ASSESSING ANTI-REFLECTIVE AND ANTI-SOILING COATINGS FOR PHOTOVOLTAIC MODULES

Program on Technology Innovation

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Report Abstract

The global deployment of PV modules has significantly increased over the last decade, a trend that is expected to continue for the foreseeable future. Since 2009, worldwide cumulative, grid-connected installations have grown by several orders of magnitude from 8 GW to over 250 GW today; they are anticipated to surpass 700 GW by 2021.[1] *There are numerous factors driving this growth, among them is the rapid decrease in the $/W price point of PV modules. From 2009 to 2015, the average sales price for PV module has fallen over three-fold to approximately $0.60/W.*

Module cost reductions have historically come from supply chain economies of scale, oversupply from rapid manufacturing build out, as well as improvements in manufacturing technology and understanding (e.g., material inputs, equipment, processes). Gains from economies of scale are beginning to asymptote on a linear scale, placing greater emphasis on improvements in module power to continue $/W reductions. R&D focus is broadening beyond the cell, which has garnered the majority of attention for power increases, and now includes module-level innovations, such as anti-reflective and anti-soiling coatings.

From 2009 to 2015, anti-reflection coatings (ARC) on PV modules have been rapidly adopted, yet they have received little mention or fanfare. During that time, their market penetration has risen to over 85%. ARC has enabled a 0.3% (absolute) efficiency gain—for example, boosting a 15.0% efficient module to 15.3%—at relatively minor cost increase, thus benefiting module manufacturers who sell on a $/W basis.[2] *Additionally, ARC has the ability to be tailored to provide anti-soiling properties, which brings potential to decrease the operations and maintenance costs of PV plants.*

Ongoing research is endeavoring to better quantify the benefits of ARC and anti-soiling coatings (ASC) and improve their performance. Climate, regional, and location-specific environmental factors all impact how ARC and ASC perform in the field; in rare instances, they are detrimental to power output. This variability makes it difficult to generalize and, subsequently, monetize energy gain, which is why ARC has been rapidly adopted for its upfront $/W gains versus the $/kWh gains offered by ASC. Of concern, the average field life of ARC is estimated to be 14 years, short of the 20+ years a module may be in service, which affects energy predictions. Research efforts are underway to extend the lifetime of coating products and increase their functionality.

This report highlights technical analysis completed to date of PV module coatings, detailing their purported benefits versus their field-tested capabilities. It also conveys the near-term market adoption and product landscape for coatings, as well as some of the longer-term technology R&D innovations in the space.

Introduction

Historically, decreases in PV module prices have been driven by economies of scale—primarily derived from the build-out of a large, geocentric PV supply chain in Asia; supply-demand boom-bust cycles; and gains achieved via the manufacturing learning curve. Technology innovation has also been a steady undercurrent of $/W reductions. To date, however, most R&D efforts have been focused at the cell level, such as those which seek to improve silicon wafer yield and quality (the starting point for a PV cell), as well as others that pursue changes in cell architecture and cell metallization. The combination of scale and cell innovation has progressed the industry to its current global average PV module sales price of approximately $0.60/W (see Figure 1).

The tens of gigawatts of PV modules being annually deployed worldwide share a common genesis. The overall structure of today's crystalline silicon PV modules is similar to those made 30 years ago. The module's non-cell bill of materials comprises a front sheet of glass, a couple layers of encapsulant, a backsheet, an aluminum

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This white paper was prepared by Michael Bolen of the Electric Power Research Institute.

[1] *Global Solar Demand Monitor Q3 2016*. GTM Research. Boston, MA: July 2016.

[2] *PV Efficiency Improvements: Crucibles, Diamond Wires and Better Doping*. Bloomberg New Energy Finance. Research Note. New York, NY: April 2016.

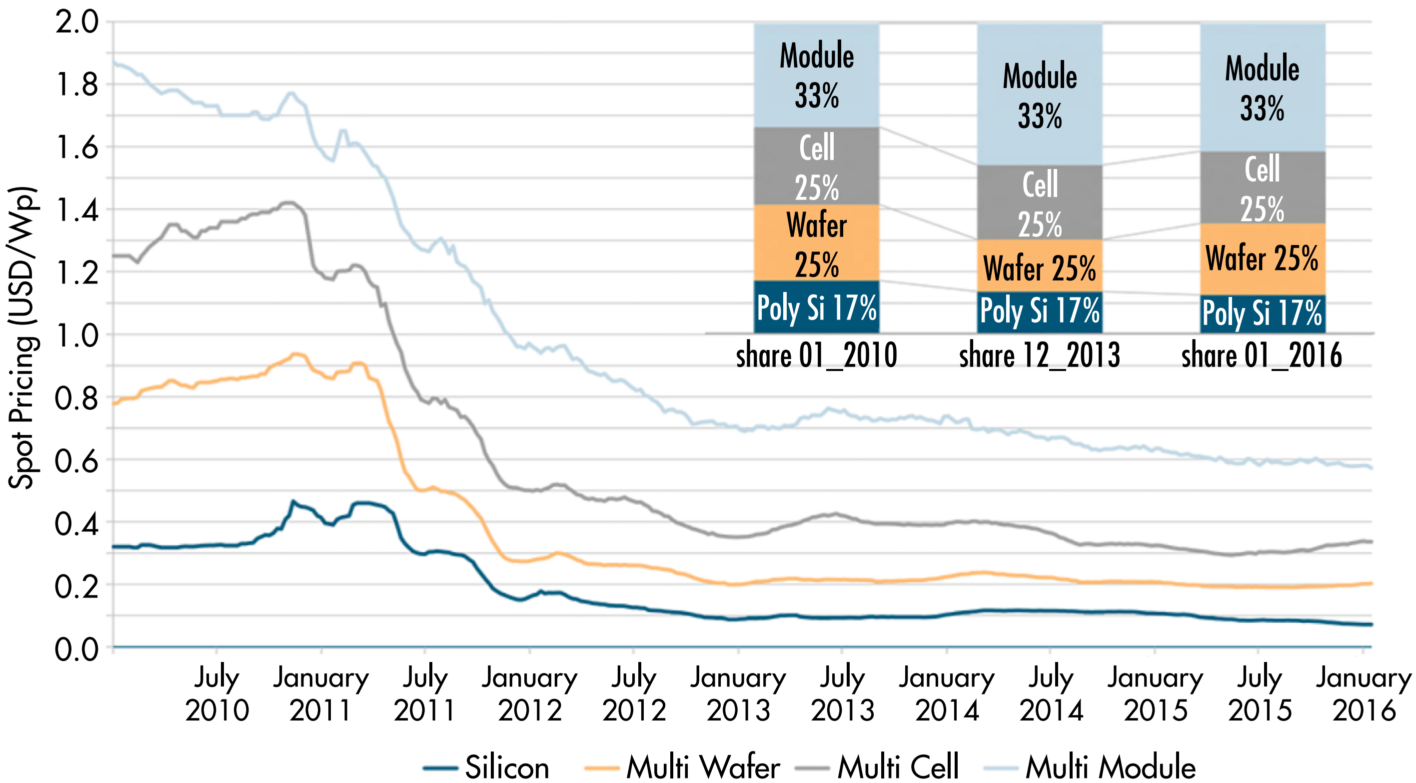

Figure 1. Global average $/W price buildup of multi-crystalline silicon PV modules
Source: International Technology Roadmap for Photovoltaic (ITRPV), 7th Edition

