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Self-Cleaning Technologies on solar modules and their effect on performance

Sami Virtanen

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Supervisor(s)
Kallberg Elja, Nuutinen Marjukka

Assigned by
Chuangchote, Surawut

Abstract

Solar PV systems are being installed all over the world now more than ever. Global energy crisis is leading countries to develop more policies on energy sector, especially creating incentives for renewable energies so that the production would slowly shift towards more environmentally sustainable forms. One interesting form of renewable energy is the solar PV, as it is quite care-free production method, however currently efficiency is low and soiling further lowers the efficiency.

Task was to build a small-scale solar PV system on a rooftop to monitor the effect of soiling and how self-cleaning technologies effect the system performance. Components were to be ordered and panels tested on Standard Testing Conditions (STC) before being coated with the chosen self-cleaning technologies. Objective was to find most suitable self-cleaning method for the subtropical climate in Thailand.

Results were analyzed by using quantitative methods to raw numerical data, and as a whole the study was analyzed as a case-study. Scientific sources were mainly from the internet, but some of the sources were gathered by interviewing personnel of JGSEE and CSSC. Raw data was gathered with suitable datalogging machine and analyzed with Excel.

Result was to find out which type of self-cleaning method would be the most suitable for Thailand's climate, and see how it impact the panel performance. Hypothetically company-made hydrophilic coating should've been the best type of coating to be used, but results show that the most suitable coatings are actually self-made synthetized coatings and hydrophobic coatings. As a conclusion, throughout planning should be made when planning to use self-cleaning methods on solar PV systems to obtain maximum efficiency.

Keywords/tags (subjects)
Solar PV, Solar, Self-cleaning, anti-soiling, hydrophilic, hydrophobic

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Tiivistelmä

Maailmanlaajuisen energiakriisin vuoksi nykyään asennetaan aurinkosähköjärjestelmiä kaikkialla maailmassa enemmän kuin koskaan. Valtiot kehittävät jatkuvasti erilaisia asetuksia ja säädöksiä energiantuotannon säätelemiseksi, ja tuottajia houkutellaan erilaisten houkuttimien ja tariffien avulla. Yksi kiinnostavimpia uusiutuvan energian muotoja on aurinkosähkö, sillä tuotanto on melko vaivatonta. Hyötysuhteet nykypäivänä ovat kuitenkin edelleen alhaiset, ja yksi syy tähän on paneelien likaantuminen.

Tarkoituksena oli rakentaa pienen kokoluokan aurinkosähköjärjestelmä Thaimaassa sijaitsevan kerrostalon katolle, jonka paneelit pinnoitettiin kolmella erilaisella pinnoitteella. Likaantumisen ja itsepuhdistusmenetelmän vaikutusta paneelien tuottoon. Aluksi tuli hankkia tarvittavat materiaalit ja testata paneelit Standard Testing Conditions eli STC-olosuhteissa ennen pinnoittamista itsepuhdistusmateriaaleilla. Tarkoituksena oli vertailla mikä pinnoitteista olisi parhain energiansäästön kannalta.

Tutkimuksessa käytettiin case study-menetelmää ja kvantitatiivista tutkimustapaa numeerisen datan analysointiin. Lähteet kerättiin enimmäkseen internetin tieteellisistä palveluista ja osittain haastattelemalla CSSC:n ja JGSEE:n henkilöstöä. Paneelien tuottamaa ampeerimäärää kerättiin käyttämällä soveltuvaa dataloggeria ja analysointiin käytettiin Microsoft Officen Excel-ohjelmistoa.

Tavoitteena tuli löytää paras mahdollinen itsepuhdistusmenetelmä testatuista menetelmistä Thaimaan ilmastolle, ja tutkia menetelmien vaikutusta paneelien tehokkuuteen. Itse syntetisoitu hydrofiilinen pinnoite oli lopputulosten perusteella parhain pinnoitteista. Loppupäätelmänä itsepuhdistusmenetelmiä käytettäessä paneeleissa tulisi suunnitella tarkoin ajankohdat, jotta ympäristövaikutukset eivät heikentäisi itsepuhdistusmenetelmien vaiku-

Avainsanat (asiasanat)
Aurinkosähkö, aurinkosähköjärjestelmät, itsepuhdistusmenetelmät, hydrofiilinen, hydrofobinen

Muut tiedot

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1 Introduction

The growing concern about the future energy crisis and climate change is leading the world to innovate and increase the use of renewable energy. Maybe one of the most promising renewable energy source is the sun and the energy that the sun emits. Technology to harness energy from heat and irradiation have already been used for decades, but due to the cost-to-efficiency ratio, the systems has not been so attractive to the masses. During the last five years, governments, as well as different national organizations, have promoted the use of renewable energy through incentives, and this has lead to a positive growth in the use and installed number of solar modules. Amount of 59 gigawatts were installed globally in 2015, which meant a 34% growth from the year 2014. (Munsell 2016) The popularity of renewable energies can be seen in the power sector by studying the growth in the capacity installed annually. In the end of the year 2016 it was estimated that nearly 62% of the net addition that was globally installed were in fact renewable energy sources. From this amount the solar power accounted roughly for 47%.

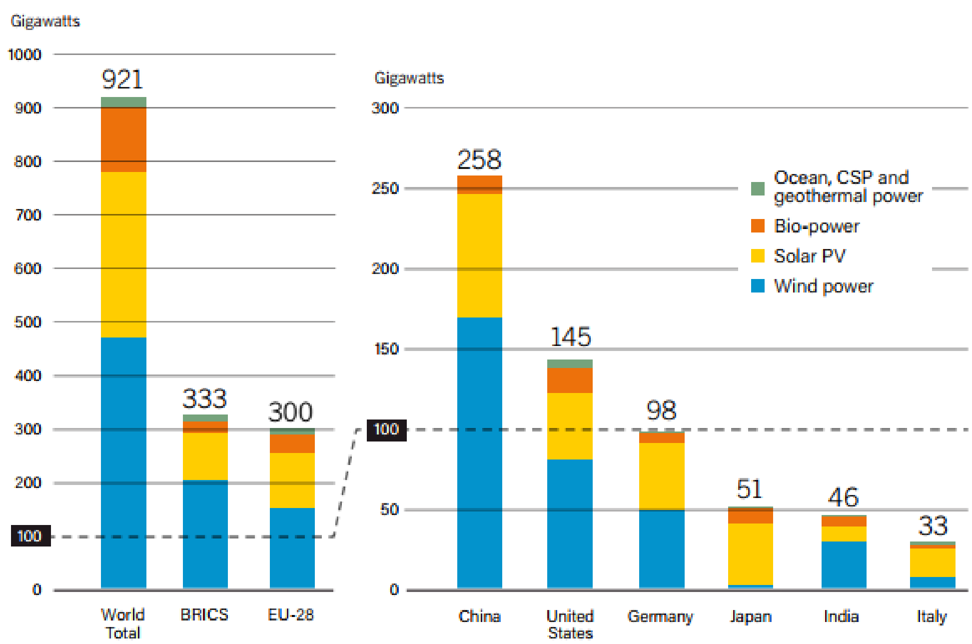

Figure 1. Renewable Power in the world and top 6 countries total installed amount 2016 (REN21 2017)

