RESUME – Zi Wei CHEO

Personal Information

Name	:	Zi Wei CHEO
Nationality	:	Malaysian
Date of Birth	:	4th May 1991
Gender	:	Male
Tel No.	:	+60 18-772 8677
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Highest Education Level	:	Master of Electrical Engineering (2016); Specializations: 1. Smart grid 2. Renewable Energy (Solar PV) 3. Demand Side Energy Management
Language Ability	:	1. Mandarin – mother language 2. English – confident 3. Malay – confident
Software Ability	:	1. Microsoft Office (Word, Excel Power Point) 2. AutoCAD 3. MATLAB 4. Programming languages: Java, JavaScript, C#, php, HTML 5. PostgreSQL, MySQL Database
Qualifications	:	1. Board of Engineers Malaysia (BEM) - Graduate Engineer in Energy Systems (License no: GE-91133) 2. Solar Energy International (SEI) – PVOL 202 Advanced PV System Design
Publication	:	The 1st EAI International Conference on Smart Grid Assisted Internet of Things (2017), Ontario, Canada *Smart Home/Building Energy Management System for Future Smart Grid Architecture with Automated Demand Response Applications*

Zi Wei CHEO – EDUCATION

<table>
<tr><th>Year</th><th>Education and Major Achievement</th></tr>
<tr><td>Sep 2014
until
Aug 2016</td><td>National Cheng Kung University (NCKU, Taiwan)
Master Degree

➢ Electrical Engineering (energy and power system, smart grid)

➢ Participating in:
• Project Manager: collaboration project with VTT, Finland
- H/BEMS in VTT apartment
- Integration and automation of Tatung’s smart home appliances
- Integration of VTT’s distributed renewable resources
- Integration of VTT’s BESS and EVs
- Integration of demand response and OpenADR 2.0b
- Managing a team of 8 members

• National Energy Program Phase II (NEP II)
- Long-term, short-term PV output forecasting

• 2016 Schneider Electric Go Green in the City
- A standardized and digitized battery-based energy trading system – embracing the new IoT (Internet of Things) Era
- Third prize in Taiwan’s final
- Team leader

• Collaborative research with Applied Materials (USA)
- Fault current analysis with fault current limiter</td></tr>
<tr><td>Feb 2010
until
Dec 2013</td><td>The Australian National University (ANU)
Undergraduate Degree

➢ Renewable Energy Engineering (solar system, power plants)

➢ Participated in:
• Chief Engineer in Engineer Without Borders (EWB)
- Rural electrification in Cambodia
• Academic mentor in Engineering and Mathematics
• Senior Resident in Ursula Hall (residential hall)</td></tr>
</table>

Zi Wei CHEO – EXPERIENCES

Year	Company and Work Experience
Jan 2018 onwards	***Self-Employed (Malaysia)*** Software programmer and hardware monitoring services • Factories power consumption monitoring • Solar power plants generation monitoring • Retail and wholesale handphones accessories stock monitoring • 100% in front of computer during working hours
Jun 2015 to Dec 2017	***Acmepoint Energy Services Co., Ltd. (Taiwan)*** R&D Engineer • String inverter monitoring and fault analysis (peer to peer (P2P), trend tracking) • Power plant performance ratio analysis – common platform setting up for O&M team • Off-grid solar PV system design and real-time operation control (output control, zero-export to national grid) • Hybrid system design (battery with solar PV), battery maintenance charge/discharge control • Demand-side management – smart office design with energy saving
Sep 2014 to Sep 2016	***National Cheng Kung University (NCKU, Taiwan)*** Researcher • Project Manager: collaboration project with VTT, Finland - H/BEMS design and system implementation at VTT Finland's employee apartment (system includes solar PV, wind, BESS and EVs) - Integration and automation of Tatung's smart home appliances - Integration of automated demand response under OpenADR 2.0b standard - Managing a team of 8 members - Academic paper published as attached • National Energy Program Phase II (NEP II) - Long-term, short-term PV output forecasting (for EMS)

NATIONAL CHENG KUNG UNIVERSITY

on the recommendation of the faculty of
the Graduate Institute of Electrical Engineering,
College of Electrical Engineering and Computer Science
has conferred upon

CHEO ZI WEI (周梓為)

the degree of

Master of Science

together with all the honors, rights and privileges belonging to that degree.
In witness whereof, this diploma is issued with the university seal in June 2016.

Huey-Jen Su, Sc.D.
President

Certificate No.: 201701-6004

NATIONAL CHENG KUNG UNIVERSITY
Tainan,Taiwan

Student ID Number：N26035025　　　　**Issued Date**：01/05/2017

CERTIFICATE OF DEGREE

This certificate is to certify the statement in respect of the academic records of the named person below.

Name：CHEO ZI WEI

Date of Birth：May 04, 1991

College：Electrical Engineering and Computer Science

Graduate Institute：Electrical Engineering

Date Enrolled：September 2014

Degree：Master of Science

Year of Graduation：June 2016

Huey-Jen Su

Huey-Jen Su, Sc.D.
President

NATURAM PRIMUM COGNOSCERE RERUM

THE AUSTRALIAN NATIONAL UNIVERSITY

THIS IS TO CERTIFY THAT

FOLLOWING THE COMPLETION OF
AN APPROVED PROGRAM OF STUDY

Zi Wei Cheo

HAS BEEN AWARDED THE DEGREE OF

Bachelor of Engineering

WITH HONOURS

GIVEN UNDER THE SEAL OF THE AUSTRALIAN NATIONAL UNIVERSITY
ON THE EIGHTEENTH DAY OF DECEMBER 2013

Chancellor

Vice - Chancellor

126085

RECORD of COMPLETION

This is to certify that

Zi Wei Cheo

has completed the course

PVOL202: Advanced PV System Design - Nov. 2013

December 1, 2013

Kathryn Swartz
Executive Director
Solar Energy International

Solar Energy International
Solar Training & Renewable Energy Education
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Contact Training Hours: 60

Smart Home/Building Energy Management System for Future Smart Grid Architecture with Automated Demand Response Applications

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Abstract. A home/building energy management system (H/BEMS) is the fundamental unit for smart-grid development. This paper proposes a pilot project developed for smart H/BEMS, where the load (power consumption) can be scheduled, controlled, or optimized. The proposed energy management system (EMS) integrates the Virtual End Node (VEN) for OpenADR 2.0b Alliance platform such that demand-side management can be performed automatically according to the event issued from the Virtual Top Node (VTN). Wireless sensors using Bluetooth 4.0 (Bluetooth Low Energy, BLE) as the communication protocol are also developed and integrated in the EMS architecture. Finally, the developed EMS architecture has been implemented into 24 households with smart meter each installed in public housing in Taipei, Taiwan for testing and demonstration. Results show that the proposed EMS has successfully reduced the power consumption of a household averaged about 12.62% for the past 12 months.

Keywords: Automatic demand response, demand side management, scheduling, web-based user interface, wireless sensors

1 Introduction

The energy consumption in home or building contributes a large portion of energy demand. According to Taiwan Bureau of Energy, 19.45% of the electricity users are from residential area [1], which consumes up to 44.9 TWh of electricity per year. At the same time, the energy consumption of residential area keeps increasing. Therefore, a home energy management system (HEMS) is required to be integrated with advanced metering infrastructure (AMI) such that large portion of energy consumption can potentially be reduced.

