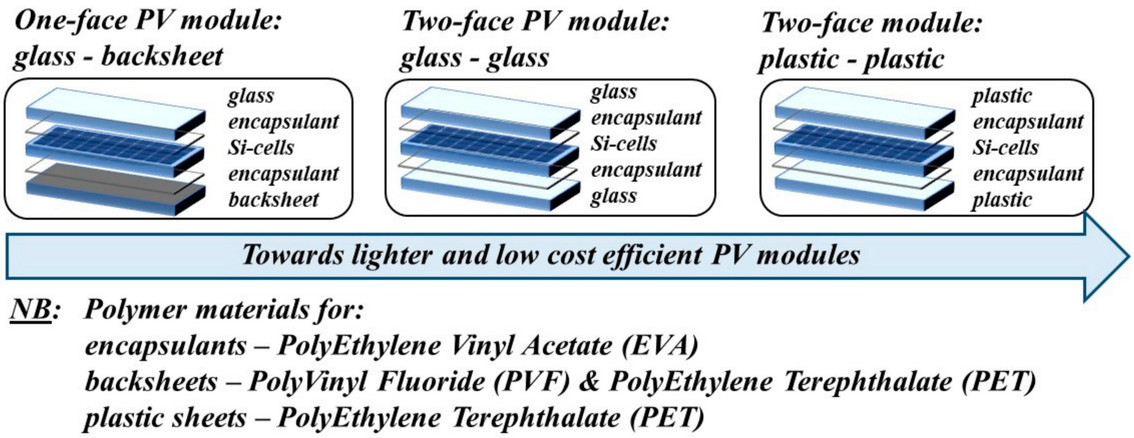
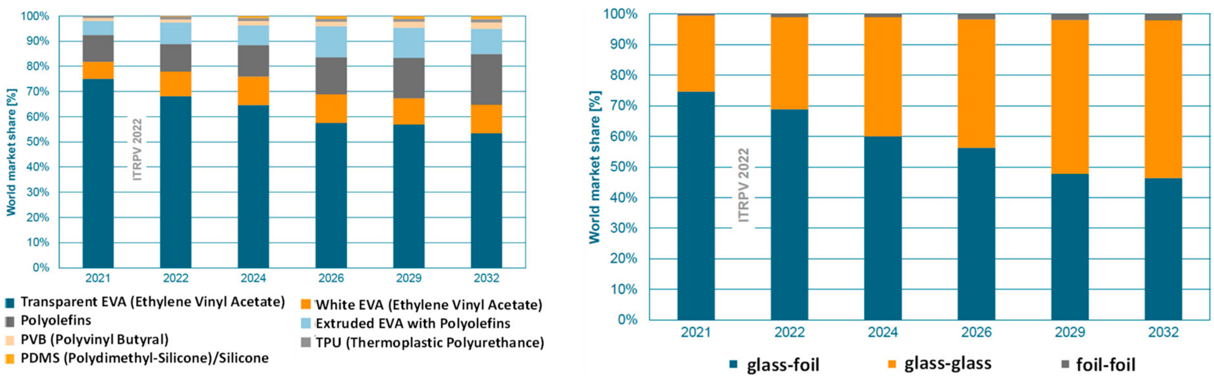


Figure 1. Evolution of Si-cell PV module technologies/devices.

However, as discussed accurately in International Technology Roadmap for Photovoltaic (ITRPV)—2022 [35], the encapsulant and backsheet/cover are key component materials, and both are also major cost contributions in PV manufacturing. Obviously, the balance between production costs and insurance of the module service lifetime must be established. Based on data available in the ITRPV report, EVA is the most considered and most widely used encapsulant material, as shown in Figure 2a [35]. EVA is expected to keep a quite constant market share of about 10% over the next years. It is important to note that polyolefins are one incoming alternative to EVA, especially when considering tow-face plastic–plastic modules and Si-heterojunction PV modules. As shown in Figure 2a [35], the market share for polyolefins is expected to increase by 20 times in the next 10 years, while other encapsulant materials are estimated to keep a low market share for these specific niche applications.



