Experimental Field Trial of Self-cleaning Solar Photovoltaic Panels

Dr. Kenneth A. Walz, Madison Area Technical College

Dr. Walz completed his Ph.D. at the University of Wisconsin in Environmental Chemistry and Technology, while conducting electrochemical research on lithium-ion batteries with Argonne National Laboratory and Rayovac. His studies also included research with the University of Rochester Center for Photo-Induced Charge Transfer. Since 2003, Dr. Walz has taught chemistry and engineering at Madison Area Technical College.

Dr. Walz is the Director and Principal Investigator for the Center for Renewable Energy Advanced Technological Education (CREATE). With funding from the National Science Foundation, CREATE seeks to advance renewable energy education nationwide by supporting faculty and academic programs in renewable energy.

Dr. Walz is an alumnus of the Department of Energy Academies Creating Teacher Scientists (DOE ACTS) Program, and he is an instructor for the National Renewable Energy Laboratory (NREL) Summer Institute, providing professional development for middle and high school teachers. Dr. Walz has been recognized as Professor of the Year by the Carnegie Foundation and the Council for Advancement and Support of Education, and as the Energy Educator of the Year by the Wisconsin Association for Environmental Education.

Mr. Joel B. Shoemaker, Madison Area Technical College

Joel Shoemaker is a Wisconsin state-certified Master Electrician with over 18 years of experience with photovoltaic systems, and currently serves as a Co-Principal Investigator for the National Science Foundation-funded Center for Renewable Energy Advanced Technological Education (CREATE). He has been teaching at Madison Area Technical College for the past 12 years. In 2011, the Wisconsin Bureau of Apprenticeship Standards and the Wisconsin Apprenticeship Advisory Council recognized Shoemaker as a Centennial Educator. He has taught solar photovoltaic trainer programs offered by CREATE and Solar Energy International and led the inception of Madison College’s STEM Educator Solar Institute for high school and community college teachers. Shoemaker will spearhead the design and construction of a model energy storage lab facility at Madison College that will be integrated into the existing solar energy installation lab and used for teaching about the interaction of these complimentary technologies.

Ms. Ashley Jordan Scholes, Madison Area Technical College

Ashley Scholes is a Madison College student working towards a transfer degree in mechanical engineering as well as the renewable energy certificate. Her interest in renewable energies came from an opportunity to become involved with a photo-voltaic system on Madison College campus. As a recipient of the JB Straubel Engineer of the Future Award in 2017 she has been grateful to focus further on her studies.

Hao Jiang, University of Wisconsin, Madison

Hao Jiang received the Ph.D degree from the University of Wisconsin - Madison, USA, in 2018.

He was a Research Assistant at the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC), his research interests include modular multilevel converter, integrated power converter, and energy harvesting converter for renewable sources.

Dr. Jessica M.S. Silva, Azelis

Jessica Silva is the construction solutions laboratory director for Azelis, a specialty chemical distribution company. She specializes in formulation concepts using the Azelis line of construction additives and admixes for the mortar and concrete industry. Previously, Jessica worked as the principal scientist for the startup construction consulting company Concrete Process and Science (CPS). Before joining CPS Jessica was the Senior Scientist for CalStar Products a masonry products company specializing in the use of supplementary cementitious materials. Early in her career she performed numerous research projects for the Federal Highway Administration and through the University of Wisconsin-Madison including the use of nanomaterials for use in construction materials.
Mrs. Jennifer Sanfilippo M.S., L.A.T., University of Wisconsin, Madison

Currently Jennifer Sanfilippo, MS, LAT is an athletic trainer and coordinator of Badger Athletic Performance within the Department of Intercollegiate Athletics at the University of Wisconsin-Madison. Previously she worked for the Water Chemistry and Engineering Laboratory specifically with nanoporous thin film coatings for numerous applications. Some of her patented work on nanoporous thin-films for self cleaning glass applications lead to other applications with packaging, plastics, batteries, and solar panel materials.

Dr. Walter A. Zeltner, Microporous Oxides Science and Technology, L.L.C.