On the other hand, distributed energy resources (e.g. solar photovoltaic) have been installed at an increasing rate. Excessive installation of distributed resources may have some negative impacts on the power grid, including over-voltage issue or reverse power flow. Clearly, there is a limit on the penetration of the distributed resources [2], [3]. To better manage the high penetration of distributed resources, several smart grid techniques have been proposed, like optimal management of active and reactive power control using smart inverters and load management [4]. To have a building energy management system (BEMS) is thus the fundamental technique for the power consumption management.

Several papers have been proposed on different types of energy management system. In [5], an HEMS has been proposed based on power-line communication (PLC) to handle or to control networked devices. However, optimization of the energy consumption is not considered in this work. References [6] and [7] further consider the consumption analysis for the home electrical devices, but without considering the impact of distributed renewable resources. More recent work in HEMS proposed considers both energy consumption and generation, simultaneously, to minimize the energy cost. In [8], a smart HEMS including renewable energy generation management has been proposed. The proposed system is expected to have energy-saving effects.

Some studies have been done on HEMS combined with automated demand response (ADR). In [9], the demand response (DR) programs have been shown to be able to provide regulation of demand side at critical peak hours by shifting or shedding loads. In [10], the author proposes an algorithm for HEMS combining with DR applications and studies the impact of HEMS operation on customer comfort. Currently, most of the DR studies in the literature generally consist of human interventions [10]. In [11], a dynamic control space matrix has been proposed and simulated at VTT Smart Grid Research laboratory. The proposed matrix helps to balance energy production and consumption within a building. Consider that a fully automated DR hasn't been presented in practical applications, this paper proposes a smart home and building energy management system with fully automated DR application algorithm, and discusses on the practical issues on DR event when dealing with human comfort and human decision.

The rest of the paper is organized as follows. Section 2 describes the overall system structure and its corresponding communication protocol. Section 3 describes the main function of the developed EMS. Section 4 discusses about contribution of the developed EMS and finally Section 5 concludes the paper.

2 System Structure Corresponding Communication Protocol

Fig. 1 shows the architecture of the system, with the corresponding communication protocols employed. The proposed H/BEMS was implemented at VTT's research apartment with the electrical appliances and devices, including dish washer, washing machine, sauna, cooking stove, floor heating and room ventilation system. The appliances and devices are all wirelessly connected to the main gateway. The smart devices are added to the apartment for intelligent controlling, including the consumption management during DR event.

In addition, the Wireless Sensor Network (WSN) installed in the apartment consists of thirteen 2.4GHz Bluetooth Low Energy sensor nodes (BTLE-node) including temperature, humidity and air pressure sensor (THP-node). Further, wireless carbon dioxide (CO_2) and air pressure difference (PD) sensor are also equipped in the WSN.

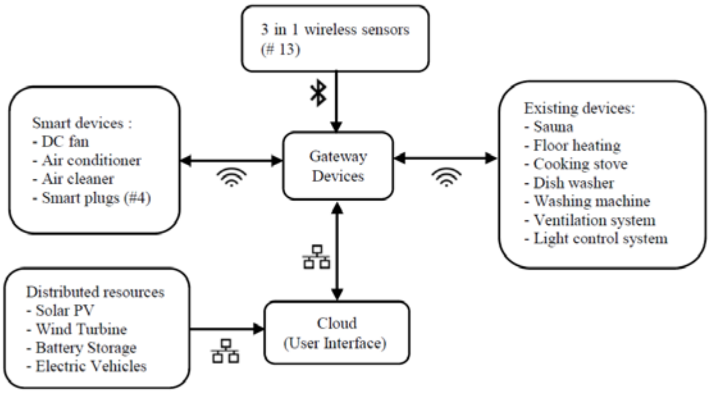

Fig. 1. System structure and corresponding communication protocol

Fig. 2 (right) shows the installation of the WSN in the apartment. The rooms, balcony and ventilation machines intake, exhaust, supply and return channels are equipped with the battery operated THP-node. CO_2 and PD–nodes are installed in the living room. The BTLE-sensors utilizes the property of Bluetooth message advertising where BTLE-peripheral device broadcasts the sensor data in certain constructed packet so that the devices around can listen and receive the broadcasted messages. By advertising the sensor data, there is no need for establishing connection between the peripheral device and the receiver unit. This improves reactiveness as making a connection is much slower than advertising the message. It is also more energy efficient since the radio is on only for a short period of time during broadcasting and wide spacing of the three advertisement channels prevents interference from other 2.4GHz devices. The receiver gateway is a credit card size CPU with BTLE interface which then further sends the data through Wide Area Network (WAN) interface into the cloud servers.

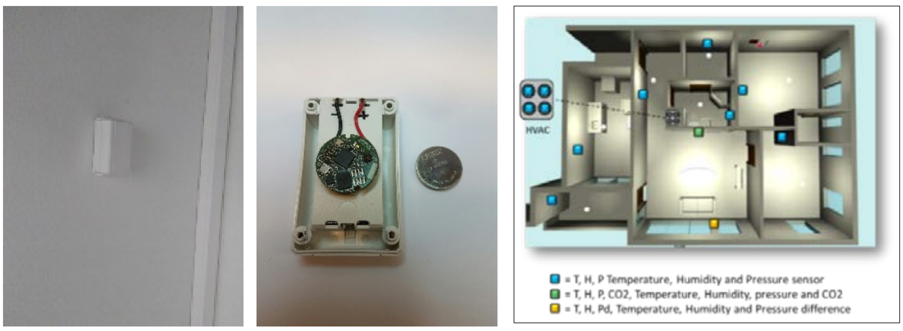

Fig. 2. VTT's Bluetooth wireless sensor and the installation of WSN in the apartment

Finally, at the main office of VTT Oulu (right beside the apartment), distributed resources including 7.2 kW_p of solar PV, 5.5 kW of small scale wind turbine, 58 kWh of energy storage system (ESS) with 400V 3-phase 15kW inverter and two electric vehicles charging posts are installed. These devices are connected to the cloud using Ethernet cable. The power generation or consumption data are stored in the cloud for further data analysis. Fig. 3 (left) shows the VTT's local energy production test site.

3 Key Functions Developed for Energy Management

The proposed EMS contains four main energy management functions, as will be discussed in the following sections.

3.1 Remote Monitoring and Control

The smart devices can be controlled remotely using the user interface (UI) developed (Fig. 3 right). The proposed system provides automation of smart devices according to user-defined input. If a device is set to function automatically, it will only operate when the corresponding user-defined parameters have been triggered. For example, the existing ventilation system will function according to (1)

$$\text{Mode} = \begin{cases} On & if\ \ C_{CO_2} > upper\ \ limit \\ Off & if\ \ C_{CO_2} < lower\ \ limit \end{cases} \tag{1}$$

where C_{CO_2} is the concentration of carbon dioxide (CO_2) (measured by the WSN). The upper and lower limit are user-defined parameters. The same principle is applied to the other smart devices in the apartment.

The intelligent Light Control System (LCS) installed in the apartment is distributed using CAN-bus based system, which consists of outputs for all lamps and inputs for every switch and sensors. LCS consists of motion and light sensors for every room. VTT's gateway allows control interfaces to the LCS and produces current measurements for every lamp.

