Dust Mitigation in the Desert: Cleaning Mechanisms for Solar Panels in Arid Regions

Ali Alshehri*, Brian Parrott*, Ali Outa, Ayman Amer, Fadl Abdellatif, Hassane Trigui, Pablo Carrasco, Sahejad Patel and Ihsan Taie
Saudi Aramco Research & Development Center, Dhahran, Saudi Arabia 31311.

***Abstract*-- This review includes a comparative survey of cleaning mechanisms for solar power plants, with a focus on their application in arid regions. In these regions, dust accumulation can have a severe and detrimental effect on the productivity of solar arrays. The primary concern of this study is to address the need for a commercially viable cleaning solution and present candidate technologies that show promise in enabling solar technologies in the sun-rich, arid regions of the world. In addition to comparing the cleaning mechanisms categorically, specific examples from each category will be referenced to demonstrate the specific attributes of such tools. The survey will focus primarily on currently available product categories for the analysis, while developing technologies are reviewed for their potential strengths and weaknesses. The categories of cleaning solutions considered in this study include the following: manual cleaning, mechanized cleaning, hydraulic cleaning, installed robotic cleaning and deployable robotic cleaning.**

***Keywords:* solar cleaning, photovoltaic, robotics, renewable energy.**

I. Introduction

The world energy consumption and demand is increasing and alternative energy sources are vital to meeting this growing demand worldwide, even within oil rich countries such as the Kingdom of Saudi Arabia. Solar energy represents an additional important energy resource in the oil rich Kingdom, which makes this field of great interest to the industrial and research activities of the market. This high priority led The Custodian of the Two Holy Mosques, King ‘Abd Allah ibn ‘Abd Al-‘Aziz Al Sa’ud, to issue a royal order to establish King Abdullah City for Atomic and Renewable Energy (K.A. CARE) in 2010; and solar energy represents a significant part of their research activities. Also, many research programs within the universities and research centers have emerged, focusing on this sector as a promising source of energy for the future. Significant projects have been established recently throughout the Kingdom, including the King Abdullah Petroleum Studies and Research Center (KAPSARC), where a 3.5 megawatt solar energy field was inaugurated in 2012. Despite the high level of solar energy that is potentially harvestable within the Kingdom, challenges with keeping the solar panels clean have prevented solar power from being as competitive in the energy market as desired. To maximize solar power plant profitability and viability, it is necessary to avoid the reduction in the conversion efficiency, which results from accumulated dust and debris, and to minimize any associated process costs. Currently, reduction in efficiencies of over 40% have been recorded, and the panels are cleaned using laborers, which is expensive, uses significant amounts of water resources, and often results in mistakes that damage the panels. Renewable energy is an active topic of research and the technology is becoming widespread throughout the world, especially in the wealthier nations of Europe [1, 2], Fig. 1. Among these technologies, it has been suggested that solar power provides what will one day be the largest source of harvested energy on the planet [3, 4] due to limited alternatives and growing global demand, Fig. 1 (a). Despite the popularity of renewable energy, and the clear role that solar energy must play in the future energy sector, the portion of global energy currently being produced via solar is only about 3% according to some estimates made by Siemens Company, which is one of the world’s leading electrical and energy companies, Fig. 1 (b), and it is estimated that fossil fuels will continue to dominate the energy sector through at least 2030. Though there are diverse reasons for this, including the relatively high cost associated with the installation of solar power plants, many of the challenges preventing widespread solar power deployment are being addressed via innovative and focused research that has recently brought solar plants within reach of grid parity in optimal conditions. The regions where yearly solar insolation is highest around the equator are primarily desert regions with the significant challenge of

*Authors to whom correspondence should be addressed. Electronic addresses: ali.alshehri@aramco.com and brian.parrott@aramco.com

Authorized licensed use limited to: FUNDACAO UNIVERSIDADE DO RIO GRANDE. Downloaded on August 29,2020 at 21:46:20 UTC from IEEE Xplore. Restrictions apply.

pervasive dust and insufficient rain to naturally remove any accumulated dust resting on the panels.