(**a**) (**b**)

Figure 2. World market share for (**a**) different encapsulant materials and (**b**) glass and foil as front and back cover materials. Based on data from International Technology Roadmap for Photovoltaic (ITRPV)—Report 2022 [35].

It is worth noting that the foils will stay mainstream as back coverings, although, for bifacial c-Si modules, it is expected that the glass will gain a significant market share as backsheet cover materials, and it is estimated to obtain ca. 45% share in the next 10 years, as shown in Figure 2b [35].

However, over time, different polymer materials have been considered for use in the production of PV modules, and, currently, the most popular encapsulants are based on (i) elastomers, such as poly-ethylene–vinyl–acetate (EVA) and silicones, (ii) thermoplastics, such as polyvinyl butyral (PVB) and ionomers, (iii) thermoplastic elastomers, such as thermoplastic silicone elastomers (TPSE), thermoplastic polyolefins (TPO), and polyolefin elastomers (POE). Therefore, this review provides an overview of the aforementioned different encapsulant materials, their main advantages and disadvantages in adoption for PV production, and, in relation to encapsulant technologies, additives and the interaction of these materials with other PV components.

2. Encapsulant Materials for Si-Cell PV Module

The encapsulant polymer-based materials in PV modules must provide proven mechanical stability, electrical safety, and protection of the cells and other module components from environmental impacts. Therefore, the most considered materials for encapsulants at the industrial scale are: (i) elastomers, such as poly-ethylene–vinyl–acetate (EVA) [18–20,27,28,32,36–38] and silicones [39–46], (ii) thermoplastics, such as polyvinyl butyral (PVB) [47–49] and ionomers [50–52], (iii) thermoplastic elastomers, such as thermoplastic silicone elastomers (TPSE) [53], thermoplastic polyolefins (TPO) [54,55] and polyolefin elastomers (POE) [37,38,56], because of their good balance between performance and costs. To achieve even better performance in PV protection, all of these polymer encapsulants must be processed by appropriate technologies to ensure accurate cells embedding and ribbons protection, and they must be treated with suitable additives, such as crosslinkers, stabilizers, and adhesion promoters. The main technical specifications of encapsulant polymeric materials include melting and glass transition temperatures, volume resistivity, moisture transmission rate, light absorption, and elastic modulus.

Figure 3 shows a classification of the encapsulant polymeric materials. Based on their chemical structures and bonds, they form the chemical or physical crosslinking structures of encapsulant films. All of these encapsulant polymeric materials are discussed, and Table 1 summarizes the main physical properties of the PV modules encapsulant materials, along with their advantages and disadvantages in adoption as encapsulant protection films.