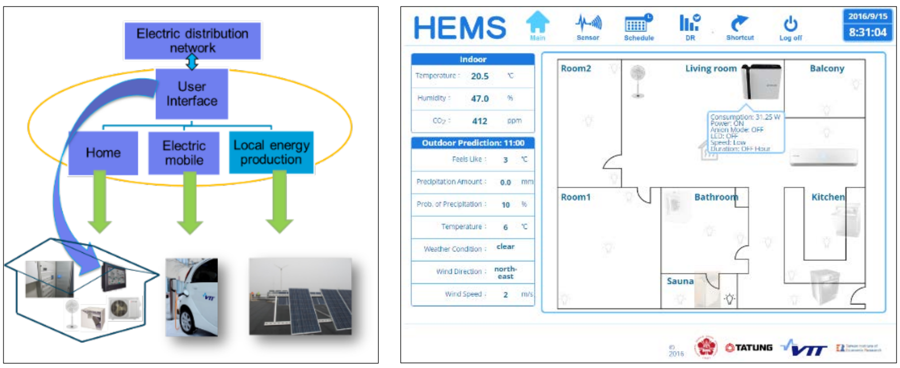

Fig. 3. VTT's local energy production test site and HEMS user interface

Monitoring of the data from the distributed resources (solar PV, wind mill, ESS, and electric vehicle charging posts) is another important function. These information is required since schedulable load like electric vehicles or ESS can be scheduled to connect to the grid for fast charging or discharging. The Ethernet cable communication is now set to exchange data every minute (Fig. 4), with the data recorded to the database.

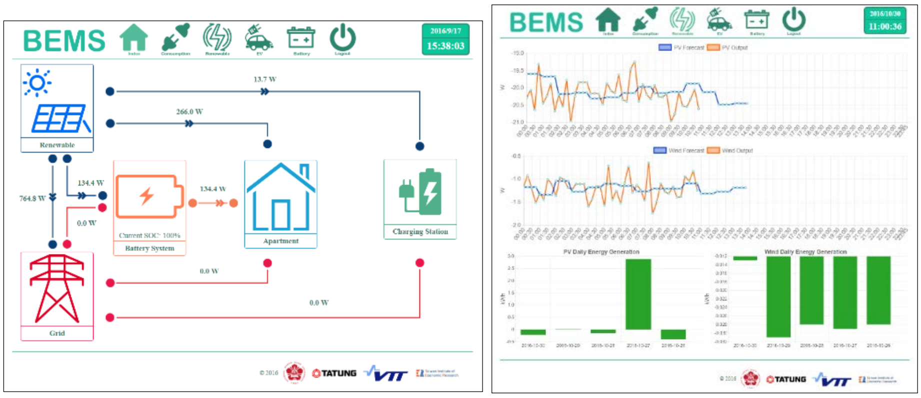

Fig. 4. BEMS real-time monitoring and renewable (solar and wind) generation record

3.2 Smart Scheduling of Appliances

The proposed HEMS in the literatures mainly simulated smart scheduling by using a few assumptions including users' comfort or users' requirement; however, in the proposed EMS, these kind of user parameters are given to the users to define. The proposed algorithm will start to give scheduling when the parameters on the user interface has been changed. In Fig. 5 (left), the proposed EMS algorithm schedules the devices such that the electricity cost will be minimized. The objective function and the required limiting functions are shown in (2).

Objective function: min (B_{24})

$$B_{24} = \sum_{1}^{a} \sum_{t=t_s}^{t_e} p_t \times C_{avg} \tag{2}$$

subject to

$$t_e \leq end\ \ time \tag{3}$$

$$t_s \geq \text{start time} \tag{4}$$

where B_{24} is the total amount of electricity cost for the next 24 hours. p_t is the electricity price at time *t*. C_{avg} is the average power consumption of appliance a. In this paper, the value of C_{avg} for each appliances was obtained by averaging the power consumption for one normal operation period. *a* is the number of appliance while t_e and t_s are the end time and start time of each appliance (defined by the user).

Different power contracts can also be compared (Fig. 5 lower left). Users can select the appropriate power contract that best suits the users' power usage pattern. In the proposed EMS project, the tariff information was obtained from Helen Ltd's official website. In the next phase of the project, the electricity tariff is going to be updated dynamically using Nord Pool electricity market. The results shown in the user interface can therefore be updated every time when the price information is updated.

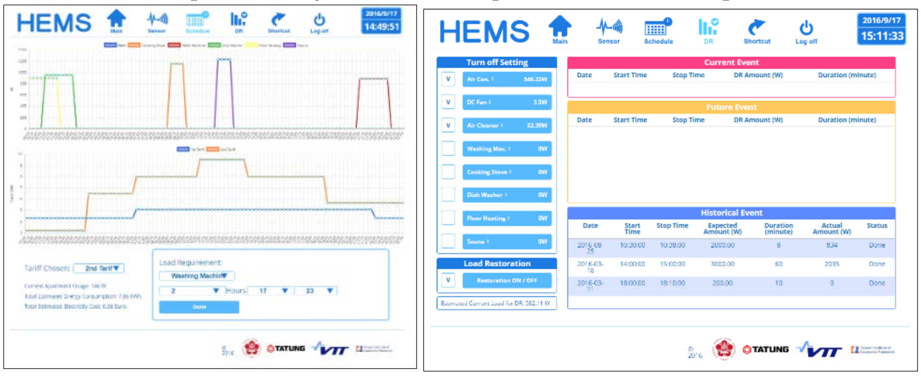

Fig. 5. Devices scheduling and demand response

3.3 Automatic Demand Response

The proposed EMS integrates the VEN (Virtual End Node) server in the International OpenADR 2.0b Alliance. The VEN server automatically extracts the DR event generated by the power company or center aggregators (VTN, Virtual Top Node) where the detailed information will be passed to the HEMS user interface for the user. Normally, the current VEN server algorithm checks for DR event every one hour. It is possible to check for DR event every 15-minutes during peak period. In the proposed algorithm, 15-minutes is set as the minimum checking frequency. During DR event, the proposed EMS will cut off the available and controllable loads by trying to meet the demand required by the VTN. The block diagram of the DR event is shown in Fig. 6.

Beside the proposed DR algorithm is fully automatically executed, it is also different from the DR algorithm proposed in the literature, as listed below:

1. Users can decide whether or not to participate in the DR event, by selecting the devices to contribute to the event.
2. The amount of load shedding is calculated according to the actual amount of power consumption of the devices; the consumption data is measured using smart plug for each device.
3. Users can decide the order of the device list during DR event; the proposed EMS cuts off power supply of the devices according to the sequence in the device list. This helps to minimize the discomfort to the users.
4. Users can select whether to abstain from the DR event. If any of the devices is removed from the device list during DR event, the EMS algorithm will automatically restore the device to its original state. Users are therefore removed from the award list for participating in DR event.
5. After the DR event, the EMS will restore the affected device to the original state before DR event. Users can also select whether to or not to restore the affected devices. For example, if the user would like to leave the home during DR event, then the user would select not to restore the affected devices after the event has finished.

