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FUTURE PV MATERIALS: NON-POLAR POLYMERS, SILANE & DURABLE DESIGN

***Rahul Kumar Yadav**

India.

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***Corresponding Author: Rahul Kumar Yadav**
India.

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ABSTRACT

Solar PV module reliability and performance, particularly for TOPCon solar cell technology, are strongly influenced by encapsulant material selection and formulation. Key factors include moisture ingress (WVTR as per ASTM F 1249), electrical insulation as per IEC, and interfacial adhesion, which collectively impact long-term durability under stress conditions such as damp heat (DHT), thermal cycling (TC 200 -TC 600), potential induced degradation (PID 92 Hour -288 hours), and field operation.

This study examines the role of polymer polarity, silane coupling chemistry, and crosslinking in enhancing encapsulant performance, with implications for reliability and ESG outcomes. Non-polar polymers such as polyolefin elastomers (POE) exhibit superior moisture barrier properties (as per ASTM F1249) and enhanced resistance to PID, while polar polymers offer stronger intrinsic adhesion to glass and cell interfaces.

The role of silane coupling agents in forming covalent bonds between inorganic substrates and organic surface is analysed to explain improved interfacial durability. Moisture diffusion is modelled by using Fick's law of diffusion.

I. INTRODUCTION

The rapid global transition toward renewable energy has significantly accelerated the deployment of photovoltaic (PV) systems, increasing the emphasis on long-term module reliability and sustainability. Among the various components of PV modules, encapsulant materials play a critical role in protecting solar cells from environmental stresses such as moisture ingress, ultraviolet (UV) radiation, thermal cycling (TC), damp heat (DH), high-field (HF) stress, and electrical degradation. Therefore, the selection and optimization of encapsulant materials, including formulation design, additive selection, and raw material

purity, are essential not only for technical reliability but also for improving the financial bankability and environmental, social, and governance (ESG) performance of solar energy systems.

Encapsulants are typically polymer-based, and their chemical characteristics—such as polarity, yellowness index (YI), crosslinking density (gel content), and interfacial adhesion between organic and inorganic materials—strongly influence module durability and long-term reliability. Traditionally, ethylene-vinyl acetate (EVA), a polar polymer, has been widely used due to its excellent inherent adhesion properties. However, EVA exhibits relatively high water vapor transmission rates (WVTR ~30–35 g/m²/day), leading to increased moisture ingress, ion migration, and a higher susceptibility to potential induced degradation (PID).

To address these limitations, alternative materials such as polyolefin elastomers (POE) have been developed. POE is non-polar in nature due to its hydrocarbon (C–H) backbone, making it inherently hydrophobic with significantly lower WVTR. As a result, non-polar polymers demonstrate reduced moisture permeability, lower ion mobility, and superior electrical insulation, making them more suitable for high-voltage and high-reliability PV module applications. However, their low surface energy often leads to poor adhesion, necessitating the use of coupling agents.

Silane coupling agents are commonly employed to enhance interfacial adhesion between inorganic substrates (such as glass) and organic polymer matrices. These agents form covalent bonds with surface hydroxyl groups on glass while simultaneously interacting with the polymer network through reactive functional groups. This molecular bridging improves interfacial stability and significantly reduces the risk of delamination under DH and TC conditions. The effectiveness of vinyl-based silane chemistry is therefore critical in optimizing encapsulant reliability.

In addition to adhesion, encapsulant barrier performance is influenced by moisture diffusion behavior, which can be described using Fick's laws of diffusion, relating mass transport to concentration gradients and time-dependent dynamics. Crosslinking during the lamination process is another critical factor, leading to the formation of a three-dimensional polymer network (gel structure). This network restricts polymer chain mobility, reduces free volume, and enhances mechanical, thermal, and chemical stability.

Higher crosslinking density is directly associated with improved barrier properties, lower WVTR, and enhanced resistance to degradation mechanisms. Experimental observations

confirm that encapsulants with higher gel content exhibit significantly reduced moisture permeability, as measured by ASTM F1249.

