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Increasing the Efficiency of Photovoltaic Solar Cells

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I. INTRODUCTION

One of the two mainstream solar power technologies is photovoltaic or PV systems. When used alongside concentrated solar power, the two constitute a hybrid solar power system. Nonetheless, at the heart of PV systems are solar panels made of individual photovoltaic cells or solar cells. These cells are electronic devices made primarily of semiconducting materials that convert light into energy through the photovoltaic effect. To be more specific, semiconductors that exhibit the photovoltaic effect can convert solar radiation into direct current electricity, thus generating electrical power (Bhatia, 2014).Nevertheless, the power conversion efficiency of a particular PV system depends on the material integrity, and quality of the PV cells and the type of the underlying semiconducting material. Materials based on silicon were the first generation cells introduced in 1946 for mass production. The production of these cells, especially its fabrication and addition of enhancements, as well as the utilization of other materials, have since emerged to improve the efficiency of PV systems and make solar power a cost-effective alternative source of renewable energy (Sharma, Jain, & Sharma, 2015).

The working mechanism behind PV cells is based on the photovoltaic effect and the so-called theory of solar cells. Note that the photovoltaic effect is both a physical and chemical phenomenon first demonstrated by Edmond Becquerel in 1839 (Guarnieri, 2015). The established definition involves the change of between two but separated electrodes due to unsymmetrical illumination(Copeland, Black, & Garrett, 1942). Closely related to the photoelectric effect, electricity generation transpires because the absorption of light excites the electron, thereby bringing it to the higher-energy state (Bagher, Vahid, & Mohsen, 2015). Note that this is the same fundamental mechanism behind solar cells. However, to be more specific, three factors affect how these cells work: adsorption of light to generate the charge careers, the separation of charge careers, and the collection of these charge careers (Sharma, Jain, & Sharma, 2015; Bagher, Vahid, & Mohsen, 2015). To reiterate the above-mentioned, the capacity of the PV cells to generate electricity efficiently and economically depends on how well they promote the photovoltaic effect and address the three operational factors.

II. INEFFICIENCY ISSUES WITH PHOTOVOLTAIC SYSTEMS

Despite the fact that solar power through PV systems is a clean and renewable alternative source of energy, it has notable disadvantages that hinder widespread acceptance and further endorsement. For starters, solar cell panels are costly to purchase and install, thus negatively impacting the cost efficiency of a PV system (Bhatia, 2014). Traditional or first-generation panels based on silicon are also large, heavy, and bulky. Installing them requires a considerable amount of space, especially if there is a higher requirement for power or electricity generation (Sharma, Jain, & Sharma, 2015). The second-generation panels are considerably thinner and less expensive to produce because they are based on thin-film semiconducting materials. However, they are relatively less efficient than the traditional panels, thereby requiring a considerably a large surface area to generate power that can rival their first-generation counterparts (Bagher, Vahid, & Mohsen, 2015).

There are also issues concerning the continuity or permanency of power generation via PV systems, as well as thestorage of generated power into battery cells. Take note that a solar panel can only generate electricity under broad daylight (Bhatia, 2014). It is essentially useless during nighttime. Weather and environmental conditions such as overcast or cloudy weathers, and during the prevalence of dust or haze (Bagher, Vahid, & Mohsen, 2015). There are also concerns about geographical compatibility. For example, solar radiation in the tropics such as Southeast Asian countries is at an average of 0.25 kW/m2 while in northern European countries such as Hungary, it is only at 0.16 kW/m2 on average (Lakatos, Hevessy, & Kovác, 2011). With regard to storage considerations, because solar power via PV systems is inconsistent, there is a need to identify and utilize suitable battery technologies to maximize the use-case of installed solar panels. Of course, storage provides additional costs to the entire system (Vega-Garita, Ramirez-Elizondo, Narayan, & Bauer, 2018). An effective and efficient battery technology and overall storage system supplement and partly determine the overall effectiveness and efficiency of PV cells, the entire solar panel, and the specific PV system (Steffens, 1991).

