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Center for Solar Photovoltaics (CPV) at Surya University: Novel and Innovative Solar Photovoltaics System Designs for Tropical and Near-Ocean Regions (An Overview and Research Directions)

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Abstract

Solar photovoltaics (PV) has been globally adopted as a means to produce clean and renewable energy by harnessing sunlight energy though the current existing markets have been mostly dominated by northern hemisphere countries (i.e. U.S.A, Germany and other European countries). In fact, if utilized in tropical countries (such as Indonesia), PV technology can be even more productive because of the higher sunlight intensity presence leading to higher output energy throughout the year. Nevertheless, the concept of PV system designs typically needed for tropical and near-ocean regions, like Indonesia, must employ unique characteristics which are not usually found in those of traditional PV systems. Examples of novel and innovative PV systems suitable for tropical and near - ocean regions would be floating solar farm and solar tree/forest offering potential benefits in terms of higher reliability and output energy along with lower operational cost. Consequently, enabling such novel and innovative PV system designs requires fundamental materials research in order to overcome environmental degradation factors such as salinity, humidity and other corrosive elements, which are typically found in tropical regions especially near oceans. This article will describe such novel and innovative PV system technology along with some fundamental research directions in materials design/technology that will be the focus of the Center for Solar PV Materials and Technology (CPV) at Surya University, Indonesia.

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1. Introduction

As many commercial PV system products are marketed for northern hemisphere countries (USA, Europe/Germany and Japan), the products must be capable of withstanding northern hemisphere climates such as heavy snow, severe hail and gusty wind in order to ensure 25 years of warranty usage. However, since these conditions mostly do not exist in tropical and near - oceans regions (like Indonesia), many commercial PV products are largely overdesigned if used in these regions. In fact, tropical conditions such as high humidity, acidic rain and high concentration of salinity (especially in coastal regions) can severely degrade the standard PV system reliability because of moisture ingress and salt/acid corrosion phenomena. In addition, being located in equator region might lead to lower photon capture in the traditional PV system design resulting in lower efficiency/output. Therefore, it is essential to pursue research directions in the area of PV system materials such as polymer materials integrity, polymer fracture mechanics and glass material science to ensure high reliability for longer system durability. These areas will be the focus of the Center for Solar PV Materials and Technology (CPV) at Surya University, Indonesia.

Surya University was founded in 2013 by Professor Yohanes Surya, PhD. He is an Indonesian physicist who spends his entire career in reforming physics and mathematics education in Indonesia through encouraging many Indonesian students to join and win International Physics Olympics (a world - class global physics competition for high school students). CPV itself is a research center under Surya University focusing on research and development of solar PV systems and technologies that are more optimum design for Indonesia’s climates. In addition to pursuing research in solar PV, CPV was also founded to support research - based education in the Physics Energy Engineering (PEE) department of the university, for instance, by allowing undergraduate PEE students to experience research and enhance their research skills.

This paper is divided into three sections. The first section describes about the importance of utilizing solar energy in tropical regions in terms of higher sunlight intensity presence using quantitative approach. In the second section, some examples of novel and innovative PV system designs for tropical countries along with potential benefits will be elaborated. The final section will discuss some challenges associated with reliability, output and maintenance within the new PV system designs along with some research directions to address these challenges.

2. Sunlight intensity: tropical vs. northern hemisphere countries

The sunlight intensity magnitude received by the earth during the daylight time can be determined by projecting the incoming extra-terrestrial sunlight intensity toward the normal vector at any geographical location throughout the earth as shown in figure 1a. The extra-terrestrial sunlight intensity is defined as the ratio of sunlight power radiation over spherical surface area where the sunlight power radiation can be obtained from the blackbody radiation. Concurrently, the spherical surface area is obtained by calculating the daily distance between sun and earth based on the elliptical orbit model as shown in figure 1b.