These improvements in encapsulant performance have a direct impact on PV module reliability and service lifetime, which in turn influence project bankability. Lower degradation rates result in higher energy yield, reduced maintenance costs, and increased investor confidence. From an ESG perspective, improved material durability contributes to extended module lifetimes, reduced material waste, and lower lifecycle environmental impact, supporting global sustainability goals.

This paper presents a comprehensive analysis of the interrelationship between polymer polarity, silane adhesion mechanisms, crosslinking behavior, and diffusion phenomena—including WVTR, ion migration, and interfacial bonding—in determining encapsulant performance. By integrating theoretical understanding with experimental insights on WVTR and gel content, this study establishes a framework for designing advanced encapsulant systems for next-generation, high-efficiency, and long-lifetime photovoltaic modules.

II. Polar vs Non-Polar Polymers

Polymer polarity plays a fundamental role in determining the physical, chemical, and electrical performance of PV encapsulant materials used in photovoltaic (PV) modules. The distinction between polar and non-polar polymers arises from differences in molecular structure, which directly impact on moisture, dielectric behaviour, adhesion properties, and long-term reliability.

A. Fundamental Characteristics

Polar polymers materials exhibit functional groups like as –OHGroup , carbonyl (–C=O), or ester linkages that create dipole moments along with the polymer molecular chain. These dipoles movement create stronger intermolecular interactions and promote adhesion with polar surfaces such as glass or any inorganic surface. In contrast, non-polar polymers—such as and polyolefin elastomers (POE)—primarily consist of hydrocarbon chains with negligible dipole moments, resulting in hydrophobic behaviour and weak intermolecular forces.

Due to dipole; polar polymers exhibit relatively higher surface energy and better wettability, can create strong interfacial bonding. However, due to polarity they can create hydrophilic structure for moisture leads to increased water absorption and higher water vapor transmission rates (WVTR). Other hand, non-polar polymers exhibit lower surface energy

and very weaker intrinsic adhesion but provide superior resistance to moisture ingress due to their inherent hydrophobic nature.

B. Impact on Moisture Barrier Performance

Moisture ingress is big issue for critical degradation pathway in PV solar modules, affecting PV module electrical insulation and cell integrity, Bonding etc . The permeation of water vapor through polymeric materials is created by porosity in polymer by solubility and diffusion mechanisms.

Polar polymers can exhibit higher water solubility due to favourable interactions between water molecules and polar functional groups. This can increases the overall permeability:

$P=D\times SP$

where P is permeability, D is the diffusion coefficient, and S is solubility.

Non-polar polymers, on the other hand, exhibit significantly lower water solubility due to the absence of polar interaction sites. This leads to reduced permeability and improved barrier performance. In practical encapsulant systems, this behavior is reflected in lower WVTR values, such as the observed reduction from approximately 19 g/m²/day in more polar systems to around 13 g/m²/day in non-polar or modified formulations.

C. Electrical and PID Performance

Electrical insulation is another critical parameter influenced by polymer polarity. Polar polymers with higher dielectric constants and greater ionic mobility are more susceptible to leakage currents, especially under high-voltage conditions. This can accelerate degradation mechanisms such as potential induced degradation (PID), which results in power loss and reduced module performance.

Non-polar polymers offer superior electrical insulation due to their low dielectric constant and minimal ionic conductivity. Their resistance to moisture uptake further minimizes ion migration, making them highly suitable for high-voltage PV systems and PID-resistant module designs.

D. Adhesion and Interfacial Stability

While non-polar polymers provide excellent barrier and electrical properties, in there non polar polymer there is no dipole movement , so surface energy also low & leads to poor adhesion with glass and cell interfaces , poor peel bond properties. This limitation necessitates the use of high adhesion promoters such as silane coupling agents or blending with polar components ; to increase the polarity.

Polar polymers, such as ethylene-vinyl acetate (EVA), exhibit strong inherent properties adhesion due to their ability to form hydrogen bonds or dipole interactions with substrate surfaces. This makes them effective in maintaining mechanical integrity and preventing delamination during thermal cycling (RH 85 % , Temp 85°C) and damp heat exposure , Humidity freeze test , PCT .