Several studies have also focused on the disadvantageous aspects of fabricating PV cells, as well as in manufacturing solar panels that, in turn, affect the efficiency of PV systems in terms of costs and economic impact or social value. One review noted that apart from the production costs, there are also environmental concerns associated with some materials used in solar cells (Gul, Kotak, & Muneer, 2016). An article published by the Forbes magazine also reported that the production of solar panels produces so much toxic waste such as lead and carcinogenic cadmium that can contaminate bodies of water and leach into soils. There is also a problem regarding the recyclability and proper disposal of decommissioned panels (Shellenberger, 2018). A case study involving an experiment in South Korea also revealed that the operating of photovoltaic power plants had environmental costs to include loss of habitat, land degradation. and light pollution, and similar to the report by the Forbes, emission of hazardous materials. These trade-offs have detrimental effects on the local ecosystem, animal and fauna populations, and the food chain (Yang, Lim, & Yoo, 2017). The energy expenditure in manufacturing solar panels and operating solar power plants is somewhat inefficient, depending on the use-case scenario. Take note that the cost of power from PV systems remains considerably higher than the cost of power from coal power plants. What this suggests is that producing solar panels and operating solar power plants are considerably financially costly than mining coal and operating coal power plants (Grau, Hou, & Neuhoff, 2011)

The disadvantages mentioned above and consequently, the inefficiency issues with photovoltaic systems are being addressed through the development of novel manufacturing and fabrication processes, implementation of better use-case factors, and identification of new materials. As an example, a review noted that the economic viability and reliability of PV systems have increased over the years due to emerging clamor for cleaner alternative sources of energy and coupled with improvements in technology (Cengiz, 2015). The longevity of these systems has also increased. Panels from reliable manufacturers and made from quality materials can last for 25 years, thus making them ideal for use in individual homes, limited residential communities, and public and industrial buildings. Note that panels that have a 10-year or 15-year lifespan are still economically viable and, thus, cost-efficient, especially when modularized to allow easier maintenance, inexpensive servicing, and possible modular replacements or upgrades (Jean, Woodhouse, & Bulović, 2019). Aside from improving the longevity and economic viability of solar panels, their costs have been decreasing due to key factors such as promotion by governments around the world through appropriate policies, the utilization of a more affordable labor force in developing countries or emerging markets, and new methods for economical mass production (Grau, Hou, & Neuhoff, 2011).

III. IMPROVING THE EFFICIENCY OF PHOTOVOLTAIC CELLS

Of course, when considering the general efficiency of PV systems and solar panels, including PV cells, it is important to take into consideration cost drivers. There are two general key cost drivers. These are the efficiency with which sunlight is converted into power and how this relationship changes over time (Jordan & Kurtz, 2013). To address the need to improve the efficiency of sunlight-to-electricity conversion, researchers and industry players have examined, explored, and investigated different ways to improve the capabilities of PV cells either by improving their material constitutions, adding enhancements, or developing and using more efficient materials and overall design.

3.1. Thin Film Solar Cell Technologies

Remember that first-generation panels are based on silicon. Made from silicon wafers, they are the earliest and most popular solar cell technology due to their high power efficiency. There are also two subgroups under this generation: the single or monocrystalline silicon cell and the poly or multi-crystalline cell. The problem with this technology is that the resulting panels require the utilization of a large surface area because they are large and bulky (Sharma, Jain, & Sharma, 2015). They are also expensive to manufacture and fabricate compared to other solar cell technologies. Data from 2015 indicated that approximately 85 to 90 percent of PV systems used in the market are based on silicone technology or, more specifically, the combination of mono-crystalline and multi-crystalline silicon cells (Cengiz, 2015).

Thin-film technologies have been positioned as a more economical counterpart of first-generation silicon-based solar cells. However, they are generally less efficient at power conversion. A notable contender is amorphous silicon or a-Si thin-film cells, which is a non-crystalline allotropic form of silicon (Parida et al., 2011). It also has 40 times higher rate of light absorptivity than monocrystalline silicon, thus enabling it to become the top priority among all other thin-film technologies in the market (Mah, 1998). However, it only has a yield of only around 7 percent compared to the 18 percent of first-generation, silicon-based cells due to the fact that it suffers from a degradation of 15 to 35 percent because of the Staebler-Wronski Effect mechanism (Bagher, Vahid, & Mohsen, 2015). A comparison between a-Si solar cells and first-generation cells concluded that the former needs considerable research and development to improve its performance, especially their efficiency (Gul, Kotak, & Muneer, 2016).

Several improvements have been made to thin-film technologies. Cadmium telluride or CdTe solar cells have been positioned as one of the leading candidates for the development of cost-effective and economically viable thin-film cells (Sharma, Jain, & Sharma, 2015). Numerous tests for power conversion efficiencies revealed that it achieved initially 10.6 percent and 11.2 percent efficiency levels while some companies produced cells with 15 to 16 percent levels. The highest efficiency level of CdTe cells achieved was 17.3 percent—almost near the 18 percent efficiency level of monocrystalline silicon cell (Gul, Kotak, & Muneer, 2016). Numerous researchers have considered cadmium telluride as the most promising semiconducting material for PV systems because of the availability of different production techniques and the successful commercialization of the resulting PV cells and solar panels. Further research into the material and thus, development have resulted in a double-digit efficiency level from a single-digit efficiency level of 0.7 percent (Dharmadasa, Alam, Ojo, & Echendu, 2019).