a b

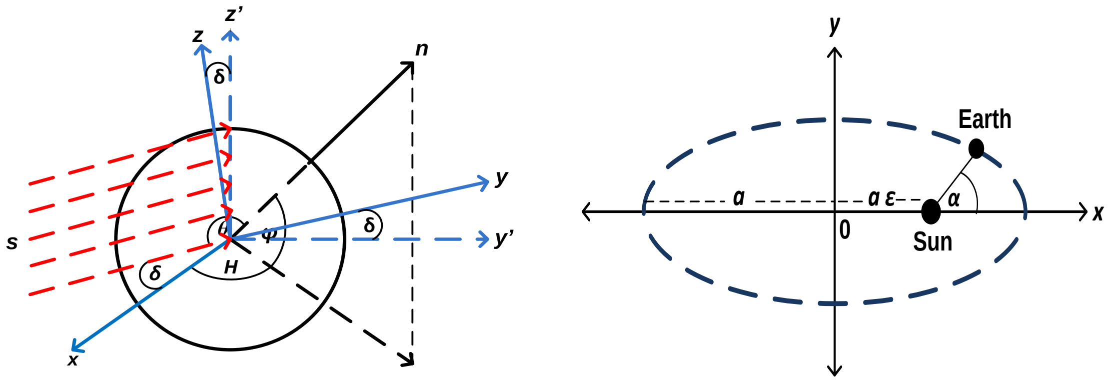

Figure 1. (a) Earth's spherical coordinate where ***s*** is incoming extra - terrestrial intensity vector (red arrow) and ***n*** is normal vector of any geographical location.; (b) Elliptical geometry of earth's orbit toward the sun

According to figure 1b, a is the average distance between earth and sun while ε is the eccentricity coefficient depending on the earth's aphelion and perihelion point toward the sun. Therefore, the extraterrestrial power radiation as a function of particular day throughout the year can be described by the following equation:

$$I(d) = \frac{R_s{}^2 \sigma T^4}{a^2(1-\varepsilon^2)^2}\left(1 + \varepsilon \cos\left[\frac{2\pi d}{365}\right]\right)^2 \quad (1)$$

The term inside cosine determines the angle (α) between earth and sun at any day while R_s, T and σ are corresponding to sun radius, temperature and Stefan Boltzmann's constant respectively derived from the blackbody radiation. Projecting extra-terrestrial intensity toward the normal direction as shown in figure 1a requires the vector expressions between these intensity and normal directions. Thus, the projection angle (θ) can be obtained using dot products between these vector directions giving the following equations:

$$\cos\theta = \cos\delta \cos\phi \cos H + \sin\delta \sin\phi \quad (2)$$

$$\delta = 23.45^o \sin\left[\frac{360(d-81)}{365}\right] \quad (3)$$

From equation 2, the projection angle (θ) consists of three variables such as latitude angle (φ), azimuthal angle (H) and declination angle (δ). Latitude angle (φ) represents any geographical location with respect to the center of the earth while azimuthal angle (H) determines any specific time during the daylight period based on the earth's rotation. Declination angle (δ) from equation 3 describes the change of earth's axis from -23.45^o to 23.45^o which subsequently depends on day during the yearly cycle [1]. By combining all three equations above, the sunlight intensity received on earth at any geographical location, day and time can be obtained and plotted as shown in figure 2 below.

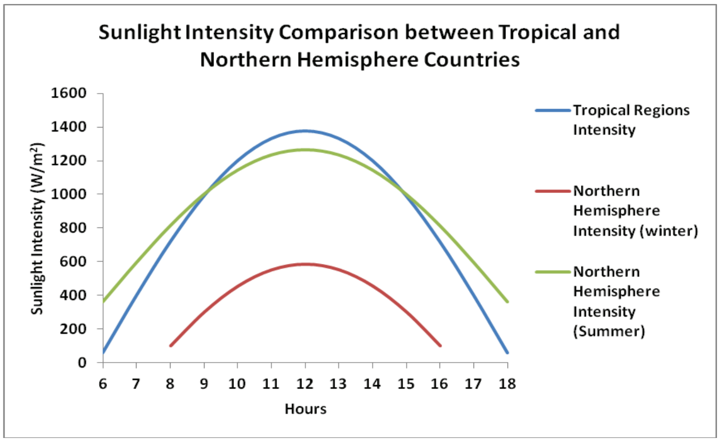

Figure 2. Sunlight intensity comparison between tropical and northern hemisphere regions.