However, high polarity can compromise in long-term stability due to hydrolysis& high WVTR (35 gram /m2/day) and degradation reactions. Therefore, an optimal balance between polarity and hydrophobicity is required to achieve both strong adhesion and low moisture permeability; due to high wvtr; after a long exposure it will become yellowish.

E. Material Design Strategy

Modern PV encapsulant systems increasingly rely on hybrid approaches that combine the advantages of both polar and non-polar polymers material . For example, blends of EVA (polar) and POE (non-polar), or functionalized POE materials, are widely used to achieve a balance between adhesion and barrier performance for solar PV application.

In such systems, the role of polarity is carefully tuned to:

- Maintain high adhesion to glass and cell surfaces
- Minimize the WVTR the water uptake – TOPCon solar cells are very sensitive to moisture.
- Improve electrical insulation& VR and PID resistance
- Enhance long-term thermal -DHT , TC , HF and environmental stability

This integrated material design approach enables the development of high-performance solar encapsulants that meet the evolving demands of next-generation PV solar modules.

F. Implications for Reliability, Bankability, and ESG

The selection of polymer resin polarity has direct implications for PV Solar module reliability and lifetime. Lower moisture ingress (Low WVTR) and improved electrical insulation, High VR can reduce degradation rates, leading to higher energy yield and reduced failure rates. These improvements enhance the financial bankability of solar projects by increasing return on investment and reducing operational risks.

From an ESG perspective, the use of durable, low-permeability encapsulants contributes to longer module lifespans, reduced material consumption, and lower environmental impact over the system lifecycle. Thus, optimizing polymer polarity is not only a materials

engineering challenge but also a key factor in achieving sustainable and economically viable solar energy solutions.

Comparison of Polar and Non-Polar Polymers for Photovoltaic Encapsulants.

Property / Test	Polar Polymer (EVA)	Non-Polar Polymer (POE)	Standard / Method
Polymer Nature	Polar (Vinyl acetate groups)	Non-polar (C–H backbone)	—
WVTR (g/m²/day)	35-40	4 -6	ASTM F1249
Moisture Resistance	Moderate	Excellent	ASTM F1249
PID Resistance	Moderate–Poor	Excellent	IEC TS 62804
Volume Resistivity	10^{14}–10^{15} Ω·cm	>10^{16} Ω·cm	ASTM D257
Dielectric Strength	~20–25 kV/mm	~25–35 kV/mm	ASTM D149
Ion Migration	Higher (due to polarity)	Very low	IEC 62804
Adhesion to Glass	Excellent (inherent polarity)	Moderate (needs silane)	ASTM D903
Peel Strength (N/mm)	~60–80	~40–70 (with silane >80)	ASTM D903
Crosslinking (Gel Content %)	75–90%	70–80%	ASTM D2765
UV Stability / YI	yellowing risk	Good UV stability	ASTM E313
Acetic Acid Formation	Yes	No	—
Damp Heat (85°C/85%RH)	Degradation possible	Highly stable	IEC 61215
Thermal Cycling	Moderate	Superior	IEC 61215
Service Life	20–25 years	25–30+ years	Field/IEC

III. Role of Silane in Adhesion

Adhesion between PV encapsulant materials and module components—such as glass and TOPCon cells—is a critical factor governing long-term module reliability. In polymer resin–based encapsulants, particularly non-polar systems like polyolefin elastomers (POE), intrinsic adhesion (peel strength) to inorganic substrates is inherently weak due to low surface energy and the absence of reactive functional groups in the polymer structure.

To overcome this limitation, silane coupling agents are widely used to enhance interfacial bonding. These agents act as molecular bridges, forming covalent bonds with hydroxyl groups on inorganic surfaces (e.g., glass) while interacting with the organic polymer matrix through functional groups. This dual reactivity significantly improves adhesion, interfacial stability, and long-term durability under environmental stress conditions.