Walter Zeltner, Ph.D., co-founder of Microporous Oxides Science and Technology, L.L.C. (MOST), is a physical chemist with over 30 years of experience in synthesizing suspensions of nanoparticulate oxides and in studying the catalytic, photocatalytic, and photoelectrocatalytic properties of these materials while working with Prof. Marc Anderson at the University of Wisconsin – Madison and for MOST. He prepared the mixed silica-titania suspension that was used to coat the solar panels for this study.

Prof. Marc Arlen Anderson, Imdea Energía, Madrid

Dr. Marc A. Anderson received his BS and MA degrees in chemistry. Between his MA and Ph.D. degree programs, the Viet Nam Conflict interrupted Dr. Anderson’s education. During this time he served as an Officer in the Chemical Corp of the USArmy and was stationed at Edgewood Arsenal, Md. Here, Dr. Anderson served as the Chief Officer Responsible for Agent Response and also worked in the “Super Toxic” Laboratories in the area of Binary Agent production. After returning to Civilian life, he completed his Ph.D. degree in Environmental Engineering at Johns Hopkins and joined the faculty at the University of Wisconsin in Civil and Environmental Engineering. Prof. Anderson is now retired but previously served on the faculty of the Materials Science Program and was the Chair of the Environmental Chemistry and Technology Program. Although retired from UW Madison, Prof. Anderson serves as the head of the Electrochemistry Division of Imdea Energia in Madrid Spain.

Prof. Andersons research efforts focus on the preparation, characterization and utilization of nanoparticulate oxides. These particles are on the order of 2-10nm in diameter and are typically used in the form of thin films cast on a variety of supports for a large array of applications. These applications include: ceramic membranes for gas and liquid separations; high surface area electrodes for use in fuel cells, batteries, capacitors and solar cells; nanoporous films for use in sensors to be employed for the detection of target species in both the gas and liquid phase; and photocatalysts for the destruction of organic compounds in the water we drink and the air we breathe. In this last area, Dr. Anderson is considered one of the foremost world-class experts in photocatalysis. Dr. Anderson’s has more than 25 patents and over 250 scientific papers.
Experimental Field Trial of Self-Cleaning Solar Photovoltaic Panels

Abstract
Solar energy has been growing at an exponential rate over the past decade, and worldwide installed solar electric capacity is expected to more than double again by 2020. Madison College and the Center for Renewable Energy Advanced Technological Education (CREATE) have been on the forefront of this trend, developing and teaching solar energy education courses for STEM students. Solar panel performance is unfortunately limited in the field when panels become soiled over time, reducing their electric output. In this student initiated experiment, solar panels were treated with a nanoporous silica/titania metal oxide thin film coating to impart self-cleaning properties. Panels from an operational 1.6 kW solar array were coated in the field to model a real-world application process. The system incorporated module level micro-inverters to monitor the power output of individual panels. The system was installed in June, and coatings applied in October 2017. Data collection and analysis is ongoing. Through this research project, students learned the fundamentals of solar photovoltaic technology, aspects of solar system design, safe installation procedures, and principles of data analysis.

Introduction
The 21st century has been characterized by a surge in the growth of clean renewable energy generation in the form of biomass, wind, and most recently solar power. Building on a decade long trend of double digit growth rates shown in Figure 1, global installed solar photovoltaic capacity has now exceeded 300 gigawatts (GW) [1]. Including projects still under construction in the fourth quarter, it is estimated that the United States alone installed approximately 12 GW of new solar photovoltaics in 2017 [2]. Even after accounting for capacity factors when the sun does not shine, these new renewable power production facilities installed in a single year provide the equivalent amount of electricity of several nuclear power plants. But what happens when the solar panels get dirty?

Soiling is a significant issue that affects the power output of solar panels [3]. The mechanism of this effect is easy to appreciate – if panels get dirty, the dirt on the top of the panel glazing reduces the transmission of light to the silicon semiconductor, and as a result photocurrent is greatly reduced. The effect is similar to having the panels shaded by a tree or other such obstruction. What many people find surprising is that even for systems with annual cleaning regimens, reductions in panel performance due to soiling frequently are found to be as much as 10-15% loss of electrical output. In extreme cases where panels are not inspected/maintained, the surface may become completely opaque with

![Figure 1) Global solar photovoltaic energy growth](image-url)
grime, in which case power output can be cut by 75% or more. Figure 2 illustrates the dramatic difference between a soiled solar panel on the right and one that has been recently cleaned on the left.