Figure 2 shows the sunlight intensity simulation between tropical region (i.e. Indonesia) versus northern hemisphere region (i.e. Wisconsin, USA) at two different seasons. Since tropical regions do not have four seasons, the intensity can be assumed to be constant throughout the year while the sunlight intensity in northern hemisphere region drops approximately by 50% from summer to winter season. Thus, the sunlight intensity reduction clearly indicates that utilizing solar PV technology in tropical regions is much more ideal than that in northern hemisphere countries. Higher and steadier incoming sunlight intensity at tropical region yields higher and steadier output energy from the PV system. Note that the sunlight intensity simulation results above are not completely accurate because the three equations above do not take sunlight intensity absorption by air molecules into consideration. However, those equations are adequate to provide sunlight intensity reduction explanation due to geographical location, time and day parameters.

3. Novel and innovative PV system designs

The idea of novel and innovative solar PV system designs suggests some characteristics improvement in terms of higher output energy and reliability together with lower operational cost compared to those found in traditional PV system design. Some examples of novel and innovative solar PV system designs especially suitable for tropical and near-oceans regions would be floating solar farm and solar tree/forest as shown in both figure 3 and 4. In fact, both of these PV designs have been previously adopted by other countries (i.e. Japan and UK respectively) [2,3] but not in Indonesia as well as other tropical and near - oceans regions. Thus, PV systems designed specifically for these regions are still considered as novel and innovative and they indeed require further significant fundamental materials research to enable them.

3.1. Floating solar farm

One important issue regarding solar farm installation in tropical regions is associated with constant high temperature. To mitigate the thermal degradation effect, the floating solar farm technology hinges on the sea water crucially (figure 3a) to maintain the panels cooler as water has higher heat absorption capability compared to that from land. Though floating solar farm is more advantageous than traditional solar farm, it must have specific design to tackle oceanic environmental degradation from humidity, salinity, acidity and extreme mechanical loading (from sea waves). Figure 3b presents a floating solar PV prototype system (using glass/glass technology in the form of a "solar boat") which was recently built at Singapore University Technology and Design (SUTD) as part of the ongoing research program in the novel and innovative PV system designs. The glass - glass solar PV system here is capable of providing ~30% of the power needed for driving the motor to move the boat. The solar boat works and it serves as a demonstration of the concept as well as subject of continued research of materials degradation in such near - water applications. The reliability and performance of this prototype floating solar PV system is currently the subject of ongoing investigation and the findings will be reported in future publications.

In terms of potential economic benefits, the floating solar farm can provide additional energy supply especially for communities living in small islands who have limited access in receiving electrical energy supply. At the same time, the floating solar farm can be used for military applications such as being the power refuelling system for navy ship in the middle of oceans or being the logistics system for the military surveillance operations in remote coastal regions especially in such a vast archipelagic country as Indonesia. Once the floating solar farm is realized throughout Indonesia, it will transform Indonesia into maritime's axis country (as envisioned by Indonesian President, Joko Widodo) with increasing maritime economic and military activities [4].

a b

Figure 3. (a) Floating solar farm in Japan [2]; (b) Prototype floating solar module

3.2. Solar tree/forest

Another example of novel and innovative solar PV designs would be a solar tree (or solar forest) (as shown in figure 4a and 4b) which is a nature - inspired PV system as tree itself is a natural PV system by employing photosynthesis ability to supply its energy needs. Solar tree has unique properties in terms of height and multi - angle orientation parameters. By employing the height parameter, solar tree requires less space consumption which can reduce the installation cost. Compared to the traditional solar farm which is oriented in a single direction, the multi-angle orientation parameter from the solar tree panels yields the potential capability to absorb higher sunlight intensity leading to higher output energy. At the same time, this parameter eliminates the necessity to install solar tracker which can reduce the operational cost.

a b

Figure 4. (a) Nature-inspired PV system design employing height and orientation parameters; (b) Solar tree [3]

Both examples of floating solar farm and solar tree/forest are the applications of research activities related in materials and technology at CPV - Surya University in Indonesia. It is CPV's main goal to pursue research directions in PV system (i.e. module - level) design, materials and technology that will be crucially needed if such novel and innovative solar PV systems (like the floating solar farm and solar tree/forest) are to be realized in Indonesia. The fact that Indonesia has the comparative advantages to utilize such PV systems will create an opportunity for CPV to lead PV materials research globally, especially in the PV technologies and designs for tropical and near - ocean regions.

