

Overview of PV module encapsulation materials

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Fab & Facilities

Materials

Cell Processing

Thin Film

PV Modules

Power Generation

Market Watch

ABSTRACT

The rapid growth of the PV market during the last five to seven years entailed a considerable expansion of the encapsulation material market, which temporarily led to shortages in the supply chain. Simultaneously, module prices decreased significantly, which resulted in intense pressure on production costs and the cost of PV module components, inducing changes in the encapsulation material market towards new materials and suppliers. This pressure – together with the huge impact of the encapsulation material on module efficiency, stability and reliability – makes the selection of encapsulation technologies and materials a very important and critical decision in the module design process. This paper presents an overview of the different materials currently on the market, the general requirements of PV module encapsulation materials, and the interactions of these materials with other module components.

Introduction

PV module set-up

Crystalline silicon (c-Si) PV modules typically consist of a solar glass front cover, a polymeric encapsulation layer, mono- or polycrystalline silicon cells with a metallization on the front and rear, solder bonds which electrically connect the individual cells, and a polymeric (or, less commonly, glass) backsheet.

Thin-film PV modules may be manufactured either via a substrate process, where the semi-conducting layers are processed on the module rear cover, or via a superstrate process, where processing occurs on the front cover (Fig. 1(b) and (c)).

The major requirements of providing mechanical stability, high transparency in the spectral response range of the solar cell and protection of the cell and metallization against exterior impacts make the use of solar glass for front-cover material the most obvious choice. For flexible technologies, polymeric front sheets are also used, which have to provide good barrier properties. Rear materials are also expected to provide mechanical stability, electrical safety, and

protection of the cells and other module components from exterior impacts.

Production process

A standard module production process consists of the following steps: glass washing and drying; tabbing of the cell ribbons and soldering of the cell matrix; module lay-up, including soldering of the cross connection; embedding; edge sealing and framing; attachment of the junction box; and a power measurement.

In general there are three different process types for embedding the cell matrix into the surrounding materials. The most common is the vacuum lamination process, which is used primarily for ethylene vinyl acetate (EVA) encapsulants, but also for a range of thermoplastic films. Another possibility, for thin-film devices, is a roll-to-roll laminator combined with an autoclave – a well-known concept in the glass industry. An alternative to the lamination process is the use of cast resins, for example silicones. In a c-Si module process, the liquid encapsulation material has to be dispensed in two steps: first to the top of the glass and second to the applied cell matrix.

Of the various module production steps, the embedding process requires the longest cycle time. The main goal of equipment producers is to decrease the process time by developing laminators which process more modules at the same time. Another option is to modify the encapsulant itself by adding optimized peroxide cross-linking agents to achieve a faster cross-linking or by using thermoplastic encapsulants.

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The main challenge in all embedding processes is to achieve uniform and sufficient curing or cross-linking levels to ensure strong adhesion and stable laminates. Consequently, the equipment