Note: Average $/W sales price is for silicon-based modules, which comprise roughly 90% of the current market. Average prices for thin film modules (e.g., cadmium telluride and CIGS) are roughly at or above those for polysilicon PV modules depending on manufacturer.

frame, and a junction box, as illustrated in Figure 2. But the cost of the module packaging today has become a greater share of the cost structure since its large cost drivers—aluminum for the frame and glass for the front sheet—are commodity materials. Photovoltaics do not command a large enough market share to drive meaningful reductions in glass or aluminum prices. Overall PV module costs are beginning to asymptote (on a linear plot) as predicted by learning curves.

The module has become a low-hanging fruit that is ripe for PV innovation. In this report, module coatings are discussed and their potential impact on $/W reductions are quantified. Further, the industry's greater sophistication and nuance in how it measures and views returns on investment is discussed. Upfront capital expense ($/W) still dominates the net present value equation of a PV plant, but it is the lifetime energy production ($/kWh) that enables the targeted return of an investment. As such, the industry is increasingly focusing on *total* lifetime costs—CAPEX plus OPEX—and energy production ($/kWh). A market pull appears to be beginning, seeking innovations that reduce a PV plant's overall cost of electricity.

Today's module coatings have two value drivers. First, anti-reflection coatings (ARC) increase a PV module's power output by increasing the amount of absorbed light. Second, anti-soiling coatings (ASC) *mitigate* the soiling of PV modules (i.e., do not completely eliminate soiling) which increases overall energy output and offers flexibility in PV plant operations and maintenance. Importantly, a single coating can have both anti-reflection and anti-soiling properties. What follows is a deeper dive into the technical aspects of both coating types, including descriptions of the technologies themselves and their hypothetical impact on plant capital and operating expenses, current market players, and innovations on the horizon.

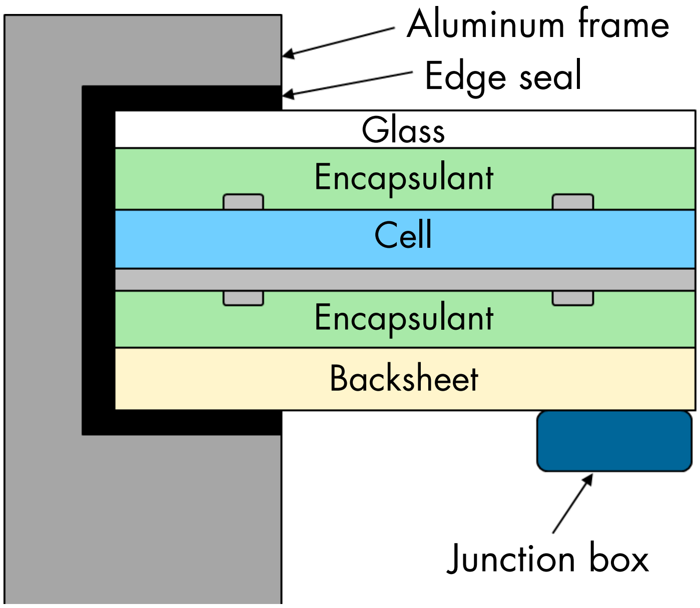

Figure 2. Illustrative cross-section of a crystalline silicon module
Source: EPRI. Solar Power Fact Book, Sixth Edition: Volume 1—Photovoltaics. Product ID: 3002006975

Technology Description

Anti-Reflective Coatings (ARC)

Light impinging on a surface is either reflected, absorbed, or transmitted. Anti-reflection coatings facilitate destructive interference of incoming light. By the law of conservation of energy, reduced reflection means more light is transmitted (since an absorbing ARC would defeat its purpose). Other important material parameters that impact an ARC's performance include its thickness and index of refraction. In theory, reflection can be reduced to 0% by using multiple materials and layers. In reality, practical implementation is bounded by cost-benefit trade-offs and the discrete menu of elements in the Periodic Table.

Under average sunny conditions approximately 1000 $W \cdot m^{-2}$ of insolation strikes the Earth's surface.[3] A bare, planar piece of glass will reflect 4% of that back into the atmosphere, as shown in Figure 3.[4] Assuming a standard PV module size of 1.6 m^2 and 15% conversion efficiency means ~10 W of potential power per module is turned away by the glass (4% reflection · 1000 $W \cdot m^{-2}$ · 1.6 m^2 · 15% PV efficiency). For perspective, a standard 60-cell (1.6 m^2) multi-crystalline (c-Si), 15% efficient PV module produces approximately 240 W under standard test conditions (STC). If coated with a theoretically ideal ARC, its nameplate power would be boosted to 250 W (i.e., 4% relative power gain).

PV module manufacturers often promote their nameplate power rating in comparison to those of competitors. ARC glass is a relatively easy drop-in replacement for uncoated glass within the manufacturing line and gives a slight marketing edge to help sell product. The boost represents a best case scenario since it is based on product coming from a clean manufacturing floor.

A couple of approaches can be implemented to reduce the reflection of light on PV modules: surface coatings and geometry (i.e., texturing the glass surface).

