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A review of photovoltaic module technologies for increased performance in tropical climate

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ABSTRACT

The global adoption and use of photovoltaic modules (PVMs) as the main source of energy is the key to realising the UN Millennium Development Goals on Green Energy. The technology – projected to contribute about 20% of world energy supply by 2050, over 60% by 2100 and leading to 50% reduction in global CO_2 emissions – is threatened by its poor performance in tropical climate. Such performance discourages its regional acceptance. The magnitude of crucial module performance influencing factors (cell temperature, wind speed and relative humidity) reach critical values of 90 °C, 0.2 m/s and 85%, respectively in tropical climates which negatively impact module performance indices which include power output (PO), power conversion efficiency (PCE) and energy payback time (EPBT). This investigation reviews PVM technologies which include cell, contact and interconnection technologies. It identifies critical technology route(s) with potential to increase operational reliability of PVMs in the tropics when adopted. The cell performance is measured by PO, PCE and EPBT while contacts and interconnections performance is measured by the degree of recombination, shading losses and also the rate of thermo-mechanical degradation. It is found that the mono-crystalline cell has the best PCE of 25% while the Cadmium Telluride (CdTe) cell has the lowest EPBT of 8-months. Results show that the poly-crystalline cell has the largest market share amounting to 54%. The CdTe cell exhibits 0% drop in PCE at high-temperatures and low irradiance operations – demonstrating least affected PO by the conditions. Further results establish that back contacts and back-to-back interconnection technologies produce the least recombination losses and demonstrate absence of shading in addition to possessing longest interconnection fatigue life. Based on these findings, the authors propose a PVM comprising CdTe cell, back contacts and back-to-back interconnection technologies as the technology with latent capacity to produce improved performance in tropical climates.

1. Introduction

The annual electrical power consumption of the entire planet can be generated by the sun in just one hour [1]. Thus, solar energy is abundant in addition to being clean, sustainable and renewable [2,3]. Surprisingly, some parts of the world are still struggling to meet their energy needs. It may suffice to say that the regions experiencing energy issues may be having energy conversion problems rather than energy supply problems [2,4]. It is projected that if 100% exploitation of the energy potentials of the sun can be achieved, the world would cease to have energy crises [2,3]. The photovoltaics are currently poised to be the promising technology to be used to harness this energy – though at reduced efficiency. The performance of a PV module can be characterised by its power output (PO), power conversion efficiency (PCE) and reliability [5–8]. The PO measures the capacity of the module and the amount of electricity (in watts) it can generate. On the other hand, the PCE quantifies the percentage of power generated by the module in comparison with the total solar energy available to the module. Thus, a module may generate more power than another module but possess a lower PCE. Generally, module reliability measures the probability that it will perform the intended function over a specified interval under stated conditions. Therefore, mean-time-to-failure (MTTF) and cycle to failure are terms associated with the rate of failure of PVMs and thus used in its reliability measurements [9,10]. The major components of a PV module are the cells, contacts and interconnections. These components are selected for investigation because they are known as the key

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determinants of module performance as well as the failure mode [11]. The overall performance of a PV module is dependent on the individual performances of the components.

Ambient conditions significantly influence the level of performance of PV modules. These are the intensity of solar radiation, cell temperature, wind speed and humidity [12–14]. PV modules are designed to operate under standard test conditions (STCs). The conditions are: solar radiation of 1000 W/m^2, cell temperature of 25 °C, wind speed of 1 m/s and air mass (AM) of 1.5. These STCs are different from actual operating conditions which vary with climatic zone [15]. This review focuses on the tropical climate. The zone is characterised by high-temperature and humidity, high density of tall trees and vegetation, heavy cloud cover and high rates of precipitation. High precipitation produces cloudy skies and more shades on some days of the year. The high-temperatures range from 18 to 40 °C and forces the PV cell temperature to rise up to 90 °C. The relative humidity is in the range of 35–85% with wind speeds of 0.2 m/s and lower [12–15]. Consequently, PV modules operating in the tropics possess higher failure rates than those in temperate climates. The failure modes observed in the field include delamination and discolouration of EVA, solder bond and ribbon degradation and cracking as well as burn marks [11,16,17]. Since the tropical climate ambient significantly deviates from the STCs, further research aimed at providing more information is needed to predict the performance of PV modules in the climatic zone [18–23] accurately.