4. Research directions

While new PV system designs above seem promising to be established in tropical especially near - oceans countries, some challenges exist in realizing this new PV system technology. In tropical and near - ocean countries, the humidity percentage could reach approximately between 70% and 100% level and this high level could induce severe premature aging. The influence of humidity level on PV module has been demonstrated by Q. Wang *et al* where crack formation on backsheet material shown in figure 4a was observed after being exposed inside damp heat chamber for 1500 hours under 85% relative humidity and 85 ^{o}C temperature [5]. At the same time, F. Fabero [6] reported salt corrosion on metal interconnection within the solar cells (figure 4b) based on the salt mist test. This corrosion can cause electrical short circuit which could lead to potential big fire. Therefore, common solar PV modules found in existing market are not suitable to be installed in tropical and near - ocean environment.

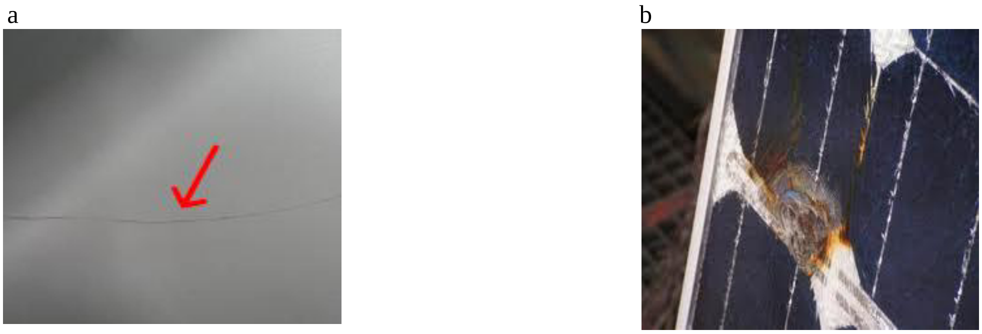

Figure 4. (a) Crack formation on backsheet material after 1500 hours damp heat test; (b) Salt mist corrosion on solar cell metal interconnector

In order to address these challenges, fundamental materials research associated with polymer encapsulant, backsheet and glass materials are necessary. While majority of research activities are focusing on improving the efficiency of solar cells, research directions on PV module materials have the same importance to ensure high reliability and durability yielding 25 years of warranty use.

CPV intends to collaborate closely with the Thin Silicon Solar PV research group at Singapore University of Technology and Design (SUTD) in the areas of solar PV materials degradation, fracture mechanics and testing led by Professor Arief S. Budiman. Prof. Budiman's group has been acknowledged recently and widely accepted as one of the centers for expertise in solar PV materials research especially in the area of silicon PV cell fracture mechanics and advanced silicon-based systems mechanics and reliability [7-13].

4.1. Polymer materials integrity and polymer fracture mechanics

In solar PV industry, there are different types of encapsulant and backsheet materials used to laminate the PV modules [14,15,16]. Such encapsulant materials include Ionomer, Ethylene Vinyl Acetate (EVA), Polyvinyl Butyral (PVB), Thermoplastic Polyurethane (TPU), Polydimethyl Silicone (PDMS) and Polyolefin while there are TPT and Polyester used as backsheet materials. The arising question would be identifying which polymer encapsulant and backsheet materials capable of withstanding extreme oceanic environments such as high humidity, temperature and salinity. In this research direction, several different types of polymer encapsulant and backsheet materials laminated on mini PV modules will be tested inside environmental testing chamber (oven) by incorporating humidity, temperature, acidity and salinity parameters in order to simulate tropical and near - ocean climates. By doing so, it would enable to identify which polymer materials produce degradation characteristics such as delamination (figure 5a), crack formation, salt corrosion or even discoloration.

a b

Figure 5. (a) Backsheet delamination on PV Module [17]; (b) Delamination tester [18]

The second question is to determine whether the delamination/crack can be delayed which will require fracture mechanics approach. After being tested by environmental testing chamber, the adhesion strength of polymer materials will be quantitatively characterized using delamination tester (figure 5b) to find the mathematical formula of the de-bonding growth rate [18]. Within that formula, certain variables need to be characterized in order to delay the delamination/crack formation enabling to identify polymer materials with higher fracture resistance. The way delaminator tester works is by applying tensile force, which is proportional to the crack driving force (G), and measuring it with respect to the displacement resulting in load - displacement curve similar to figure 6. From that curve, the critical crack driving force (G_c) can be determined when the curve deviates from the linearity.