It has been known to science and engineering for many years that glass can be enhanced with self-cleaning properties by applying a transparent thin film coating of nanoparticulate titania, TiO$_2$. These nanoparticulate thin films have very high surface area (of magnitude ~ 10$^2$ m$^2$/gram), and very high porosity, which makes them super hydrophilic. These properties help glass surfaces to wet; when water (rain) is applied, it tends to sheet, rather than bead on the glass. Titania is also a photo-active material that acts as a semiconductor with a bandgap in the ultraviolet range. When titania particles absorb a photon, electron-hole pairs are generated. The holes have significant redox potential, and can oxidize organic surface contaminants, converting them into volatile gasses or water-soluble decomposition products. Much of this science has been explored in the laboratory of Dr. Marc Anderson at the University of Wisconsin-Madison, and additional details can be found in various publications from that laboratory group [5,6].

Although self-cleaning glass technology has been known for many years, it is only relatively recently that attempts have been made to apply the concept to photovoltaic panels. This study was conducted as a joint effort between a local start-up company, SolarKleenTech, and Madison College. SolarKleenTech was founded by two UW-Madison alumni both of whom worked as undergraduates in the chemical technology lab of Dr. Anderson at the time the company was launched. SolarKleenTech’s aim is to develop self-cleaning coatings for solar photovoltaic panels. Madison College is the lead institution for the NSF funded Center for Renewable Energy Advanced Technological Education (CREATE). CREATE’s mission is to advance renewable energy education by promoting novel energy educational initiatives at two year colleges nationwide [7]. SolarKleenTech approached Madison College to pursue a real-world field test to deploy their technology and test its performance using a system that is part of the college’s solar instructional laboratory that it uses to train electricians and solar technicians. The experiments described in this paper were conducted by three students working under the supervision of two Madison College faculty members and a consulting laboratory scientist. The students completing this research worked as volunteers either as part of an independent study or an honors project. These included an electrical engineering graduate student from UW-Madison, and two mechanical engineering undergraduate students from Madison College.

**Experimental Methods**
The coating materials used in this experiment were deposited from a nanoparticulate suspension containing a mixture of titania, TiO$_2$, and silica, SiO$_2$ metal oxides. The precise preparation of
these materials is a proprietary process belonging to SolarKleenTech LLC, but the general methods are known to science and can be shared here. The metal oxides were prepared using sol-gel chemistry techniques. The process involves mixing of a metal alkoxide (e.g. titanium isopropoxide as shown in Figure 3) with water and a catalyst (typically a strong acid or a strong base). The metal alkoxide reactant first undergoes hydrolysis reactions that cleave the alkoxide groups, replacing them with hydroxyls, and resulting in the formation of an alcohol byproduct. Subsequent condensation between two metal hydroxyl centers then results in the formation of metal-oxygen-metal bonding (e.g. Ti-O-Ti). As this process repeats, an amorphous metal oxide solid is formed. The size of solid particles can be controlled by adjusting the rates of reaction by controlling variables such as temperature, catalyst selection and concentration, and the composition of the solvent (primarily aqueous, but co-solvents and surfactants may also be added depending on the specific application). The sol gel process is illustrated in the figure below.

**Figure 3: Synthesis of TiO$_2$ nanoparticle coating materials via sol-gel chemical processing.**

In the case of the SolarKleenTech materials, the sol-gel process was manipulated to result in nanoparticulate suspensions of titania and silica. A photo of the two suspensions shown below illustrates that the particles are so small that they are not easily visible to the naked eye, however, they are capable of scattering light such as that of a green laser. Particle size distributions were measured using a Zetasizer dynamic light scattering instrument (see Figure 4).