Currently, the total amount of non-hydro renewable power in the world totals at 921 GW as seen in Figure 1. The highest contributor to using non-hydropower renewable energy currently is China with 258 GW installed, and 564 GW if hydropower is included. 45% of the capacity added by China in the year 2016 was solar PV. The runner-ups in the total amount of installed renewable energy, non-hydropower were the United States, Germany, Japan, India and Italy respectively. (REN21 2017)

Solar modules face the same problem as many other surfaces on daily basis, the effect of contamination from various sources such as pollen, dirt or animal feces. The accumulation of material on top of the surface leads to reduction of efficiency up to 30%. (Crawford 2012) As the efficiency reduces due to soiling, it also leads to a loss of power and profit for the user. Solar panels have already quite low efficiency, around 15% to 20% with the equipment on the market, so that the impact of having a loss of up to 30% can accumulate in massive losses in solar farms and households.

This study focused on studying the effects of self-cleaning technologies in solar modules and their effects on the total efficiency of the system. In this particular study, the passive self-cleaning technologies were studied to find the best possible way to enhance the maximum power output, as well as, the lifetime of the module. Types of modules available to testing are thinfilm, mono- and polycrystallized modules, but this study focuses on using the polycrystallized ones as they are one of the most widely used module types globally. (Fraunhofer Institute for Solar Energy Systems 2016) A set of modules is placed on a platform with the necessary tools for measuring the data. In this study, two sets of four panels were used. One set was a reference set, and it was left untouched until the end of the study, while the other set was cleaned every week. In the set, one of the panels was not coated and here on, it is addressed as the reference module. The other modules were coated each with a different technology to determine which one was the most suitable and to see the effects on overall efficiency when compared to the reference module.

As this study was carried out by following the JAMK University of Applied Sciences curriculum, many aspects had to be eliminated to keep the study within the time limits and reasonable funding. As the study was conducted within three months, during which one month was spent with material acquisition and two months with recording, the results are sufficiently reliable to be used as a base for future studies, but not sufficiently reliable to be used in marketing purposes. This study did not take temperature changes in the climate and on the surface of the panels into account due to financial issues. Wind speed and direction were not considered either because of the lack of equipment. This study is relevant in the tropical climates, such as that in Thailand, in subtropical areas near seashore and with similar distance from the equator. The results and conclusions given in this study may not be accurate in other climates.

The thickness of the soiling layer was not measured, as there was no equipment available at the JGSEE for measuring. The uniformity and thickness of the coating material couldn't be verified as the equipment were unavailable at the time.

2 About the Joint Graduate School of Energy and Environment

The Joint Graduate School of Energy and Environment (JGSEE) was established in 1998, and it is an international school focused on awarding Master's and Doctorate degrees in the fields of energy and environmental research. JGSEE is a consortium project as it involves the five leading institutions in Thailand, which are King Mongkut's University of Technology Thonburi (KMUTT), King Mongkut's Institute of Technology North Bangkok (KMITNB), Prince of Songkla Univesity (PSU), Chiang Mai University (CMU) and Sirindhorn International Institute of Technology-Thammasat University (SIIT-TU). JGSEE conducts research on both fields to support the financial growth of Thailand and to develop the skills of the students. JGSEE's vision is to be an internationally recognized research and education center in the fields of energy and environmental technologies.

JGSEE has an objective to be known as a university that educates human resources that are needed in the governmental, private energy and environmental sector as well as a university that enhances the quality and number of postgraduate students. JGSEE also works closely on research and development with the government and private sector companies, and they focus on researching fossil fuels, renewable energy and energy management, as well as environmental topics related to them. (JGSEE N.D)

JGSEE is located on the main campus of the King Mongkut's University of Technology Thonburi (KMUTT). The campus is in Bangkok, in the Bangmod area. KMUTT is one of the leading universities in Thailand, and it has been ranked in the top 50 in the Asian countries' university ranking by Times Higher Education World University Rankings 2012. (King Mongkut's University of Technology Thonburi. N.d.)

3 Solar power currently

The estimated share of the total capacity of renewable energy from the global electricity production in the end of 2016 was roughly 25% and from that amount solar PV had the share of 1.5% being the fourth largest renewal energy contributor. By the end of year 2016, the total installed capacity went over 301 GW, with increase of over 33% compared to the year 2015. The largest contributors were China with 34.5 GW and the United States with 14.7 GW. (BP N.D.) Thailand's annual installed capacity in the third quarter of 2016 was 740 MW, and the cumulative installed capacity was 2761 MW.

Successful policies and a high number of sunny days are some of the reasons why Thailand is highly interesting to the investors and why the country has invested in growing the amount of solar power. Thailand was the first country in The Association of South East Asian Nations (ASEAN) that introduced feed-in-tariff (FiT), which was initially as high as 8 baht/kWh solar as seen on Figure 2.

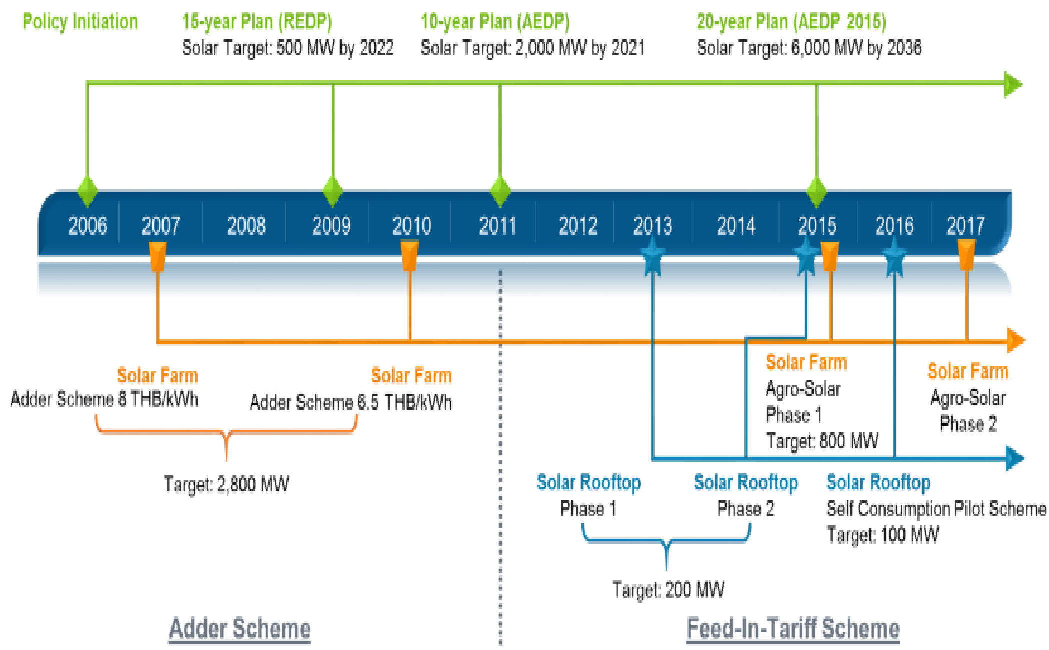

Figure 2. Timeline of Thailand's solar PV policy (Federal Ministry for Economic Affairs and Energy)