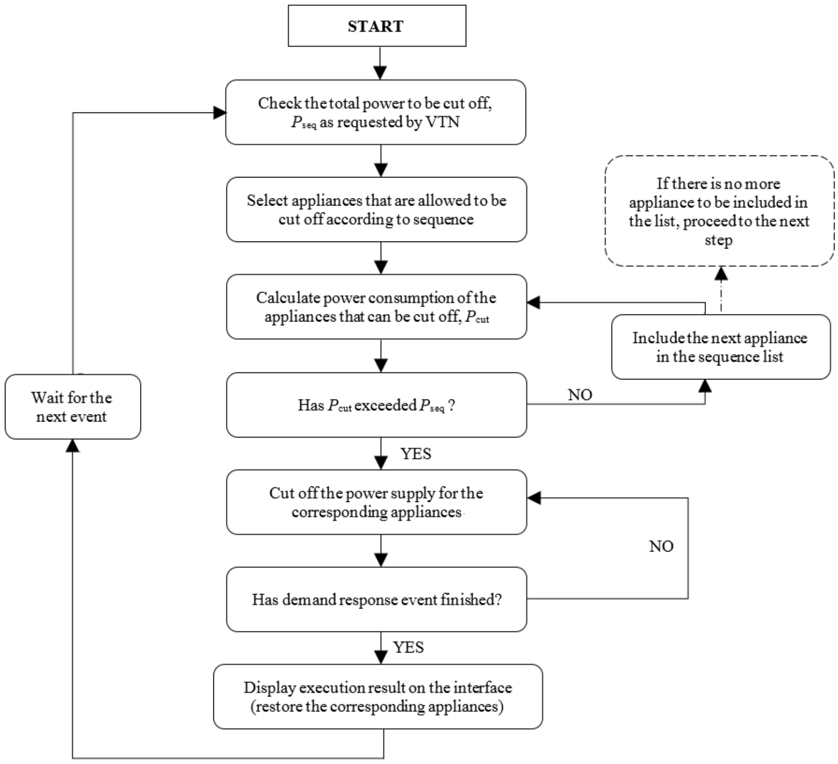

Fig. 6. The flow chart of demand response

3.4 Power Consumption Analysis

In Fig. 7, the developed EMS provides three important information for the users. First, "Historical Energy Usage Pattern" indicates how much electricity the user has been using each day. Second, "Current Power Usage Distribution" shows where the power is being used at the moment. It is worth to mention about the power usage amount of the item "others". The power usage of "others", P_{others} is calculated using (5)

$$P_{others} = P_{total} - \sum_{a=1}^{n} P_{appliances} \tag{5}$$

where P_{total} is the total power consumed by the apartment at the moment. $P_{appliances}$ is the power consumed by each of the appliances and n is the number of appliances in the apartment. If P_{others} is always showing a significant number, that means there must be some other unknown appliances which are consuming power. It is also possible that there can be power leakage in the apartment where inspection of the electrical system should be done. Finally, "Power Usage Today" allows the user to know the accumulated electricity that has been used for each appliances at the day. The above information allows the user to know the electricity consumption pattern and allows the users to try to minimize electricity consumption.

Fig. 7. The user interface of power consumption analysis

4 Contribution of the Developed H/BEMS System

In the National Energy Project (NEP) in Taiwan, the developed energy management system was implemented into 24 households (out of 272 households) in Xinglong public housing 1st block (18 floors in total). The developed EMS includes visualization of energy usage (for each household) and also simple remote controlling of lightings and air-conditioners. The project was launched at March, 2016.

From the launching date until March, 2017 (one year around), the electricity usage for households with and without HEMS installed are analyzed and compared. The daily average electricity usage of the 24 households with HEMS and the next 24 households without HEMS are calculated with the following limiting functions:

$$E_{avg} - 3\sigma < E_{daily,n} < E_{avg} + 3\sigma \quad (6)$$

$$E_{daily,n} \geq 1 \quad (7)$$

Equation (6) indicates that the if the daily electricity usage for household n, $E_{daily,n}$ lies outside $\pm$ three standard deviations, 3σ, then it is considered as an outlier which shouldn't be included in the average values. Equation (7) indicates that if the daily electricity consumption is less than 1 kWh, this implies that the householder might not be at home and hence the corresponding data is not included in the average values.

Fig. 8 shows the daily electricity usage and corresponding electricity saving households with and without HEMS installed. As can be seen, households with HEMS installed achieve positive energy saving most of the days throughout the whole period. The overall energy saving is calculated using mean absolute percentage error (MAPE) and result shows that total energy can be saved with HEMS installed is 12.62%.

At the same time, the developed automated DR algorithm was also implemented at Taipower Research Institute (TPRI) Shulin Campus in Taiwan. As one of the successful seven DR events practically implemented in year 2016, shown in Fig. 9 is a realistic DR event with about 60kW of load (electrical appliances) shed throughout BEMS for two hours on 19th July 2016 from 13:30 to 15:30. During the event, 50kW of power was also discharged from the ESS controlled by the proposed EMS to achieve the targeted goal of DR with less impact on the customers. With large number of the developed EMS in households/buildings, it is expected to have more than hundreds of kW demand side management available in the grid of a community. The demand side management via the developed EMS may become an effective tool in maintaining power balance of the grid, especially during peak hours.

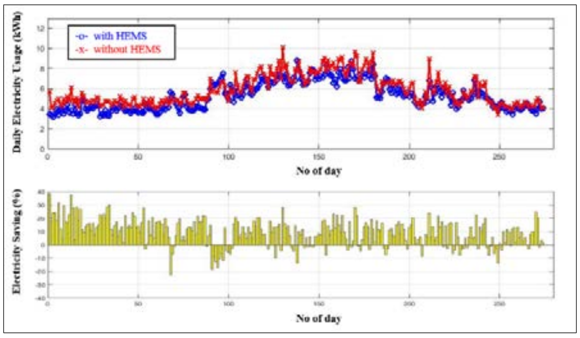

Fig. 8. Daily electricity usage and corresponding electricity saving

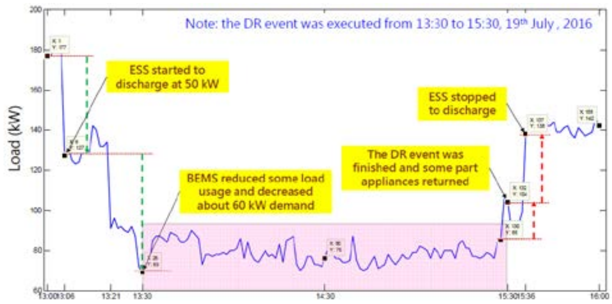

Fig. 9. Load profile during the DR event at TPRI Shulin campus on 19th July 2016

Finally, the wireless sensor network developed by VTT under the smart home architecture has also been proved to be a successful solution. As the sensor network is critical, the 2.4GHz Bluetooth Low Energy sensor node help to eliminate the complex wiring of the sensors. Users can add (remove) or relocate the sensors easily, which largely promote the development of smart home to the public.

4 Conclusion and Future Prospects

Energy management system is the essential basic element in smart grid architecture. VTT's demonstration project has successfully shown how a basic building block of EMS can be installed, with the controlling algorithm developed in the paper. There are a few items to be improved or to be included in the next phase of the project.

1. With smarter appliance developed, it is possible to foresee the power usage pattern throughout its whole operating period. Hence, the estimated power consumption can be more accurately monitored.
2. The proposed algorithm can be applied to real-time or spot-pricing power market. In a smart grid architecture, power company or market may broadcast real-time pricing information about the real power and auxiliary service demands via the AMI system. The EMS may react and provide dynamic load control as requested based on the preference defined by the users ahead of time.

3. Besides the load shedding during demand response event, the proposed system can provide dynamic voltage or frequency control over short term period with smart devices (e.g. smart inverter) installed.

Finally, the proposed system can be extended to the other different units, like supermarket, commercial offices, or industrial sectors, which is under planning in the next phase of the project.

Acknowledgements

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Research School of Engineering

College of Engineering and Computer Science

ASSIGNMENT COVER SHEET

THIS SHEET SHOULD BE THE FIRST PAGE OF YOUR ASSIGNMENT WHEN IT IS SUBMITTED.

STUDENT ID NUMBER : u4699207

COURSE NAME : Advanced Topics in Solar Energy Technologies

COURSE CODE : ENGN8527

DUE DATE : 28th October 2013

Submission of this assignment constitutes a declaration that:

- No part of this work has been copied from any other person's work except where due acknowledgement is made in the text; and
- No part of this work has been written by any other person except where such collaboration has been authorised by the course lecturer concerned; and
- No part of this work has been submitted for assessment in another course in this or another part of the University except where authorized by the lecturer(s) concerned.

