Self-cleaning Technologies for Solar Panels

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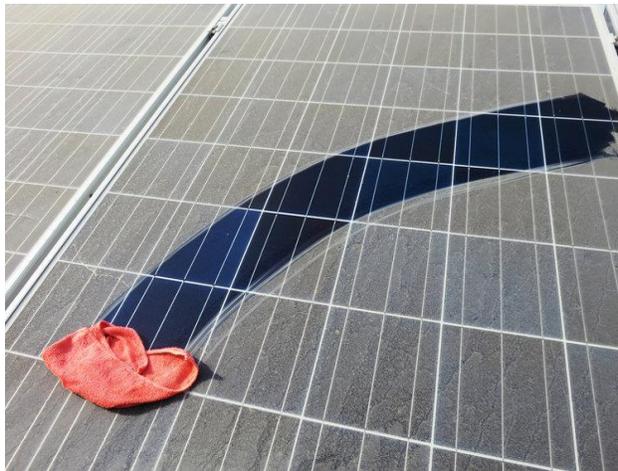
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Today, there are 89 Petawatts (PW) of potential solar energy production available on earth, making solar the world's most abundant available source of power. Over a million solar systems have been installed in the U.S. alone. In 2018, homeowners can get affordable quotes for solar panels in the 20 to 23 percent efficiency range anywhere in the U.S. Unfortunately, efficiency drops quickly with solar panel contamination, since any dirt or obstruction on the way between the sun and the solar cells blocks sunlight and reduce collected energy.

Solar panel efficiency and how it is affected by contamination

Dependent on many factors, in a dusty environment, a photovoltaic (PV) module can accumulate 80–300 mg·sq. meters of dust per day, and every 100 mg·sq. meters of dust accumulation causes an additional output loss of 0.4–0.7% [1]. After being exposed to ambient dust for one month, the soiled PV module will typically be able to produce 85% of the electricity it could if it was clean. Annual losses caused by this trend due to soiling ranges from 1.5% to 6.2% depending on the location of the PV plant. After a slight rain, the efficiency of some PV panels declined sharply, whereas the performance

of other panels was improved [2]. At least 20 mm of rainfall is needed to clean the surface of PV systems, otherwise the systems will continue to experience power loss due to the dust and soil. In general, there are two types of soil shading on PV modules, which are known as hard shading and soft shading. Soft shading takes place when some materials such as smog are in the air, while hard shading occurs when a solid such as accumulated dust blocks the sunlight. Soft shading affects the current of the PV module, but the voltage

Fig.1: Dust-contaminated solar panel

remains the same. For hard shading, the performance of the PV module depends on whether some cells are shaded, or all cells of the PV module are shaded. If some cells are shaded, then as long as the unshaded cells receive some solar irradiance, there will be decrease in voltage generated by the PV module. Other research [3] revealed that airborne contamination over northern and eastern China, the most polluted regions,

reduce annual solar power generation by up to 1.5 kWh/sq. meters per day relative to pollution-free conditions, a decrease of up to 35%.

Another aspect of solar panel dependence on environmental factors is the useful life of a solar panel. Panels usually don't die suddenly, they experience a slow decline in efficiency. The usual efficiency decline (not related to surface contamination) is typically 0.8% a year, something that is highly dependent on the type of solar cell material, and quality of production. Crystalline solar cells degrade on average at about 0.5% per year, whereas thin-film cells degrade at about 1% per year. Environment does play its role in such degradation: snow and ice accumulation would not only decrease efficiency due to loss in light transmission, but also could bend the frame, exposing internal panel components to moisture and ice.

Incumbent technologies for panel cleaning

Obviously, cleaning solar panels is one of the most important and economically urgent problems to solve for both incumbent and emerging technologies.

Currently, most solar panel installations rely on one or combinations of a few of these cleaning methods:

1. **Rain and wind:** They are free but irregular, and rain is rare in arid places. Therefore, the reliability of this cleaning method is problematic when contamination is intensive and rainfall is not enough, either in quantity or in intensity, to wash off the soil. Moreover, sharp declines in performance have been noticed in various cases after a light rainfall. Wind can also assist to reduce or eliminate soiling to a certain extent, but there is a need of water to clean the surface for optimum power generation.