Although the initial feed-in-tariff that was introduced was as high as 8 THB/kWh, the break-through in the growth of solar power happened after 2010, after the tariff had been adjusted. The reason why the growth was in a stand-still during the beginning of the program was probably the high cost of solar PV technology at the time. Moreover, the instability of the market caused investors to be cautious about investing in projects based on new policies. (The World Bank 2014)

The feed-in-tariffs have been adjusted since then, favoring those who produce less than 10 kWp with the tariff of 6,85 THB/kWh, although new reports from government suggest that tariffs would be removed from small-scale producers and shift towards the more self-consumption driven market. In the utility scale sector, the feed-in-tariff is estimated to be lowered by roughly 30% from 5.66 THB/kWh to 4.12 THB/kWh.

Thailand introduced a program in 2015 called Alternative Energy Development Plan (AEDP 2015) which had a set of targets to be achieved by the year 2036. The program was reviewed and accepted by the National Energy Policy Council (NEPC) in September 2015. The total renewable energy produced by the year 2036 should be 30%

from the consumption of electricity, heat and fuel. Electricity made with renewable energy should be between 15-20% from the consumed energy, totaling in the installed capacity of 19684 MW. Thailand has set a goal of 6000 MW installed solar energy by the year 2036. Currently, Thailand has 2761 MW of installed capacity, with 2631 MW being installed as solar farms and 130 MW as solar rooftops. Figure 3 depict both the installed annual capacity as well as the cumulative capacity of Thailand's Solar PV. (Federal Ministry for Economic Affairs and Energy 2017)

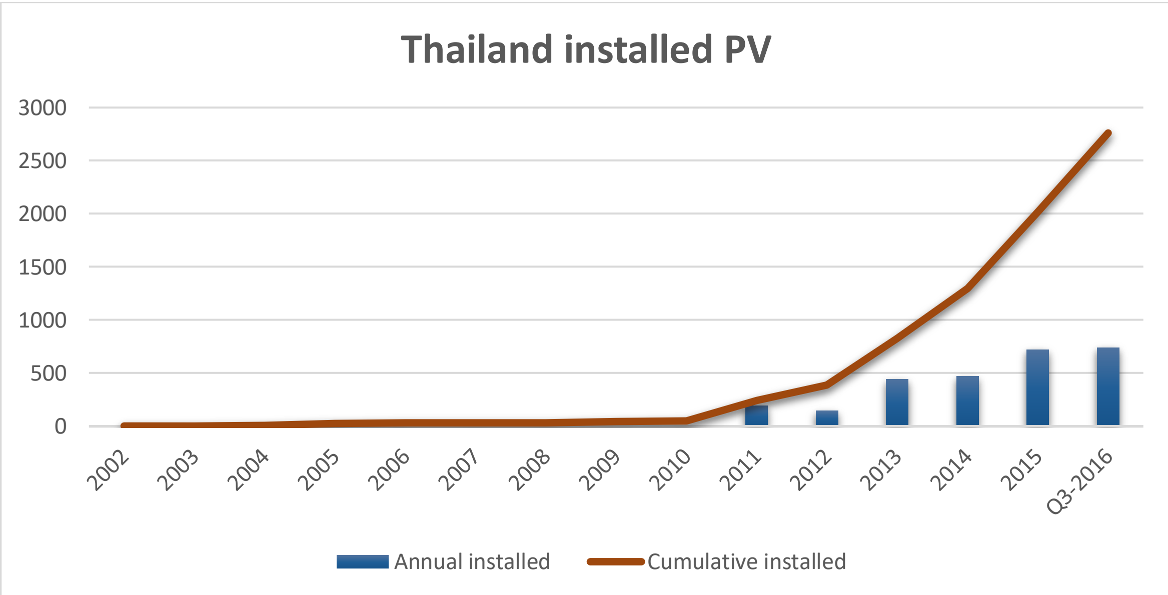

Figure 3. Total installed PV capacity in Thailand

4 Methods

4.1 Preparing the testing

The test was conducted on the rooftop of a six-story building in the KMUTT Bang Khun Tian campus. Rooftop management belongs to the CES Solar Cells Testing Center (CSSC) so the permission to use the rooftop had to be requested from the director of CSSC, Dr.Dhirayut Chenvidhya. After obtaining the permit to use the rooftop as the testing site the next step was to gather materials and necessary equipment for collecting the data from the panels. A data logger was provided by the CSSC and JGSEE, and shunt resistors were ordered from an electronics store. The shunt resistors were rated 10 A and 75 mV with a resistance of 7.5 mΩ. As the shunt resistors might have variations in the parameters, they had to be tested to measure the real resistance. Testing was done with an oscilloscope and with a reference shunt resistance with the rates of 1 A and 1 V. (Appendix 1.)

After gathering and testing the necessary components, the next step was to build a suitable rack for supporting the solar panels. The rack material was a square profiled galvanized steel tube sized approximately 22 x 22 mm, with a tiltable mounting system. The system angle was adjusted to 14^{o} to achieve the optimal irradiance for the latitude in Thailand.

Figure 4. Finished rack for the solar panels

In Figure 4, there is the reference rack that was not cleaned during the testing. The angle of the rack was confirmed with a digital angle gauge, and the panels were facing south to maximize irradiance during the day.

Figure 5. Rack for shunt resistors

After building a suitable rack for the solar panels, a rack was built for the shunt resistors inside the server room located in the rooftop as in Figure 5. The resistors should be installed somewhere where the temperature can be kept constant, as the resistance varies in different temperatures. The server room had an AC unit, and the temperature was set to be 27 degrees Celsius.