**Figure 4: SiO$_2$ and TiO$_2$ sols, scattering of green laser light, and particle size distributions of the metal oxide nanoparticles suspended in the sols.**
A solar photovoltaic array was installed at Madison College consisting of nine SolarWorld 175 Watt monocrystalline PV panels. The panels were mounted on an aluminum racking system with electrical bonding provided by Wiley WEEB connections. The panels were all of the same model and age. The panels had been deployed previously in the field by Madison College students over the previous 5-6 seasons of use, so all of the panels were known to be in good working condition. The panels were all cleaned prior to installation using a dilute mix of detergent and water, and then rinsed thoroughly to remove any soapy residue.

In a traditional string inverter PV system, solar modules are wired in series and DC voltages add together, typically summing to a range around 400-500 DC volts for the input of the string inverter which then inverts the DC electricity into AC for connection to the electrical grid. Almost all modern inverters made today feature maximum power point tracking, which will adjust the current drawn from the string to optimize power output. Although string inverter systems are very common, this type of PV system would not be suitable for experiments testing self-cleaning panel treatments, because if the performance of a single panel is affected by soiling, it compromises the performance of the entire series string. By comparison in a microinverter system, each panel has its own module level electronics that performs maximum power point tracking and conversion of DC to AC for the individual panel. The AC output of the panels are then combined in parallel and connected to the grid. This allows each panel to operate, and be monitored, independently from the others, making this type of system ideal for a research project such as this.

Figure 5: Students install photovoltaic panels at Madison College

Figure 6: Line drawing schematic of the solar photovoltaic system
Each of the SolarWorld Panels is equipped with an Enphase 215 Watt, 208 Volt three phase AC microinverter. Data output for each panel is monitored continuously and logged via an Enphase Envoy Communications system with an ethernet Internet connection. The array was installed on a pitched roof facing due south with an open solar window (no shade from fixed position obstructions such as buildings, trees, etc). The system was installed by three students as an independent study project under the supervision of faculty members. The solar array was installed on June 19, 2017. All of the panels were cleaned prior to installation, and the system was then left to operate undisturbed for 16 weeks to collect baseline data.

**Figure 7: Photo of Enphase microinverter and conversion of DC to three phase AC current**

![Diagram showing DC to AC conversion](image)

Of the nine panels in the solar array, five were designated to receive the SolarKleenTech self-cleaning coatings, and four were designated as uncoated controls. To account for the variability of weather, it was necessary to schedule the panel coating application on a day without rain in the forecast, and with minimal winds. The coating was applied in the field with the panels remaining fixed in their positions on the roof racking system. Plastic sheeting was deployed to cover the control panels to ensure that they remained uncoated. Cardboard shields were inserted between individual panels to prevent overspray during application.

To prepare the liquid suspension used to coat the solar panels, the SolarKleenTech process involved mixing the two precursor sols in appropriate volumes, along with additional proprietary wetting agents to arrive at the desired formulation for the given field application. A non-aerosol sprayer (Milwaukee Atomizer) was used to deposit the coating material. The spray can was filled 2/3 with the coating material, and then the head space was

**Figure 8) Spray application of coating materials**

![Spray application of coating materials](image)
pressurized to 60 psi using a bicycle pump. A thin film was deposited by holding the spray can roughly 25 cm from the surface of the solar panels, while moving the sprayer at a horizontal rate of about 0.25 m/second. The panels were allowed to air dry after the application, and a second coat was then applied. The coating was completed on the morning of October 02, 2017. October 2 was a sunny day with clear skies, as were the next few days thereafter. This is important to note, because it is known that metal oxide thin films containing photoactive materials such as titania are capable of sintering upon excitation from ultraviolet radiation [8]. This UV induced sintering process serves to chemically bond the nanoparticles to one another, and to the panel’s glazing surface, rendering a durable thin film that is resistant to wear and dissolution.