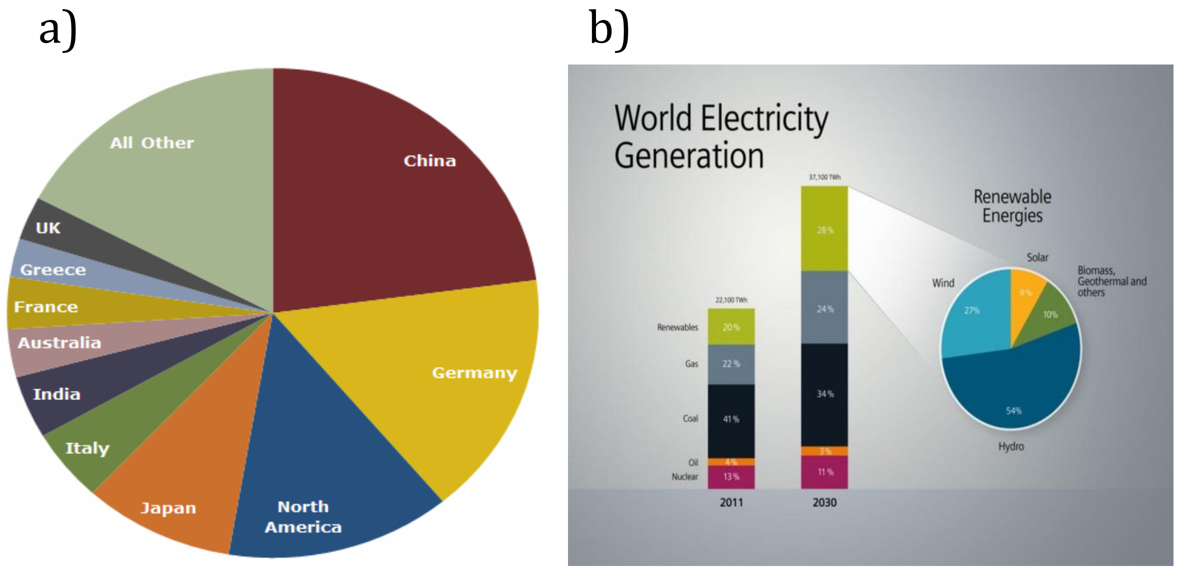

Figure 1: Distribution of installation of the 2GW of installed photovoltaic plants in 2013 (a). Source: Solarbuzz 2013 [5, 6]. b) Renewable energies are growing throughout the world. Siemens predicts that energy from renewable sources will account for 28 percent of the global power mix in 2030. According to Siemens' estimates, global power consumption will rise from 22,100 terawatt-hours (TWh) to 37,100 TWh in 2030 [7].

II. Qualitative Assessment of Cleaning Technology Strategy: Overview of Cleaning Technologies

Though there are a variety of techniques used to clean solar panels, the various technologies currently being used can be divided into categories that serve to simplify the analysis. In this paper, five categories are used, including: Tools for manual cleaning, mechanized tools (such as tractor mounted brushes), installed hydraulic systems (such as sprinklers), installed robotic systems and deployable robots. Table 1, below, shows a summary of the qualitative assessment of these various strategies, all of which will be discussed in further detail in the next section.

Table 1: Qualitative assessment of cleaning technology strategy

Category	Capital Cost	Water Usage	Labor Usage	Potential for Damage
Manual Tools	Low	High	Very High	High
Mechanized Tools	High	Med-High	Medium-Low	Med-High
Installed Hydraulic Systems	Med	Very High	Low	Low
Installed Robotic Systems	Med	Low	Low	Med-Low
Deployable Robotics	Med	Low	Medium	Med-Low

Within each technological category, there exists a variety of products, each of which might score slightly differently than the category average. This table exists solely for the purpose of providing a quick overview of the various cleaning strategies with a more detailed discussion to follow.