Finally, the solar panels were tested in a IEC-standard approved testing facility to make sure that the modules were working as intended. The panels were tested visually for any punctures, scratches or any other visible damages and defects that could make the panel operate in a faulty way. One of the panels did not pass the test, and it was sent back to the factory and replaced. Next, the panels were sent to performance test. They were tested in the Standard Testing Conditions (STC) laboratory that follows the IEC-standard IEC 61215 for polycrystalline PV modules. The module temperature was set to 25 degrees Celsius and irradiance to 1000 W/m^2. Table 1 shows the results of the STC-test done to the panels that were used in the study.

Table 1. STC-test results for the solar panels

CONDITION FOR TESTING: Module temperature: 25 °C and Irradiance: 1000 W/m^2

RESULTS:

TEST CODE	Pmax (W)	Isc (A)	Voc (V)	Imp (A)	Vmp (V)	Eff. (%)*	FF. (%)
60086PV001	139.4	8.48	22.4	7.97	17.5	13.7	73.3
60086PV002	139.1	8.48	22.3	7.84	17.7	13.7	73.6
60086PV003	136.0	8.40	22.0	7.90	17.2	13.3	73.7
60086PV004	137.5	8.45	22.1	7.99	17.2	13.5	73.7
60086PV006	136.0	8.38	21.9	7.90	17.2	13.3	74.0
60086PV007	138.7	8.46	22.3	7.92	17.5	13.6	73.7
60086PV008	138.8	8.47	22.3	7.93	17.5	13.6	73.3
60086PV009	141.6	8.67	22.4	8.08	17.5	13.9	73.0

*Eff. = Module efficiency

UNCERTAINTY: The measurement uncertainty for all values of power measurement is 2.24% with coverage factor 2.0

As it is quite impossible to manufacture solar panels with perfect uniformity, the STC-test is needed to measure the parameters of each module accurately. As on the figure 6, the results of the STC test are shown and the results show that there can be up to 4% difference in the maximum power output P_{max}. Efficiency of the panels are normal, as the efficiency ranges between 13-16% normally with the polycrystalline panels. (Maehlum, M. A. 2015) FF means “Fill Factor” and it describes the ratio of areas between I_{sc} - V_{oc} curve and I_{mp} - V_{mp} curve. After the performance test, the panels are tested in the insulation test. This test measures the safety of the panel, so that when the panel is operating, there will be enough insulation between the electricity conduction components and the frame. If the panel has insulation problem, it can lead in worst cases to serious damages or fatalities. The minimum insulation resistance shall not be less than 40 MΩ per square meter. Table 2 shows the results from the insulation test. (Arndt, R., Puto, I.R. N.D)

Table 2. Insulation test results

TEST CODE	DC withstand test	Insulation resistance	
60086PV001	PASS	168 $M\Omega \cdot m^2$	PASS
60086PV002	PASS	201 $M\Omega \cdot m^2$	PASS
60086PV003	PASS	1.08 $G\Omega \cdot m^2$	PASS
60086PV004	PASS	0.94 $G\Omega \cdot m^2$	PASS
60086PV006	PASS	0.98 $G\Omega \cdot m^2$	PASS

4.2 Coating

In the beginning of the experiment three different self-cleaning technologies were compared and chosen and they were two different type of hydrophilic coatings and one hydrophobic coating. Mechanical and electrical cleaning were left out due to short amount of time and the growing expenses. Hydrophobic and hydrophilic coatings were chosen, as they are relatively cheap, and the coating is easy to apply on solar panel surfaces. Both hydrophilic coatings were applied to the panels with a pressure sprayer and the hydrophobic coating was applied with a sponge and a squeegee. Hydrophilic coatings were sprayed three times both horizontally and vertically throughout. Hydrophobic coating was applied three times as well to ensure the coating is applied evenly. Before applying the coating to the panels, they were cleaned with isopropyl alcohol to remove all excess oil and dirt from the surface. Figure 6 shows the company representative applying the hydrophilic coating on one of the solar panels.

Figure 6. Applying the hydrophilic coating

Hydrophobic coating was added to the surface using rotational movements with the sponge that was soaked in the coating compound. Cleaning should be done without any tools, such as sponges or squeegees, as it may damage the sensitive surface. Damaged surface may lose the effectiveness from applied coating.

One of the coatings used in the study was synthesized by the JGSEE. Coating was made by using titanium(IV) butoxide, isopropanol and distilled water. 70ml of Titanium(IV) butoxide was mixed with 80ml of isopropanol in a magnetic stirrer with a speed of 600 revolutions per minute (Figure 7).

Figure 7. Titanium(IV) butoxide and isopropanol mixing

After mixing the titanium(IV) butoxide with isopropanol into the mixture was added some zeolite. Zeolite will act as a binder material for the finished titanium dioxide, as the titanium will form bonds with silica-dioxide molecules that are released from the zeolite during the process. (Woodford, C. 2016) The mixture was mixed for 30 minutes at 630rpm and after pouring the mixture to a wider bowl for settling, no sediment was discovered. After the mixture set from liquid to a gel-like form, the gel was put to oven over the night at 38 °C to make it solid. Solid material was grinded in a mortar as fine as possible, and the fine powder was causticized at 560 °C in a high temperature oven. Causticized powder was then grinded again and added to the company made TiO_2 coating. (Roongraung, K. 2017)

4.2.1 Hydrophobic coatings

Two panels in total, one in each rack, were coated with a hydrophobic coating. Hydrophobic coating creates a "lotus-effect" on the surface of the panel. This means that rain drops will form a more round-shaped droplet of water, which will then roll down from the surface. As the surface of the solar panel is coated with hydrophobic coating, it will become nonpolar and resist the polar water molecule. Because of this the droplet will form a round, ball-like shape, and so the friction from the surface is lower thus resulting that the droplet will slide down easier.

When raining, or during cleaning, the droplet rolls down the surface and collects particles resulting in a cleaner surface.