There is an emerging body of literature dedicated to exploring the different breakthroughs or innovations, techniques, and processes employed to improve the efficiency of CdTe solar cells. An earlier solution introduced in the 1980s to advance the material as an efficient semiconductor was electroplating. The result was solar panels of 0.96 m2 thickness, with an efficiency level of 10.6 percent (Cunningham, Rubcich, & Skinner, 2002). Further developments have stalled from the 1990s to 2000s due to the emergence of novel candidate materials, lack of support to the photovoltaic industry, and introduction of other alternative energy technologies (Dharmadasa, Alam, Ojo, & Echendu, 2019). There were still some developments. For example, heterojunction structures with n-type cadmium sulfide or CdS have been considered as one of the best options for improving the efficiency of CdTe. The heterojunction between the two results in an improved and excellent electrical behavior that, in turn, leads to a high fill factor level of 0.77 percent. The same CdTe/CdS configuration has achieved an efficiency level of 16.5 percent in the laboratory as early as 2001 (Fang, Wang, Wu, & Zhao, 2011).

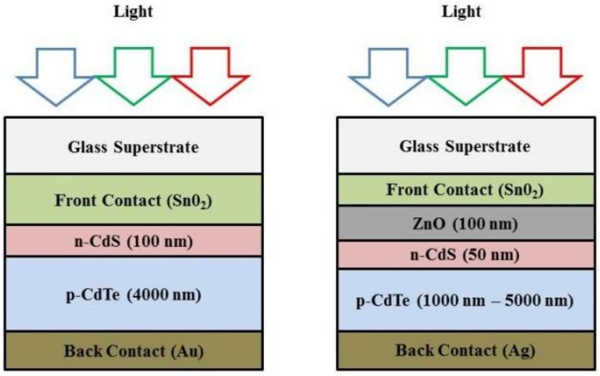

Figure 1. *A conventional CdTe solar panel on the left versus a modified CdTe panel demonstrating design modifications and engineering configurations (Khan, Rhaman, Haque, & Dhar, 2004)*

Furthermore, the years within the early 2000s also brought forth dramatic advancement in thin-film solar cell technologies based on cadmium telluride. The use of better quality glass, improvement in the transparency of oxides, the introduction of more sensitive and resistive films, treatment improvements, doping, and higher deposition temperatures produced efficiency levels higher than 16 percent. The level increased further to 20 percent due to small-area cell conversion efficiency and improvement in champion module efficiency during 2003 and 2004 (Basol & McCandless, 2014). Other processes used to improve the performance of this semiconducting material includes the addition of a variety of substrates such as metal, insulator, rigid structure, and flexible structure, among others, as well as the use of different fabrication techniques to include plasma-based or hybrid processes. The inclusion of substrates can promote or tackle adsorption, reflectivity, contact, and buffer issues (Choppra, Paulson, & Dutta, 2004). Nevertheless, a more recent study revealed that the addition of the element selenium in the treated CdTe material resulted in a record-breaking efficiency level of just over 22 percent. Although the exact and more detailed mechanism of the role of selenium remains unknown, the study explains that the element generally works by overcoming the effects of atomic-scale defects in CdTe that reduces light-to-electricity conversion efficiency. The findings have advanced further the potential of CdTe solar cells (Fiducia et al., 2019).

3.2. Organic Solar Cells and Biological Photovoltaics

Another classification of PV or solar cells falls within the third-generation, and they are collectively organic solar cells. Based on the principles of organic electronics, these PV cells are based on conductive organic polymers or small organic molecules that are capable of demonstrating the photovoltaic effect (Pulfrey, 1978). To explain further, these materials are labeled organic because they are constructed from carbon-based or organic polymers using synthetic techniques and based on the principles of organic and polymer chemistry (Klauk, 2006). Nevertheless, when applied in PV systems, organic electronics provide several advantages. One example is that organic solar cells can be fabricated at low cost and large volume because they can be manufactured at high throughput (Nelson, 2011). When compared to silicon-based solar cells, especially those based on first-generation technology, aside from the fact that they are more inexpensive to fabricate, they are also more lightweight and considerably disposable. They can also be engineered and, thus, customized on the molecular level. There also have fewer extreme drawbacks to the environment (Luther et al., 2000).