Manual cleaning tools are likely the most prevalent cleaning solution that is currently being used to address the challenge of mitigating the impact of dust and other contamination that reduces solar panel efficiencies. A major factor in this widespread usage is likely the low capital cost of purchasing manual cleaning tools. A single person equipped with such a tool can maintain a significant number of panels, especially in areas where rainfall provides a significant portion of the cleaning needs, and so both residential and small commercial solar arrays have often been serviced by such a solution in the past. These manual tools are also readily available due to the need to keep windows clean on large buildings, meaning that the technology was available and ready to use when the first solar arrays were being built. Additionally, though the technology generally uses a significant amount of water to wash and then rinse the panels, water use was not a primary concern while installing panels in the less-arid regions of the original markets for renewable energies.

The operational cost of manual cleaning comes primarily from the large amount of water and labor that is required. The actual cost of this water is relatively low, but the true cost (due to the amount of the oil that is used to desalinate the water) is actually much higher than the apparent cost. In addition to the

Authorized licensed use limited to: FUNDACAO UNIVERSIDADE DO RIO GRANDE. Downloaded on August 29,2020 at 21:46:20 UTC from IEEE Xplore. Restrictions apply.

cost and problems associated with the significant amount of water used, there is a high labor cost associated with manual tools. This labor is primarily unskilled workers, and it has been reported that there is a reasonable rate of damage being done when under-qualified workers are employed for this purpose. On the other hand, skilled laborers performing manual cleaning can also perform inspection simultaneously, but this would further increase the labor cost.

Mechanized tools for solar cleaning are a popular solution for larger solar plants, as they are able to clean a large surface area relatively quickly. These tools are very expensive in terms of capital cost. Therefore, even though these systems reduce labor dramatically, and can reduce water significantly in some cases, they require high utilization to amortize the large capital investment.

The operational cost of mechanized tools is less than that of manual tools by a significant margin. They still generally require water, labor, and, additionally, an energy source. Some of these systems use steam instead of just water, which allows them to reduce water usage. Despite using much fewer laborers, the laborers need to be skilled operators of heavy equipment. The labor costs should be relatively low, but maintenance costs must be factored into the equipment cost. Finally, although these mechanized tools come with safety mechanisms to prevent damage to the panels they are cleaning, a malfunction of such a large system could cause catastrophic damage to an array.

Hydraulic systems can be highly competitive in non-arid regions, as they can be fully autonomous, are reasonably inexpensive, and have relatively low operating costs apart from the cost of water. In arid regions, these systems use the highest volume of water, which leads to a high operational cost.

The initial capital cost of such a system is proportional to the size of the surface area that needs to be cleaned. Though it seems there are a variety of suppliers for this type of system, a preliminary search does not reveal any significant technological differences between different suppliers. Therefore, it can be assumed that the capital cost would be primarily dependent on the cost of materials and labor to assemble such a system. This means that the capital cost should be moderate, as there is a significant amount of piping and support needed, but almost no expensive technology.

The cost of actually using such a system in an arid region could be very significant. While all of the other methods that use water combine some type of mechanical cleaning method to break particles free more quickly and easily, sprinkler systems such as these do not have this advantage, and so it can be assumed that the same cleaning job would require significantly more water from such a system than any of the other alternatives unless the water is highly pressurized. The cost of creating ion-free water in a region using desalination plants for much of its water supplies is significant, and so the use of large amounts of water alone might make such systems far less practical in arid regions.

Labor costs should be minimal, as the systems can be automated to require no human intervention. Additionally, the chance of such a system damaging the solar panels is extremely low since there is no mechanical contact between the system and the panels during the cleaning process. Since all items are fixed in place, there should be no significant impact of a system failure other than wasted water. With these considerations in mind, minimal costs in addition to the water cost and installation cost make this a reasonable system anywhere that water is plentiful.

While there is some overlap between installed robotic systems and deployable robotics with certain technologies fitting uneasily into either section, the distinction is primarily in the way that they navigate and the integration of cleaning solutions into the system as a whole. Some robots, which technically are not installed into the system, can be manually moved from one row to the next. But they are considered to be in the category of installed systems because they are designed to fit these specific rows, and could conceivably be integrated as an installed system where each very long row has a single robot for cleaning. This difference between the sections will be further clarified after reviewing the deployable robotics.