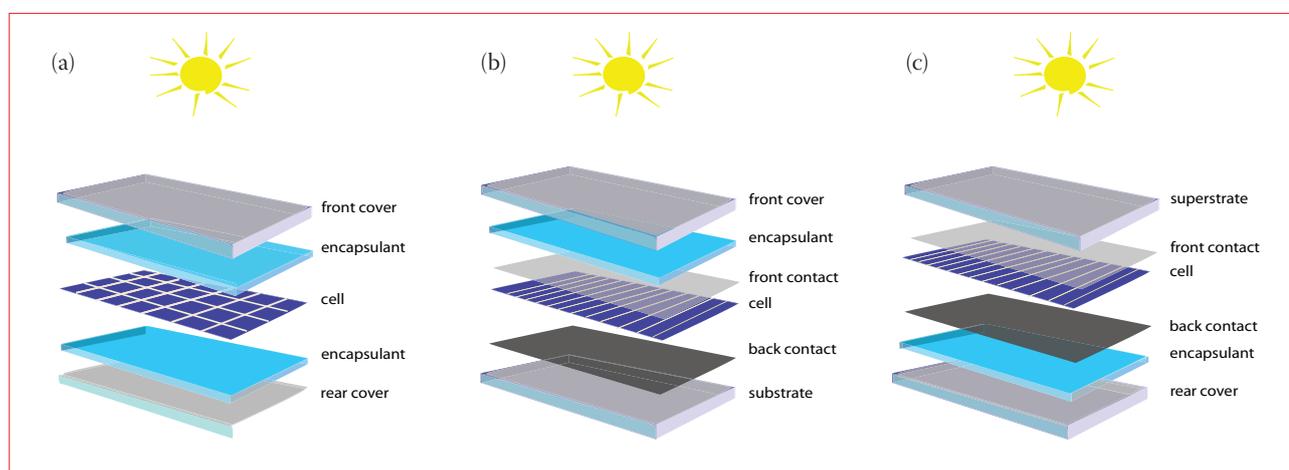


Figure 1. (a) General set-up of a c-Si PV module; (b) substrate-type thin-film PV module; (c) superstrate-type thin-film PV module.

must provide excellent heat and pressure uniformity, a high accuracy in temperature control, and long-term stability of the process parameters.

Loss mechanisms and interactions with other components regarding module efficiency

The cell-to-module (CTM) efficiency ratio can be defined as the efficiency of an interconnected cell matrix, measured within a module lay-up in relation to the average cell efficiency measured in contact with air. The CTM value strongly depends on the embedded cell type. For a highly efficient solar cell with a homogeneous anti-reflective texture and high response in the blue light spectrum, the CTM loss is usually higher than that of a low-efficiency cell embedded in the same module materials.

From cell to module, there are several factors affecting efficiency, mostly with a negative impact. These factors are losses due to inactive areas in the module, which only affect the module efficiency and not the actual power output. Factors that influence power output can be separated into optical and electrical effects; the electrical losses arise mainly from serial resistance losses within the cell interconnections.

Several interacting optical effects can be observed after encapsulation (Fig. 2). First, reflection losses occur at every material interface where the refractive index changes. Second, there are absorption losses in every module layer located in front of the cells. The reflected light from the cell surface, which includes the finger area and the busbar or ribbon area, can be partially or totally redirected to the cell. By using a highly reflective backsheet, incident radiation in the cell gap is scattered backwards. If it hits the first interface of the module, usually glass–air, it is partially or totally reflected, depending on the incidence angle. Some of this radiation then hits the cells in their active area and increases cell current and power output. For the embedding materials it is most important to achieve negligible absorption in the relevant section of the spectral response (350–1200nm for c-Si technology).

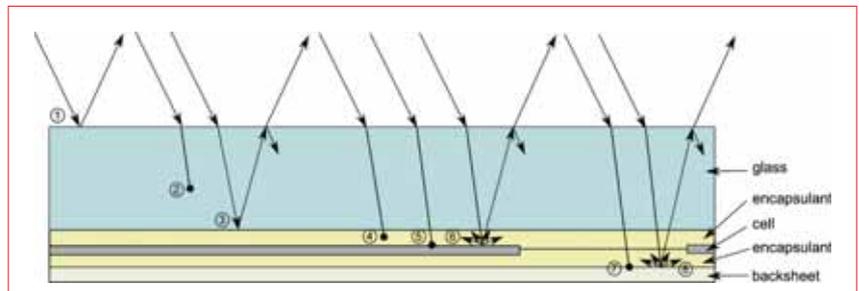


Figure 2. Optical losses in a c-Si PV module [1].

There are various loss mechanisms which reduce the amount of light reaching the cell. These mechanisms (indicated in Fig. 2) are:

- ①,③ reflection losses at the air–front and front–encapsulant interfaces;
- ②,④ absorption losses in the front and encapsulation material;
- ⑤ absorption of the cell;
- ⑥ reflection of the cell surface, and partial or total re-reflection at the front–air interface;
- ⑦ absorption of the backsheet material;
- ⑧ reflection of the backsheet material, and partial or total re-reflection at the glass–air surface.

The refractive index of the encapsulant influences the reflection losses at the glass–encapsulant interface and at the silicon–anti-reflective coating (ARC)–encapsulant interface. The optical gain due to optical coupling becomes less relevant for a cell with an efficient light-trapping texture and ARC.

Properties of encapsulation materials

Requirements for encapsulation materials

The requirements for PV module encapsulants in terms of optimizing module efficiency can be divided into five categories: electric yield, electrical safety, reliability, module processing and cost.