Of course, they also have disadvantages and limitations, especially when placed side-by-side with first-generation and second-generation solar cells. They have low power conversion efficiency levels, stability problems, and low overall power generation capacity (Nelson, 2011; Luther et al., 2000). Research and development have tried to address these issues. For example, researchers were able to demonstrate a 10 percent level of efficiency in 2013 via organic solar cells and through a tandem structure (You et al., 2013). Another study advanced further the proposition for organic solar cells as researchers were able to achieve a 17.3 percent level of efficiency via the same tandem structure (Chen et al., 2017). There are also components or materials applied to these organic materials to increase their light-trapping or optical in-coupling effects (Park, Vandewal, & Leo, 2018).The use of nanotechnology has the potential to improve the viability of these materials as well. Nanostructures based on carbon such as fullerenes, nanotubes, and graphene have potential complementary applications because of their excellent electronic, optical, thermal, and mechanical properties (Pathakoti, Manubolu, & Hwang, 2018). In addition, the use of flexible substrates allows the introduction of polymer electrodes with embedded scattering particles that, in turn, can improve further light trapping effects (Park, Müller-Meskamp, Vandewal, & Leo, 2016). Another laboratory experiment involved the fabrication of periodic surface textures through the use of direct laser interference patterning, thus resulting in efficiency enhancement of up to 21 percent (Müller-Meskamp et al., 2012). Essentially, increasing further the efficiency level of these cells could open new opportunities for PV systems because of the low manufacturing cost involved, especially when compared to silicon-based semiconducting materials (Nelson, 2011).

A further boost in the efficiency levels of organic solar cells will essentially make these materials candidate rivals for both first-generation or silicon-based cells and second-generation or thin-film technologies. One review study explained that organic materials are more suitable for large-scale power generation because they are less expensive to manufacture compared to inorganic semiconducting materials because of the suitability of applying a roll-to-roll technique (Pathakoti, Manubolu, & Hwang, 2018) The possibility for mass production also corresponds to a production capacity of 1 GW per day (Hösel, Angmo, & Krebs, 2013). It is also important to reiterate the fact that the manufacturing and fabrication of these materials can be done on a massive scale because the process can be automated. Even the screening and quality evaluation processes can be done with the aid of automation. What is more interesting to note is that different organic materials can be tested for their potential application as organic solar cells (Amador-Bedolla, Olivares-Amaya, Hachman, & Aspuru-Guzik, 2013).

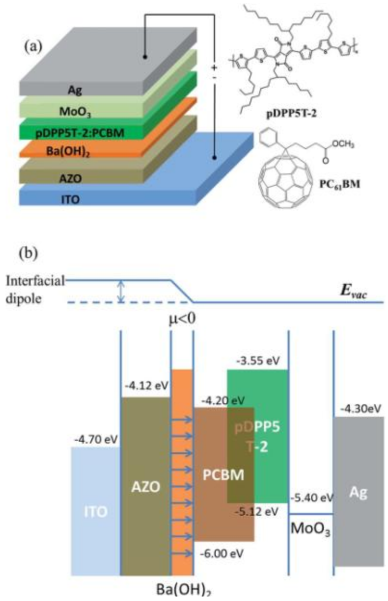

Figure 2. *(a) Schematic of the inverted organic solar cell structures and chemical structures of pDPP5T-2 and PC 61 BM. (b) Energy level diagram of the organic solar cells investigated in this work (Zhang et al., 2014)*

There are also other technologies related to organic solar cells. For example, researchers in 2015 successfully develop inexpensive organic solar cells based on chitin and chitosan, which are organic polymers found in the shells of shrimps and other crustaceans. The process involved using hydrothermal carbonization to create the carbon quantum dots from these organic polymers before applying a zincoxide nanorods coating to produce the individual PV cells. The researchers explained that the power conversion efficiency level remained low, but it could be improved through the inclusion of other materials or improvements in the fabrication process (Briscoe, Marinovic, Sevilla, Dunn, & Titirici, 2015). There are also the so-called biological photovoltaics that are based on exploiting oxygenic photoautotrophic organisms or a fraction thereof to harvest light energy from the sun and generate electricity (Bombelli et al., 2011). These living materials have notable advantages over inorganic materials and even other organic materials. For starters, a biological PV system is capable of self-assembly and self-repair because of their living and organic components. The system can also have its own natural and organic storage owing to the natural ability of the involved organisms (Tschörtner, Lai, &Krömer, 2019). Take note that scientists have been expanding the possibilities of using living organisms within engineered biological systems, especially for electrical energy storage. The underlying principle is the utilization of photosynthetic cells both for capturing energy from the sun and storing them as fuels for future consumption (Salimijazi, Parra, & Barstow, 2019).