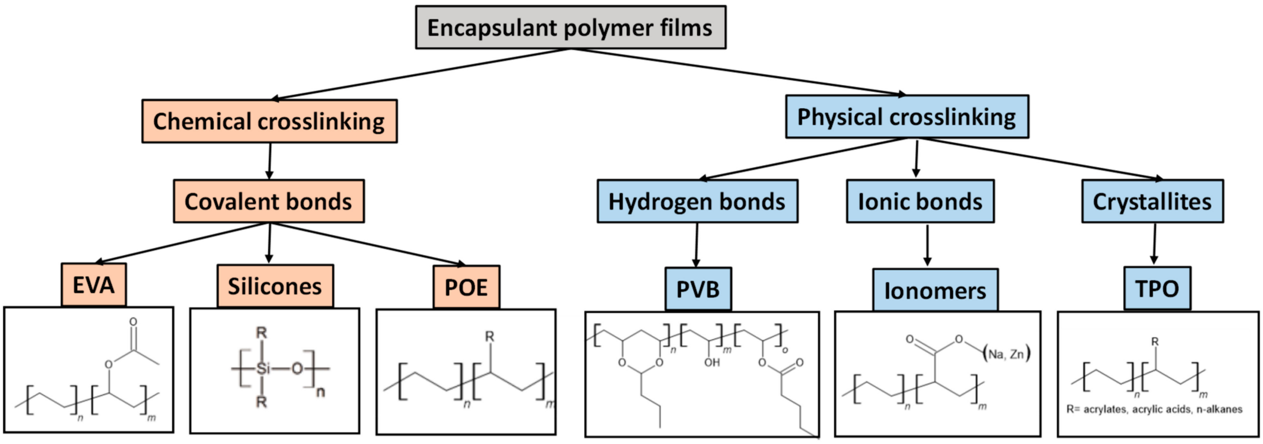


Figure 3. The encapsulant polymeric materials in PV modules and their characteristics.

Table 1. Encapsulant materials for PV modules production, their main physical properties, and their main advantages and disadvantages.

Encapsulant Materials	Main Physical Properties (*)	Advantages (+)	Disadvantages (−)
Elastomers			
EVA	Tg = −30/−40 °C E = 65 MPa RI = 1.48–1.50	(+) good balance performance/costs (+) easy cell encapsulation (+) random radical crosslinking (+) good compatibility with additives, such as UV adsorbers, stabilizers, and antioxidants	(−) discoloration and yellowing (−) acetic acid formation as degradation product (−) EVA degradation products could react/interact with degradation products of stabilizers and antioxidants
Silicones	Tg = −40/−50 °C E = 10 MPa RI = 1.35–1.50	(+) excellent chemical inertia and oxidative and thermal resistance (+) very good transparency in UV range	(−) specific processing conditions and equipment (−) reinforcement additives must be used to improve the mechanical resistance (reduced mechanical resistance)
Thermoplastics			
PVB	Tg = +10/+20°C E = 10 MPa RI = 1.48	(+) current formulations based on PVB require bland vacuum lamination conditions (+) thermal stability and reduced aging rate(+) good transparency in UV range and low cost	(−) water uptake and hydrolysis (−) the considered formulations require high pressure and temperature during roll-to-roll lamination, combined with autoclave (−) use of different additives
Ionomers	Tg = +40/+50°C E = 280 MPa RI = 1.49	(+) very good UV resistance (+) very good mechanical performance	(−) high production (synthesis) costs (−) specific processing conditions and equipment
Thermoplastic elastomers			
TPSE	Tg = −100 °C E = 250 MPa RI = 1.42	(+) excellent mechanical properties in a large temperature range (+) good electrical insulation (+) physical crosslinking through hydrogen bonds	(−) high synthesis and production costs (−) specific lamination conditions

Table 1. *Cont.*

Encapsulant Materials	Main Physical Properties (*)	Advantages (+)	Disadvantages (−)
TPO	Tg = −40/−60 °C E = 30 MPa RI = 1.48	(+) good mechanical performance and UV resistance (+) low synthesis and production costs	(−) high water permeability (−) chemically crosslinked TPO shows discolouration and reduced UV resistance
POE	Tg = −40/−70 °C E = 55 MPa RI = 1.48	(+) low synthesis costs (+) good elasticity and toughness (+) good UV resistance and no discolouration	(−) reduced adhesion ability (−) chemically crosslinked POE shows discolouration

Note: (*) Tg—glass transition temperature; E—elastic modulus; RI—refractive index. The values are based on the available literature.

2.1. Elastomers as Encapsulant Materials

2.1.1. Poly-Ethylene–Vinyl–Acetate (EVA)

EVA has been the most considered encapsulant material in the last twenty years, but although its formulation has been significantly improved, it shows drawbacks related to discolouration and yellowing [18–20,26–28,32,36–38]. EVA degradation phenomena have been extensively studied and described, and, according to the literature, it degrades by deacetylation, hydrolysis, and photothermal decomposition [18–20,26]. Moreover, the photothermal degradation of EVA could be accelerated because of the photothermal degradation of additives such as UV absorbers, stabilizers, and antioxidants.