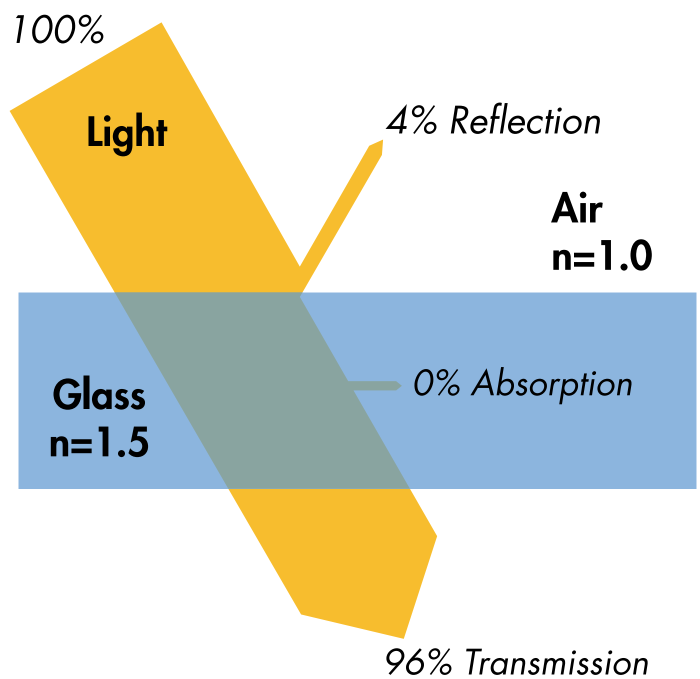

Figure 3. Uncoated, planar glass reflects 4% of incoming light, or ~10W of lost opportunity for a PV module
Source: EPRI
Note: The index of refraction, denoted "n", is listed for air and glass.

[3] *Solar Power Fact Book, Sixth Edition: Volume 1—Photovoltaics*. EPRI, Palo Alto: CA: December 2015. 3002006975.

[4] OPAL 2 by PV Lighthouse: https://www2.pvlighthouse.com.au/calculators/opal%202/opal%202.aspx.

Figure 4. Sunlight reflecting from water due to index of refraction difference between air and water
Source: EPRI

Surface Coatings

Abrupt changes in the index of refraction between surfaces is a source of light reflection.[5] For example, consider the sun setting over water, as shown in Figure 4. The index of refraction difference between air and water causes a partial reflection of the sunlight.[6] Gradually changing the index of refraction from one medium (e.g., air) to another (e.g., glass) can theoretically reduce reflection to 0%. In practice, this can be achieved by applying multiple layers of coating to a surface. For reasons described further below, however, multiple coatings do not make economic sense for flat-plate PV modules. As such, only the value of applying a single layer of anti-reflection coating is examined herein.

Power and Energy Impact

Compared to uncoated glass, ARC decreases reflection from 4% to 2%, on average, translating to a 6W nameplate power boost to a hypothetical 15% efficient module. Note: this calculated nameplate increase is only relevant for when the sun is shining normal to the PV modules.[7] Figure 5 shows the angle of incidence light response, which is important for collecting additional diffuse light and direct normal irradiance during morning or evening hours (i.e., quantifying how much additional light can be captured throughout the day and, in turn, converted to electricity). From normal incidence through 40 degrees, the bare glass (green line in Figure 5) has a relatively flat response at 4% reflectivity before starting an exponential rise at 45 degrees to 100% reflection at 90 degrees. The ARC (orange line in Figure 5) reduces reflectivity to approximately 2% from normal incidence to 50 degrees before a similar exponential

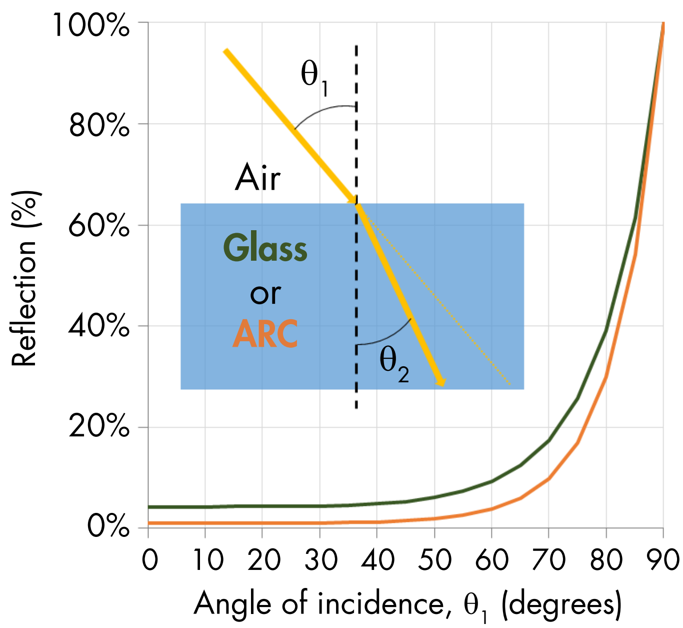

Figure 5. Glass with an ARC (green line) has lower reflectivity than uncoated glass (orange line) as the sun transits across the sky (i.e., angle of incidence); this increases energy output.
Source: EPRI via simulations performed with OPAL2

rise to 100% reflectance at 90 degrees. The exact benefit of reduced reflectance and increased collection angle is site specific, depending on the interplay of module tilt versus geographic latitude and early morning or late afternoon shadowing. Anecdotally, one ARC vendor claims a 4% energy increase during a sunny day, with 3% (absolute) of the gain due to midday performance enhancement and

5 Reflection is the light that bounces off a surface. Refraction happens when light is transmitted through a medium with a different index of refraction. It is responsible for making a pencil appear bent when partially submerged in a glass of water.

6 The amount of light that is reflected or refracted is governed by the Fresnel equations.

7 "Normal" refers to light shining perpendicularly to the module. In real world conditions, this happens during clear sky days approximately around noon-time for directly south oriented modules and at latitude fixed-tilt.

the remaining 1% (absolute) due to the angle of incidence effect.[8] Another claims its product increases energy by 5% under "actual conditions" with 2.4% (absolute) of the gain attributed to normal incidence and the remainder of the gain to off-normal.[9]

Manufacturing Considerations

Modules are often considered a commodity and compared and sold purely on a $/W basis. This paradigm sets an upper limit for how much the ARC layer can cost. Adding the ARC cannot increase the module's overall marginal $/W cost. For example, assuming a module costs $0.40/W, and an ARC power boosts of 6W, the coating cannot cost more than $2.40 ($0.40/W · 6 W) or else it will be detrimental to the module's overall cost structure. This relatively low dollar amount implies that the ARC manufacturing technology and process need to be well-known and the raw materials relatively cheap.