Nevertheless, among the candidate species for biological photovoltaic technology are cyanobacteria. Note that these series are photosynthetic. What this means is that they are capable of capturing radiant energy from the sun and converting them into a usable energy form. Engineering these species can result not only in the improvement of their photosynthetic capabilities but also in equipping them with photoelectric capabilities and, by extension, photovoltaic capabilities (Tschörtner, Lai, &Krömer, 2019). Of course, aside from using while and living organisms, biological photovoltaics can also involve the use of subcellular components of photosynthetic organisms such as thylakoid membranes (Bombelli et al., 2011). The photosystem can also involve indirect sunlight-to-electricity conversion. Instead, a system based on the extraction of electrons on the water and its further donation to the anode at a more negative redox potential (Carpentier, Lemieux, Mimeault, Purcell, & Goetze, 1989)

3.3. Hybrid Photovoltaic Systems

There is also an established research and commercial interest on hybrid solar cells. Note that this specific classification also falls under the third-generation categories of PV cells. By definition, they are a mixture of inorganic semiconducting materials such as silicon or other second-generation materials and conjugated polymers. The polymers function as a component for absorbing light and, thus, as the donor and transport holes. On the other hand, the inorganic material component serves as the acceptor and electron transporter (Moulé, Chang, Thambidurai, Vidu, & Stroeve, 2012).Note that the usual configuration involves a combination of organic polymer and nanoparticles. The principle behind designing and engineering hybrid cells made of inorganic materials and conjugates polymer center primarily on the need to exploit the respective advantages or best properties of each material. For example, polymers, especially organic materials, have high flexibility, while inorganic materials such as nanoparticles have higher charge mobility (Milliron, Gur, & Alivisatos, 2005). It is also worth mentioning that nanoparticles allow the tuning and amplification of optoelectronic properties to include band gap and electron affinity. Also, because their surface area to volume ratio is large, these minuscule particles allow better charge transfer to occur (Ueda, Mu, & Wu, 2005).

Note that there are other types of hybrid solar cells apart from polymer-nanoparticle hybrids. As an example, hybrids that include carbon nanotubes demonstrate high electron conductivity, high thermal conductivity, robustness, and flexibility (Charlier et al., 2002). However, for these materials to become suitable in hybrid systems, they need to have features or characteristics for improving the photovoltaic effect in a particular hybrid system. Doing so could involve addition electron-accepting impurities to the photoactive region. The high surface area of carbon nanotubes natively provides a potential for excitation dissociation (Cinke et al., 2002). The application of metal nanoparticles to the exterior of carbon nanotubes can also increase the excitation parathion efficiency. A metallic material essentially provides a higher electric field at the interface of the hybrid cell, thereby augmenting the exciton carriers for more effective electron transportation (Somani, Somani, & Umeno, 2008).

Another type of hybrid PV cell is dye-sensitized solar cell. The configuration involves a photo-sensitized anode, an electrolyte, and a photo-electrochemical system formed with organic materials and inorganic materials, including titanium dioxide (Wei, 2010). Nonetheless, this hybrid PV cell type provides an economically viable and technically visible alternative to the current p-n junction photovoltaic devices because light absorption and large carrier transportation take place in two separate areas under this hybrid configuration. Note that the photo-sensitized anode is responsible for light absorption while charge carrier transportation transpires in the conduction band of the semiconductor to the charge collector (Grätzel, 2003). The preferred inorganic material for this hybrid system is titanium dioxide due to the fact that it is easy to synthesize, and it functions as an n-type semiconductor owing from its donor-like oxygen vacancies (Aboulard, 2020). There are also suggestions for using specific types of dyes to improve the performance of dye-sensitized solar cells. One experiment utilized three natural dyes extracted from different fruits and leaves. Essentially, these dyes were used as sensitizers for dye-sensitized solar cells. Findings suggest that natural dyes have the potential for lowering the cost of manufacturing panels and PV systems based on dye-sensitized solar cells because they are easy to extract using simple techniques. In addition, preliminary investigations suggest that these natural dyes can efficiently absorb ultraviolet radiation while also demonstrating photoluminescence properties (Ammar, 2010).

There is also a similar technology called bio-hybrid solar cell. It generally involves the combination of organic and inorganic components. However, the particular organic component comes from an actual organic matter such as thylakoid membranes from living organisms. The operational principle is to recreate the natural process of photosynthesis to obtain greater efficiency in solar energy conversion. The inorganic materials complement the entire cell by providing additional energy conversion efficiency (Bagher, Vahid, & Mohsen, 2015). It is important to reiterate the fact that some of the advantages of a standard biological PV system include the capability for self-assembly and self-repair because of the living and organic components. The system can also have its own natural and organic storage owing to the natural ability of the involved organisms (Tschörtner, Lai, &Krömer, 2019). A photosystem protein also has two major advantages. The first is that it has fewer impact exertion by the other electron transfer chain members, while the second centers on better transfer of generated electrons because of the close proximity between photosynthetic organs and proteins (Molamohammadi, Jalli, & Riazi, 2018).A PV system based on bio-hybrid solar cells also features these advantages with the inclusion of other advantages from using inorganic materials. As an example, titanium dioxide remains the most preferred material for the immobilization of pigment-protein complexes in terms of both cost and efficiency (Musazade et al., 2018). Remember that this material is also easy to synthesize, and it functions as an n-type semiconductor owing to its donor-like oxygen vacancies (Aboulard, 2020). Nevertheless, depending on the biological and organic material uses, including the protein complex, bio-hybrid solar cells have demonstrated a power conversion efficiency potential of around 4 percent. Further research and development in this area could improve the efficiency levels, especially with the discovery and engineering of new complexes, design of hybrid systems, and inclusion of efficiency-boosting materials (Molamohammadi, Jalli, & Riazi, 2018).