Date: _20 / 10 / 13_

Table of Contents

1. Literature Review: The Effect of Dust Accumulation

This literature review summarizes previous works that have been done on the effect of dust accumulation on photovoltaic modules. Different works or results produced from different point of views will be discussed.

1.1. Period of Time Exposure to the Environment

Perhaps the easiest method to quantify the effect of dust accumulation is to calculate the performance drop after a period of module exposure to the environment (i.e. how much time the module has been exposed to the environment). This simple criterion is used in the earlier stage to investigate the effect of dust accumulation on photovoltaic module[1]; however, the results obtained can be very different. Based on the review that was done by Sarver et al. (2013), part of the result was sorted out and summarized in Table 1.1.

Table 1.1: PV performance drop after a period of time in different locations

Location	Authors	Year	Module Performance Drop
Saudi Arabia	Nimmo & Saed	1979	40% in 6 months
Kuwait	Wakim	1981	17% for only 6 days
Oregon, USA	Ryan et al.	1989	1.4% per year
Saudi Arabia	Said	1990	7% per month
Saudi Arabia	Hassan et al.	2005	33.5% and 65.8% in 1 month and 6 months
Cairo	Elminir et al.	2006	17.4% per month
Belgium	Appels et al.	2011	3 to 4% and saturates after 5 weeks

The conclusion made by simply correlating the performance drop and time exposure has a lot of limitations. First, dust accumulation may reach a steady value after a period of time. Also, even in the same location (see Saudi Arabia), the results reported by different authors in different times can be very different. Clearly there are other factors that are affecting the result. The location and local weather can be those factors.

1.2. Location & Local Weather Dependence

From Table 1.1, clearly modules in Middle East (dry location) are suffering for high quality dust accumulation; the module performance drop is significantly larger. In the States (temperate climate in Oregon) and Belgium, the performance reduction is only marginal. Hence, the effect of dust accumulation may be more serious in dry region, especially for Middle East and North Africa where solar resource is abundant. Interestingly most of the

[1] Also for solar thermal collectors

papers that investigate the effect of dust accumulation are concentrating at the Middle East. A few of them might be looking at the US or India; but those locations are still always located in dry region like desert area.

1.3. Glass Transmittance Loss

Some papers looked at the transmittance of the module glass after dust accumulation. Garg (cited in Sarver et al., 2013) reported a 30 % transmittance reduction for horizontally installed glass and 2% reduction for vertically installed glass. A more detailed result reported by Sayigh et al. (cited in Sarver et al., 2013) claimed that for 0°, 15°, 30°, 45° and 60° tilted angle, the corresponding reductions in glass transmittance are 64%, 48%, 38%, 30%, and 17%. The two results claimed above show that the larger the tilted angle, the smaller the reduction in glass transmittance. At this stage it is unclear how the glass transmittance is measured in relation to the angle of incidence of the light. Angle of incidence of the light has significant impact on the transmittance; the conclusion should clearly indicate how the transmittance was calculated. Unfortunately retrieving the original paper was not successful and so further conclusion can't be made. At this stage it was suspected that horizontally installed surface may allow more dust to accumulate on the surface, and hence transmittance loss can be higher.

1.4. Angle of Incidence of the Incoming Light

Hammond et al. (1997) on the other hand correlated the dust effect with the angle of incidence of the incoming light. The amount of loss was reported to have a maximum of 3% only for 0° angle of incidence (with natural raining throughout the experiment period). The amount of loss can increase to 4.7% for 24° and 8% for 58° angle of incidence. They also concluded that cleaning non-tracking systems can be cost effective while cleaning tracking systems may not be cost effective. It is because tracking system can always keep the angle of incidence to be small, and hence the amount of loss can be kept small.

1.5. Seasonal Variations & the Effect of Natural Raining

Zorrilla-Casanova et al. (2012) have reported that the effect of dust accumulation may be highly correlated to seasonal variations. Radiation loss can exceed 20% during summer (dry seasons); while in other seasons (wet seasons) the average radiation loss is less than 5%. They have reported that natural rain water can efficiently clean the module to a very clean level; and hence soiling loss can be minimized (see Figure 1.1).

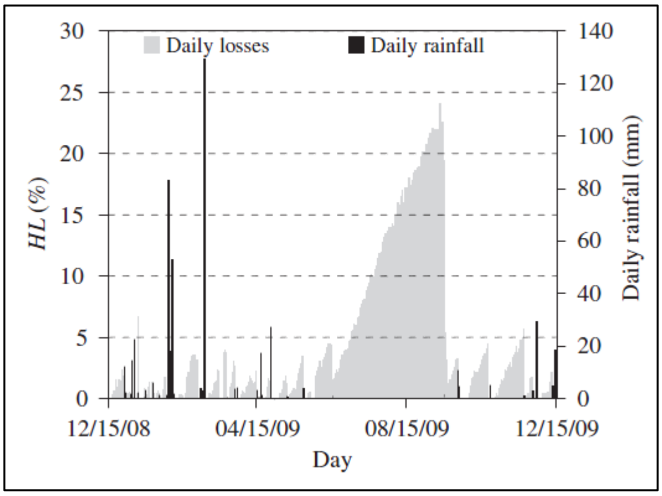

Figure 1.1: The relationship of the daily rainfall and radiation loss (HL) in a year (Zorrilla-Casanova et al., 2012)

This may seem to be good news for this topic. However in earlier paper, Anagnostou and Forrestieri (cited in Sarver et al., 2013) from USA have reported that each of the succeeding washing can only "recover less"; in addition, the module may show a permanent loss in the performance, but it will reach a steady value after several hundred days[2].

On the other hand, Appels et al. (2011) reported that natural rainfall has a little cleaning effect on smaller particles (2 to 10 μm); while larger dust particles can be washed away. However, the effect of smaller particles on the module power loss is not discussed.

1.6. Bird Droppings and Non-uniform Dust Distribution

Most of the papers investigated the general dust accumulation on the module. The effect of bird droppings is not investigated. Bird droppings (especially after dry) can hardly be cleaned by natural rainwater. Loss that can be caused by bird droppings may be large; especially if we consider that bird droppings may be dropped in a random spot on the module, and hence provide random shading. In fact, random shadings may even result in a larger loss in module performance. Lorenzo et al. (2012) have investigated the effect of dust accumulation from a different point of view. Most of the papers have made a common assumption such that dust is uniformly distributed over the module; and hence only effective incident radiation will be affected (i.e. current generated). Lorenzo et al. (2012) observed the non-uniformity of dust accumulation on solar array and translated this into I-V curve for each individual module. They reported that strongly non-uniformity of dust accumulation can cause more significant power (voltage) loss than just current reduction from transmittance loss. Significant hot spot

[2] Retrieving the original paper was not successful

heating can occur (see Figure 1.2), which will lead to a threat to module lifetime. Unfortunately, it is still unclear how non-uniformity of dust can present or form in the field.