Over 90% of today's ARCs are applied by the "Sol-Gel" technique. Sol-Gel has been used to make many types of materials, including various carbides, nitrides, oxides, and fluorides. In 1959, one of the first industrial-scale uses of Sol-Gel provided abrasion resistance and ARC to rear view mirrors in automobiles. Today's PV module ARC chemistry, which consists of various silicon-oxide complexes, is not a significant deviation from those used in other industries. The process starts with a liquid solution (i.e., the "Sol" part of Sol-Gel) containing a solvent, such as water, and a solute that becomes the solid film. The solution can be applied through a variety of well-known manufacturing processes, such as spraying, dip coating, slot die, or rolling. After application, heat is usually applied to evaporate the solvent, forcing the solute molecules closer to one another, and eventually gelling them together (i.e., the "Gel" part of Sol-Gel).

The input solution and its processing all determine the film's final properties, such as thickness, density/porosity, and hardness. In most cases, the film is in the low hundreds of nanometers thick or approximately one-thousandth the diameter of a human hair. Stalactite formation in caves helps to visualize the Sol-Gel process: Water passes through limestone, becomes saturated with minerals (i.e., calcium carbonate), then drips off leaving a small amount of mineral behind that grows the stalactite.

ARCs are often deposited and cured during the glass tempering process. Glass formation is a large batch process that starts with a molten liquid containing all the ingredients of the final product (silica, desired impurities, etc.). The liquid is poured and floats on a tin bath to achieve desired thickness and flatness (a.k.a., the Pilkington or float glass process). The molten glass is cooled in a controlled manner to create the desired material properties. For instance, tempered glass is cooled relatively quickly to set up the competing compressive and tensile forces that enables the glass, when broken, to fracture into many small pieces. It is during this cooldown period that the ARC is often applied. The tempering process provides a solid surface for depositing the ARC solution, usually by roll-coating, and enough heat to evaporate the solvent and gel the solute.

Combining processing steps can aid the cost effectiveness of ARCs. First, the majority of glass used in PV modules is tempered (for safety and durability reasons), which supports the market adoption of ARCs. Second, coating an already manufactured PV module adds cost through extra manufacturing steps and increases the potential for yield loss. The elevated temperatures needed to cure Sol-Gel coatings, often a couple hundred degrees Celsius, are not compatible with materials in a PV module, such as the encapsulant, backsheet, and junction box. High energy, surface specific heating processes compatible with assembled modules do exist, such as flame, plasma, and/or laser treatments, but are not common in PV manufacturing. At sufficiently high surface temperatures, the glass can lose its temper, which creates an upper bound on the Sol-Gel curing temperature.

Long-term Field Performance

PV modules with ARC have successfully passed the barrage of infant mortality testing required by standards and certification bodies; however, their real-world lifetime, on average, is less than the 20+ year service life of most PV projects. For instance, all PV modules undergo testing under IEC 61215, which includes ultraviolet exposure, thermal cycling, humidity freeze, hail impact, and damp heat. Anecdotally, humidity freeze is the test most often failed by ARC. ARC glass is also tested against the European standard, EN1096-2, which applies to the broader coated glass industry, including building windows and car windshields. The testing procedure includes abrasion and acid/base testing to infer a product's ability to withstand common cleaning products and tools. However, these accelerated tests are not an accurate predictor of service lifetime. There are too many externalities that affect product performance in the field versus a controlled laboratory environment.

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8 DSM. *Anti-Reflective Coating on PV Cover Glass*. PV Taiwan Forum. Taiwan, PRC: October 2014.

9 AGC Solar. Spec sheet for Solar Plus Anti-Reflective Coating (SPARC) product, as of Aug. 22, 2016.

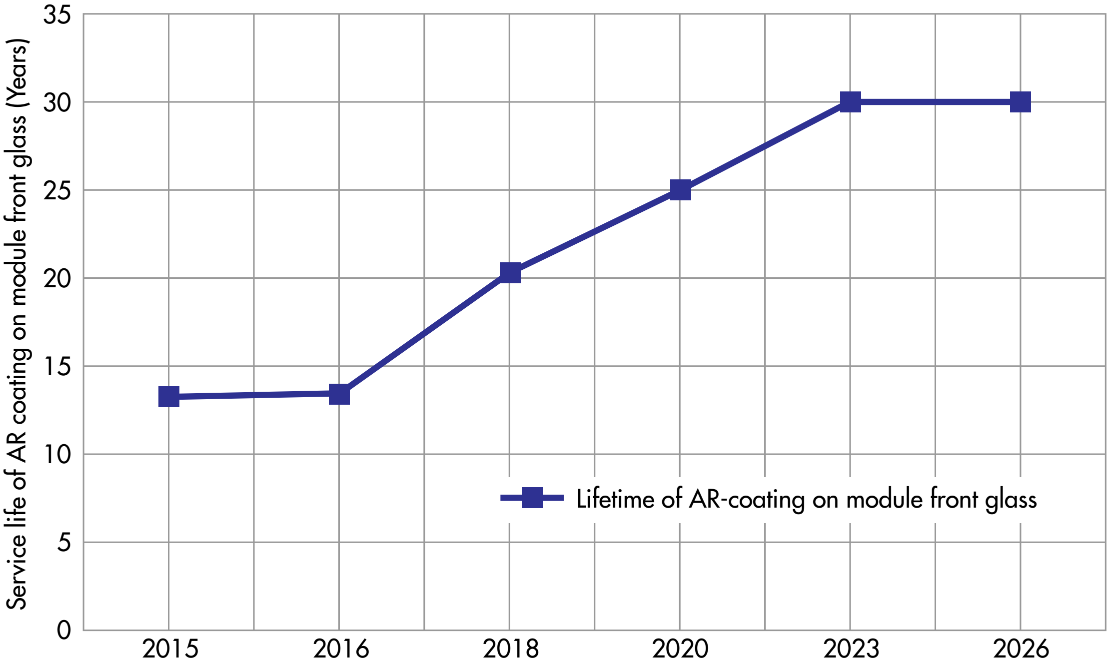

Figure 6. The reliability of ARC is expected to increase over time from product innovation
Source: International Technology Roadmap for Photovoltaic (ITRPV), 7th Edition

Based on interviews and market data, expected lifetime of current ARC coatings seems to be somewhere between 5 to 15 years. Again, there are a wide range of factors that affect performance, such as the ARC product itself, climate, location-specific factors (e.g., size and type of dust, wind speed, plant orientation with respect to the prevailing wind), as well as washing frequency and cleaning approach (i.e., dry vs. wet). Figure 6 shows data from a PV industry technology roadmap committee report that estimates the lifetime of ARC now versus in the future. Note: The report is only intended to raise awareness of the lifetime issue; no technical details are given on product innovations that would lead to extended lifetime of future ARC products.