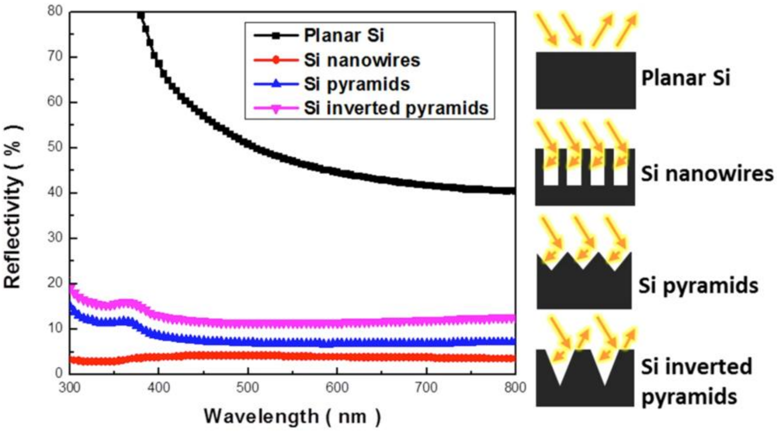

Figure 3. *The reflectivity of silicon textures with inclusions of additional materials such as Planar Si, Si nanowires, Si pyramids, and Si inverted pyramids for improving light-capture efficiency (Li, Hung, & Chen, 2017)*

Specific advantages of hybrid solar cells revolve around inexpensive manufacturing cost and the possibility of improved power conversion efficiency levels due to better design. Studies revealed that the potential for low-cost production translate to scalable power conversion and thus, mass deployment of PV systems and solar power based on hybrid cells (Milliron, Gur, & Alivisatos, 2005). Of course, it is also worth mentioning that the current major challenge of this technology is efficiency. Hybrid solar cells have achieved an efficiency level of around 5 percent. Note that a CdSe-PVE hybrid system has a low efficiency level of 2.4 percent compared to the 20 percent efficiency level of PV cells based on silicon and second-generation tin film technologies (Ueda, Mu, & Wu, 2005). Hybrid systems based on dye-sensitized solar cells also have an efficiency level of around 2 percent (Ammar, 2010). There are also current limitations stemming from incompatibilities among different types of materials. For example, in systems based on nanoparticles, there are still compatibility issues with several intradevice interfaces and the uncontrolled aggregation of nanocrystals during the step in which the nanocrystals are mixed into the polymer matrix(Nguyen, Kim, & Park, 2014). Of course, the performance of hybrid devices is still improvable through further research, better engineering, and improved designs (Briscoe, Marinovic, Sevilla, Dunn, & Titirici, 2015). One study noted that progress in the future would depend on the discovery, engineering, and design of novel nanoparticles such as cadmium telluride tetrapod. These new materials can have the potential to enrich the light absorption capabilities of hybrid solar cells while improving further charge transport. The same study also recommended the inclusion of application-specific organic components to improve performance further. Examples of these components include electroactive surfactants for controlling the physical and electronic interactions between the inorganic and organic components of the hybrid solar cell (Milliron, Gur, & Alivisatos, 2005).

3.4. Improving Efficiency Through Coatings

Aside from the identification and utilization of semiconducting materials, novel engineering and design configurations and considerations, and a combination of different existing technologies, another way researchers are improving the power conversion efficiency of PV or solar cells are through the identification of coating materials (Khan & Rahman, 2019). The primary principle behind this method is to use anti-reflective coatings to increase light input or absorption of radiant energy, reduce optical losses, increase electrical yield, and improve the lifespan of the panels. Two of the most common antireflective materials used in the glass fabrication industry are aluminum oxide and tantalum pentoxide. When used in solar panels, they are applied as a coating of a double layer. Several studies revealed improvement in efficacy at various levels. Note that another advantage of these chemicals is that they are cost-effective (Rajvikram &Leoponraj, 2018).