The panels installed on the Madison College system have been in continuous operation since October 2, 2017, and are currently collecting additional data at the time that this manuscript is being prepared. All of the data for the system is recorded and logged by the Enphase System Manager Software and is stored virtually in the Enphase cloud database. The data can be accessed at any time, from any computer having an Internet connection. Figure 9 illustrates the energy output for the entire solar system for the period from July 1 to Dec 1, 2017. Clear differences can be seen in daily solar output (due to differences between clear sky and cloudy days), as well as seasonal output due to changes in day length in the northern latitudes. There was no appreciable accumulation of snow during this time period, so the measures are not affected by snow cover. Total energy produced was within 92% of that predicted by PV Watts modeling software [9] using system component specifications and 30-year average insolation and climactic data for the installed location, thus indicating that the system was properly installed and all components were functioning correctly. A total of 1.07 MWh was produced over the six-month period, having a value of about $150 in electrical savings for the college.

Figure 9: Solar system output for Q3 and Q4 of 2017.

Results
The spray deposition process required a bit of a learning curve. Prior to working with the solar panels, several hours were spent getting used to the function of the sprayer and mastering the application technique. Initial practice was conducted simply spraying a cardboard surface with a water and ethanol mixture with viscosity similar to that of the intended coating sols. This allowed students to get a feel for the deposition rate and to experiment with different size spray
nozzles. Additional practice was then conducted using an identical SolarWorld panel that was not intended for use in the field trial. It immediately became apparent that issues such as streaks and runs would be a challenge. When the process was transferred to the field for actual application to the installed solar system, additional complications arose. In order to work safely on a pitched roof surface, the student needed to wear a safety harness along with a retractable tether that was attached to an anchor point along the ridgeline of the roof. While this equipment ensures the safety of the operator, it also somewhat restricts motion. This made it challenging to maintain a constant distance between the spray can and the panel, to keep a perpendicular orientation of the spray nozzle relative to the panel surface, and to replicate consistent spacing between horizontal passes across the panel surface. As a result, the very first panel coated was somewhat of a learning process, and some minor streaking did occur during application.

The output of the solar system is monitored using the Enphase System Manager Software. The software is capable of recognizing each individual panel, according to the serial number of the inverter which is recorded at the time of the installation using a smart phone app with a camera enabled to scan the bar code that is affixed to each microinverter unit. Figure 11 shows the array layout. Panels in positions #1, 4, 7, 8, and 9 were treated with the self-cleaning coating, while positions #2, 3, 5, and 6 served as controls.

The Enphase software provides a visual graphical user interface (GUI) that is illustrated in the screenshots taken below. To make analysis simpler for this publication, we have chosen to focus our analysis only on data collected for clear sky days. It is very easy to determine if the sky is not clear (i.e. cloudy) because a temporal plot of the data will show that the output of the entire array is erratic over a 24-hour period. Figure 12 shows the total system output for a single week, and it is easy to view the difference between the clear days at the start and end of the week as compared with the cloudy days during the middle of the week where solar production was reduced to varying degrees.
Figure 12: Solar system output for one week in October 2017.

Figure 13 shows data for a clear sky day shortly after installation, with all of the panels freshly cleaned and uncoated. This information is useful because we can observe that there is some inherent variation among the panels that is not due to the application of the coating or due to soiling.

Figure 13: Solar system output for a clear sky day shortly after system installation.

<table>
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<tr>
<th>Panel</th>
<th>Energy (kWh)</th>
<th>% deviation from mean</th>
</tr>
</thead>
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<td>1.56</td>
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<tr>
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<td>1.04</td>
<td>1.56</td>
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<tr>
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<td>1.56</td>
</tr>
<tr>
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<tr>
<td>5</td>
<td>1.02</td>
<td>-0.39</td>
</tr>
<tr>
<td>6</td>
<td>1.01</td>
<td>-1.37</td>
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<tr>
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Mean: 1.024 StDev: 0.015 Relative StDev: 0.015

Figure 14: Solar system output for a clear sky day just before the coating was applied

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<th>% deviation from mean</th>
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<td>-4.47</td>
</tr>
</tbody>
</table>

Mean: 1.068 StDev: 0.028 Relative StDev: 0.028

Daily Output shortly before coating application on a clear sky day, roughly 16 weeks after initial installation of panels.
Figure 14 shows data for the panels on a clear sky day shortly before the coating was applied. It should be noted that the power output of all the panels is higher than it was in June when the system was first installed. We attribute this to cooler temperatures in the fall. As temperatures drop, PV panel output voltage rises, resulting in concomitant increases in power. Note that in the sixteen weeks since the panels were installed, the standard deviation has nearly doubled, this may be a result of differential weathering and soiling of panels.