2. **Manual cleaning:** Manual labor is used to scrub the soil off the surface, brushes with special bristles are designed to prevent scratching of the modules. Some brushes are also connected directly to a water supply to perform the washing and scrubbing concurrently. Labor expense, work safety, cleaning efficiency and throughput are very problematic.

3. **Robots:** machinery is utilized to perform the cleaning task and a storage for water supply. Frequent cleaning cycles are recommended to mitigate impact of dust, weekly cleaning during dry seasons and daily washing recommended for intensive dust accumulation. Mechanical cleaning can damage glass surfaces while requiring vast amounts of potable water: a scarce commodity in desert regions. Still, robots are increasingly used, especially in large sonar panel installations. Here are few examples:

Fig. 2: Ecoppia's E4 solar panel cleaning robot

Ecoppia: The E4 is a water-free cleaning system, that uses a combination of three factors: a special microfiber that wipes soil away, controlled airflow over the panel surface, and gravity to ensure dirt is moved downwards and off panel rows (Fig. 2).

Scrobby: A solar-powered, autonomous robot prototype designed to keep domestic solar panels clean and clear. It requires neither external power nor water to run as it collects both from the environment. It has a solar panel to charge its batteries, but the clever part is that it has a collector on its docking station to catch rainwater, meaning that it can be a truly independent and autonomous device (Fig.3).
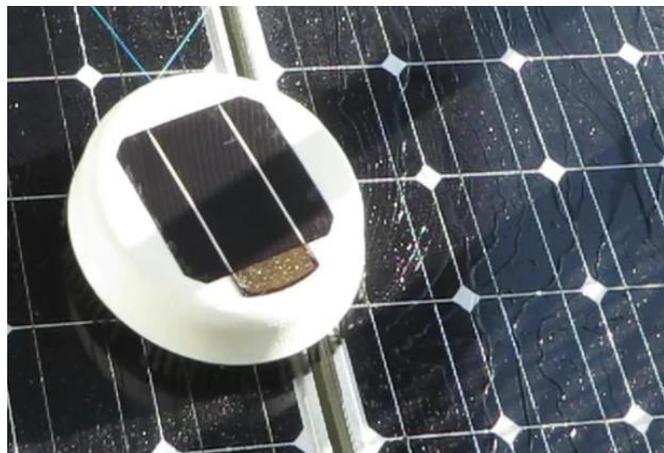
Fig. 3: Scrobby's autonomous solar panel cleaning robot

Emerging technologies — Self-cleaning

Self-cleaning means that the cleaning operation does not require any manual labor, movable mechanisms or robots to be attached to the solar panel for cleaning purposes. Thus, the surface the panels can keep clean by repelling all contamination, or actively clean themselves as needed and when needed, independently of time of the day,

availability of sun or rain. Among emerging technology solutions for solar panel cleaning, we should distinguish between passive and active self-cleaning technologies.

Passive self-cleaning solutions

Passive self-cleaning includes a few different types of surface coatings. This method is based on surface energy modification or photo-chemical reactions. Three major types of coatings could be used for this purpose:

• hydrophobic/superhydrophobic (low surface energy coatings),
• hydrophilic/superhydrophilic (high surface energy coatings), and
• photo-catalytic (chemical decomposition using UV light and water)

Superhydrophobic coatings

These are low surface energy coatings, which repel all contaminants from the surface (so nothing would stick to it). The self-cleaning surface technology is often related to the "lotus leaf" effect, where the contact angle of the water is high, drops bead on the surface, roll easily across the surface, and collect all contaminants on itself.

Fig. 4: Superhydrophobic coating Kleen-Boost™

Commonly found commercial products are disposable spray or hand-spreadable coatings such as RainX, SurfaShield G by NanoPhos, GlassParency, KleenBoost from ARDL (Fig. 4), etc.