Installed robotic systems can have a wide range of capital costs involved with their procurement and installation. Assuming that such systems are deployed to be significantly autonomous, this generally requires a large number of cleaning systems. The number is usually dependent on the layout of the solar array, as it is relatively easy for such robots to navigate rows, but more difficult to cross large gaps or move from one row to another. Assuming the plant uses relatively long rows, and the robots are made to be economical, the capital costs would be moderate.

The operational cost of autonomous installed robotic systems is, at least in some cases, the lowest of all the systems. This is especially true when the systems operate without the use of water, as there is then almost no operational cost aside from maintenance and a very small amount of power. One concern with dry systems is that they might not clean the 6 panels perfectly. This is also true of many of the other systems, and the reduced cost of operation means that such systems could be utilized at a higher frequency, and so minimizing the time that dust is reducing the efficiency of the panels. As with any system that is in mechanical contact with the array, there is a possibility of the system damaging the panels. A properly engineered system should have a reasonably low chance of such damage.

Authorized licensed use limited to: FUNDACAO UNIVERSIDADE DO RIO GRANDE. Downloaded on August 29,2020 at 21:46:20 UTC from IEEE Xplore. Restrictions apply.

Deployable robotics for cleaning are distinguished from the installed robotic system category, in that they are designed to be deployed as needed. They may range from remote controlled systems to completely automatic systems.

A few challenges were noted with some of these robotics products, including the inability to remove hard dust, the fact that removed dust blows back onto panels as the robot moves along the next row, and the fact that the robot gets very dirty during the cleaning. This particular system can be programmed to be completely automatic, but generally operates in a semi-automated manner to prevent the operator from driving the robot off the edge of the panels. Some of these robots do not use water, but many robots in this category use at least a small amount of water. Unfortunately, this battery driven solution has a limited charge, creating a challenge for high capacity cleaning. The majority of deployable robots are attached to a tether that provides power and water. This allows them to perform a more thorough cleaning and eliminates the challenge of limited power. This also adds to the operating cost though, as the water and deployment both cost more. Overall, while the capital cost for such a system might be slightly less than that of the installed robotic systems due to the need for fewer robots, the extra labor costs might make deployable systems more expensive in large-scale solar power plants.

III. Research-Stage Cleaning Technologies

Electrostatic Curtains

The manned missions to the moon and the more recent rover missions to Mars required robust technologies for solar panel cleaning and dust removal, as this was critical to the success of these missions, and continues to be an important challenge in space exploration. As with many government-funded projects, the technologies developed during these missions will lead to improved dust mitigation for electronic equipment, solar panels, installed cameras, mirrors and other installed instrumentation. One of the most heavily researched technologies being developed for these missions involves the utilization of electrostatic means for the removal of dust.

Recent studies [8-10] have demonstrated transparent, flexible electrodynamic screens (EDS) that prevent obscuration of solar panels by designing patterns of conductive and transparent electrodes that are then deposited over the glass panels, which represents the solar energy collectors.

These conductive tracks are embedded under a thin, transparent dielectric fluoropolymer film or silicon dioxide coating. When they are energized by an applied voltage, the electromagnetic waves propagating through these lines will charge the particles on the surface and exert coulomb and dielectrophoretic forces to lift the dust from the surface and transport it to an edge of the collector, thereby clearing the screen. The EDS can be integrated into the collector during manufacture or retrofitted to existing conventional collectors. In the case of muddy and wet conditions this technology will not work. Similarly, this technology would be unlikely to remove solidified dust or very large particles.

Figure 2 represents the schematic diagram for an EDS where the electrodes are deposited on the glass with specific dimensions based on the desired electric conductivity.

A thin film of transparent dielectric is applied to coat the glass and the electrodes. The dielectric medium is typically either polyester urethane or ethylene tetrafluoroethylene (ETFE) [10]. As shown in the graph, when the voltage is applied, a travelling electromagnetic wave is generated and the electric fields charge the dust particles and transport them away from the panel. This principle of moving particles using electric fields is not new and was reported as early as the 1970s [11-12].