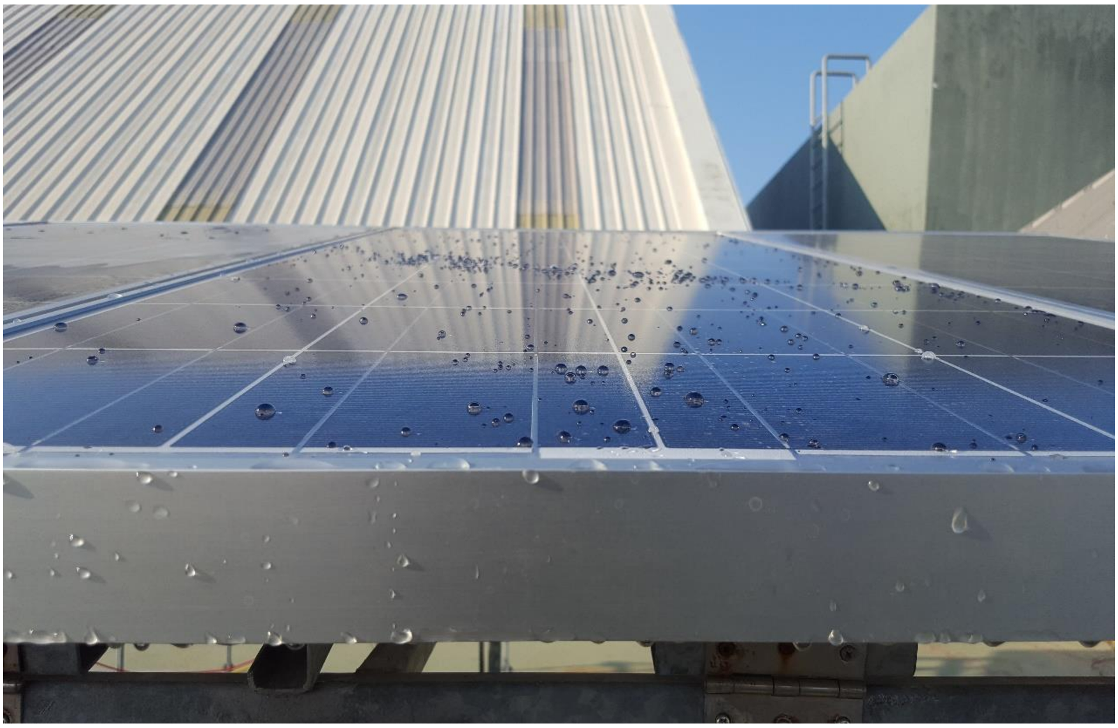

Figure 8. Water droplet on a hydrophobic surface

As seen on the Figure 8, after pouring water on the hydrophobic surface it will form cluster of droplets, instead of forming trails of water.

4.2.2 Hydrophilic coatings

Hydrophilic coatings are basically the opposite of hydrophobic coatings. Hydrophilic coatings attract water, so that the water will form a thin uniform layer on the surface (Figure 9). As seen in comparison, the hydrophilic coating forms a uniform layer compared to the round droplet made by the hydrophobic coating. These two different methods of self-cleaning drive the same ultimate purpose.

Figure 9. Hydrophilic panel (left) and hydrophobic panel (right).

Hydrophilic coatings form a polar layer onto the applied surface, which will attract polar molecules, such as water. Because of the polar properties hydrophilic coatings have, they are excellent in humid climates, such as Thailand. The coating will absorb moisture from the air, wetting the surface. In this case, when the surface of the solar panel is wet, the coating will begin photocatalyst process which will activate oxygen atoms in the water molecules. (TOTO Ltd. N.D.)

Photocatalysis is a photochemical reaction, where light activates the reactant to an excited state. Reactant then will react with other compound, in example a normal hydrocarbon and result in two reaction products. Preferred reaction is one where the catalyst returns to its original state after the reaction. Figure 10 shows the picture of ideal photocatalytic process, and Figure 13 shows a simplified photocatalytic reaction. (König, B. 2013)

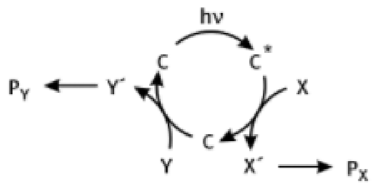

Figure 3.2: Reaction scheme for a photocatalytic reaction.

Figure 10. Ideal photocatalytic process. (König, B. 2013)

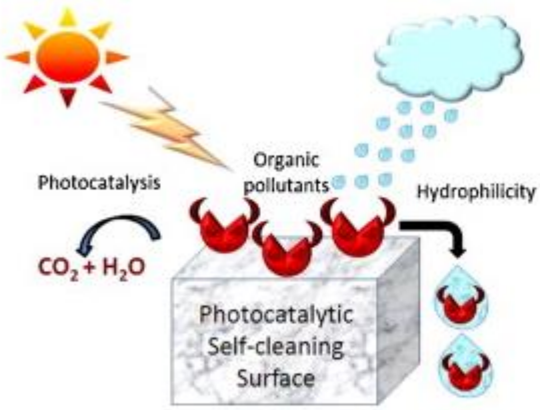

Figure 11. Simplified photocatalytic reaction (Banerjee, S., Dionysiou, D., Pillai, S. 2015)

Photocatalyst titanium dioxide forms activated oxygen from the oxygen atom in water molecule, or from surrounding moisture in air, when reacted with ultraviolet light. In natural surroundings the UV light is all around in the form of sunlight. UV light will react with TiO_2 creating the activated oxygen from moisture. From the process hydroxyl radicals are created, which have strong oxidation properties. Radical hydroxyls have the ability to kill microorganisms, viruses and other organic contaminants. Super oxides can decompose organic materials. (Wu, et.al. 2014)

This study chose two different hydrophilic coatings to be part in the study. Both hydrophilic coatings were titanium-dioxide based compounds that had the ability to break organic matter. Both coatings were manufactured in Japan by the same company, but the JGSEE further developed one of the bought coatings to see how added titanium-dioxide will behave in the compound. At start, both compounds were transparent with a slight white hue, but after further addition of TiO_2 by JGSEE, the other batch wasn't transparent anymore as it was visibly white-colored compound. The particle size in the original product was 25nm, and on the mixed compound the particle size of the added TiO_2 couldn't be measured as no suitable equipment was available.

5 Results

After all the preparations were completed, the testing was ready to begin. The reference panels had already been installed before the coated panels because the coated panels had to be left to a warehouse to dry-off before installing to the rack. The testing began by connecting all the panels to the data logger, followed by the proper cleaning and testing of the coated panels. The cleaning was done by pouring roughly two liters of clean water evenly on each panel. Each panel was photographed before and after each clean-up, although no photographs were taken before the first clean-up. The panels were photographed so that every time a photograph was taken at the same spot as the last time. For photographing the accumulated dust, a 40x zooming lens was used on a mobile phone camera. Due to the instability of a hand-held camera, the photos may not have always been precisely from the same spot, but they were sufficiently close for determining the effect of the cleaning. Figure 12 shows the photographs before and after the cleaning of the same panel.