In order to realize a "lotus leaf" effect of self-cleaning, a coating should be *super*hydrophobic. It means it should have a low surface energy, with the water contact angle >150 deg. Usually, it requires the following: 1) coating to be made from low surface energy materials, for example, fluorinated polymers, and 2) superhydrophobicity requires larger surface area, which could be obtained by texturing or microstructuring. Texturing could be achieved using special surface etching techniques (wet or dry). Another approach is to use nanoparticles in a mixture with hydrophobic chemicals. The last method's environmental aspect is very questionable. Micro- or nanostructuring could be done by patterning a material's surface using various lithography methods: nanoimprint, optical (for example, RML process, Fig. 5), self-assembly, colloid lithography, or laser ablation [4]. Interestingly, micro- or nanostructuring for achieving superhydrophobic surface could also be used to reduce reflection from the surface — which has an additional advantage for solar efficiency enhancement. This structure is known as "Moth eye", since it resembles the surface texture of moth's eyes, which makes them invisible to predators.

Fig. 5: Superhydrophobic glass coating fabricated using RML patterning technology (Rolith, Inc./Metamaterial Technologies)
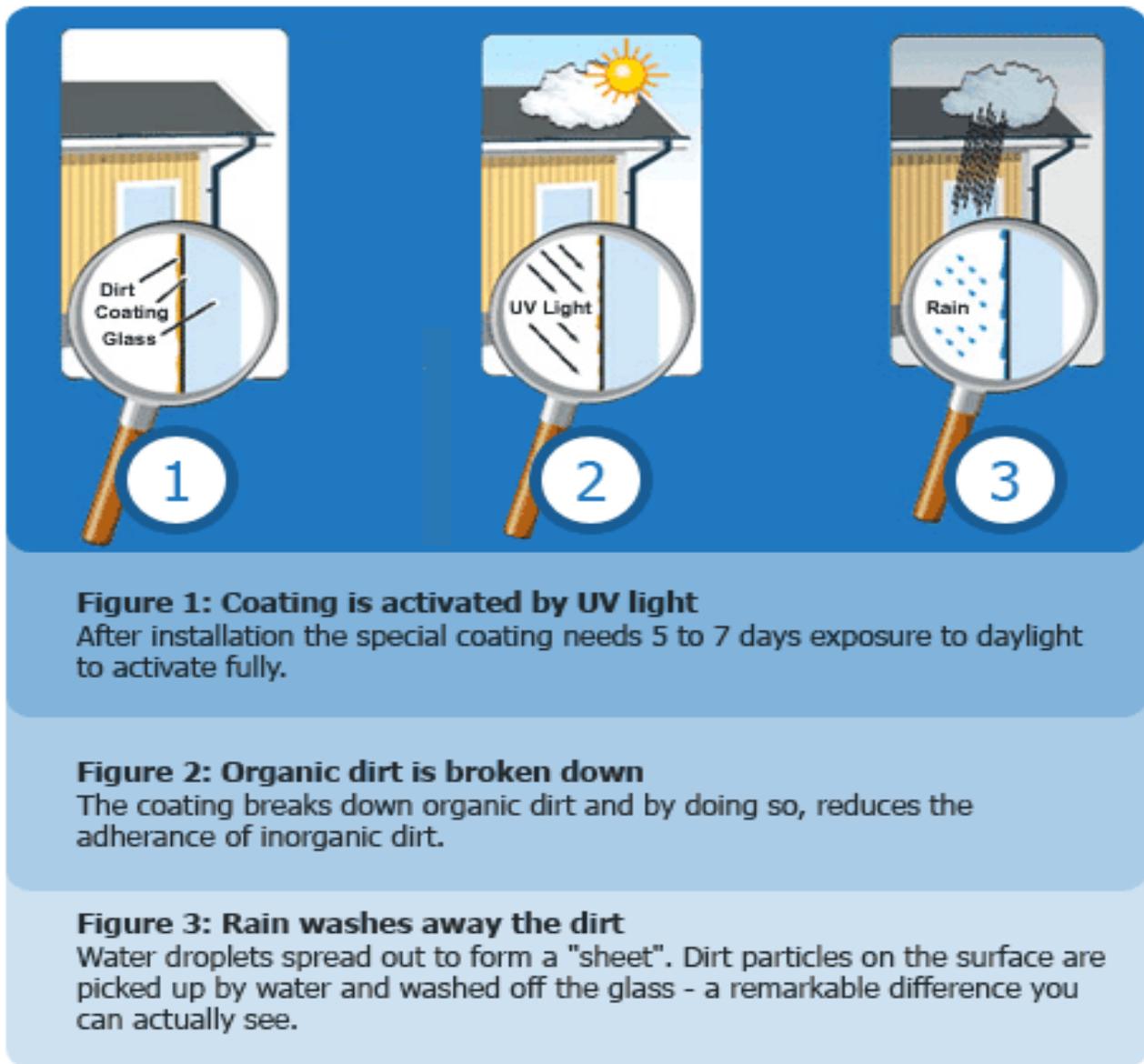
Superhydrophilic coatings