- The encapsulant has to provide low light absorption and an adapted refractive index to minimize interface reflectance.
- A high thermal conductivity reduces operating temperatures and thus improves electric yield.
- For electrical safety, only very low leakage currents are allowed by standard type-approval testing in accordance with IEC 61215.
- In terms of PV module reliability, the encapsulant properties are critical in respect of UV irradiation, humidity, temperature cycles, extremely low or high ambient temperatures, mechanical loads, electric potential relative to ground, etc. The encapsulant has to maintain strong adhesion to the other module components and protect the cell and metallization from external impacts.
- A module manufacturer will also look at material cost, processing cost and processing time, shelf life and quality assurance issues.

Parameters and methods for evaluating encapsulation material

On the basis of the requirements stated above, there are several crucial parameters which have to be taken into account when choosing a suitable PV encapsulant (see Table 1). Besides basic material properties – such as glass transition or melting temperature, which can be determined by characterization techniques like differential scanning calorimetry (DSC) or dynamic mechanical analysis

Parameter	Method	Relevance
Glass transition temperature T_G	DSC, DMA, etc.	Limited variation in material properties within the temperature range of exposure
Melting temperature T_M	DSC, DMS, etc.	Processability
Young's modulus E	DMA, tensile testing	Mechanical stress on cell
Refractive index n	Refractometry	Minimizing optical losses
Absorption	Fourier transform spectroscopy	Minimizing optical losses
Volume resistivity	Resistivity test	Electrical insulation
WVTR OTR	Permeation measurements	Knowledge about mass transport processes within the module

Table 1. Overview of the most important aspects of encapsulation evaluation.

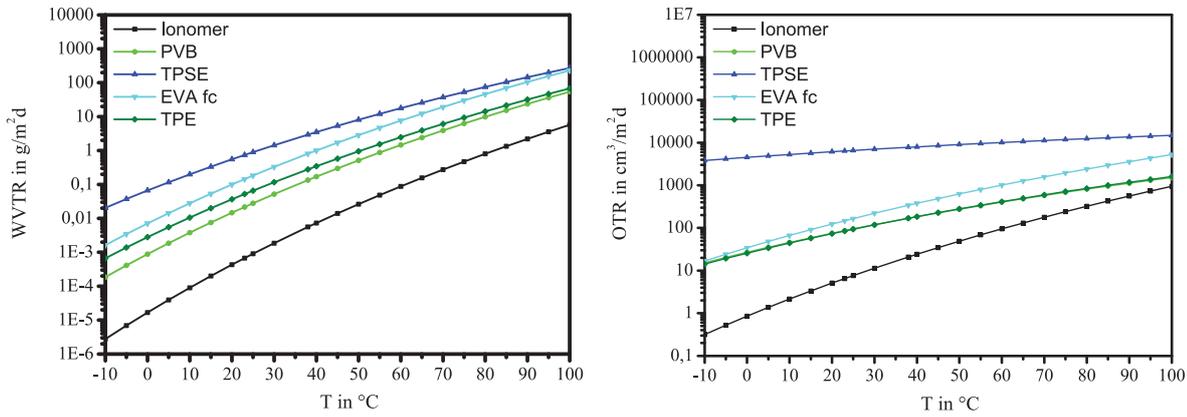


Figure 3. Temperature dependency of WVTR and OTR for different encapsulation materials [3].

(DMA) – the mechanical properties are also very important in order to achieve buffering properties to withstand mechanical impacts and mechanical and thermomechanical loads.

Important factors influencing a PV module’s durability are the diffusion properties of the backsheet and the encapsulation material with regard to gases such as oxygen or water vapour [2]; both of these can accelerate degradation reactions by penetrating the PV module through the surface of the polymeric backsheet and by diffusing through the encapsulation polymer until they reach the area between the solar cell and the front glass. A commonly neglected fact is the significant dependency of the water vapour transmission rate (WVTR) and the oxygen transmission rate (OTR) of an encapsulant on the temperature. Since permeation processes are greatly accelerated by the temperature, as shown in Fig. 3, particularly high transmission rates at high temperatures result in rapid inward and outward mass transport processes of the module.

Another interesting tool for material characterization and evaluation is Raman Spectroscopy – this has recently been reported as a quick and non-destructive method for analyzing the encapsulation degradation of small test laminates or full-size PV modules [4].

Encapsulation materials

Market survey

In the 60s and 70s, mainly polydimethylsiloxane (PDMS) was used for the encapsulation of the first PV modules. This has since been replaced by other materials such as EVA, which has now dominated the market for several decades. All the polymers used are thermoplastic materials or elastomers; the latter, however, require cross-linking during the lamination process, which increases the cycling times and production costs. The need to reduce the costs of PV modules opens the market for new encapsulation materials, although reliability risks must be considered to be critical, given the long-lasting performance guarantees that PV manufacturers have to offer for their PV modules.