It is too early to know how the degradation of ARC affects the PV module's energy output over time. Clearly, there will be a loss of module power as the ARC wears away. It is not readily apparent if the coating uniformly thins or creates microscopic surface texture that could trap dust and particles. Further, many ARC products promote their ability to block humidity ingress into the module. Once the ARC degrades, it is not known if the susceptibility to potential induced degradation increases.[10] Real-world installations will provide answers and feedback for product improvements over time.

Highly Textured Glass

Often, the front surface of PV glass is not completely smooth. It has a shallow texture to reduce glint (i.e., the mirror-like reflection from a flat surface). From an anti-reflection coating perspective, making the surface texture deeper would provide a gradual increase in index of refraction between air and glass and provide additional surface area for capturing reflected light, thereby coupling more light into the module.

Figure 7 depicts a ray tracing drawing that illustrates how a deep surface texture concept works. The texture increases the amount of glass surface per unit area through variations in height—the triangles in this hypothetical case, shown in Figure 7. This increased surface area provides more chances for light to be captured, including the initial impinging light and any reflections caused by subsequent layers within the module. For instance, the initial incident light may strike within a valley of the textured pattern, be reflected across the valley, and then given another chance for collection. This technique is successfully used in all silicon PV cells to capture more light and generate as much short-circuit current as possible.

The glass is patterned via rollers during its cooling phase. One or both of the rollers have the desired embossed pattern, which is pressed into the glass. This technique is relatively common in the glass industry; for instance, it is used to make privacy glass for shower doors. For PV applications, the properties of the pattern—its shape, size, depth, and periodicity/randomness—can be optimized with ray tracing software. Modeling the different textures for an air/glass interface with OPAL 2 from PV Lighthouse, a program

[10] Potential induced degradation is a power reducing phenomenon seen in the cells of some modules operating at hundreds of volts above ground. For more information, see *Literature Study and Risk Analysis for Potential Induced Degradation*. EPRI, Palo Alto, CA: December 2014. 3002003737.

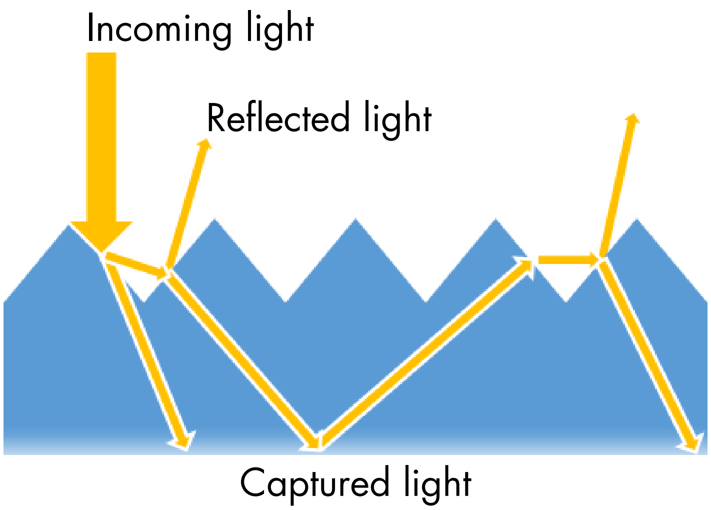

Figure 7. A textured glass surface causes multiple surface reflections and increased opportunity for light capture
Source: EPRI

that simulates the optics of a PV cell, suggests that reflection can be reduced below 1%.

To date, highly textured glass has had limited market success within the solar segment. It is currently being employed by only 1% of the PV market, and future projections do not anticipate share growth. Among the possible reasons for the market's tepid reception are manufacturing cost differences between coated versus texturing, increased soiling potential brought by the additional surface area of textured glass, and the deleterious effect of textured glass on module washing (the texture traps dirt thereby reducing the efficacy of module washing).[11] The limited amount of product in the field and associated results makes it difficult to confirm these adoption barrier hypotheses.

Anti-Soiling Coatings (ASC)

"Anti-soiling" is a misnomer. ASCs do not, in fact, prevent PV modules from soiling; they instead provide soiling resistance. For consistency with industry, however, "anti-soiling" or ASC will be used throughout this paper. Also of note, ARC and ASC are not mutually exclusive, some anti-reflection coatings have anti-soiling properties.

Power and Energy Impact

Calculating the benefits of ASC is not as straightforward as ARC. Intuitively, it is easy to visualize less light getting through a soiled piece of glass. But modeling and predicting the impact of soiling on actual PV plant performance is quite challenging in terms of determining the associated reductions in both power and energy. When installed outdoors, ARC's efficacy proportionally diminishes as the PV module becomes soiled. Sandia National Laboratories found that their lab-created soil mix (composed of common minerals found in U.S. soils) blocked 10% more blue light (350 nm) than infrared light (1200 nm) and had a nearly linear response for wavelengths in between those end points.[12] Most PV modeling software does not currently take into account any spectral changes or shifts, which impacts how soiling can be modeled.

Furthermore, in terms of energy production, tests performed by Photovoltaik-Institut Berlin demonstrated that the normalized current output of soiled and unsoiled modules remained the same for angles of incidence below 30 degrees. Beyond 30 degrees, the soiled modules lost current faster than unsoiled modules.[12, 13] Based on these results, soiled modules are likely to produce relatively less power than clean modules during the morning and evening hours.

NREL's System Advisor Model (SAM) contains a soiling default that blindly assumes a 5% derate factor.[14] But actual soiling depends on climate zone, regional and local conditions, and plant design. For instance, the climate matters because individual plant sites may have high soiling variability based on weather and rainfall. Regional factors matter because of the type of ground conditions in and around the plant. Local conditions matter because siting close to roadways, industrial plants, and agriculture, all deposit different types and amounts of debris on the modules. Plant design matters because module height off the ground (the higher the module, the less the soiling) and module orientation with respect to prevailing wind makes a difference to soiling accumulation.

An anti-soiling coating must have a handful of physical properties for it to be effective, including:

- hardness for durability against abrasion (e.g., from sand storms or washing);

[11] T. Weber, PI Berlin. "Impact and Consequences of Soiling and Cleaning PV Modules." PV Module Reliability Workshop. Golden, CO: February 2015.

[12] P. Burton, B. King, *Artificial Soiling of Photovoltaic Module Surfaces using Traceable Soil Components*. SAND2013- 4760 C. 2013.

[13] W. Hermann. "Impact of Soiling on PV Module Performance for Various Climates" TUV Rheinland. 4th PV Performance Modeling and Monitoring Workshop, Cologne, Germany: October 2015.