These are high surface energy coatings, which work by making water spread (sheet) on the surface. As the result, water flows freely on the surface, washing all contaminants away. Unfortunately, it usually does not help to detach stubborn contaminants (bird poop, plant deposits burned by sun and heat). Superhydrophilic performance is achieved using texturing or nanostructuring of a surface, similar to superhydrophobic coatings, coupled with depositing high surface energy materials. Another approach is just taking a native hydrophilic substrate (which could be, for example, glass) and clean it properly with plasma or UV ozone exposure. Obviously, such cleaning is very short-lived, and once exposed to the normal atmospheric environment and airborne pollution it gets contaminated with organic, mostly hydrophobic pollutants, so the nanostructured surface will lose its high hydrophilicity state and sometimes even flip to a hydrophobic state.

Photo-catalytic coatings

This coating is a mixture of organic materials matrix with titanium oxide nanoparticles. When exposed to an ultraviolet light source, such as the sun, the coating's oxidative property decomposes organic substances. Obviously, not all of contaminants are organic, for example, sand is inorganic—silicon oxide, which limits applicability and efficiency of this method. The hydrophilic nature of the coating causes water that comes into contact with it to form an even layer, thereby allowing the dust and dirt that have

accumulated on the surface to be washed away. Unfortunately, the method does require both water and UV light to be effective, thus no self-cleaning is expected in drought conditions or cloudy days. TiO2 coatings have a higher refractive index than the glass of the substrate that increases the reflectivity. Major glass companies have their lines of products with photocatalytic coatings: Pilkington Activ (Fig. 6), SunClean of PPG, Neat Glass of Cardinal Glass Industries, Planibel Easy Clear of AGC Europe, etc. A couple of years ago some companies changed the marketing of these coatings from "self-cleaning" to "easy-cleaning", which probably demonstrates acceptance of the limitations of this solution for self-cleaning tasks.

Figure 1: Coating is activated by UV light
After installation the special coating needs 5 to 7 days exposure to daylight to activate fully.

Figure 2: Organic dirt is broken down
The coating breaks down organic dirt and by doing so, reduces the adherance of inorganic dirt.

Figure 3: Rain washes away the dirt
Water droplets spread out to form a "sheet". Dirt particles on the surface are picked up by water and washed off the glass - a remarkable difference you can actually see.

Fig. 6: Pilkington's Activ photo catalytic self-cleaning coating

All methods based on coatings have problems with environmental stability, mainly resistance to mechanical impact like scratching by additional wiping, removal of stubborn deposits, impact of hail, etc. And unfortunately, the better self-cleaning performance (better superhydrophobicity) the worse environmental stability: better hydrophobicity means higher aspect ratio of nanostructures, which obviously are more prone to damage by mechanical impact. Chemical resistance of hydrophobic coatings, especially in prolonged contact with water and acids in the rain is also problematic. Photocatalytic coatings contain nanoparticles, which could be released into environment.

There is a need for automatic sensing and cleaning of solar panels to keep them free of contamination all the time. This could be realized using technology, which would sense contamination and start cleaning immediately, without human intervention.