However, the degradation of EVA and its additives is also accelerated by the formation of hot spots due to the presence of some Si-cells defects, which cause a local temperature increase of up to ca. 350 °C [57]. Unfortunately, this causes an uncontrolled acceleration of EVA and additives thermal degradation/decomposition and acetic acid formation. As documented in the literature, the thermal degradation of EVA, although in a reduced way, could be slightly slowed down by introducing polyolefin constituents [26].

To be a good encapsulant, EVA must be transformed in elastomer by adding suitable crosslinking agents and being subjected to prolonged thermal treatment and high pressure. The peroxide radical crosslinking of EVA is a random process, and its occurrence must happen during the lamination process, considering the high volatility of low molecular weight crosslinkers.

Therefore, EVA is considered to be a good encapsulant material because of the good balance between performance and costs. Unfortunately, easy degradation of EVA, with the formation of acetic acid, discolouration, and yellowing, compels the producers of PV modules to search for other encapsulant materials with a good balance of performance and costs.

2.1.2. Silicones

There are inorganic–organic materials based on silicon, hydrogen, and oxygen atoms (-Si(X,Y)-O-) [39–46]. They are very promising materials, but due to their high cost and the need for highly specialized equipment for their lamination process, silicon materials are not considered for large-scale applications. These encapsulant materials are more suitable for special conditions applications, for example, for encapsulation of devices for extra-terrestrial use and applications. As is widely known, the silicones show excellent chemical inertia and resistance to oxidation and heat, good transparency in the UV range, and very low water uptake. Unfortunately, due to the nature of silicone, these encapsulant materials require specific processing conditions and equipment. Their use could be justified, even considering high costs, in high-performance applications. Moreover, these materials show very low mechanical resistance, and the use of suitable reinforcement additives, that could penalise the optical properties is imperative.

2.2. Thermoplastics as Encapsulant Materials

2.2.1. Polyvinyl Butyral (PVB)

The second-most considered encapsulant material is PVB, which has costs similar to that of EVA [47–49]. The first-considered formulation of PVB for encapsulants required high pressure and temperature during the roll-to-roll lamination, combined with an autoclave. Currently, upon accurate correction of the PVB composition, PVB can be laminated in bland conditions, under lower temperatures, and in less time using vacuum lamination. That makes PVB encapsulants mostly easy to process.

PVB shows good thermo- and photo-oxidative resistance in comparison to EVA, although the use of different additives is absolutely requested in order to have low pressure and temperature processing. Additionally, PVB shows a high hydrolysis tendency due to its water uptake, and, obviously, this represents a limit issue for its large-scale use.

2.2.2. Ionomers

There is a new high-cost class of PV module encapsulants that are based on ethylene and unsaturated carboxylic acid co-monomers, such as ethylene–methacrylic acid copolymer [50–52]. Ionomers have high production costs for synthesis, which, in the last ten years, due to their good UV stability, have been considered suitable materials for different wire and cable applications. The ionomers form physical-crosslinked structures, due to their polar nature, and there is no necessary chemical crosslinking. The chemical nature of the considered co-monomers, in some specific cases, could require prolonged processing time in order to ensure good adhesion between the encapsulant sheets and cells. Ionomers show good mechanical performance and resistance, and they have been considered for thin-film solar modules, but there are other promising encapsulants for c-Si modules.

2.3. Thermoplastic Elastomers as Encapsulant Materials

2.3.1. Thermoplastic Silicone Elastomers (TPSE)

These relatively new kinds of encapsulant materials combine good silicone performance and easy thermoplastic processability [53]. Until now, their synthesis and production costs have been relatively high, and, for this reason, they are not considered for large-scale applications, but they could be considered promising candidates for special PV module applications. TPSE could form physical crosslinking structures, and controlling the sequence and length of the plastic and elastomer units could allow them to obtain excellent mechanical performance, water permeability, and electrical insulation. By including more silicone units, it is possible to synthesize materials having a good resistance to large temperature ranges.