“The need to reduce the costs of PV modules opens the market for new encapsulation materials.”

The growth of the PV market in recent years has led to an increase in the number of suppliers of EVA-based materials. In parallel, the number of non-EVA materials has also increased during the last few years:

nine companies with 23 non-EVA products have been documented [5]. Yet, despite all the different polymers in use, the PV market – compared to the total annual production volume – is still a niche market for suppliers of base polymers. Manufacture of the compounds is therefore usually done by smaller companies. Fig. 4 shows the number of products in each of the different material categories.

Material properties and stability

The encapsulation materials can be divided into 1) non-cross-linking thermoplastic or thermoplastic elastomeric (TPE) materials, and 2) elastomeric materials; the latter form covalent bonds between the polymer chains. The most widely used encapsulation material, EVA, and two-component silicone and urethane (TPU) materials have to be subjected to a cross-linking process which can be induced by high temperature levels or UV irradiation or via a chemical reaction (two-component systems). The thermoplastic or TPE materials polyvinyl butyral, TPSE and ionomers, as well as modified polyolefines (PO), melt during the module manufacturing process without forming chemical bonds between the polymer chains (cross-linking).

EVA

The copolymer EVA is the most popular PV module encapsulant worldwide and has been used in the PV industry for more than twenty years. Over this long period of time, the durability of PV EVA, which is highly influenced by the additive formulation used, has been improved tremendously, especially with regard to the degradation problem of discoloration (yellowing) [6,7]. This yellowing phenomenon, which has been described extensively for the first PV plants, is most likely caused by the photothermal degradation of additives such as UV light stabilizers, UV absorbers and antioxidants [8,9]. Besides additive decomposition, the main degradation reactions of EVA are

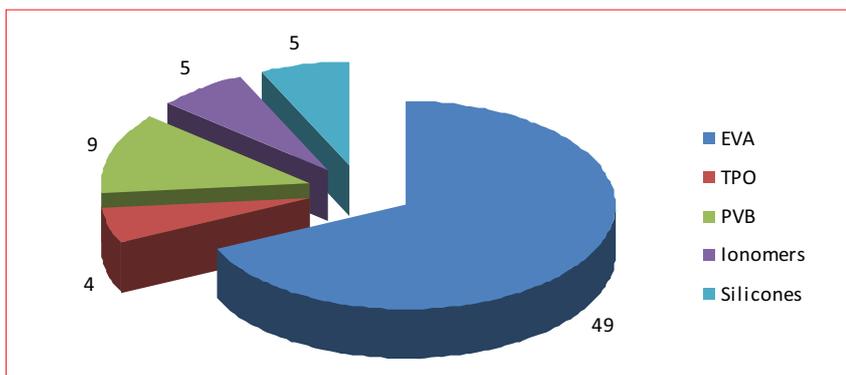


Figure 4. Number of products in the different materials [5].

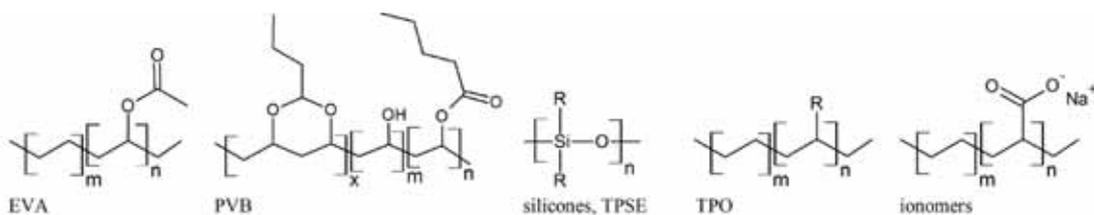


Figure 5. Chemical structures of the most common PV module encapsulation materials.