Active self-cleaning solutions

Active self-cleaning solutions do not rely on coatings, but provide active and controllable, on-demand or fully automatic, cleaning operation. Though there could be many more technologies for active self-cleaning, the following two types look the most promising: electrostatic and ultrasonic self-cleaning.

Electrostatic self-cleaning

NASA's Kennedy Space Center has developed an active technology to remove dust from surfaces during exploration missions [5]. The Electrodynamic Dust Shield (EDS), which consists of a series of embedded electrodes in a high dielectric strength substrate, uses a low-power, low-frequency signal that produces an electric field wave that travels across the surface (Fig. 7). This non-uniform electric field generates dielectrophoretic and electrostatic forces capable of moving dust off of these surfaces. Implementations of the EDS have been developed for solar radiators, optical systems, camera lenses, visors, windows, thermal radiators, and fabrics. EDS panels over solar radiators showed dust removal that restored solar panel output reaching values very close to their initial output (Fig. 8).
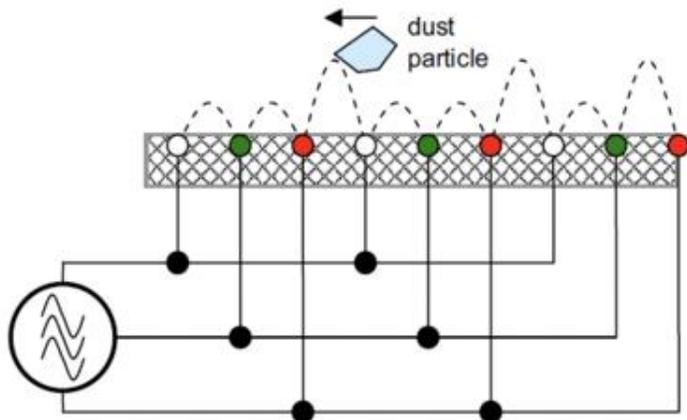
Fig. 7: Dust particle motion on a three phase EDS [5]

Fig. 8: EDS before (up) and after (down) the voltage applied [6]

EDS could be designed to have traveling-wave or standing-wave alternating electric fields. Compared to the traveling-wave design, the standing-wave EDS design requires simpler electrical circuits and less complex high-voltage sources.

The Solar Clear project at Stony Brook University has received a $150,000 grant from PowerBridgeNY to advance self-cleaning technology, which utilizes the next generation of EDS to remove dust particle from the panels. When a voltage (varied from 0 to 10 kV) is applied to the electrode, a strong electric field charges the dust particle and repels it away from the panels. It involves transparent electrodes that are embedded in solar panel glass, while being water–free and fully automatic.

It is worth mentioning that the electrostatic method of self-cleaning did work in space in a vacuum and without moisture in the environment. It would work only for dust particles not bonded to the surface (or, at least, loosely attached). This is not the case for dust and other contamination found in desert solar farm fields, where dirt is being "cemented" on glass surfaces with moisture and other types of liquid deposits, and additionally burned and glued to the surface by exposure to heat and sun. Thus, use of EDS here on Earth is more problematic than in space.

Ultrasonic self-cleaning

Standard ultrasonic cleaning involves the use of high-frequency sound waves (above the upper range of human hearing, or about 20 kHz) to remove a variety of contaminants from parts immersed in aqueous media. The contaminants can be dirt, oil,