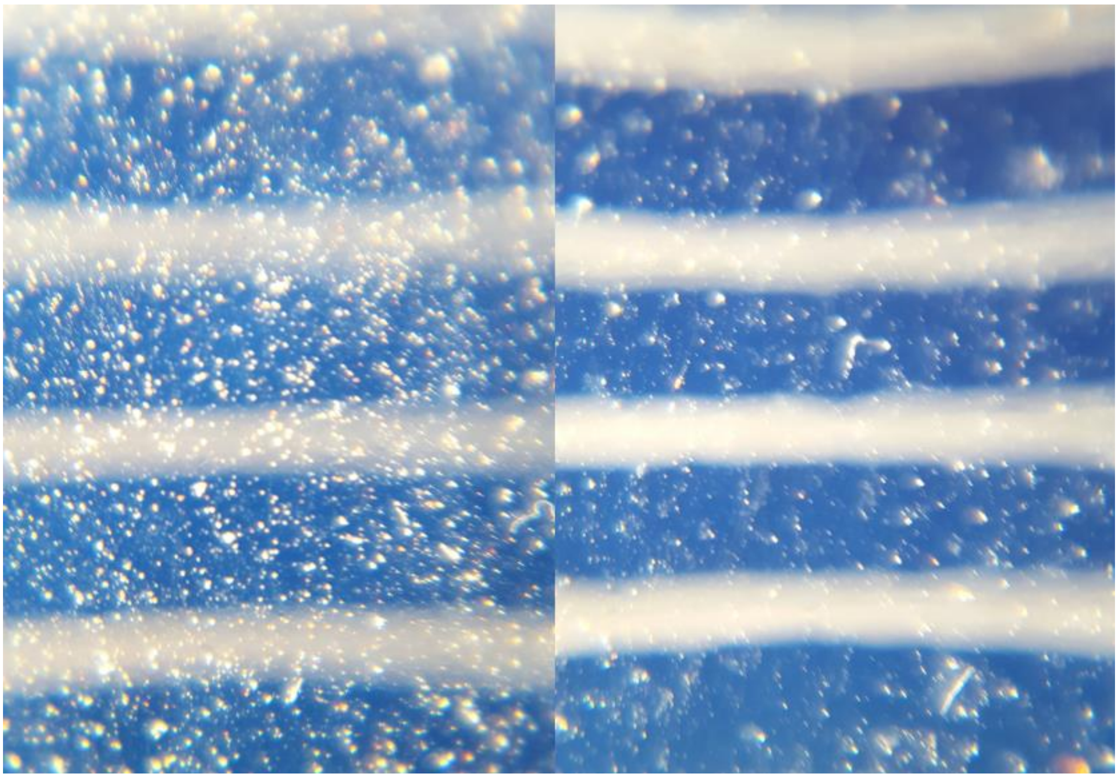

Figure 12. Before and after cleaning

Figure 12 depicts the company-made hydrophilic coated panel on rack 1. The white horizontal lines are the conductor strips on the cell, and the white crystals and dots are the impurities, mostly microscopic dust. As seen, the difference is considerable when compared to the state before cleaning. With this type of method used in the cleaning, all of the dust could not be removed because some of the dust formed electrostatic bonds between the particle and the surface. (Yilbas et.al. 2015)

Panels from reference rack 1 were cleaned once per week, on every Monday during the midday. Each week, the photographs were analyzed to determine the accumulated matter and then compared with the fluctuation in the short circuit current data collected from the data logger. Typically, the climate in Thailand during January-May is dry and hot with very little rainfall. Rainfall lowers the total amount of irradiation received from the sun due to the thick layer of clouds. Decrease in irradiation also lowers the performance of the solar panels momentarily, but self-cleaning technology should compensate the decrease in the long run. Figure 13 shows the I_{sc} charts from a normal sunny day compared to an unstable rainy day. The graph in Figure 13 is from a panel in reference rack 2, and by further inspecting the graph a momentary rise in the I_{sc} can be noticed. The maximum output starts to degrade in the following day, highly because of the accumulated dust.

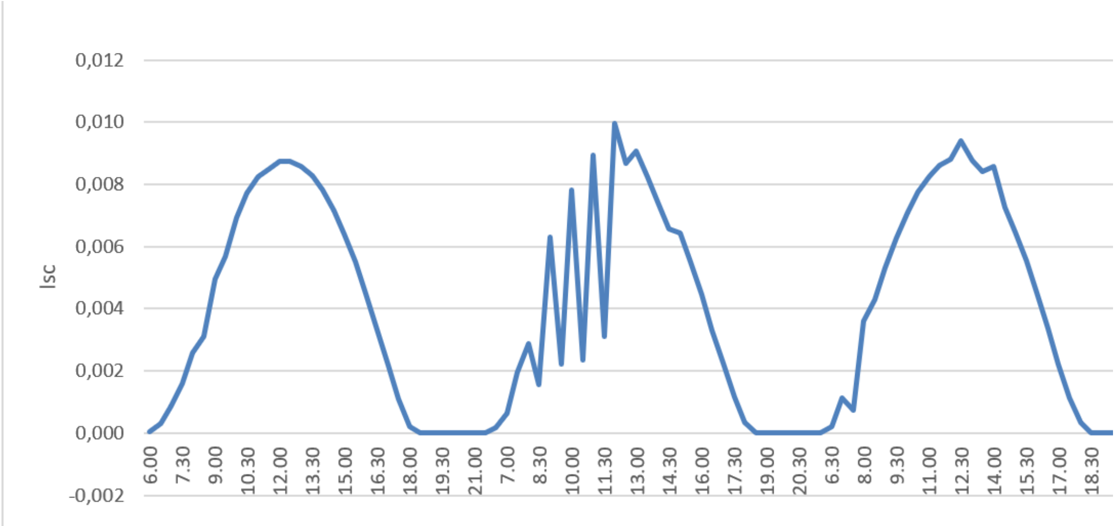

Figure 13. I_{sc} difference on a normal day compared to a more unstable day

The hypothesis in the beginning of the study was that the hydrophilic coating would suit the sub-tropical climate of Thailand, especially as it was the end of the rain season when the study began. The hypothesis was based on the fact that the hydrophilic coatings would capture moisture from the humid air more easily and that the photocatalysis would break the organic matter, resulting in a cleaner surface. Hydrophobic coatings are better in areas with more rainfall, as the surface of the panel will not stay wet for long periods of time, thus resulting in less light lost due to the refraction. Hydrophilic coatings work well in hot areas as water forms a thin layer on the module and dries faster. After each weekly clean-up, it took roughly 20 minutes for the hydrophilic panels to dry, roughly 30 minutes for the uncoated panel and almost 50 minutes for the hydrophobic panel to completely dry. This strengthened the hypothesis of hydrophilic coatings being more superior than the hydrophobic coatings.

When the data was collected, it had to be normalized in order to be comparable. As some panels had higher efficiency and higher I_{sc} values than other panels, they could not be compared as the values favored those panels that had higher efficiencies. The panels were normalized by the I_{sc} values, so that panel 1 was the reference panel, and every other panel's I_{sc} values were adjusted to those values. Normalization was done simply by comparing ratios between the I_{sc} values to panel 1's I_{sc}. (Table 3.)