Some research work is still at the initial stages of exploration to implement ultrasonic systems to remove dusts through vibrating mechanisms [13]. This technology does not remove fine particles and this makes the electrostatic removal of charges the most valid and practical approach.

Self-Cleaning Hydrophobic Materials

This mechanism is based on using hydrophobic materials on the solar panel, which allows them to be self-cleaning [14-19]. This characteristic is found naturally in lotus leaves,which have superhydrophobic nanostructures with high contact angles that make the water droplets roll off easily and, therefore, lift the dust particles and clean the surfaces. Hydrophobic coatings enable rain water to diffuse over an entire surface and rinse the dust more easily. This method is not naturally useful in arid regions where rain occurs seldomly. Still, using hydrophobic materials can be a good option in such rainless conditions, because a lot of water can be saved in the process of cleaning the panels. Many research activities are focused now on developing such materials, focusing on durability, effectiveness and cost.

The research focused on hydrophobic materials for solar panel coatings aims to make the coating easy to apply during manufacture or after the installation, to make the coating last for a longer time and to protect the panels at the same time. The applied material should be as thin as possible and transparent so as not to affect the light transmittance to the cells. Creating an ultra-thin surface is an advantage and can increase the solar efficiency and prevent losing the light transmission. It is important to take into account factors related to the reflection loss and refractive index of the coated material. Hydrophobic materials provide an interesting

Authorized licensed use limited to: FUNDACAO UNIVERSIDADE DO RIO GRANDE. Downloaded on August 29,2020 at 21:46:20 UTC from IEEE Xplore. Restrictions apply.

research challenge and necessitate dedicated resources in nanotechnology.

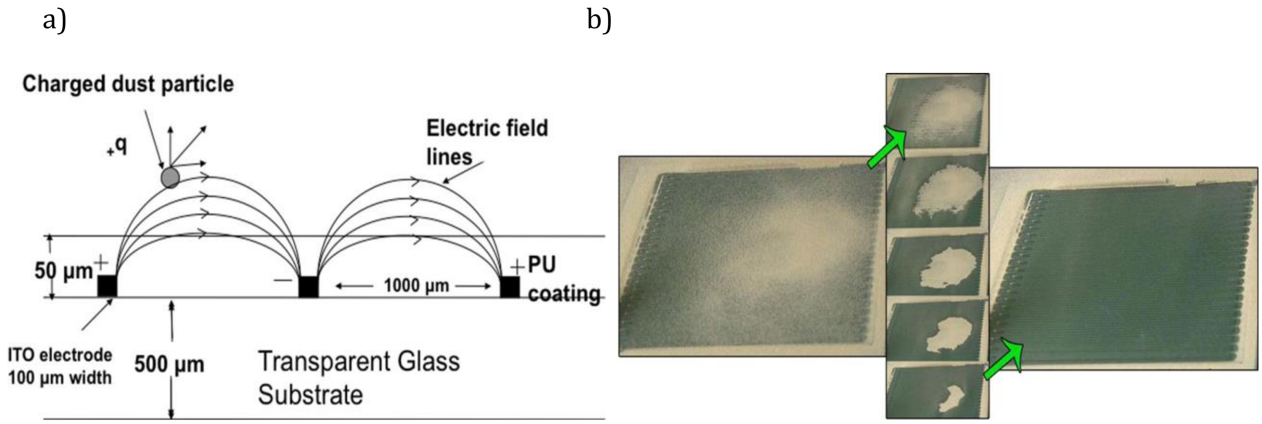

Figure 2: Schematic view of a cross-section EDS developed by Mazumder et al. (a), when the electrodes are activated by phased voltage; the dust particles on the surface of the film become electrostatically charged and are removed by the traveling wave generated by applied electric field. Photographs of an EDS panel (b) being cleaned after throwing some desert dust samples on it. Over 90% of deposited dust was removed within 2 min, using a very small fraction of the energy (less than 0.1 %) produced by the panels themselves. No water or mechanical movements are required. The images are taken from [9].