grease, buffing/polishing compounds, and mold release agents, just to name a few. Materials that can be cleaned include metals, glass, ceramics, and so on. In a process termed cavitation, micron-size bubbles form and grow due to alternating positive and negative pressure waves in a solution. Just prior to the bubble implosion, there is a tremendous amount of energy stored inside the bubble itself. Temperatures inside a cavitating bubble can be extremely high, with pressures up to 500 atm.
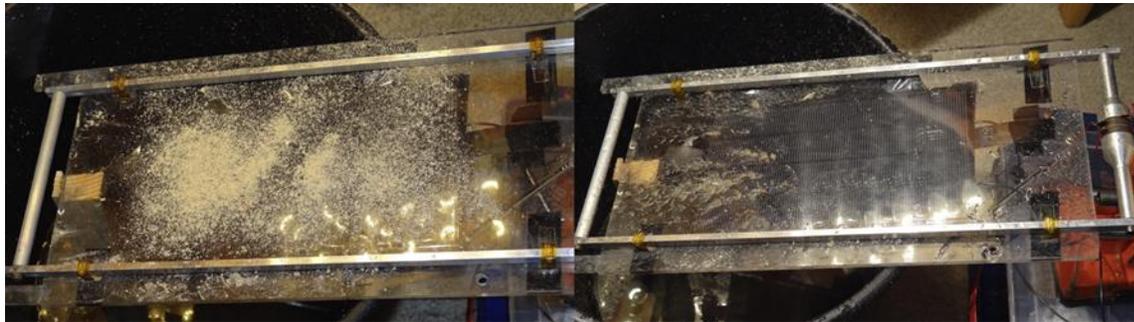

Fig. 9: Solar panel glass before and after ultrasonic cleaning with 20 kHz [7]

The implosion event, when it occurs near a hard surface, changes the bubble into a jet about one-tenth the bubble size, which travels at speeds up to 400 km an hour toward the hard surface. With the combination of pressure, temperature, and velocity, the jet frees contaminants from their bonds with the substrate. Because of the inherently small size of the jet and the relatively large energy, ultrasonic cleaning has the ability to reach into small crevices and remove entrapped soils very effectively. The resonant frequency of the transducer determines the size and magnitude of the resonant bubbles. Typically, ultrasonic transducers used in the cleaning industry range in frequency from 20 to 80 kHz. The lower frequencies create larger bubbles with more energy.

Again, the standard configuration for ultrasonic cleaning is immersion in a standalone bath. There have been numerous attempts to move this process from the standalone equipment onto the surface to be cleaned—window, windshield, solar panel. It was demonstrated [7] that for flat surface cleaning it is enough to have a thin liquid layer <1 mm to create cavitation for cleaning the surface.

A CalTech patent [8] suggested self-cleaning of PV panels by piezo-elements coupled to a panel to cause vibration, where the piezo devices are located only in an edge region, and are coupled to the photovoltaic panel in positions that allow the formation of rotating air currents above the photovoltaic panel when piezo devices are vibrated (Fig. 10).
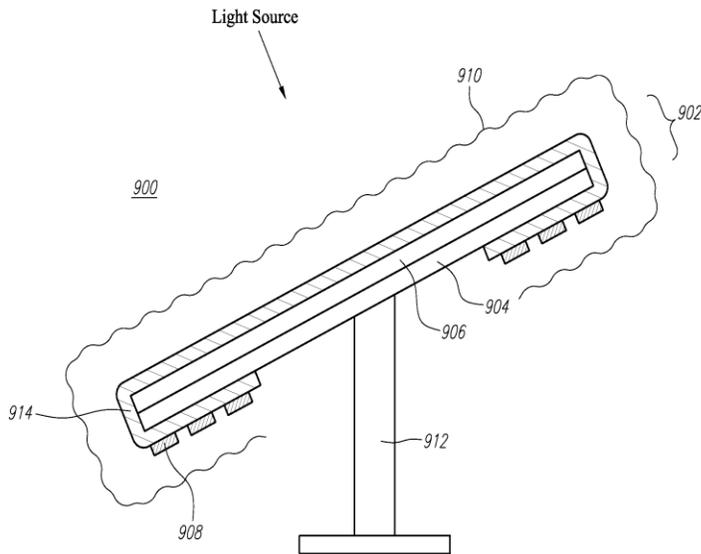
Fig. 10 (Left): Piezoelectric self-cleaning concept from CalTech [8]

Piezoclean: A start-up in Jordan, has been developing an active self-cleaning technology for solar panels using piezoelectric materials. A provisional patent application is filed.

Cavitation is not the only possible mechanism of cleaning surfaces from contamination. Echovista Systems, a German company, has been developing an ultrasonic self-cleaning system for car windshields, which suggests other modes of operation: removing water drops from the surface by pushing it with ultrasonic wave and/or evaporating it by transferring ultrasonic energy to every drop (Fig. 11).