2.3.2. Thermoplastic Polyolefin (TPO)

As an alternative to EVA encapsulant, thermoplastic polyolefins (TPO) are newly developed non-crosslinking or crosslinking materials for photovoltaic (PV) module lamination [54,55]. According to the literature, TPO shows a lower discolouration tendency and better optical and thermal properties degradation before and after artificial weathering [55]. This makes these encapsulant materials very attractive, although some problems, related to good adhesion between the encapsulant sheets and cells during lamination, have been encountered. TPO encapsulants are copolymers based on ethylene–propylene rubber and ethylene–octene rubbers, and their synthesis and production are cheaper than other encapsulant materials. TPO shows good mechanical properties and UV resistance, and, according to the literature, the discolouration of TPO is around nine times slower than that of EVA. In 50 days of weatherability tests, the transmittance of EVA significantly reduced while that of TPO remained almost unchanged. Unfortunately, TPO shows significantly higher water permeability than EVA. Some crosslinking TPO shows better adhesion properties, and, similarly to EVA, they show discolouration and reduced ageing resistance. Fortunately, the degradation pathways do not develop volatile by-products, such as acetic acid, that could cause the corrosion of metal ribbons.

2.3.3. Polyolefins Elastomers (POE)

The POE are copolymers of ethylene and other alpha-olefins, such as butene or octene, and they are very promising encapsulant materials [37,38,55,56]. POE could be synthesized using metallocene catalysis, and controlling the ethylene/comonomer sequence and comonomer content could produce polymers with tailored elasticity. The presence of comonomer units disrupts the polyethylene crystallinity while the macroscopical mechanical behaviour of POE could be controlled by manipulating the molecular weights. Additionally, POE shows very good resistance to UV ageing and no discolouration upon exposure to sunlight, but, unfortunately, the use of adhesion promoters to improve the adhesion between the glass and the embedded cells is required.

The main physical properties of the above-discussed PV module encapsulant materials, and their advantages and disadvantages in adoption as encapsulants, are listed below in Table 1.

As mentioned before, in case of accidental "hot spot" formations due to incorrect PV module function, local temperatures rise to up to ca. 350 °C. This issue is an enormous problem for all organic encapsulant materials, and especially for EVA. This problem is exacerbated due to the favourable conditions for acetic acid formation and volatilization, which causes sheet delamination and ribbon corrosion.

3. Technologies for PV Cells Embedding

The solar cells can be embedded between encapsulant sheets using different technologies, such as the vacuum lamination process, roll lamination combined with autoclave, and the casting process, as summarized in Table 2 [58–60].

Table 2. Currently adopted technology for PV cells embedding.

Technology for Cells Embedding	Encapsulant Materials	Processing Conditions
Vacuum lamination	EVA, PVB, TPSE, TPO, POE ionomers	$T_{processing}$ = 140–170 °C $t_{processing}$ = 7–20 min
Roll-to-roll lamination combined with autoclave	PVB, TPSE	$T_{processing}$ = 140–170 °C $t_{processing}$ = 7–20 min
Casting process	Silicones	$T_{processing}$ = 80 °C $t_{processing}$ = 20 min

Therefore, the most considered processing technology is the vacuum lamination process, which has been adopted successfully for almost all encapsulant materials, such as poly-ethylene–vinyl–acetate (EVA), polyvinyl butyral (PVB), thermoplastic silicone elastomers (TPSE), thermoplastic polyolefins (TPO), polyolefin elastomers (POE), and ionomers. The processing conditions, such as temperatures and time for treatment during the vacuum lamination process, are chosen considering the chemical nature of the encapsulants. They are usually $T_{processing}$ = 140–170 °C and $t_{processing}$ = 7–20 min.