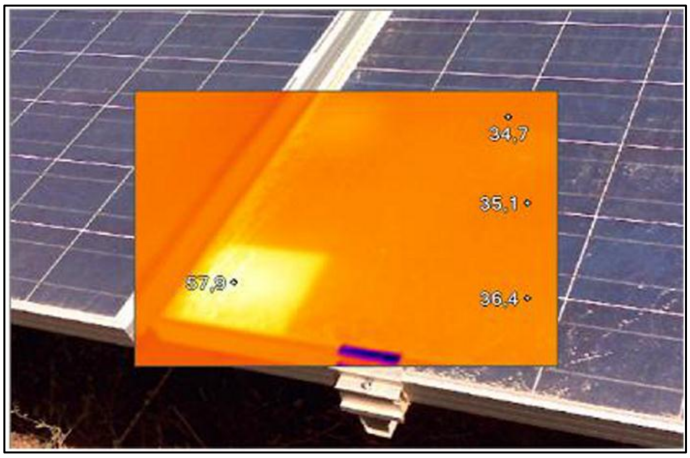

Figure 1.2: Hot spot heating in module due to non-uniformity of dust accumulation (Lorenzo et al., 2012)

1.7. Dust Accumulation due to Wind Direction

In Lorenzo et al.'s paper, it was suspected that non-uniformity of dust accumulation was a result of complex combination of breeze winds and arrangement of the array. Goossens et al. (1993) have investigated the effect of wind direction and wind speed on dust accumulation and distribution (field investigation). They concluded that dust accumulation is strongly dependent on the wind direction and the orientation of the PV panel; and hence this may result in significant non-uniformity of dust accumulation. However, note that the conclusion they made was based on effect of dust storms in arid region (Israel). It is still unclear the applicability of this result at the other moderate weather locations in the world.

1.8. Dust Composition and Grain Size

People seldom looked at what the dust actually is. Qasem et al. (2012) investigated the dust's grain size and its material composition using microscope, image processing software and x-ray diffraction analysis method. Part of the result is shown in Figure 1.3.

D(μm)	% of the total sample	Grain type
1000–500	0.00	Coarse grained
500–250	0.00	Medium grained
250–125	0.82	Fine grained
125–63	4.78	Very fine grained
63–31	8.16	Coarse silt
31–16	16.47	Medium silt
16–8	23.82	Fine silt
8–4	20.19	Very fine silt
<4	25.75	Clay

Figure 1.3: Dust grain distribution and types

The dust sample was collected in Kuwait, again an arid region. It was found that dust mostly consists of smaller size (diameter) grain. Goossens and Van Ketschaever (cited in Sarver et al., 2013) reported that fine dust deposition has significant effect on cell power output; but no further research was done to investigate the relationship between the dust grain size and module power output. In Qasem et al.'s paper, they further investigated the spectral transmittance of module glass for different dust accumulation density. They reported that shorter wavelength is affected more by dust accumulation (see Figure 1.4). Although it was not concluded in the paper, it may be related to the small grain size that was found in the dust sample. Smaller size grain contributes more for the dust sample which may consequently affect more on shorter wavelength. Further investigation may be required to confirm this.

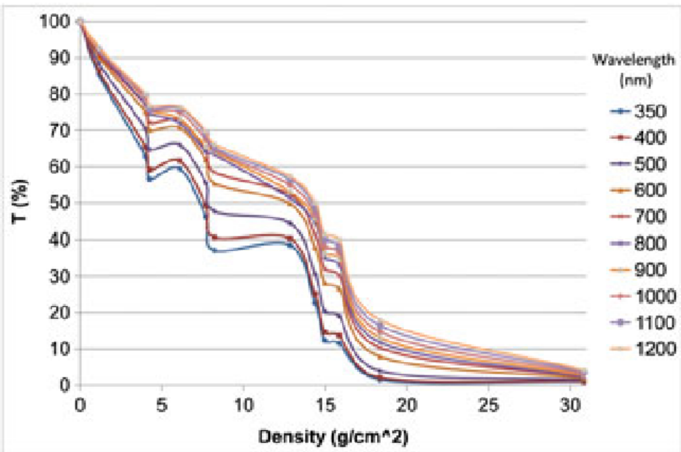

Figure 1.4: Glass spectral transmittance for different dust densities (Qasem et al., 2012)

On the other hand, Cabanillas and Munguı´a (2011) have reported a different result for dust composition. They reported that particles of diameter 52 μm represent the largest fraction of the dust sample. This is contradicting to Qasem et al.'s result where smaller particles will contribute more to the dust sample. However, both of them reported that grain size of diameter above 400 μm is not detected.

Although the two dust samples were collected from dry area (Kuwait and Mexico), which are susceptible to dust accumulation; there seems to be some discrepancies between the results. This has further shown the complicated uncertainties of the investigation in this topic.

1.9. Different Photovoltaic Technologies

Alamoud (cited in Sarver et al., 2013) was probably the first to report that the effect of dust accumulation on photovoltaic performance is also dependent on the type of module used. The difference in performance reduction can even exceed 10% (for different PV technologies). In 2011, Cabanillas and Munguı´a further proved this conclusion. They reported that amorphous silicon module experiences a larger reduction in maximum power (13% reduction); while for monocrystalline silicon or polycrystalline silicon, maximum power reduction is reported to be between 4% and 7%. They reported that the difference can be explained by the material used to cover the modules. In their experiment amorphous silicon module possesses an undulating plastic cover while monocrystalline and polycrystalline module have a glass cover. They therefore concluded that solar modules with plastic coverings require regular cleaning more frequently.

Qasem et al. (2012) used spectral transmittance difference to explain this result. They have reported that shorter wavelength will show larger reduction in module transmittance. As a result, they suggested that wider band-gap material will be affected more by dust accumulation, since wider band gap material stops absorbing radiation at a shorter wavelength. They confirmed this hypothesis by investigating other photovoltaic technologies.

Density (mg/cm^2)	a-Si (%)	CIGS (%)	CdTe (%)	c-Si (%)
1.2	−10.8	−9.1	−9.7	−9.1
4.25	−33.0	−28.5	−30.1	−28.6
14	−66.0	−59.6	−61.9	−59.6
19	−77.4	−70.6	−73.1	−70.6
30	−98.4	−97.8	−98.1	−97.8

Figure 1.5: Reduction in photocurrent for different dust densities and PV technologies (Qasem et al., 2012)

In Figure 1.5, amorphous silicon has the highest band gap (1.6 eV). The reduction is always the highest (compared to the other three modules) for different dust densities. Smaller band gap material (crystalline silicon) on the other hand shows smaller reduction in photocurrent.

Compare the reduction difference for amorphous silicon and crystalline silicon in the two papers. In Qasem et al.'s paper the reduction difference is relatively smaller; averaged at 3.98% for different level of dust accumulation. For 30 mg/cm^2, the difference between the two modules is even smaller (less than 1%). In Cabanillas and Mungui´a's paper, they concluded that reductions in power for a-Si can double the reduction in power for c-Si; they also reported a linear relationship of dust accumulation and power. Their conclusions seem to have large discrepancy[3].

1.10. Universal Method or Artificial Dust for Soiling Studies

People start to look at if there is a universal way to determine the effect of dust accumulation for different locations in the world. Qasem et al. (2012) have produced a factor called soiling ratio to determine the effect of dust accumulation for different inclination angle, air mass and different PV modules. They claimed that this soiling ratio can be reproduced in the lab with the combination of dust samples collected from the specific region that the measurement of dust affect is desired. However, the applicability of this method is still unclear. Also note that the transmittance value is obtained by normal incident light. That means the effect of dust accumulation for different angle of incidence of the incoming light is still not included in this model.

Burton and King (2013) have demonstrated a laboratory technique to artificially apply soil to a sample to quantify the effect of light transmission through the sample. They claimed that the response from an uncoupled system may not replicate the actual result from a laminated module, but the trend of the result can be studied. However, again the artificial dust still needs to be tailored to match different environmental conditions; the work is still currently underway.