IV. CONCLUSIONS

This paper has presented a clear comparative survey of five different categories of cleaning technologies available for solar panels, with an analysis of each. Though every technology has advantages in specific applications, the qualitative comparison of the currently available technologies indicates that the installed robotic systems, mechanized systems, and installed hydraulic systems are likely the three most promising technologies for use in cleaning solar panels in arid regions from an economic standpoint. This survey, therefore, provides an early means of selecting categories of currently available cleaning technologies that offer the most promise toward financially feasible methods of cleaning solar panels in arid regions. In addition to the review of currently available products that can be applied in the near-term, this review also reveals various research-stage technologies such as electrostatic curtain technologies and ultrasonic shaking and hydrophobic nanocoatings. Though these technologies may already be useful in specific cases, it is possible that they will never be financially feasible for use in utility-scale terrestrial solar power plants. Hydrophobic polymers show perhaps the most promise in aiding water-based cleaning techniques since they might allow these methods to use significantly less water while providing a higher level of cleaning. This might make hydraulic cleaning solutions a highly competitive cleaning solution in the future, depending on the cost of the coating. An interesting application of this technology might be for heliostats, where the curved, moving surfaces would make robotic applications much more difficult to implement. It is recommended that this research option be investigated from the perspective of developing a long-lasting and inexpensive hydrophobic coating. Areas of focus could be functionalizing the material to provide resistance to mechanical wear while investigating transparency, optimum thickness to get light transmission, mechanical adhesion to the surface and, importantly, the cost to produce and apply the coating. It is the aim of this analysis to present the average technological advantages in the qualitative analysis to those who wish to develop a new technology. Alternatively, for those wishing to invest in a cleaning solution, the quantitative analysis provides estimates associated with the most cost-effective products in each category to provide an accurate cost estimate for each type of available technology.

V. ACKNOWLEDGMENTS

We would like to acknowledge and extend our gratitude to the Research & Development Center of Saudi Aramco for the support in the development of this paper.

VI. REFERENCES

[1] Tara C. Kandpal, Lars Broman, Renewable energy education: A global status review, Renewable and Sustainable Energy Reviews, Volume 34, June 2014, pages 300-324, http://dx.doi.org/10.1016/j.rser.2014.02.039.(http://www.sciencedirect.com/science/article/pii/S1364032114001762), Date of access: April 13, 2014

[2] EC (European Commission) (2005), "The support of electricity from renewable energy sources: Impact assessment," SEC (2005) 1571, pp. 55, Brussels, http://ec.europa.eu/governance/impact/ia_carried_out/docs/ia_2005/sec_2005_1571_en.pdf. Date of access: April 13, 2014.

Authorized licensed use limited to: FUNDACAO UNIVERSIDADE DO RIO GRANDE. Downloaded on August 29,2020 at 21:46:20 UTC from IEEE Xplore. Restrictions apply.

[3] Borchers, A.M., Duke J.M., Parsons G.R. “Does willingness to pay for green energy differ by source?” Energy Policy 2007; 35(6):3327–34.

[4] Meijer A., Huijbregts M.A.J., Schermer J.J., Reijnders L. “Life cycle assessment of photovoltaic modules.” Progress in Photovoltaics Research and Applications 2003; 11:275e87.

[5]http://www.solarbuzz.com/news/recent-findings/solar-photovoltaic-demand-reach-31-gigawatts-2013-according-npd-solarbuzz

[6]http://www.epia.org/index.php?eID=tx_nawsecuredl&u=0&file=/uploads/tx_epiapublications/Market_Report_2013_02.pdf&t=1397480243&hash=3516a6cd990b96874aa1055eeb0fba8827042fd3, date of access: April 13, 2014

[7]http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2012/energy/e201210007.htm, date of access: April 13, 2014

[8] M.K. Mazumder, M. Horenstein, J. Stark, P. Girouard, R. Sumner, B. Henderson, O. Sadder, I. Hidetaka, A. Biris, and R. Sharma, “Characterization of Electrodynamic Screen Performance for Dust Removal from Solar Panels and Solar Hydrogen Generators,” IEEE Transactions on Industry Applications, vol. 49, no. 4, July-August (2013).

