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SOLAR ENERGY POTENTIAL AND ITS UTILIZATION IN PEROVSKITE-BASED SOLAR CELLS FOR SELECTED SITES IN NEPAL

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ABSTRACT

The measurements of solar radiation for Biratnagar (BRT), Kathmandu (KTM), Pokhara (PKR) and Jumla (JML) have been undertaken using CMP 6 pyranometers from SAHR/IOE/TU, Nepal. Solar radiation and the other meteorological data have been collected from the archives of Department of Hydrology and Meteorology, Government of Nepal (DHM/GoN) to analyze the daily Global Solar Radiation (GSR). In this study, perovskite-based solar cells with the configuration Au/SpiroOMETAD/$MAPbI_3$/TiO_2/FTO have been simulated using Solar Cell Capacitance Simulator (SCAPS). The power conversion efficiency (PCE) of the cell is found to be 22.67, 22.69, 22.77 and 22.80% in BRT, KTM, PKR and JML respectively, almost similar and better performance, whereas the solar cell performs better in JML due to the high solar irradiance.

Keywords: solar radiation - perovskite-based solar cell - SCAPS - simulation - performance.

INTRODUCTION AND OBJECTIVE

The energy in the form of electromagnetic (em) wave from the sun is considered as solar energy or radiation. So far, widely used energy source in this world is fossil fuel whereas the easily available energy is the solar radiation.

The combustion of fossil fuel has harmful effects due to emission of huge amount of CO_2 which is not all consumed by the plants, and other greenhouse gases (GHG). Consequently, the rate of the global warming is increasing. Fifth assessment of Intergovernmental Panel on Climate Change (IPCC) has reported that the each decade has been successively warmer. Consequently, global mean sea level has been continuously raised up (IPCC 2014). The increase in temperature eventually increases frequency and severity of natural disasters (Petritsch 2000). The limited supply and environment deteriorating nature of current major energy sources such as the fossil fuel is forcing us to an optimal use of the clean and green renewable energy sources. Among the renewables, solar energy is inextinguishable and easy of use. It is equally essential to discuss the prospect of renewable energy in particular to the potential of solar energy and allied technologies for its efficient utilization.

Solar energy

The sun has three major layers and two additional layers called atmosphere of the sun. Every second 700 million tons of hydrogen is converted into 695 million tons of helium in core of the sun. The remaining 5 million tones are being turned into em energy, which finally radiates from the sun's surface (called photosphere) out into the space. It is estimated that in a billion years, it will radiate only 10^{26} kg which is less than 1.00×10^{-8} part of total mass (Liou 2002).

The solar energy emitted per second from the sun's surface is approximately 3.844×10^{23} kW for around 5 billion years and will continue the same for some billion years more. Radiation that reaches the earth is only 1.743×10^{14} kW (Iqbal 1983 & Pidwirny 2006). It shows the great potential of solar energy.

Solar energy approaching the earth surface varies with latitude, atmospheric condition (clouds, aerosol, air molecules, etc), season, day of the year, time and length of the day and location concerned. Since the early civilizations, development has been possible due to wise full utilization of various sources of energy like solar, fossil fuel, hydropower, wind, biogas, geothermal, etc. With the rapid development, the energy consumptions rate is also increasing accordingly. In this context, solar energy, which is green and clean, is becoming one of the most promising renewable energy sources available to us. Efficient usage of solar energy is complicated owing to variational nature of solar radiation. Nevertheless, its abundance in nature and the access with ease have greatly surpassed any other energy sources.

Solar energy potential in Nepal

Based on the ground based measurements for selective sites, the mean GSR in Nepal is found to vary from 3.6 to 6.2 kWh/m^2/day. The mean sun shine duration is about 6.8 hours per day. The sun shines for about 300 days a year; the number of sunshine hours amounts to almost 2100 hours per year and an mean insolation intensity is about 4.7 kWh/m^2/day (WECS, 2010) where Adhikari et al., (2013) also observed the similar value. This value of solar radiation is greater than 4.39 kWh/m^2/day as measured by (Janjai 2006) for Lao PDR and 4.51 kWh/m^2/day selected sites of Nigeria (Augustine & Nnabuchi, 2009) and smaller than 6.1 kWh/m^2/day in Egypt (Elom & Nnamdi, 2012). Thus, solar energy in Nepal has a great potentiality for efficient utilization (Adhikari et al. 2013 & 2014).

Solar cell, photovoltaic (PV), in Nepal

Owing to the development and achievement of science and technology, life style of the people and industries has been advancing and hence the energy demand is increasing day by day. World energy generation capacity is nearly 18 TW (Kosyachenko 2011). The main source of energy, worldwide, is the fossil fuel based energy. Actually it is unsustainable and also contributes substantially to climate change and global warning.