Figure 15 shows data for the panels on the first clear sky day after the coating was applied, showing that the application of the coating did not have any sort of major adverse effect on the panels output. This is an important finding, because skeptics of the self-cleaning technology have often incorrectly assumed that the application of a coating would reduce the light transmission significantly enough to reduce the panel’s power output. As observed in the figure, the coated panels show little if any reduction in performance. Even in the case of panel #1, the difference in performance is minimal. This was the first panel coated, when the initial spray attempt resulted in drips/runs that were visible after the coating dried. The barely measurable change suggests that the field application process is robust enough that even minor errors or accidental drips that occur during deposition will not have tremendous adverse effects.

Figure 16 shows data for a clear sky day in January. It can be seen that the power output for all of the panels is lower than in June or October. This occurs because the day length this time of year is considerably shorter, so there are fewer hours of sunlight to absorb.

Figure 17 shows data for a clear sky day in February. It can be seen that the power output of every panel is abysmally low. These data are taken for a day immediately following a winter storm that deposited 5-6 inches of snow in the Madison Area. All of the panels were covered with snow on this date, and as a result the power output for each of them is minimal.
Figure 17: Solar system output for a clear sky day in February. The inset photo shows that the panels are completely covered in snow; as a result the energy produced was very low.

Discussion
The data collection efforts at Madison College are ongoing. At this time, we do not yet have enough data to definitively say whether or not the self-cleaning coatings have had an improvement on long-term performance. Nevertheless, the field trials have already yielded several other useful findings that will be helpful in the future efforts of SolarKleenTech.

Findings #1 - Application Process Variables
Several challenges were observed related to the field application for the thin films using the non-aerosol spray applicator. One problem that was probably foreseeable, and a bit of a minor annoyance was the clogging of the spray head. As the sprayer was used over time, some of the nanoparticles adhered to the spray nozzle orifice, and gradually shut down the flow. We had to change the nozzle on more than one occasion, and we were only coating 9 panels. If a similar field application was going to be attempted for a utility scale solar farm, some type of more elegant sprayer would be necessary to prevent clogging (such as one with an ultrasonic vibrating head).

Weather was also a major variable for field applications of the coating. On two sequential days we had to cancel plans to coat the panels due to rain. On the day that we were finally able to proceed, we began the day with a nice calm sunny morning. However, after applying the first coat and beginning the second, a pressure front began to move into the area and winds picked up. We eventually had to cease application after two coats because the winds had built to 7mph and were blowing overspray uncontrollably.
Lastly, spraying panels that are mounted on an incline is challenging. For anyone that has ever painted before, they know a horizontal surface is easy, but vertical walls are challenging due to the formation of drips and runs due to gravity. The same is true when spray coating solar panels, only the application is much less viscous so it runs even faster. From a commercialization standpoint, this means that SolarKleenTech ideally would prefer to spray panels before they are installed while they can still be laid flat on the ground. If they must be sprayed after mounting, the applicator technicians need to be made aware that high pitch roof structures will be significantly more challenging than those with lower slopes. In addition, for residential roof mounted arrays that are arranged in a layout similar to the ones in this study, spray application of panels in the middle of the array would be almost impossible due to the inability of a technician to reach the panel. In this experiment, the center panel was treated as an uncoated control for this reason. Field application of the self-cleaning coatings would be much easier for ground mounted or flat commercial roof mounted applications where panels are typically installed in rows with spacing between them. This layout prevents each forward-facing row from shading the next row immediately behind it. This type of panel arrangement would allow the technician to simply walk between the rows, having a good orientation for easy application of the coating.