[14] System Advisor Model (SAM) is a renewable energy performance and financial modeling package developed by the National Renewable Energy Laboratory.

- smoothness to prevent soiling in surface crevices;
- hydrophobicity to promote water shedding and self-cleaning;
- low surface energy to prevent chemical bonding of soil;
- tack-free surface to prevent van der Waals bonding of soil;
- the ability to be easily cleaned; and
- chemical stability for resistance against UV oxidation, hydrolysis, and other environmental factors that could reduce service lifetime.[15]

Soiling is a complex process that is influenced by many different factors including soil type, weather (e.g., windiness) and climate (e.g., humidity and precipitation), local surrounding environment, and land use (e.g., being next to a highway or factory). Soil types vary widely across the globe, EPRI has alone incorporated hundreds of types in various analyses, such as corrosion tests.[16] The soil can range in size from a few to hundreds of micrometers and be acidic or basic, implying a diverse range of mineral/chemical compositions. This diversity makes it difficult to generalize results, such as predicting an anti-soiling coating's performance impact.

There are two approaches to ASC based on whether the coating creates a hydrophobic (i.e., water repelling) or hydrophilic (i.e., water attracting) surface. Figure 8 illustrates the difference between a hydrophobic and hydrophilic surface. Hydrophobicity causes water to bead up, and hydrophilicity causes water to spread out across the surface. In general, glass is hydrophilic, meaning a drop of water spreads out on its surface.

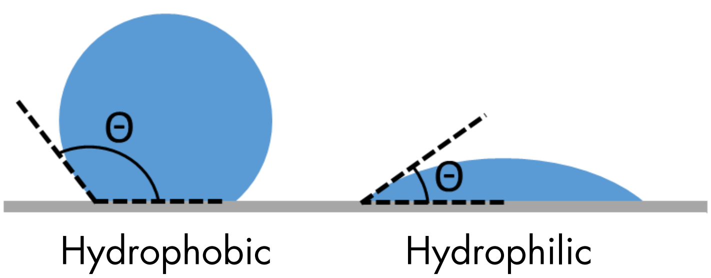

Figure 8. Two means to mitigate soiling is by making the glass either hydrophobic (water beads up) or hydrophilic (water spreads out)
Source: EPRI
Note: Uncoated glass is naturally hydrophilic.

Hydrophobic coatings enable a "self-cleaning" effect. Under wet conditions (morning dew, rain, snow, etc.), water beads up and has less surface area to hold it on the glass. In the case of tilted PV modules, gravity provides enough force to pull water down the glass surface, taking dirt and debris with it. This also means hydrophobic coatings tend to be easier to clean via manual washing.

Hydrophilic coatings prevent dust from reaching the glass itself. In a seminal soiling study, multiple layers of soil accumulated on a single PV module. The soil that was hardest to remove was adsorbed on the glass itself and could only be removed through manual washing. The two other layers of identified soiling were progressively easier to remove the further away from the glass surface they were located.[15] A hydrophilic coating tends to trap a thin layer of water at the glass surface, preventing direct contact between the soil and the glass and mitigating formation of the hard to remove directly adsorbed soil layer.

Economic Considerations

Keeping modules clean is an important aspect to getting the most energy possible out of a PV plant. Active (e.g., module washing), passive (e.g., anti-soiling coatings), or a combination of the two (e.g., washing anti-soiling coated modules) are viable options. Deciding on the approach that makes most economic sense depends on a litany of inputs: the energy off-take agreement, local soiling and weather conditions, the amount of energy lost, and the cost of washing. Table 1 relates a hypothetical situation to help put the cost-benefit impact of anti-soiling coatings into context. It assumes a 10 MW_{ac} plant that's located in a relatively low soiling environment, such as the southwestern U.S., where 0.5% energy can be gained back, as compared to the common soiling assumption loss of 3%.[17] Under these simple assumptions, anti-soiling is worth approximately half the cost of module washing. As mentioned, actual benefits will, however, rely on the specifics of the PV plant and its location.

What is not considered in this simplistic scenario is the interplay between ASC and washing. Coated modules could provide an extra lever to decide what frequency to wash or perhaps forego washing. Further, the coating could make washing quicker or easier which would reduce cleaning costs. Over time, less washings may increase the service lifetime of the coating and increase the plant's overall energy output.

[15] E.F. Cuddihy P.B. Willis, "Antisoiling Technology: Theories of Surface Soiling and Performance of Antisoiling Surface Coatings" November 15 1984, Jet Propulsion Laboratory Publication 84-72.

[16] *Corrosion of Buried Steel for PV Solar Power Plants*. EPRI, Palo Alto, CA: 2016. 3002007077.

[17] B. Brophy, K. Schexnaydre. "Three Year Field Performance of Anti-Soiling Coatings at Multiple Locations." 32nd EU PVSEC. Munich, Germany: 2016.

Table 1. Simplistic anti-soiling cost-benefit analysis for a hypothetical 10 MW_{ac} PV plant

PV Plant Characteristics	
DC Capacity	12 MW_{dc}
AC Capacity	10 MW_{dc}
Energy*	25,000 MWh/yr
Maintenance	
Washing Cost	$1,000/$MW_{dc}$-yr
Off-take agreement	
PPA	$50/MWh
Simplistic cost-benefit analysis	
Assumed Energy Gain from Anti-Soiling	0.5%
Additional Energy Yield	125 MWh/yr
Additional Revenue from Anti-Soiling vs. Washing cost	*$6,250/yr vs. $12,000/yr*

Note: In this scenario, washing is more beneficial than gains from ASC alone.
**Assumes single-axis tracking*

Manufacturing Considerations

ASCs, labeled as such, have not made it into mainstream production. It is likely that ARC products will be tuned to provide ASC properties. Market adoption is limited by 1) the ability to predict the benefit of ASCs, and 2) modules being sold on a $/W basis instead of an energy-related metric. If ARC products are adapted, it is expected that the Sol-Gel process, described previously, will be used for manufacturing.

The Market Landscape

Market Adoption

Module coatings, particularly ARCs, have experienced a rapid uptake in recent years, growing in market share from 20% in 2010 to approximately 85% in 2015.[18] If mapped onto year-on-year global PV installations, this suggests over 130 GW of ARC PV modules are in operation today, representing half of the world's approximately 260 GW of PV install base.[1] The other half of deployed modules use uncoated, planar glass. Figure 9 estimates the efficiency boost over time of ARC versus uncoated PV modules. Taking this a step further, it is possible to estimate the market capitalization of ARC. Assuming 85% ARC market penetration, a 3% power boost, 59 GW of installed PV modules in 2015, and a global average module sale price of $0.60/W leads to a 2015 ARC market capitalization of roughly $900M.