[9] M.K. Mazumder, R. Sharma, A.S. Biris, J. Zhang, C. Calle and M. Zahn, “Self-Cleaning Transparent Dust Shields for Protecting Solar Panels and Other Devices,” Particulate Science and Technology: An International Journal, 25:1, pp 5-20, (2007).

[10] Biris, A.S., D. Saini, P.K. Srirama, M.K. Mazumder, R.A. Sims, C.I. Calle, and C.R. Buhler. “Electrodynamic removal of contaminant particles and its applications,’’ in Proceedings of the IEEE-IAS 39th Annual Meeting, Seattle, Washington. Washington. Inst. of Electrical and Electronic Engineers (IEEE), Inc., New Jersey, USA. vol. 2, pp. 1283-1286, (2004).

[11] Masuda S., Fujibayashi K., and Ishida K., “Electrodynamical behavior of charged aerosol particles in non-uniform alternating fields and its application in dust control,” Staub- Reinhaltungs del Luft, 30 (11), 449-456, (1970).

[12] Masuda S., Kamimura T., “Approximate methods for calculating a non-uniform travelling electric field,” Journal of Electrostatics, 1, 351-370, (1975).

[13] Piotr Vasiljev, Sergejus Borodinas, Regimantas Bareikis, Arunas Struckas, “Ultrasonic system for solar panel cleaning, Sensors and Actuators,” A: Physical, Volume 200, pp 74-78, (2013).

[14] Masuda S., Washizu M., and Iwadare M., “Separation of small particles suspended in liquid by non-uniform travelling field produced by three phase electric curtain device,”presented at IEEE-IAS Annual Meeting, Toronto, ON, Canada, Oct. 6-11, (1985).

[15] Gaofa He, Chuande Zhou, Zelun Li: “Review of Self-Cleaning Method for Solar Cell Array,” Procedia Engineering, Volume 16, pp 640-645, (2011).

[16] Park Y.B., Im H., Im M., et al. “Self-cleaning effect of highly water-repellent microshell structures for solar cell applications.” Journal of Materials Chemistry, 21, pp 633-636, (2011).

[17] Zhu Jia, Hsu Ching Mei, Yu Zongfu, et al. “Nanodome solar cells with efficient light management and self-cleaning.” Nano Letter, 10, pp 1979–1984, (2010).

[18] Niu Jun Jie, Wang Jian Nong, Xu Qian Feng, “Synthesis of superhydrophobic silicon oxide nanowires surface on silicon wafer.” Journal of Nanoscience and Nanotechnology; 9(3): 1819-1824, (2009).

[19] Ivan P. Parkin and Robert G. Palgrave, “Self-cleaning coatings,” J. Mater. Chem., 15, pp 1689-1695, (2005).

VII. Biographies

Ali Hamoud Alshehri was born in Namas city in Saudi Arabia, on March 5th, 1982. He graduated from King Abdul Aziz University with his BS and from University of Surrey, in the UK with his MS and PhD.

His employment experience has included work with Siemens Company and Saudi Aramco. His current fields of interest include radio frequency nanoelectronics and intelligent systems.

During his graduate studies in the UK he has been recognized with multiple awards of excellence from Saudi Arabian cultural bureau in London.

Brian Parrott was born in Seattle in the USA, on September 29th, 1987. He graduated from the University of Washington with his BS and from King Abdullah University of Science and Technology (KAUST) with his MS.

His employment experience has included work with the Puget Sound Naval Shipyard in the USA and Saudi Aramco. His current fields of interest include mobile robotics and intelligent systems.

As a part of the Intelligent Systems team at Saudi Aramco, he has been recognized with multiple awards including the International Federation of Inventors Association’s Glory Medal and the CEO Excellence Award from Saudi Aramco. Additionally, he has been invited to present the team’s work to the KAUST Industrial Advisory Board and the KAUST Board of Executives in addition to internal Saudi Aramco organizations.

Authorized licensed use limited to: FUNDACAO UNIVERSIDADE DO RIO GRANDE. Downloaded on August 29,2020 at 21:46:20 UTC from IEEE Xplore. Restrictions apply.