A. Chemistry of Silane Coupling Agents

The all silane based coupling agents are organofunctional chemical compounds generally represented by the formula:

R–Si(OR')3

where **R** denotes an organofunctional group **OR'** represents hydrolysable alkoxy groups

B. Mechanism of Silane Bonding

The adhesion mechanism of silane coupling agent involves a sequence reactions:

1) Hydrolysis

In the presence of moisture or water , alkoxy groups make hydrolysis &form silanol groups:

Si–OR'+H2O→Si–OH+R′OH

2) Condensation reaction with PV solar Glass layer

PV Glass surfaces mostly containing hydroxyl (–OH) groups. Silanol groups react with these surface hydroxyls group &form stable covalent bonds

Si–OH+HO–Glass→Si–O–Si (Glass)+H2O

Result: Strong covalent bond in between to the glass.

3) Interaction with Polymer resin

The organofunctional group react with the polymer through:

- **Grafting mechanism**
- **Co-crosslinking reaction with the polymer**
- **Secondary interactions through dipole movement or hydrogen bond**

Result: Integration with the polymer structure.

C. Formation of the Interfacial Network with the polymer

The combined effect of these reactions make a **three-dimensional network**:

PV Glass Surface ⇄ Si–O–Si Network ⇄ Polymer resin Matrix

This polymer -silane network acts as a **molecular bridge in polymer**, significantly improving stress transfer across the polymer interface and enhancing resistance to mechanical, chemical, UV and environmental degradation.

D. Influence on the Adhesion

The incorporation of the silane coupling agents make several improvements:

- **Increase peel Bond** between PV encapsulant and glass , Backsheet

- **Avoid delamination** under the thermal cycling and damp heat test conditions at high humidity (RH 85%)& high temp
- **Improved the interfacial durability**between layer to layer under UV exposure in UVA & UVB
- **Reduced formation of moisture pathways at interfaces**

Without silane coupling agent , adhesion is mostly govern by weak van der Waals force interactions, which are not sufficient for long-term reliability of PV module in outdoor environment conditions.

E. Coupling agents Role in Non-Polar Encapsulant Systems

Non-polar polymers such as POE offer excellent moisture barrier properties (low WVTR/MVTR), along with superior electrical insulation and high volume resistivity. However, a key limitation is their inherently poor natural adhesion due to low surface energy and absence of polar functional groups.

Silane coupling agents therefore become essential in such systems, compensating for the lack of polymer polarity by enhancing interfacial bonding.

In advanced POE encapsulant formulations, silane chemistry enables:

- Strong bonding to glass surfaces despite the hydrophobic nature of POE
- Improved compatibility between the crosslinked polymer network and inorganic substrates
- Stable, long-term adhesion under harsh environmental conditions, including high humidity and temperature

F. Silane coupling agent chemistry is closely integrated with the polymer crosslinking process. Certain silanes, particularly vinyl-functional silanes, can actively participate in peroxide curing systems and become chemically incorporated into the crosslinked polymer network. This imparts a dual functionality to the silane system:

- Enhanced bulk strength and peel adhesion through participation in crosslinking
- Improved interfacial bonding via chemical linkage between the polymer matrix and inorganic surfaces

This synergistic effect strengthens both the bulk material and the interface, leading to improved mechanical integrity and enhanced barrier performance. As a result, moisture

ingress is reduced, contributing to lower water vapor transmission and significantly improved module reliability and long-term service life.

G. Implications for Reliabilityand ESG

The role of silane coupling agent in adhesion directly impacts multiple performance dimensions:

- **Reliability:** Prevents the delamination and the degradation, maintaining structural integrity over time in PV module by bridging polymer & inorganic surface.
- **Bankability:** Reduces the failure risk and performance degradation, delamination , bond failure ,improving financial confidence and return on investment on solar.
- **ESG Performance:** Enhances module lifetime, reducing material waste and reduce the carbon footprints environmental impact

So we can say silane coupling agents are a critical component in the modern solar encapsulant formulations, enabling the effective integration of non-polar polymers resin into high-performance Solar PV modules.

IV. Crosslinking and Barrier Properties

Crosslinking reduces free volume, limits chain mobility, and enhances moisture barrier performance, improving WVTR and durability.

V. Reliability and Bankability

The long-term success of Solar photovoltaic (PV) systems is fundamentally dependent on module reliability and financial bankability. PV Encapsulant materials play a critical role in determining both parameters, as they directly influence the degradation mechanisms of Pv solar Module, energy yield stability, and the service lifetime. The integration of optimized polymer polarity, silane adhesion, and crosslinking density, gel content, strategies significantly enhances encapsulant performance, thereby improving both technical reliability and economic viability.