The roll-to-roll lamination process combined with autoclave, which is very similar, in concept, to glass lamination, is suitable for the processing of polyvinyl butyral (PVB) and thermoplastic silicone elastomers (TPSE). The processing conditions are similar to that of the vacuum lamination process, i.e., $T_{processing}$ = 140–170 °C and $t_{processing}$ = 7–20 min.

The casting process is adopted for PV assembling when silicones are considered efficient encapsulant materials. It consists of a dispersion of silicones on components. The silicones form three-dimensional structures upon thermal or ultraviolet treatment. Usually, this process is considered lower temperature, i.e., ca. 80 °C, with a treatment time of about 20 min.

Regardless of the considered encapsulant materials and adopted technologies for embedding the cells, the encapsulants must provide mechanical stability, electrical safety, and protection of the cells and other components from environmental impacts.

4. Additives for PV Module Encapsulants

To achieve good stability and protection, the polymer-based encapsulants must be mixed with different additives that play different roles, for example: (i) crosslinking agents help the formation and structuration of 3D crosslinked sheets [18–20], (ii) stabilizers, such as antioxidants, that prevent the thermal degradation of encapsulant materials during the lamination process and in service, along with UV absorbers and stabilizers that protect the sheets against UV irradiation in service conditions [26,37,38], and (iii) adhesion promoters to ensure good adhesion between cells and other PV components [61,62]. All of these additives have specific and unique tasks for the formulation and use of encapsulant materials in PV modules.

4.1. Crosslinking Agents

The crosslinking agents, usually organic peroxides, help the formation and structuration of crosslinked encapsulants, improving the adhesion between the cells and other PV components and ensuring the isolation of PV modules from the environment [18–20]. The formation of crosslinked structures is usually completed during the vacuum lamination process or during the roll-to-roll lamination process. Therefore, the formation of crosslinked structures proceeds through radical random reactions, and its completion occurs upon heat of UV exposure.

4.2. Stabilizers: Antioxidants and UV Absorbers and Stabilizers

Thermal stabilizers, such as phenolic antioxidant derivatives, are usually added to protect the polymer-based encapsulant against thermal degradation during the prolonged lamination process and during thermal shock in the case of the occurrence of accidental "hot spots" [26]. Unfortunately, since the antioxidants are organic molecules, in the cases of hot spots occurrence they degrade and/or decompose quickly, and their degradation products could react with the degradation products of the encapsulant sheets.

The addition of UV absorbers and stabilizers in the composition of encapsulant materials is absolutely imperative. The presence of both adsorbers and stabilizers helps to slow down the thermo-/photo-induced degradation of the encapsulants through UV adsorption, radical capture, and/or hydrogen donation. The UV adsorbers are able to attract and adsorb the UV rays, transforming the energy into non-harmful energy and avoiding the macromolecule chain scission. The UV stabilizers are multi-functional. First, they perform radical capture, and second, they perform hydrogen donation, avoiding the propagation of radical development upon exposure to UV rays. There are different UV stabilizer classes, such as classical benzophenones, hindered amines, etc. None of these additives change the encapsulant transparency and colour, and they must be able to extend the lifespan of the encapsulants in service conditions.

4.3. Adhesion Promoters

Adhesion promoters, usually based on silanes, help the adhesion and encapsulation of cells and other components [61,62]. Unfortunately, the presence of adhesion promoters, in some cases, could cause slight hazing of the encapsulant, and this could hinder the correct function of the PV modules. Moreover, according to the literature, silanes could catalyse the formation of acetic acid in EVA encapsulants, leading to premature ribbon corrosion. Currently, the opportunity to replace the silanes-based adhesion promoters with polar waxes containing different functional polar groups has been proposed in the scientific literature [62].

The main advantages and disadvantages of different encapsulant additives are summarized in Table 3.

Table 3. Additives of encapsulant materials for PV module production and their main advantages and disadvantages.