Table 3. Normalized Isc values

Panel ISC normalization	Isc	Isc normalized
PV001	8,48	1
PV002	8,48	1
PV003	8,4	1,00952381
PV004	8,45	1,003550296
PV006	8,38	1,011933174
PV007	8,46	1,002364066
PV008	8,47	1,001180638
PV005	8,67	0,978085352

With the normalized I_{sc} value all of the data from the datalogger that was gathered were multiplied to even the differences, so that the values are comparable to see which of the coating performed worst and the best. Data gathered to the comparison was taken from irradiation of 900 W/m^2 with a 10% error margin. Data was taken and analyzed weekly from each Tuesday to make sure that the cleaning process had no effect on the data, or there weren't any issues with the electricity.

Data gathered had many surprises and didn't quite follow the hypothesis as expected. As expected the hydrophilic TiO_2 coated panels had slightly lower values compared to other panels due to the titanium-coating effecting the absorption of the irradiation, yet the self-made coating panel on rack 1 which had added TiO_2 had the best values during the first week, while worst was the non-coated panel on rack 2. (Figure 14)

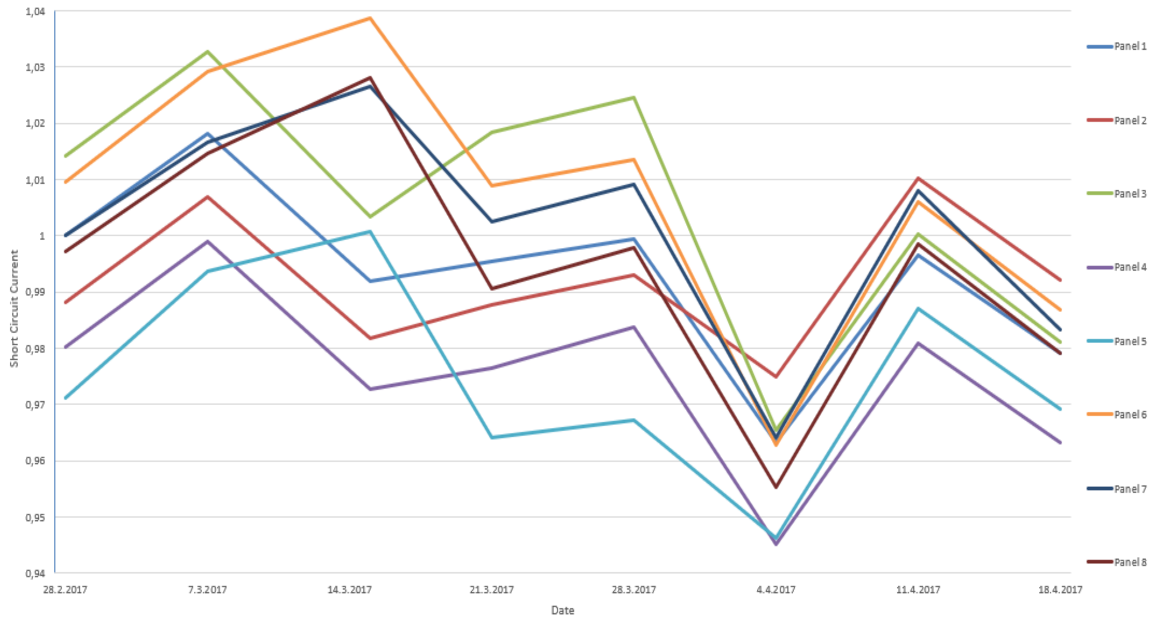

Figure 14. Comparison of the normalized values

Interestingly enough, all of the panels on rack 1 experienced a dip after the first week compared to the rack 2 which all had growth on I_{sc}. This could be explained by a possible sandstorm after the clean-up on week 2, which could actually affect the dust to form mud when on contact with moisture or liquid. The effect from the dust wouldn't be as big when on contact with a dry surface on the second rack panels and could possibly just fly over or fall off from the surface. Second rack panels experienced similar trend than the first rack panels after the second week, which can implicate that the assisted cleaning actually helped and had effect on the rack 1 panels. Trend for all panels seemed to normalize after third week, which was expected, with the hypothesis on cleaned panels having better values compared to the beginning. Interesting is that by the end of the study the rack 1 company made hydrophilic coating is actually performing worst compared to the other panels. This may be because of the added absorption from titanium dioxide and added reflection from the added water combined, since the non-cleaned hydrophilic panel performed better on comparison.

Best results were achieved by the self-made and company made titanium dioxide mixture, which is quite interesting as the company made titanium dioxides by themselves were not performing as well as expected. One reason for this type of behavior could be explained by adding more titanium dioxide with the silica binder to the company mixture, it actually formed much denser concentration of titanium dioxide which in turn accelerated the self-cleaning effect. One valid reason is also that by adding the titanium dioxide to the solution it actually didn't mix completely and in turn formed un-even layering to the surface. This could make the panel to perform better, as the coating has less absorption area.

Hydrophobic coatings performed better than expected, and especially the panel on second rack. Panel which wasn't cleaned during the testing period performed better than the panel that was cleaned weekly, although the difference is quite small. Reason for this type of behavior could be explained similarly as what happened to all panels on the rack 1 after first week. As the panels were drying after the cleaning, the hydrophobic panel had some droplets staying in the surface instead of rolling down as intended. This is because the panels angle isn't steep enough, and so some of the droplets remained in the surface. When the droplet dried on the sun and some dust particles were within the droplet, they dried as small clusters of dust. (Figure 15.)