Findings #2 - Variables related to panel soiling
There are several variables related to panel soiling that make this issue a bit more complex than one might initially expect, the first being rainfall. Rain has a naturally cleaning effect, regardless of whether or not the solar panels have had any special surface treatment. One of the reasons that this field trial might not have exhibited large effects of the self-cleaning coatings is because the coating was applied in October, and Wisconsin has had a fair amount of natural precipitation since then, which helps to clean the surface of both the coated and the uncoated control panels. From the time the coating was applied at the start of October, until the time of this manuscript preparation in early February, Madison has had over 10 inches of rain. By comparison large parts of the southwestern U.S. receive on average less than 10 inches of rain in an entire year. It may be that in order to see a more dramatic effect from the coatings the company either must wait until Wisconsin goes through a drier spell, or they might want to replicate their field trial in a location that receives less naturally cleansing rain.

Another variable that we were not able to account for is deposition rate of soiling material. We did not make any attempt to measure or to characterize this. However, we could assume that soiling in Madison would be due to some of the same components that make up our urban air pollution – namely particulate matter soot that results from smokestack and tailpipe emissions. This is an interesting case, because these emissions have actually been dramatically reduced in the years immediately preceding this field trial. Since 2010, PM 2.5 measures in the Madison Area have dropped by almost 1/3. This is due to several factors, but major ones of note include the conversion of three power plants from coal to natural gas, and the implementation of a city ordinance that prohibits diesel trucks from idling while being unloaded, or overnight at truck stops for heating the cabin. This reduction in particulate matter may mean that solar panels in Madison are less likely to get dirty today than they were 5-10 years ago.

Another variable to consider is the local microenvironment for panel soiling. Given the location of Madison College’s campus in an industrial corridor, one might expect that this location would...
experience some significant smokestack particulate emissions and tailpipe emissions from diesel semi-trucks that would soil the panels. However, in the months immediately preceding this experiment, one of Madison’s largest employers, Oscar Meyer, shut their main production facility. This processing plant is located directly across the street from Madison College. Thus, the largest possible source of airborne particulate matter soot and tailpipe exhaust was removed from the equation before the experiment even began. The reduction in local sources of airborne material for soiling panels makes the observation of self-cleaning properties more challenging. In the future, it might be easier to conduct experiments like this in a microenvironment where soiling is more assured of taking place. Examples might be at or near a waste operations center or trash dump where open incineration is practiced, or near an automotive racetrack where vehicles that are not required to have exhaust after-treatment burn large amounts of fuel.

When considering the efficacy of self-cleaning coatings, we also should consider the type of soiling material that is targeted for removal. In Madison, this material is most likely particulate matter soot. However, in other areas, such as the desert southwest it may be more likely to be aluminosilicate dust originating from dry soil that is dislodged and carried by the wind. In more humid and tropical areas, soiling often results from biological materials such as algal or fungal growth. The author’s have actually experienced this first hand in Costa Rica where a PV system was installed and left unmaintained. In a single year’s time upon return and re-inspection, the entire panel was found to be covered in a thick blackish-green biofilm slime that had essentially reduced the panels output to near zero. The function of the self-cleaning coating will operate differently in these various cases. Since aluminosilicate materials cannot be oxidized by the TiO2, cleaning in that case will be dependent on the hydrophilic properties of the coating, and a sufficient volume of rain will be necessary to wash things clean. On the other hand, in the case of a biofilm, the oxidative properties of the TiO2 could be extremely important, since this might be capable of killing the biological microorganisms that grow a panel surface, or possibly preventing them from even colonizing the panel surface in the first place.

A final variable that is not yet well understood, but certainly has an effect in Wisconsin is snow. As was already illustrated above, when panels are covered with snow, their output is reduced. This phenomenon has been well documented since the early years of solar research. It is also well known that the angle at which the panels are installed can make some difference as to how quickly the panels shed snow. What is not certain is if coatings such as that used in this study will affect snow cover and shedding. At least one study has attempted to quantify this, but the results were inconclusive [10]. Knowing that the TiO2 coatings are porous and hydrophilic, will that make the snow more or less likely to stick to the panel when it falls? Will it make the snow more likely to melt? And will it influence whether or not the snow might slide off in sheets? These are questions for which we still do not have answers. As of February 4, 2018 Madison received its first appreciable accumulation of snow this winter, and the panels are currently covered in snow as this manuscript is being written. Attention will be paid to this line of investigation throughout the remainder of winter.