Current Market Participants

There are a handful of companies selling meaningful volumes of ARC into the PV marketplace—notably 3M, Royal DSM, and Asahi Glass Company (AGC), in addition to less established startup ventures. As well, a number of Chinese manufacturers supply ARC, but little information is known about these companies, their products, and their market share. Generally, Chinese manufacturers apply their ARC during the glass tempering process, though there is scant data on the products' long-term field performance.

3M, a multibillion dollar international company headquartered in Minnesota, sells a combination anti-reflection and anti-soiling product known as AS Liquid 600. Little is publicly known about the commercial offering. Based on spec sheet, it is a "water-based liquid that forms a hydrophilic coating on glass, providing resistance to dry-dust soiling." The predicted product lifetime is three years in an arid environment. Of note, the product is designed for in-field application as opposed to being cured during the glass formation process. Meanwhile, there is inadequate information available to assess whether it can be cost-effectively incorporated into periodic panel washing. The manufacturer's recommended application process is lengthy, and includes deionized water rinsing and squeegeeing to create a pristine glass surface, then using a paint roller to apply the ARC, waiting 30 seconds, and finally squeegeeing off excess ARC product.

In 2013, EPRI published a report examining the efficacy of using a commercially-available, off-the-shelf glass treatment product intended for automotive applications to provide anti-soiling for small-scale PV.[19] The product was applied in the same manner as suggested by 3M (but it was not 3M's product), and was advertised as being able to create a hydrophobic glass surface over a one year effective lifetime per application. After a year of testing, the product did work as advertised. However, the cost of the product and its application was orders of magnitude greater than its monetized energy return, even when using retail electricity rates as the upper boundary for behind-the-meter cost recovery. The small-scale test provided insights into some of the market adoption challenges that the 3M coating may face. These include short lifetime in the field, the large

[18] SEMI. *International Technology Roadmap for Photovoltaic (ITRPV): 2015 Results*. Seventh Edition, March 2016.

[19] *Program on Technology Innovation: Evaluation of Hydrophobic Nano Coating on Solar Photovoltaic Panels*. EPRI, Palo Alto, CA: 2016. 3002002420.

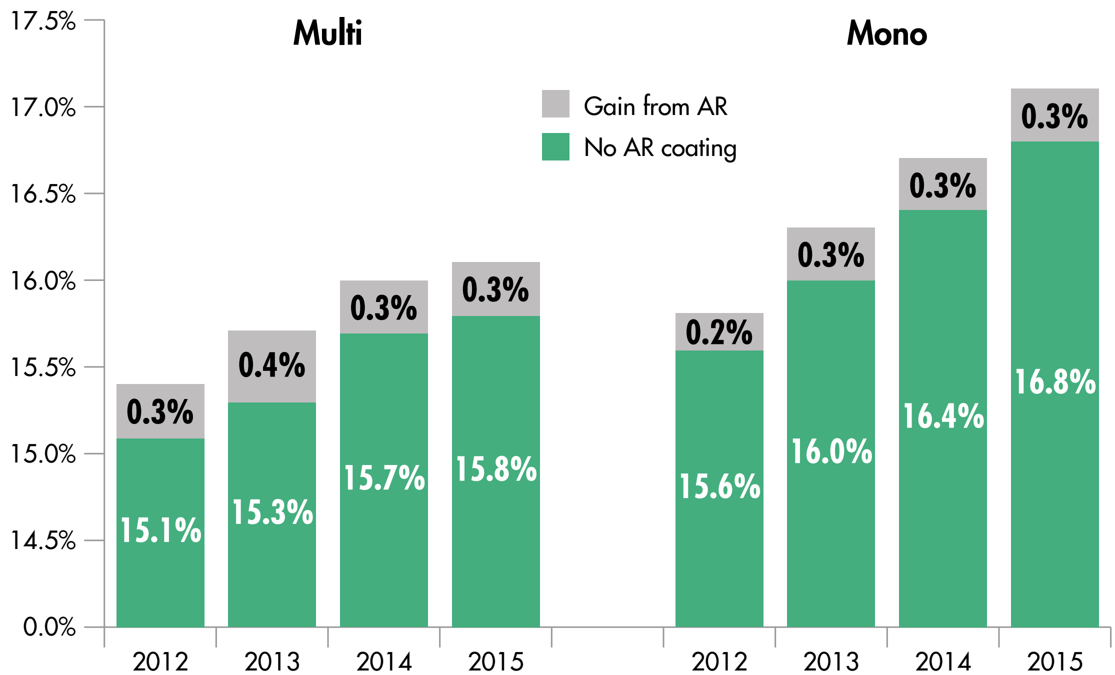

Figure 9. Estimated power boost attributable to ARC in crystalline silicon PV modules. Source: Bloomberg New Energy Finance

numbers of modules to be coated, and a relatively lengthy application process.

Royal DSM, based in the Netherlands, is another multibillion dollar international corporation. It offers a Sol-Gel processed, silica-based anti-reflection coating labeled under the KhepriCoat brand name. The product has passed testing under both IEC 61215 (crystalline silicon PV module infant mortality test), IEC 61730 (thin-film PV module infant mortality test), and EN1096-2 specifications. To further expand its product offerings, DSM is currently researching and developing a pyramidal textured surface coating specifically designed for the backside of glass-glass or bifacial modules. The texture works in the same way described in the above section about ARC textured glass; however, instead of rolling the glass to form the texture, Royal DSM relies on nanotechnology to self-align microscopic pyramids across the glass surface. Using it solely for the module's backside suggests there is some incompatibility with the front side, such as trapping small dust particles in the valleys of the pyramids, poor abrasion resistance to manual washing, or some other lifetime or performance limiting phenomena. Royal DSM did not provide comment.

Asahi Glass Company, located in Japan, is a third multibillion dollar international conglomerate in the ARC space. One of its product families includes PV-specific glass products. The company's Solar Plus Anti-Reflective Coating (SPARC) can be applied during tempering to its clear, patterned glass products labeled under the Solite and Solatex brand names. The product spec sheet states the ARC creates a hydrophilic surface and has passed specific tests within IEC 61215 and EN1096-2 specifications. There is no information on the chemical make-up of the product nor about its expected lifetime.