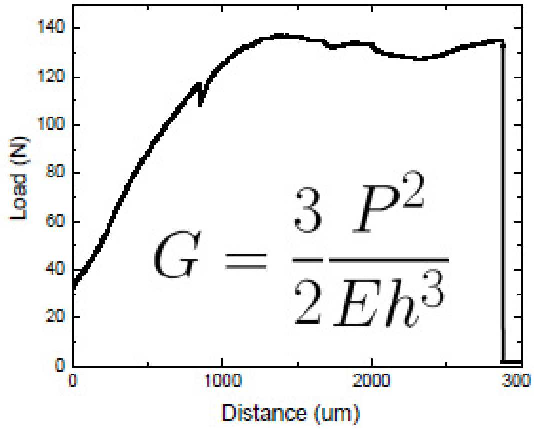

Figure 6. Tensile load - displacement curve from delaminator tester [18]

4.2. Glass research

Although tropical regions receive higher sunlight intensity compared to that in northern hemisphere regions, the incoming sunlight intensity will reach at lower incidence angle with respect to the solar panel normal direction (figure 7a). Therefore, rather than being transmitted into the solar cells, more light are reflected resulting in lower output energy. To address this issue, the usage of textured glass was suggested by T.M. Walsh *et al* [19] to ensure that more sunlight intensity are transmitted into the solar cells as shown in figure 7b below.

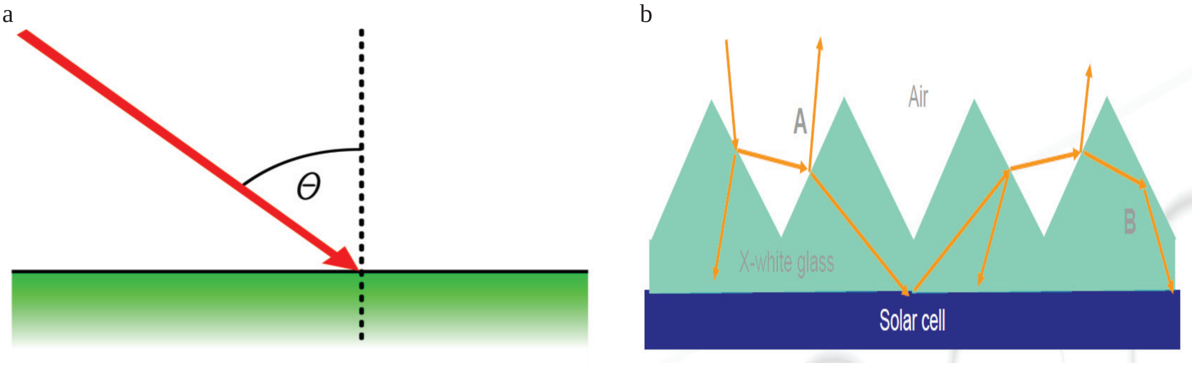

Figure 7. (a) Low light incidence angle toward normal direction on solar panel plane; (b) Surface texturing on glass surface [19]

Though surface texturing seems plausible, the problem arises related with maintenance procedures. The texture formation will make the glass surface prone to dust and particle accumulation leading to higher maintenance cost and lower energy output. One possible research direction that can be explored is to apply hydrophobic coating on the glass surface while optimizing the optical transparency. The purpose of applying hydrophobic coating is to enable the glass surface repelling external particles accumulation much more easily. By doing so, it is hoped that maintenance cost can be reduced significantly while maintaining the same output performance.

5. Conclusion

In conclusion, novel and innovative PV system designs especially for tropical and near - ocean regions seem much more promising than traditional solar PV system. Enabling new PV system designs with high reliability and performance with lower operational cost requires the capability to withstand environmental degradation factors. Therefore, research directions related in PV module components such as polymer materials integrity and fracture mechanics along with glass research are necessary in addition to common research activities in increasing solar cell efficiency. Once the new PV system designs are realized, tropical countries will emerge as the next global PV markets in addition to northern hemisphere countries.

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