**Findings #3 – Aim for panel replicates and long data collection intervals**

Self-cleaning coatings are just one factor that can affect solar panel performance. Other variables that are largely outside of the experimenters control include the amount of sunlight, temperature, inter-panel variation, transient clouds, rainfall, snowfall, and wind speed (for
convection cooling). Of these variables, some are very strongly correlated with well-defined mathematical relationships; for example as shown in Figure 18, the effects of insolation and temperature can be easily displayed mathematically by plotting I-V curves of panel performance. Other variables such as rainfall and snow are less well understood, and likely have weaker correlations. Nevertheless, it seems clear that to do any rigorous statistical analysis of the self-cleaning coating effectiveness, it will be necessary to conduct a multivariate analysis of covariance (MANCOVA), treating insolation and temperature as covariates. Given the fact that the number of variables is large, several replicate panels are likely necessary for studies such as these, and data gathering must take place over long time periods. Especially in areas with seasonal weather patterns, it is probably necessary to monitor panel performance for at least a full year in order to account for wet vs dry, and winter vs summer conditions.

**Figure 18** Effect of insolation and temperature on IV curves of a photovoltaic module [11]

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**Findings #4 – Educational Value in Real World Research**

Regardless of the ultimate outcome of the study, this activity was a great independent study learning project for the three students involved. The project provided a real-world experience with the engineering design process. Students were able to meet with a client, define a problem, brainstorm solutions, refine their design, implement the design, gather and analyze data, and share the results with the client. They also were able to learn several skills not easily taught in a traditional classroom such as experimental design, materials specification and acquisition, and project management. Since the data set being generated is quite large, the students will be exposed to data manipulation and statistical analysis techniques that are generally more advanced and more complex than that typically taught in an undergraduate course in statistics. These students were also able to work with a local start-up company, and got a small glimpse into how new discoveries are made, how laboratory discoveries are translated from the research to the development phase, and how this process contributes to commercialization and business planning. The students were able to experience hands-on work conducting the installation of a live solar PV system, and they are also co-authors on this paper.

One of the students has since completed an additional honors project conducting bench scale lab activities to complement this study. She has presented her work at a National Science Foundation meeting in Washington, DC as a member of a panel and as a poster exhibiter. She has additional plans to present at upcoming regional conferences in April and June of 2018. This sort of experience provides important opportunities for students to develop both written and oral
communication skills. These are skills that are sought after by employers, but are underdeveloped for many prospective young engineers. By helping our students to grow their abilities in these areas, collaborative independent study projects such as this one have the benefit of better preparing students for the workforce, making them more valuable (and potentially better compensated) future employees.

There is a potential for future joint R&D pursuits between the company and the college. The college is currently in the process of installing another much larger solar photovoltaic rooftop system that will include over 5000 panels and have a rated power output of 1.8 MW. This will be a massive increase in scale compared to the system used in this study. If the company determines that it is worthwhile to conduct further field trials in the Madison area, it may be possible to spray coat a large number of panels for the rooftop system, which would help to address the need for a larger number of data points for statistical analysis.

**Conclusion**

This study demonstrated a successful field application process for the deposition of self-cleaning coatings for solar photovoltaic panels. It also demonstrated an experimental apparatus suitable for making experimental measurements of the performance of self-cleaning glass coatings for solar panels. Important lessons were learned about the field application techniques for the self-cleaning coatings, which will be useful for the development of the commercialization plans for this product. Although further research is needed to reach a firm conclusion on the efficacy of the self-cleaning coating, this study is ongoing. We anticipate that as the data set grows in the years ahead, the analysis will allow for a more definitive statistical analysis of the coating benefits. The project is a model of how a partnership between a research university team, a two-year primarily undergraduate educational institution, and a start-up company can provide valuable educational benefits to students that are not otherwise easily gained through classroom studies. As the project continues, it will allow for several more students to be engaged, providing future engineers and technicians with hands-on experience in practical real-world field testing protocols.

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[11] Figure adapted from Canadian Solar CS6k-265M module data sheet. Available at: https://www.canadiansolar.com/fileadmin/user_upload/brandportal/Datasheet_All_Black_CS6K-M_en.pdf