[3] The reduction in photocurrent (Qasem et al.'s paper) is compared directly to the reduction in power (Cabanillas and Mungui´a's paper). The difference in voltage can be ignored in this situation, since non-uniformity of dust accumulation was not considered in the papers. Current reduction is the decisive factor.

1.11. Conclusion

In conclusion, the investigation into the effect of dust accumulation is still limited to individual's work. The major difficulty or challenge is that the effect of dust accumulation is a combination a wide variety of environmental factors, such that no single conclusion can be made for this topic by just correlating one or two factors. People have started to look at if it is possible to combine a few different factors into one single soiling ratio, but that is still at an early stage.

Generally, it can be concluded that natural rain can help to minimize the accumulation of dust. If the system is not installed in an arid region, then the effect of dust accumulation is small or can be ignored. Future work should be focused on arid region where the solar resource is large. Also, dust accumulation can never bring any benefit to solar modules. Future work should also look at possible technologies to prevent the dust to accumulate on the solar modules.

2. The Optics Challenge: Self-Cleaning Module Glass Using Water

Currently there are two main active areas where people look at the way to clean the module glass automatically using natural rainwater. They are hydrophobic glass and hydrophilic glass.

2.1. Hydrophobic Self-Cleaning Module Glass

Hydrophobic self-cleaning mimics the lotus effect where very high water repellence is exhibited on the surface of the module glass. Water on this surface will then form almost spherical droplets which can easily roll away carrying dust with them (hence clean the glass). The two requirements for a hydrophobic self-cleaning surface are a high water contact angle and a low roll-off angle. Water contact angle is the angle between the tangent of the water edge and the horizontal plane; while roll-off angle is the minimum inclination angle required for a droplet to start to roll off (Parkin & Palgrave, 2004). The former requirement has been thoroughly studied while the latter requirement has been discussed only to a limited extent (Marmur, 2004). However roll-off angle is relatively less important in this case since modules will hardly be installed horizontally (or close to horizontal). Water contact angle on the other hand is related to the surface free energy. To have large water contact angle, the wetted surface should be less energetically favourable than the dry surface (Parkin & Palgrave, 2004), i.e. the surface energy has to be low.

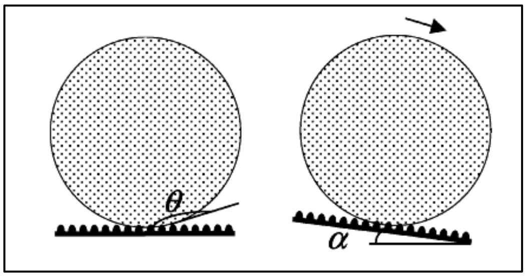

Figure 2.1: Water contact angle, θ and roll-off angle, α (Marmur, 2004)

According to Parkin & Palgrave (2004), there are several techniques for micron-scale patterning of hydrophobic surfaces. However, none of these techniques are suitable for solar module glass. Besides batch processing hydrophobic surface is a costly and time consuming process; the surface produced can become hazy, which is not suitable for module cover.

Shin et al. (2011) were investigating the low reflectance of light at moth-eye nano-patterns surface. They further found that surface energy of glass can be decreased through the introduction of moth-eye nano-patterns; hence the surface becomes hydrophobic which can exhibit a self-cleaning effect. They introduced another coating called heptdecafluoro-1, 1, 2, 2-tetrahydrodecyl trichlorosilane based self-assembled monolayer (HDFS based SAM); this coating can be coated directly on moth-eye nano-patterns surface to make the surface even more hydrophobic (without affecting the transmittance of the surface).

In their study, the moth-eye patterns were fabricated using UV nano-imprint lithography (UV-NIL) with methacryloxypropyl terminated polydimethylsiloxane (M-PDMS) as the UV imprinting resin[4]. After the UV nano-imprint process[5], M-PDMS nano-patterns were exposed to oxygen-based plasma; and then HDFS based SAM can be directly coated to the surface as HDFS based SAM will form stable covalent bonds to SiO_2 surface[6].

For a bare glass without any coating, the water contact angle is usually about 50° [7]. After the surface is coated, water contact angle is measured to be 133.7° (see Figure 2.2, bare). This indicates that the surface energy is largely reduced and hence can result in self-cleaning effect.

[4] In the paper a commercially available NIP-K28 resist, composed of a mixture of perfluorated acrylate resins was also used as a reference resin for comparison. But the authors found that M-PDMS resin was more suitable for fabricating moth-eye nano-patterns on protection glass of photovoltaic module. It is because M-PDMS has better mechanical properties; while still having similar transmittances.

[5] For detailed discussion of the fabrication process, see Shin et al., 2011.

[6] For more detailed information, see Shin et al., 2011

[7] Generally, water contact angle of more than 90° is considered to be hydrophobic, and vice versa. The larger the contact angle, the easier the water to roll off and hence the better the self-cleaning ability.

The durability of the coating on glass substrate was also tested under high acidic[8], high temperature[9] and high UV irradiation[10] conditions. Again from Figure 2.2 it can be concluded that the water contact angle is not affected by the exposure to harsh environment.

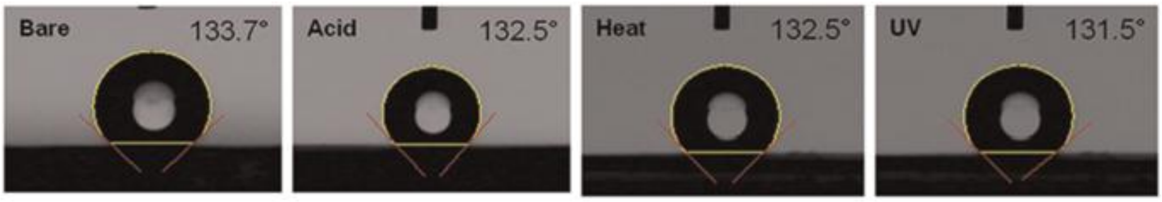

Figure 2.2: Water contact angle with M-PDMS and HDPS based SAM coating under different conditions (Bare: without any treatment) (Shin et al., 2011)

The authors concluded that the nano-pattern can achieve high self-cleaning properties by forming large water contact angle. However, the cost of fabrication process is not yet known. Also, the self-cleaning ability of the surface under field test is not investigated, which is a omission before further conclusion can be made. Future works include trying to integrate the fabrication process into the current module manufacturing process; and hence make this coating commercially available.

2.2. Hydrophilic Self-Cleaning Module Glass

Hydrophilic works in a similar way. Titanium dioxide (TiO_2) coating has been well-known for its hydrophilic self-cleaning ability on module glass. The self-cleaning process requires two steps. First, UV light from the sun is required in order to decompose or break down the organic dirt on the glass. Dirt can then be easily washed away by the "spread" rainwater (low contact angle). There are two main reasons why this well-known technology is not commonly used. First, the photocatalytic property of TiO_2 is typically lost after 5 years (Sakhuja et al., 2011). Second, inorganic dirt cannot be decomposed and hence cannot be washed away. TiO_2 also reacts with silicone which will then require specialist glazing (BalcoNano, 2013).

Sakhuja et al. (2011) have showed a different hydrophilic surface without using TiO_2. They showed that hydrophilic glass can also be achieved by fabricating nano pattern directly on the glass substrate. The reason is that the patterned surface (rough surface) can have a large contact area with water droplet, and hence this can reduce the contact angle and eventually an extremely low water contact angle can be observed. Two types of nano-patterned structures

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[8] Soaked in sulfuric acid solution with pH value 2 for 48 hours.
[9] Convection oven at 120°C for 48 hours
[10] 300 mJ/cm^2 of UV light (equivalent to approximately 60 times of AM 1.5 condition) for 40 hours

were evaluated – nano-holes and nano-pillars. The fabrication process for both of the nano-patterns was thoroughly discussed in the paper.