Encapsulant materials act as the primary barrier layer in protecting solar cells from these stress factors. Poor PV Encapsulants material performance can lead to several degradation modes, including:

- Moisture ingress, due to high MVTR/ WVTR – high ingress the moisture direcly impact on PID, corrosion, life of solar module.

- Potential Induced Degradation (PID), due to high movement of free Na ion can reduce power output
- Discoloration and UV degradation, reduce the light transmission& increase YI
- Can increase chances of Interfacial delamination, compromising mechanical stability layer to layer.

The use of non-polar Polymer resin , highly crosslinked PV encapsulants with effective silane coupling significantly reduces the above risks. Lower the WVTR / MVTR and minimize the moisture diffusion, while strong interfacial bonding prevents delamination cell & glass. Additionally, improved electrical insulation& VR , can reduces leakage currents, thereby mitigating PID.

B. Impact of Polymer material Design on Reliability

The reliability of encapsulants is critical aspect of the by a combination of material properties:

1) MVTR Performance

Lower WVTR values directly correlate with reduced the moisture ingress inside the cell or module . As demonstrated in the experimentally, increasing crosslink density (gel content) leads to a reduction in WVTR , so gel content / crosslinking of the polymer play very important role.

Encapsulant Type	**Gel Content (%)**	**WVTR (g/m²/day)** ***(ASTM F1249)***	**Observation**
EVA (Polar)	70–75	35	High moisture ingress
EVA (Polar)	80–90	25–30	Slight improvement with crosslinking
POE (Non-Polar)	60–70	8	Moderate barrier
POE (Non-Polar)	70–80	7	Good barrier performance
POE (Non-Polar)	80–85	4	Excellent moisture resistance

2) Electrical Insulation

Electrical insulation is a critical requirement for PV encapsulants, particularly in high-voltage modules such as TOPCon and HJT. Proper insulation prevents leakage currents, minimizes power losses, and reduces the risk of potential induced degradation (PID).

Non-polar polymers like POE exhibit superior electrical insulation properties compared to polar materials like EVA. This is due to their low polarity, low ionic content, and reduced moisture uptake, resulting in:

Property	**EVA (Polar)**	**POE (Non-Polar)**	**Test Standard**
Volume Resistivity (Ω·cm)	10^{14}	$>10^{16}$	ASTM D257
Surface Resistivity (Ω)	10^{13}	$>10^{15}$	ASTM D257
Dielectric Strength (kV/mm)	27	25 – 35	ASTM D149
Leakage Current	Higher (moisture-driven)	Very low	IEC 62804
PID Resistance	Moderate to Poor	Excellent	IEC TS 62804
Ion Migration	Higher	Very low	IEC 62804
Damp Heat Stability (85°C/85%RH)	Moderate	Superior	IEC 61215

VI. ESG Considerations

Environmental, Social, and Governance (ESG) considerations are increasingly central to the evaluation and deployment of solar photovoltaic (PV) systems. Beyond technical performance and financial returns, modern energy solutions are assessed based on sustainability, societal impact, and governance practices.

Encapsulant materials—such as POE and EVA—though often overlooked, play a crucial role in ESG outcomes by influencing module lifetime, reliability, and overall environmental impact. Improved durability and longer service life directly contribute to reduced material waste, enhanced green energy generation, and a lower lifecycle carbon footprint.

VII. CONCLUSION

This study highlights that PV encapsulant design—through polymer polarity, silane coupling, and crosslinking (gel content)—is critical to module reliability, bankability, and ESG performance.

Polar polymers like EVA offer strong adhesion but suffer from higher WVTR and moisture-driven degradation. In contrast, non-polar polymers like POE provide superior moisture

barrier, electrical insulation, and long-term stability, though they require silane chemistry to enhance adhesion.

mobility of ion VR is High , DES high & other electrical insulation, making them more suitable for high-reliability and high-voltage solar Encapsulant applications.

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