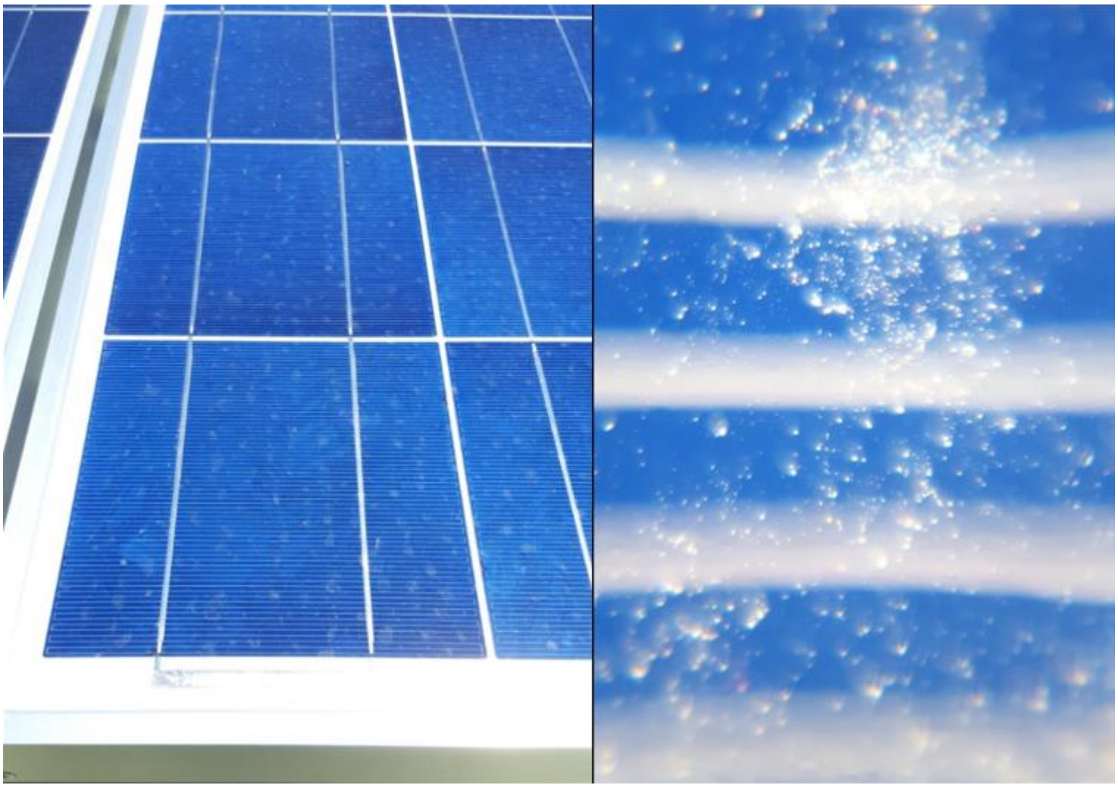

Figure 15. Dried droplets on the surface (left) with a 40x zoom on a droplet (right)

Having the dust clusters on the panel had no doubt effect on the performance, whilst the panel which wasn’t cleaned didn’t have this sort of clustering. Judging from the data the hydrophobic is actually working better in Thailand’s climate compared to non-coated or company-made hydrophilic coating. Table 4 shows the pros and cons listed for each type of coating.

Table 4. Pros and cons of the different coatings

Coating type	Pros	Cons
Self-made hydrophilic	Performed well, worked best in both racks. Dries quickly when wet, dust and other matter fairly even scattered on panel. Animal feces disappeared from the surface faster compared to hydrophobic	Requires the commercial made hydrophilic coating as a base. Requires a bit more work and equip-ment when coated com-pared to hydrophobic. Uniform moisture layer may attract more dust compared to droplets.
Hydrophobic	Performs quite well, es-pecially works well on wet climate. Coating pro-cess easier than hydro-philic.	If the angle of the panel is not steep enough, may result in dust clusters on the surface of the panel. Droplets take long time to dry.
Commercial hydrophilic	Transparent, had no visi-ble hue on the coating. Short drying time. Animal feces disappeared from the surface faster com-pared to hydrophobic	Performed worst com-pared on other coatings. Requires a bit more work and equipment when coated compared to hy-drophobic. Uniform mois-ture layer may attract more dust compared to droplets.

6 Conclusion

In conclusion, the study was conducted between January and May 2017, during the dry season in Thailand. The first part of the project was the purchase and acquisition of materials, followed by testing the materials used in the study and finally by setting up the system. Data was gathered by a datalogger and processed using Excel. Solar panels were installed in two different racks, which were tilted 14-degree angle. One rack would be the reference rack, which wasn't cleaned during the whole process, whilst the other rack was to be cleaned every week. Both racks had one panel which wasn't coated in any way. Coatings that were used were company-made hydrophilic coating, company-made hydrophobic coating and self-made coating which was a mix of synthetized titanium dioxide and company made hydrophilic coating. Hypothesis for the results of the study were that the hydrophilic coating purchased from a company would be most suitable for the Thailand's subtropical climate, whilst non-coated would perform worst and hydrophobic coatings somewhere between.

Results show that actually the self-made coating performed the best out of any other method and company made hydrophilic coatings didn't perform as well. Hydrophobic coatings performed quite well, being the 3rd and 4th best options. Hydrophobic coated panel that wasn't cleaned periodically performed better than the cleaned one. Company-made, non-cleaned, hydrophilic coated panel shares the 5th place with reference panel from rack 1, and followers being reference panel from rack 2 and commercial hydrophilic coated panel from rack 1 respectively.

Judging from the results it's clear that when planning on installing solar PV systems the self-cleaning methods can have quite large impact on the performance. Self-cleaning technologies should be considered with time and care, so that the right type of coating or system is installed to maximize the effectiveness. Results show that during the cleaning many aspects should be considered, such as when the cleaning should be done, and how the cleaning should be done. Cleaning during a dry and windy season could actually create soiling on the surface as dust particles form mud with moisture, and when using the hydrophobic coating the angle of the rack should be enough that all of the droplets actually fall off. This problem could be resolved by using a motorized rack, which tilts the angle steeper when the panels are sprayed with water.

7 Comments

The idea of the study was interesting, but the short amount of time was a problem. To get clear vision on the effect of the dust and self cleaning the data provided should be from a longer period. Seven weeks of data would be okay for laboratory conditions, where no other forces could intervene with the data, such as wind, direction of wind, sandstorms, possible animals and ofcourse heat of the module and the cooling done by wind.

The schedule was problematic, as in the beginning of the study every component and part had to be ordered, with the exception to the rack and some minor tools. The STC testing scheduled for the panels also got delayed by three weeks, which meant that basically nothing could be done at that time. Also some weekends and during the week the datalogger was turned off either by user or by some electric work done in the campus area. All these contributed to the lose of data and time.

By the end of the test the original plan was to test the solar panels once more in the STC test, but with all setbacks during testing it couldn't be done. The STC test would've been important on seeing the effect of the coating to the overall output of the panel in the STC conditions, as the conditions are the same on each panel. Standard temperature on each panel, as well as standardized irradiation, which can have some fluctuation on the field. One of the ideas that could've been quite interesting and probably quite relevant for the study as well, would've been the use of electron microscope to see the uniformity of the module coating and how the self-made coating differs from the company manufactured.

Overall, I'm pleased with the study and I believe the data is relevant, even if there is small amount of it. In the end, one of the meanings for this study was to be a base for a larger scale study and I believe this is a good base to start more throughout study.

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Appendices

Appendix 1. Shunt resistor testing results

Pyranometer	$16.31*(10^{-6})$ V/Wm^2		Y = Isc
RD-IN-028	Y = 0.1346X	0,1346	X = mV
RD-IN-019	Y = 0.1318X	0,1318	
RD-IN-025	Y = 0.1361X	0,1361	
RD-IN-026	Y = 0.132X	0,132	
RD-IN-024	Y = 0.1337X	0,1337	
RD-IN-018	Y = 0.135X	0,135	
RD-IN-022	Y = 0.1345X	0,1345	
RD-IN-027	Y = 0.134X	0,134	