In the paper it was shown that nano-patterned hydrophilic surface can give a better self-cleaning ability in longer term (if compared to hydrophobic self-cleaning surface). Sakhuja et al. (2011) created hydrophobic surface in their experiment by adding Perfluorodecyltriethoxysilane (PFTS) coating; while hydrophilicity of the glass can already be observed after the fabrication of the nano-structure. Figure 2.3 (a) shows the water contact angle for different surfaces. Both nano-pillar and nano-hole surfaces show very low water contact angle (less than 5°); and hence strong hydrophilicity. On the other hand, after the surfaces were coated with PFTS, water contact angle increases significantly (larger than 167°), which indicates a strong hydrophobicity.

The glass samples were exposed to the outdoor environment. The samples were mounted on the rooftop at 23° tilt angle for 12 weeks; the average temperature is 23°C and the amount of rainy day is 15 days/month. From Figure 2.3 (b), the water contact angle for hydrophobic surface dropped significantly (more than 20%). The authors claimed that the self-cleaning effect may fade away gradually for hydrophobic surface. On the other hand, hydrophilicity for both nano-pillar and nano-hole surfaces was rarely affected (Figure 2.3 (b)) by environmental exposure, and so self-cleaning behaviour can be maintained.

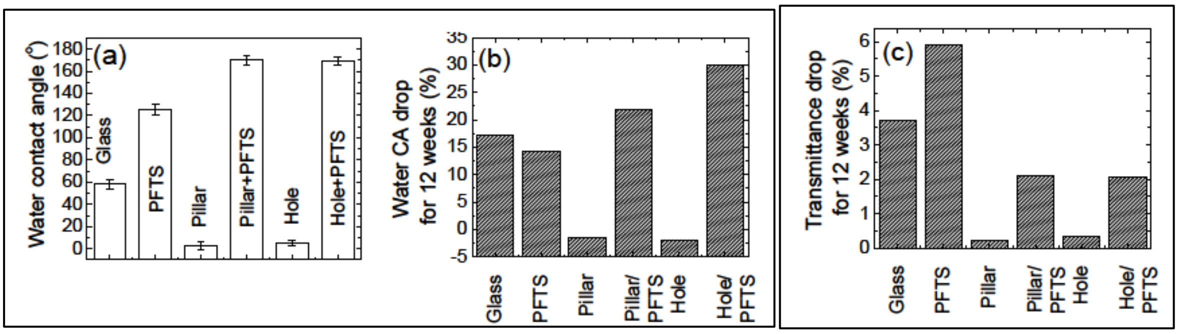

Figure 2.3 (a): Water contact angle for different surfaces.
Figure 2.3 (b): Water contact angle drop after 12 weeks.
Figure 2.3 (c): Transmittance drop after 12 weeks (Sakhuja et al., 2011)

Figure 2.3 (c) showed the transmittance drop of the module glass after 12 weeks of outdoor exposure. The authors claimed that hydrophobic surface can actually remove the dirt more effectively; but as the surface loses its hydrophobicity, dirt starts to settle on the surface, and hence result in transmittance drop. Hydrophilic glass surface has showed a better self-cleaning ability throughout the experiment period (Figure 2.3 (c)).

Note that the hydrophobic coating used in this paper is different from the coating used in Shin et al. (2011)'s paper. PFTS (used in Sakhuja et al.'s paper) has shown a higher water contact angle (approaching 170°); but the angle degraded significantly after 12 weeks of outdoor exposure. HDFS based SAM (used in Shin et al.'s paper) showed a smaller water contact angle (133.7°) but it didn't degrade after harsh environment test. The large difference in the durability of the two surface coatings seems to be abnormal. The reason for the large difference is unclear. In the future HDFS based SAM coating (used in Shin et al.'s paper) can be used as the coating for nano patterned surface so that self-cleaning ability of hydrophobicity and hydrophilicity surfaces can be re-compared again. If hydrophobic behaviour of HDFS based SAM coating doesn't degrade in the real environment, then hydrophilicity may not be still in the leading position in terms of self-cleaning ability.

2.3. Conclusion

It is still unclear whether hydrophobicity or hydrophilicity will give a better self-cleaning ability. From the review, hydrophilic glass seems to be the better choice. The competitive advantage is that hydrophilicity can be achieved by directly patterning on a glass without any further surface chemical treatment; hence the hydrophilic glass has shown a better durability over hydrophobic glass.

However, cares need to be taken if the module is installed in arid region where rain amount can be small. As discussed, hydrophilicity can result in the well-spread of water throughout the whole surface (low contact angle); hence when large amount of water flow off the surface, the surface can be thoroughly cleaned. If the rain water amount is low (1mm or less), water may stay on the surface before washing off the dust; after the water is evaporated the dust may stick on the surface which can then make it harder to be removed at the next time. Hydrophobic surface doesn't have this concern. Since larger contact angle water can hardly stay on the surface and will flow off easily even if the amount is small.

Besides the controversial point that was mentioned in the last section, future work includes scaling up the fabrication process so that these glasses can be commercially available for module glass. The two glasses also need to be tested in an arid region to further confirm the self-cleaning ability[11].

3. The Optics Challenge: Self-Cleaning Module Glass without Water

Mazumder (2013) has proved the concept of using Electrodynamic Screens (EDS) for self-cleaning surface without requiring any water or labour work force. This is done by depositing a transparent and electrically sensitive material (Indium tin oxide, ITO) on the surface. When the surface is energized by the electricity from the solar panel (less than 0.1% of solar panel production (Mazumder, 2013)), dust particles can be lifted from the surface by the travelling wave of electrostatic and dielectrophoretic forces produced by the electrodes (Mazumder et al. (cited in Greenemeier, 2010)). Usually the panels are not installed horizontally on the surface, and hence the lifted dust particles will simply fall off[12]. Mazumder (2013) claimed that this cleaning process only takes less than 2 minutes and 90% of the dust can be removed automatically[13].

In June 2013 the development of fabricating transparent Electrodynamic Screen using screen-printing process has been presented (Erickson et al., 2013). Screen printing method is chosen because it is scalable and cheap. At this stage the authors claimed that the process still requires extensive trial and error until the process can be optimized and automated.

On the other hand, the transmittance and reflectance of the additional coating on the glass surface is not presented or discussed. The additional coating deposited on the glass may affect the transmittance of the radiation (the coating was claimed to be transparent in the paper) through the glass. Further research may be required in order to confirm that the additional coating doesn't reduce the radiation that can reach the solar cell. Also, safety issue of the cleaning process have yet to be discussed.

[11] The field test was tested in Singapore where the rain water amount is large and so the effect of dust accumulation is small.
[12] There is a video showing how the dust can be removed on a surface (by Boston University). Link: http://www.youtube.com/watch?v=rJeWRAU2fWo
[13] Dust sensor will be required to be installed on the panels to trigger the cleaning process.

4. Conclusion and Future Prospect

Dust accumulation can never be an advantage for solar module. Unfortunately the effect of dust accumulation is not yet fully understood. Most of the work before focus on the effect of dust accumulation if the dust is uniformly distributed. In the future it may be required to investigate the formation of non-uniform dust accumulation in different location, so that further action can be taken.

Self-cleaning module glass is the promising method to solve the problem permanently. The topic is still in research stage. Works can be focused on those topics such that further understanding on the effect of dust accumulation may become unnecessary.

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