One of the most promising and interesting coating considerations centers on the use of antireflective nanocoatings. By definition, a nanocoating involves the implication of a thin layer of coating or chemical in the nanoscale. Moreover, this coating consideration is characterized further by having second phase particles that are dispersed into the matrix in the nanosized range or coatings having nanosized grains and phases (Saji, 2012). Some of the applications of nanocoating centers creating significant barrier properties for protecting the involved material or surface from corrosion, introducing water-proofing or hydrophobic properties, or preventing the surface material from developing blisters or degradation of lamination. Some nanocoatings can improve the tensile and impact, as well as the thermal properties of materials (Nguyen-Tri, Nguyen, Carriere, & Xuan, 2018). However, when applied in PV cells, the purpose of these coatings is to decrease the amount of light reflected off solar panels and, by extension, maximize the amount of light energy that can be absorbed and converted. The utmost goal is to increase further the power conversion efficiency of solar cells and solar panels (Kadirgan, 2006).

A study revealed that a single-layer anti-reflective coating of silicon dioxide and with a thickness of around 100 nm resulted in an increase in efficiency of between 3 to 4 percent. However, a triple layer of the same compounds resulted in an improvement in the power conversion efficiency of up to 39 to 40 percent. A multi-layer coating of nanoparticles can significantly reduce the reflective property of solar cells, thus resulting further in better absorption of light energy (Vikas, 2015). Providing these panels with hydrophobic and hydrophilic properties can also improve further their efficiency. Another study applied a coating of greater than 600 nm of thickness to PV cells. Results indicated an increased absorption of light with a maximum value of 99 percent of the wavelength. These findings suggest that nanocoating can improve the absorption of lit across the visible spectrum (Baquedano, Torné, Caño, & Postigo, 2017). There is also a study investigating the benefits of equipping solar panels with self-cleaning properties. To be more specific, the involved researchers noted that the application of nanocoatings that are capable of self-cleaning enhances the light absorption capabilities of solar cell panels. The coating essentially keeps the surface of the panels clean because it is capable of repelling dust, pollen, and other particles that could affect the quality and quantity of absorbed light. Essentially, the coating maintains the efficiency of these panels while also reducing the need for labor-driven and time-consuming manual cleaning (Yadav & Mishra, 2013). Combining the advantageous properties of nanoparticles in nanocoating can improve the performance of solar panels dramatically. For example, aside from anti-reflective and better light absorption or photoactive properties, water-proofing, anti-dust, and anti-pollen properties essentially allow both the improvement and maintenance of power conversion efficiency of these panels (Mozumder, Mourad, Pervez, & Surkatti, 2019).

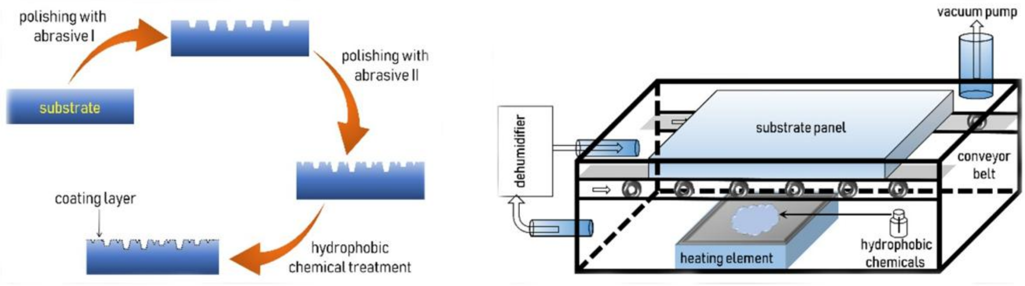

Figure 4. *A schematic illustration of the self-cleaning hydrophobic coating application procedure on the left and the enclosure for conducting the hydrophobic treatment on the right (Maharjan et al., 2020)*

There are also novel coatings under investigation for improving the efficiency of PV systems. In a particular experiment, researchers coated solar panels with a mixture of chlorophyll and polymer. Results revealed that this coating improves the power conversion efficiency of this panel by 3.1 percent. However, the same study also revealed that applying a coating of chlorophyll only resulted in an increase in efficiency of 5.5 percent (Al-Hasnawi, Abdullah, & Kamil, 2018). It is also worth mentioning that chlorophyll was used in the development of dye-sensitized solar cells with a quasi solid PVA-based electrolyte. The use of a chlorophyll dye high power conversion efficiency of 2 percent, particularly when used alongside a PVA-based double salt electrolyte (Hassan, Abidin, Chowdhury, & Arof, 2016).