Meanwhile, San Jose, CA-based startup Enki Technologies is developing an anti-reflection and anti-soiling product that can be tuned to be either hydrophilic or hydrophobic. It is meant for application via Sol-Gel during the glass tempering process. The company's field tests over the past three years with prospective customers in various locations have shown their product to be more durable than competitors'. In fact, under some circumstances, product performance appears to improve over time. Enki's experience suggests that PV module washing is the primary culprit of ARC degradation, followed by film ablation caused by blown sand or dust (i.e., sandblasting).

Future R&D Innovation

Current research and development efforts are focused on the module coating themselves as well as understanding and predicting their real-world performance. In general, coatings research strives to create films that are more durable, cost-effective to manufacture, performance enhancing, and/or able to expand capabilities (e.g., combine ARC and ASC). Two recent awards made by the U.S. Department of Energy's SunShot Initiative to Oak Ridge National Laboratory (ORNL) for coatings and the National Renewable Energy Laboratory (NREL) for understanding and predicting performance highlight representative research in the space.

ORNL: Superhydrophobic Nanocones

As is often the case with R&D, nature is providing inspiration to scientists. ORNL is developing a superhydrophobic[20] coating based on the microscopically bumpy surface of the lotus leaf that produces the Lotus Effect.[21] ORNL is first depositing a silica-based film onto a surface, glass in the case of PV modules. It is then employing thermal processing to sinter the film together, akin to the Sol-Gel process described above. Finally, a wet chemistry is being utilized to selectively etch the film, which creates high aspect ratio cones. When these spikes are grouped tightly enough together, they effectively form a uniform, solid surface upon which water beads up. This approach reduces the surface area that the water droplet rests upon, which allows the drop to tend towards its lowest surface energy shape—a sphere.

Like a bed of nails, in which a person laying upon them feels a single homogenous surface even though there are many individual nails, a liquid on such a surface feels many competing forces. Internally, it is trying to minimize its surface area by pulling itself together into a sphere. Externally, forces at the surface, such as van der Waals and various bonding types, may be trying to spread it out. (Remember, glass is naturally hydrophilic and prefers water spreading out over its surface.)

Glass nanocones also have the intrinsic benefit of grading the index of refraction between air and glass, which is important for anti-reflective properties. At the top of the array of nanocones there is more air than glass, which effectively means the index of refraction at the top of the film is air. Moving down through the film and towards the glass substrate, the cones get thicker. The effective index of refraction relies on the ratio of glass to air. Therefore, thicker cones means more glass, less air, and a proportionally higher index of refraction. Finally, at the bottom of the film, all the cones are merged together and sit on the glass substrate; thus, the index of refraction becomes that of glass.

To date, ORNL has achieved water contact angles between 155 and 165 degrees. It is working to apply its coating to more than just PV modules, envisioning uses for heliostats or trough reflectors in concentrating solar power applications, building windows, sensors, and other optics.

The film is still early in its R&D Technology Readiness Level (TRL), having demonstrated a few early prototypes, i.e., TRL 3. It is not known what its projected cost in high-volume production would be, especially compared to the incumbent Sol-Gel process.

NREL: Mapping and Predicting Soiling Rates

A recently initiated three-year project at NREL seeks to "develop a predictive soiling model and a soiling rate map of the U.S. based on available and, if necessary, additionally collected data and use it to provide O&M guidance to industry."[22] The work builds on multiple other soiling studies that have been performed over time and may pull from work completed by Arizona State University, Sandia National Laboratory, and TÜV Rheinland.

In many ways, this project and its end goals are an update to ground-breaking work performed at NASA's Jet Propulsion Laboratory in the early-1980s.[16] NREL intends to examine basic soiling mechanisms for quantifying soiling complexities, create predictive models, and potentially suggest mitigation strategies. Furthermore, work will characterize coatings, providing site-specific guidance, and assisting with international standards development.

If successful, the project could help translate $/W PV metrics into $/kWh values, and in turn abet the commercialization of ASCs.

Conclusions and Next Steps

Anti-reflection and anti-soiling coatings on PV modules have the potential to decrease the cost of electricity for photovoltaics. Their impact is, however, clouded by a variety of factors, such as the durability and properties of the coating; the solar spectrum that reaches the film and associated spectral response; weather and precipitation, type of ground conditions, and soil in and around the plant site; neighboring land use (e.g., roadways, industrial plants, agriculture); and plant design. Providing deeper insight on this knowledge gap is important for better understanding, predicting, and developing products that can more effectively reduce reflection and/or mitigate soiling.

Key takeaways from this report include:

- Anti-reflection coatings (ARC) are currently being applied to over 85% of PV modules, primarily to boost nameplate power. The

[20] Superhydrophobic is defined as a water contact angle greater than 150 degrees.

[21] The lotus effect refers to self-cleaning properties that are a result of very high water repellence (superhydrophobicity), as exhibited by the leaves of the lotus flower.

[22] *Addressing Soiling: From Interface Chemistry to Practicality. SuNLaMP Funding Opportunity*. http://energy.gov/eere/sunshot/project-profile-addressing-soiling-interface-chemistry-practicality.

PV coatings market is already a billion-dollar industry with large multi-national corporations offering products.

- The average lifetime of today's ARC products is 14 years, short of 20+ year service lifetime of PV modules. Ongoing R&D is addressing this shortcoming and incremental product improvement are expected over time.
- Anti-soiling coatings (ASC) have difficulty monetizing their value due to energy yield being dependent on plant-specific location (cannot generalize ASC performance) and modules being sold on a $/W-basis instead of $/kWh-basis.
- ARC and ASC are not mutually exclusive, a single coating can have both anti-reflective and anti-soiling properties. It is anticipated that future ARC products will be tweaked and PV modules marketed for their anti-soiling ability.
- The type of soiling a plant experiences will determine whether a hydrophobic or hydrophilic anti-soiling coating is more appropriate. One type does not work best in all situations.

There are many ways that EPRI can engage in further research, development, and demonstration of PV module coatings. ASC would particularly benefit from data aggregation, more field-testing, and dissemination of results. The lowest path forward could be collaborating with existing efforts underway that are working to, among other things, circulate soiling data. Other opportunities include conducting new field tests to better understand the complicated interplay of locational-specific soiling factors, module washing processes, and coating performance. Testing could be done at any number of sites, with any number of collaborators (e.g., academia, national labs, coating or module suppliers), and at any size (e.g., coupon module, full-size module, array of modules). Further, this work could inform O&M activities at both future and existing PV plants.

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