Encapsulant Additives	Advantages (+)	Disadvantages (−)
Crosslinkers	(+) formation of crosslinked structure for the encapsulant materials	(−) not enough control of radical random crosslinking process
Antioxidants	(+) protection of encapsulants against thermal degradation during lamination and accidental hot spots occurrence	(−) products of degradation of thermal stabilizers could react with other degradation products
UV absorbers and stabilizers	(+) protection of encapsulants against UV irradiation, slowing down the photoinduced degradation	(−) products of degradation of UV stabilizers could react with other degradation products
Adhesion promoters	(+) promotion of adhesion between the cells and other components	(−) could cause premature encapsulant hazing

5. Encapsulant Materials for Organic and Perovskite Solar Cells

Although this review is mainly focused on the encapsulant materials for Si-cell PV modules, encapsulant materials for organic and perovskite solar cells have also been briefly mentioned. PV module development towards new devices is related to the formulation of organic and perovskite solar cells, but, as is well-known, these devices show poor stability [63–73]. Therefore, the poor stability of the devices must be well addressed before the large-scale industrial production and commercialization of organic and perovskite solar cells. As documented, the power conversion efficiency for organic solar cells has surpassed 14% for single junction and 17% for heterojunction devices, while the efficiency for perovskite solar cells is ca. 23%, similar to that for traditional silicon solar cells [63].

According to the literature, the encapsulant materials for both organic and perovskite solar cells are essential for correct PV device function, preventing the permeation of water vapour and oxygen, and achieving stability and the desired lifetime for these solar cells. The probable encapsulant materials for organic and perovskite solar cells are ethylene vinyl acetate (EVA) [63,64] or europium (Eu^{3+}) doped EVA [68], polyvinyl butyral (PVB) [71], thermoplastic polyurethane (TPU) [73], ethylene methyl acrylate (EMA) [67], and poly-isobutylene (PIB) [70], although these materials do not offer suitable stability for the devices. Currently, prosed encapsulant materials for organic and perovskite solar cells are UV-cured epoxy resins, and these materials could offer good device stability, but the regular disposal and distribution of the active elements is not an exactly easy matter. Therefore, the most considered encapsulant material for both organic and perovskite solar cells is EVA, although it does not offer desired stability for the device.

The roll-to-roll technology for layer assembling results in the most considered technology to produce organic and perovskite solar cells. The use of additives, such as crosslinkers, stabilizers, and adhesion promoters, is imperative in order to further improve performance and to ensure the durability and desired properties of these encapsulant materials.

6. Conclusions and Future Perspectives in Module Design

PV module development is related to the formulation of more and more performance devices with a power increase of more than 1%. The main direction for silicon PV device development is towards lighter and lower-cost devices, and, obviously, this requires higher-performance materials for next-generation PV modules.

Regarding the encapsulant materials, improving the UV cut-off to below 350 nm for PV encapsulant materials is desirable, and this could be obtained by using specific additives to ensure the cut-off effects.

Currently, EVA is the most considered encapsulant material for Si-cells, although it shows some drawbacks and the research for new encapsulants continues. EVA degradation pathways allow for the formation of acetic acids, which cause ribbon corrosion and compromise the use of this encapsulant material. Other encapsulants based on TPO, POE, silicones, and ionomers have also been developed, and all of these materials show lower degradation tendencies in comparison to EVA, with less discolouration and opacity in service conditions. Therefore, encapsulants are very important components in PV module production and assembly, and their failure could cause the failure of PV devices, significantly lowering energy recovery and conversion.

EVA or modified EVA is also the most considered encapsulant material for organic and perovskite solar cells, although these applications require materials that can prevent the permeation of moisture and oxygen and offer stability to devices.

To sum up, the research for novel encapsulants is related to the formulation of materials having a favourable cost-performance balance, an improved UV cut-off to below 350 nm, and an easy lamination process for PV cell embedding, in terms of reduced curing times and lower process temperatures and pressures.

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