Fig. 11: Echovista concept of ultrasonic surface cleaning: left - ultrasonic waves move drop of water; right: ultrasonic wave vaporizes drop of water [9]
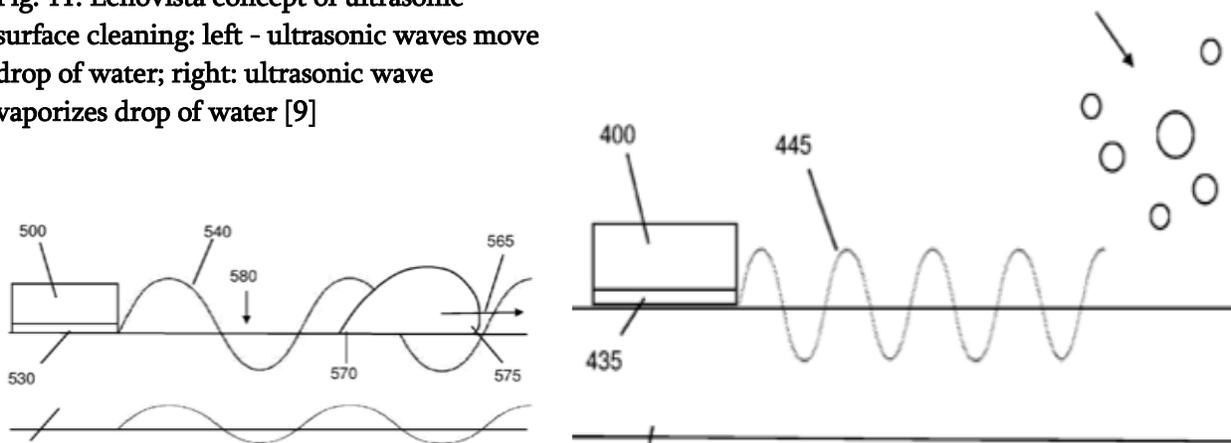
The array of ultrasonic transducers is attached to the glass surface on the periphery of a window and uses ultrasonic waves with frequencies from 100 kHz to 3 MHz to move or vaporize precipitation [9].

InnovaSonic, is U.S. company developing a new active self-cleaning technology—PiezoWipe™, which is based on disruptive concept of transparent ultrasonic transducers.

Fig. 12: InnovaSonic's microstructured piezoelectric array for self-cleaning glass
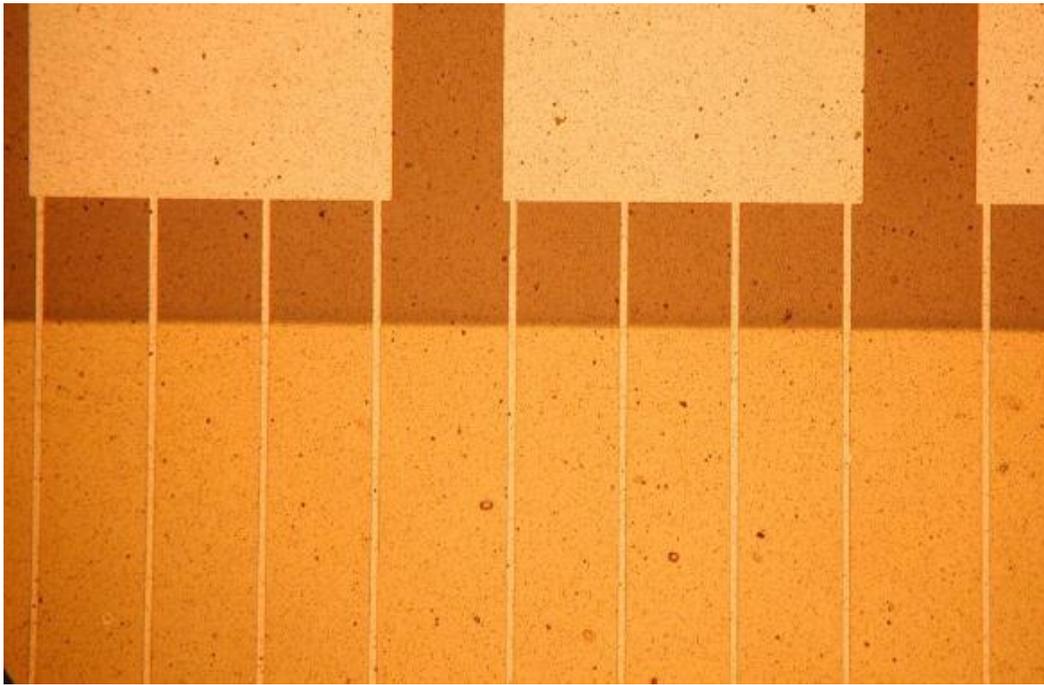
Scaling down transducer dimensions and/or electrodes to less than a few microns in at least one lateral direction makes this self-cleaning system very transparent to light and invisible to the human eye (Fig. 12). This allows it to be distributed across an entire viewable area of window or light absorption area of solar panel, without significant loss of power or obstruction of view [10]. InnovaSonic's transducers could be fabricated on glass directly (Fig. 13), or alternatively, could be fabricated on glass or Si wafers with subsequent transfer onto flexible film. This functional film is then laminated on glass surface or integrated between glass sheets as part of glazing.