IV. BENEFITS OF HIGH-EFFICIENCY PHOTOVOLTAIC SYSTEMS

Understanding the different research directions within the greater field of solar power and the photovoltaic system requires an appreciation of the potential economic, social, and environmental benefits of alternative, clean, and renewable energy sources. For starters, the National Renewable Energy Laboratory of the United States Department of Energy published a report (Grover, 2007) explaining that the solar power initiative of the U.S. government can bring forth numerous economic advantages to include better energy security, reduced dependence on importing fossil fuel for energy generation, and improving access to electricity in rural and poor communities. The report added that promoting solar power can create a viable industry and market composed of manufacturers of related technologies such as solar powers, distributors and third-party associates of these products, specialized research community within the field, and the operation of solar power plants, among others.

Another report published by the International Renewable Energy Agency (2014) identified and explained the different social and economic benefits of promoting solar power technologies. For example, it mentioned macroeconomic benefits as the resulting creation of novel industry and market would contribute to the growth in GDP, creation of businesses, value addition to the greater economy because of energy security, creation of different jobs from different fields and disciplines, and new sources of tax or public revenues. There are also microeconomic benefits centered on the empowerment of communities through better and affordable access to electricity. In addition, a study (Oisamoje & Oisamoje, 2013) noted that from an economic perspective, solar power could help improve the productivity of communities, thus resulting in value creation. It can also empower public institutions and nonprofit organizations with inexpensive electricity, help the government conserve its foreign exchange reserves due to reduced dependence to imported fossil fuels, and creation of numerous direct and indirect economic opportunities ranging from entrepreneurial pursuits to employment.

The environmental benefits of photovoltaics systems are undeniable. Climate scientists have been conducting studies for decades to explore and understand global warming and climate change. A review of the literature revealed that there is a 97 percent scientific consensus that accelerated global warming and climate change are the product of human activities, including the utilization of fossil fuels for electricity and energy production (Cook, 2013). The intergovernmental organization has also drafted and implemented universal policies that would bind member-states to follow. This has resulted in the emergence of environment and energy politics with international relations and international politics serving as the backdrop (Schreurs, Selin, & VanDeveer, 2009). One of the important policies developed form managing global warming and climate change is the Kyoto Protocol. Developed by the United Nations in 1992, the Kyoto Protocol is an international treaty or agreement that compelled signatory countries to reduce their greenhouse emissions and carbon footprints (Oberthür & Ott, 1999). The European Union has also adopted measures and programs based on the Kyoto Protocol. Interestingly, the targets are even greater than the Kyoto Protocol. As an example, through the European Climate Package approved and accepted in 2008, the European Union has agreed to a unilateral emission reduction of 20 percent below the emission level identified in 1999 (Clo, 2011). To comply with these requirements and meet their specialized and localized targets, several governments from around the world have rolled out initiatives for developing and deploying clean and renewable sources of energy. The U.S. government has rolled out its Solar America Initiative not only to meet economic targets and improve energy security but also to demonstrate its willingness to resolve environmental issues coming from the consumption of fossil fuels (Grover, 2017). In developing countries, solar power, or more specifically, relevant technologies such as PV systems have been considered essential in creating and maintaining sustainable communities (Oisamoje & Oisamoje, 2013).

Nevertheless, to actualize the benefits of alternative, clean, and renewable sources of energy, including solar power via photovoltaic systems, it is important to tackle issues regarding the lack of strong and widespread policies for supporting research and development initiatives, the availability of financial services for equipping startups, researchers, and projects with the necessary funding, the education and training of professionals that can help improve further the research and development of relevant technologies and processes, and strong coordination between policymakers, the scientific community, and industry players (International Renewable Energy Agency, 2014). Social issues and the absence of political will currently serve as barriers to the development of related technologies and the promotion of alternative energy sources. It is important to note that transitioning from fossil fuel is technologically possible and practical, but social and political hurdles remain (Jacobson & Delucchi,2011).

V. CONCLUSION

Electricity generation via solar power and through PV systems remains feasible. However, the overall concept has drawbacks and limitations, ranging from cost, power conversion, and implementation inefficiencies. These problems bar the widespread utilization of PV systems both in developed and developing countries. It appears that other sources of energy, both renewable and nonrenewable, remain considerably practical and viable. The body of literature remains optimistic nonetheless. Within the field of PV systems are specific subfields or research directions, exploring the different ways to improve the efficiency of PV cells and solar panels. Based on the review of the literature, second-generation technologies based on thin films, third-generation technologies such as organic solar cells and hybrid systems, as well as the utilization of coatings and other material inclusions for improvement, have demonstrated positive impacts on power conversion efficiency. More work needs to be done. For these developments to advance further, there should be strong support and collaboration among members of the scientific community, policymakers or the government, and investors or financiers. There is also a need to synthesize findings and all other concepts to develop a novel PV system that exhibits all of the advantages identified and demonstrated in various studies.

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