Polymer	Polymer type	Parameter			
		T_g [°C]	E [MPa]	Refractive index (n)	Volume resistivity @ 23°C [Ωcm]
EVA	Elastomer	-40 to -34	≤ 68	1.48 to 1.49	10^{14}
Silicone		-50	≤ 10	1.38 to 1.58	10^{14} to 10^{15}
PVB	Thermoplastic	+12 to +20	≤ 11	1.48	10^{10} to 10^{12}
Ionomer		+40 to +50	≤ 300	1.49	10^{16}
TPSE	Thermoplastic elastomer	-100	≤ 280	1.42	10^{16}
TPO		-60 to -40	≤ 32	1.48	10^{14} to 10^{18}

Table 2. Overview of typical physical properties of different encapsulation materials.

deacetylation, hydrolysis and photothermal decomposition [6], which may lead to the evolution of corrosive degradation by-products, especially acetic acid. These by-products in turn may accelerate metallization corrosion.

Initially a thermoplastic material, EVA can be transformed into an elastomer by the utilization of cross-linking additives activated by high temperatures or UV irradiation. This cross-linking reaction is challenging not only in terms of module processing time, but also in respect of material storage (volatilization of cross-linking agents) and quality management (determination of the degree of cross-linking by Soxhlet extraction).

Polyvinyl butyral (PVB)

PVB is a thermoplastic polymer which has been used since the early 80s as a PV module encapsulant. It represents the second most processed encapsulation material, with similar material costs to EVA.

In contrast to other encapsulation materials, PVB is very sensitive to hydrolysis because of a higher water uptake; it therefore has to be combined with a low WVTR backsheets [2]. Plasticizers are added to PVBs to improve their mechanical processability and to modify their phase-transition temperatures [10]. Advantages over EVA are better UV stability and better adhesion to glass. The UV transparency is almost as good as that of EVA. The lamination processing time can be reduced by about 50% compared with EVA [11].

The processing of PVB initially required the application of an autoclave because of the high pressure and temperature needed, but new PVB formulations allow standard lamination processes to be used. The main

applications of PVB in the photovoltaic industry are building-integrated photovoltaics (BIPV) and thin-film technology with a glass-glass configuration.

Silicones

Silicones are mixed inorganic-organic polymers which include the elements silicon, carbon, hydrogen and oxygen as the main constituents. Although very promising as a PV encapsulation material, silicone is only rarely used owing to the high price and the need for special processing machines (and techniques). Silicones are most often used in special application fields demanding very high quality, for example extraterrestrial applications.

Because of their chemical properties, silicones have excellent resistance to oxygen, ozone and UV light. Other advantages of silicone are a wide temperature stability range (-100°C to 250°C) and excellent transparency in the UV-visible wavelength range. The low Young's modulus and glass transition temperature values (see Table 2) also mean that silicone is highly resistant to mechanical stress. The refractive index of silicones can be modified between 1.38 and 1.58 by the variation of chemical groups at the silicon atom. Because of the low moisture uptake (< 0.05%), silicone encapsulants are very insensitive to moisture, making them extremely interesting for use in optical and optoelectronic applications [12].

Thermoplastic silicone elastomer (TPSE)

TPSE represents a relatively new encapsulant class combining superior silicone performance and thermoplastic processability, but, because of the

relatively high price, is currently only used in special applications. The fast curing and additive-free physical cross-linking of TPSE encapsulants, combined with their excellent mechanical properties without the use of plasticizers, make them promising candidates for continuous lamination processing [13].

Since the cross-linking is performed via hydrogen bonds, TPSE-based PV modules may be recycled more easily than EVA-based modules. TPSE shows good UV resistance and visible light transmission and can be used over a wide temperature range (-80°C to 100°C). Furthermore, TPSE encapsulants have good electrical insulation properties (see Table 2) and are highly water repellent.

Thermoplastic polyolefin elastomer (TPO)

TPO is a polymer blend consisting of thermoplastic polyolefins (e.g. polyethylene and polypropylene) and olefinic elastomers (e.g. ethylene-propylene rubber and ethylene-octene rubber). Often used in the automobile and building industry in the past [14], TPO is an interesting candidate for PV encapsulation because of its low price. The material has a high electrical resistivity, does not degrade under acetic acid formation and is resistant to hydrolysis, although the water permeation of TPO is significantly higher than that of EVA.