Fig.13: Transparent ultrasonictransducer array (InnovaSonic, Inc.)

The advantages of PiezoWipe™ technology are:

- High efficiency of cleaning and big energy savings due to ultrasonic transducers positioned in a very close proximity/right below contamination (in contrast with periphery of glass location of competition)

- Integrating transparent ultrasonic emitting array with sensor array would allow to detect location of contamination and forward all energy to a specific spot to further optimize cleaning and reduce energy waste

- No mechanical movable parts or fixtures required

- No labor required for operation

- High transparency, invisibility

- Electrodes of piezoelectric microstructure stack could be used for collecting electrical energy (as electrodes of solar cells)

Conclusions

Huge PV power plants are being built in desert regions around the world at highly competitive generation costs (increasingly < 3 cents/kWh), but PV module soiling makes this cost advantage disappear [11]. Cleaning is absolutely necessary in regions where the panels tend to get dirty fast and cleaning strategy is a major element in highly competitive PV project proposals in desert locations. There is a wide range of cleaning methods and solutions—both wet and dry. A large variety of cleaning technology vendors are vying for business, but only a few solutions are effective and bankable. In regions where labor costs are relatively high, soiling very high and/or water cost is high, robotic cleaning wins. But robotic cleaning itself comes at a cost of $10-12/Wp, deployable at specific time intervals, and has a danger of damaging solar panels.

Self-cleaning solutions have a potential to drop this cost down and enable highly efficient, 24/7 maintenance of solar panels in all geographic areas. Among a variety of self-cleaning methods, the ones that are based on coatings do not provide reliable performance and need to be reapplied and complemented by other cleaning operations. Active self-cleaning technologies have a better chance to satisfy stringent requirements of cleaning solar panels in the field. Electrostatic self-cleaning has already demonstrated good performance, but only in space, with no moisture and limited types of contaminants. Ultrasonic cleaning is a well-established technology for cleaning parts in stand-alone equipment (baths). The new emerging technologies that manage transition of ultrasonic cleaning process from a bath environment directly to the object being cleaned—solar panel—are poised to have a great success in satisfying growing solar power generation market requirements.

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About the Writer

Boris Kobrin is a Senior Associate Analyst with n-tech Research. He is an experienced high-tech industry executive with 30+ years of leadership in micro and nano-fabrication, micro optics, thin films, coatings, MEMS and process equipment technology. Kobrin has a proven track record of successful disruptive technology development and introduction of new products to the fast-paced marketplace

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As a serial entrepreneur, Kobrin has founded two companies and participated in multiple start-ups in the U.S., Canada and Israel and successfully raised seed and early-stage rounds for hardware and advanced products start-ups, attracted numerous strategic commercial partnerships with the world's largest tech companies. He has provided technology scouting and evaluation, technology transfer consulting services to investment banks, venture funds and commercial companies.

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