A number of researches have focused on the performance of PV cells in tropical climatic conditions [24–29]. Ike C.U [24] in his study, investigated the effect of ambient temperature on the performance of PV modules in Nigeria tropical climate. His results show an indirect proportionality between ambient temperature and power output. He reported that PV modules in the test region demonstrated high PO at low ambient temperatures while the reverse is the case at high ambient temperatures. Mekhilef et al. [28] in their study, investigated the individual and combined effect of dust, humidity and air velocity on the efficiency of photovoltaic cells. They reported that USA demonstrated 1–4.7% reduction in PCE in a two month period, 32–40% reduction for 6–8 months period in Saudi Arabia, 17–65% reduction over 38 days in Kuwait, 33.5–65.8% reduction over for 1–6 months period in Egypt and 11% reduction in Thailand. These findings indicate the poor performance of PV cells in tropical climate. They indicated that humidity and dust deposition resulted in low heat dissipation and shading respectively hence PCE reduction while increased air velocity improved PCE. Ndiaye et al. [27] investigated the degradation of PV modules in the Senegal tropical climate. They focused on the degradation of short circuit current (I_{sc}) and open circuit voltage (V_{oc}) which translate to PO and PCE. They reported a 13% and 11% reduction in I_{sc} and V_{oc} respectively over a ten month period. Although Ike, Mekhilef, Ndiaye amongst other researchers in their respective studies have investigated the performance of PV modules in tropical climate, they have not carried out wide spread researches as their results are solely based on the mono crystalline silicon PV cell. Our study, however, aims to review available PV cell technologies: commercially available and state-of-the-art, as will be thoroughly discussed in Section 2 of this paper.

Walsh et al. [25] in their study, proposed an optimised PV module for the Singapore tropical climate. They highlighted the poor performance of some commercial PV modules under the Singaporean climate. Their optimised PV module was developed by making material changes in glass, encapsulant and back sheet parts of the conventional PV module. Their aims to reduce reflection and increase the surface area exposed to radiation led to changes in glass material, increased radiation transmittance led to encapsulant change while increase in thermal conductivity resulted in change in back sheet material. However, there were no changes to the PV cell material, type of contact or interconnection technologies hence no mention of PCE, PO and reliability which are the measures of PV module performance. These, amongst other gaps were identified by our study. In order to promote robustness, increase reliability and all round improved performance of PV modules in tropical climate, this paper proposes model of PV module which includes the cell, contacts and interconnection technologies as will be discussed in Sections 2–4 respectively. There has been no such research which dissects the major parts of the PV module so as to identify the particular technologies which demonstrate best performance in tropical climate.

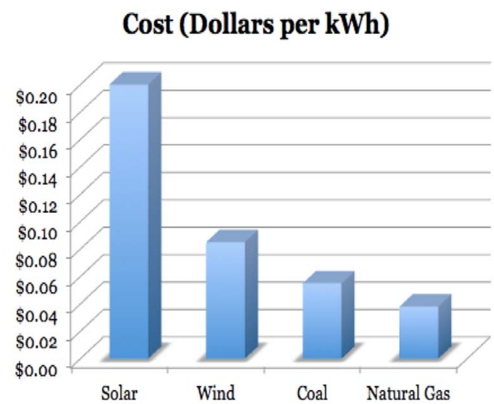

Fig. 1. Price comparison of energy sources [161].

Cost has been identified as an important factor in the choice of energy sources especially in the developing countries. In order to increase the adoption of the module globally and especially by the developing countries, the cost has to be as low as possible. It is basic experience that cost determines the choice of energy for the individual, company, community or nation. Fig. 1 presents a chart with plot of cost of different energy sources in USD ($) which also applies for any mention of cost in this paper. It can be seen in the plot that the cost of energy from PV (solar) is highest. Currently, the fossil fuels cost $0.50/W while the cheapest PV modules cost $0.75/W [30]. It is pertinent to mention that there has been urgent, aggressive and on-going research to reduce the cost of PV modules as well as the energy payback time (EPBT) while increasing the net energy ratio (NER) of the cells. The trend of the achieved cost reduction is depicted in Fig. 2. However, despite the progress, people generally choose fossil fuels because they are cheaper while neglecting the detrimental environmental effects [31].

A plot of the quantity of greenhouse gases (GHG) emitted by different electricity generation sources is presented in Fig. 3. The plot shows that GHG emission by Solar PV is about 7.95% of the quantity emitted by Lignite – which has the largest quantity of emission.

Fig. 4 depicts the plot of world energy consumption from 1990 to 2012. It shows a significant increase in the consumption of renewables (including hydro) compared to the fossil fuel. To progress this trend, it

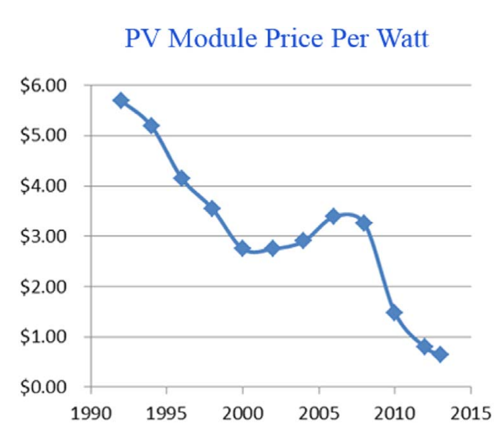

Fig. 2. PV module price over time [160]