Ionomers

Ionomers, more specifically ethylene ionomers, belong to the category of thermoplastic encapsulant materials and are produced from ethylene and unsaturated carboxylic acid co-monomers (e.g. ethylene-methacrylic acid copolymer EMAA). In the solar industry, ionomers

Polymer	Condition		
	Equipment	$T_{\text{processing}}$ [°C]	$t_{\text{processing}}$ [min]
EVA	Vacuum laminator	140–160	8–20
Silicone [27]	Casting process, dispenser	80	30
PVB [28]	Vacuum laminator, roll lamination and autoclave	140–160	8–20
Ionomer [29]	Vacuum laminator	140–160	10
TPSE [30]	Vacuum laminator, roll lamination and autoclave	160–170	7–10
TPO [31]	Vacuum laminator	140–160	10–14

Table 3. Overview of processing conditions for selected materials.

represent a different class of encapsulation materials, with high production costs. The good UV stability of ionomers has already been demonstrated in architectural applications in the last 15 years [15]. Ionomers are also used as encapsulants in wire and cable applications [15].

A physical cross-linking between the ionic components of the polymer is automatically induced during the synthesis and does not require any extra steps for a (chemical) cross-linking as in the case of EVA processing. Furthermore, no formation of acetic acid is observed during weathering [16] and a much longer shelf life is achieved (up to three years) [17]. During the last two years the focus of ionomer research has been on thin-film solar technology, because of the highly improved moisture sensitivity and lower WVTR compared with EVA [18]. The first frameless CIGS modules with incorporated ionomers have recently been realized [19]. The enhanced adhesion of ionomers to backsheets also allows their prospective use in c-Si technology [20]. Ionomers demonstrate high volume resistance and a high degree of mechanical stability (see Table 2).

The processing temperature and time for selected encapsulants are shown in Table 3. With certain materials, the parameters vary over a broad range and can be modified by the addition of special additives. When two-component silicones are cured, the processing time and temperature can differ as a result of using different catalysts, leading to curing times of 5–50 minutes and processing temperatures between room temperature and 120°C.

Interactions with other PV module components

The corrosion of inorganic PV module components (i.e. the metallization) is, besides polymer degradation, one of the most important aspects of PV module degradation. Significant decreases in PV module performance are caused by the corrosion of the cell (e.g. of the anti-reflective coating) or the corrosion of the grid, the solder bonds and the rear metallization [21,22]. Since EVA degradation may be accompanied by the

formation of corrosive by-products, such as acetic acid, the metallization corrosion can thereby be accelerated [23,24]. In addition, water ingress facilitates the delamination of EVA from the cell [25] and therefore grid corrosion [26].

New cell and module designs and their impact on PV module requirements

High-efficiency crystalline solar cells ($\mu > 19.0\%$) achieve their high power output by, among other things, increasing the spectral response in the blue/UV light spectrum. It therefore becomes more important to shift the UV cut-off of the encapsulants to below 350nm, which can lead to a relative power increase of more than 1%.

Another requirement relates to the reduction of the module weight by using thinner front glass or by even replacing it with rigid polymeric layers. In the case of the latter, encapsulants have to be modified in order to obtain a good adhesion to these alternative materials, for example polymethyl methacrylate (PMMA). If the rigid layer is transferred to the back side of the module, a wide range of material groups can be used, starting with glass-fibre materials or even structured aluminium alloys. The front side can be covered with a polymer film that has high light transmittance, such as ethylene tetrafluoroethylene (ETFE). Whenever the situation of embedding brittle solar cells using polymeric materials arises, the mismatch of thermal expansions has to be damped by a more compliant encapsulant.

A new cell technology which is presented on R&D platforms involves the use of copper-metallized crystalline solar cells. Common encapsulants therefore have to be verified in respect of their chemical reactivity with copper.

Conclusion and perspectives

Because of the strong influence of the encapsulation material on efficiency and reliability, the selection of an appropriate material is an important aspect in module design. With regard to durability and safety, encapsulants have to fulfil very demanding requirements over long periods of time

in various climatic and operational conditions. For the polymeric materials used, the microclimatic conditions are crucial in those degradation processes which are strongly influenced by other materials in the modules, especially the front and rear materials. Thus the selection of an adapted combination of materials for encapsulation is absolutely vital.

In addition to the described technical requirements, there is an increasing economic pressure on the module market and therefore on production costs. On the one hand, improved transmission properties in the UV range are required, and on the other hand, materials allowing faster production processes need to be taken into account in order to reduce manufacturing costs. In view of the long warranty periods given by module manufacturers, which restrict the introduction of new materials or production processes, only a few types of material are being considered. Although EVA still dominates the market, mainly because of its good cost–performance ratio and the decades of experience gained from its use, the number of other encapsulation materials and types has nevertheless increased significantly.

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