World nuclear energy report 2014 highlighted the fact that "the nuclear share in the world's power generation declined steadily from a historic peak of 17.6% in 1996 to 10.8% in 2013". Thirty-one countries with 388 reactors are currently generating 333 GW. Sixty-seven reactors are under construction since July 2014 with a total capacity of 64 GW (Schneider *et al.* 2014). Nuclear energy data indicate that it would not meet the current energy demand, and its production can be quite hazardous to mankind too. The renewable sources like hydroelectricity, geothermal, wind, bio-fuels are limited. On the other hand solar energy is inexhaustible, nonhazardous and environment friendly too which can directly be converted into heat and electricity. The potential capacity of generation of electricity from the sun light is 1000 times higher than the current world energy demand (Kosyachenko 2011). Moreover, production of photo-electricity of a day is sufficient for a year by using even less efficient photovoltaic solar cell. So, it would be the best option to resolve the world future energy demand.

Photovoltaic (PV) is a technology and device which converts solar energy into electrical energy where its performance depends on the inclination of the PV module as well. In the context of Nepal, the first PV, in 1963, used for navigation purpose at Bhadrapur Airport Jhapa, Nepal Telecom (NTC) was the first PV user organization and Nepal Electricity Authority (NEA), in 1988, installed 50 kWp solar PV systems in Simikot (Das et al 2015, Adhikari 2017). Since that time, solar energy and PV have been used to address the energy concerns in Nepal. Furthermore, photovoltaics could be the best option for rural electrification, even for urban electrification too, as a clean and green energy.

This paper aims to study and analyze the solar energy potential in four different sites: Biratnagar, Kathmandu, Pokhara and Jumla of Nepal and numerical simulation of perovskite-based solar cell to evaluate the power conversion efficiency (PCE) of the cell in the above mentioned four different sites of Nepal.

MATERIALS AND METHOD

Data acquisition and processing

Solar radiation data were measured and collected from Solar and Aerosol in Himalayan Region (SAHR) Project, IOE/TU, Pulchowk, and the archives of DHM/GoN and Nepal respectively. Kipp and Zonen product: CMP 6 pyranometers were installed at the location of interest with data logger which record the solar insolation data in W/m^2 in every minute in SAHR Project and in every 15 minutes and 1 hour in DHM/GoN. The pyranometer collects the data at local time in SAHR Project and GMT time in DHM/GoN. It can be used in all weather conditions (Kipp & Zonen 2006). For the simplicity, the collected data were processed in spreadsheet and Trapezoidal Sum Rule is used to calculate the daily solar radiation. Furthermore, for solar radiation calculations, GMT time has been converted into local time. Data sets were processed into required formats on different time scales for instance, day, months, and year. Extraterrestrial solar radiation and maximum possible day length were calculated using the day of the year, latitude, and declination.

Daily data of sunshine duration in hours is collected from DHM/GoN that was recorded by Campbell-Stokes sunshine recorder. The relative humidity, maximum and minimum temperature and rain fall were collected from the archives of DHM/GoN. These data were also processed in spreadsheet to change into useful and desirable form.

Simulation of perovskite based solar cell

Simulation is a crucial technique to realize a physical operation of the solar cell devices. Among the various simulation models, SCAPS-1D (Niemegeers 2014) is one which is used to simulate a solar cell. In this study, a planar hetero-junction perovskite-based solar cell was simulated. The active layer in this solar cell is a low doped p-type methylammonium lead iodide peovskite ($MAPbI_3$) with the thickness 400 nm and relative permittivity 30. It is sandwiched between p-type 2, 2', 7, 7'-tetrakis-(N,N-dimethoxyphenyl-amine)-9,9'-spirobifluorene (Spiro-MeOTAD) of relative permittivity 3 as a Hole Transporting Material (HTM) and n-type titanium oxide (TiO2) of permittivity 100 as the Electron Transporting Material (ETM). The system with three layers was sandwiched between FTO of work function 4.4 eV and gold (Au) of work function 5.1 eV as a front and back contact respectively for effective transport and collection of electrons and holes. Simulations were carried out under 1 Sun illumination. The band tails of 10^{14} $eV^{-1}cm^{-3}$, interface traps of 1.0×10^{9} cm^{-2}, acceptor concentrations of 2.14×10^{17} cm^{-3} (Poplavskyy & Nelson 2003, Wang et al. 2009, Laban, et al. 2013, Liu et al. 2014, Wojciechowski et al. 2014, Adhikari et al. 2016), and 300 K as working temperature were used. The donor concentration of ETM and acceptor concentration of HTM were taken as 5×10^{19} cm^{-3} and 3×10^{18} cm^{-3} (Poplavskyy & Nelson 2003, Canadas & Bisquert 2006, Liu et al. 2014, Adhikari et al. 2016) respectively as baseline data.

Theory

Distribution of solar insolation

Based on Iqbal (1983) and Liou (2002) treatment, the extraterrestrial irradiance (rate of energy/m²) on a surface normal to the rays from the sun is expressed in terms of solar constant (W/m²) as given below:

$$\dot{I}_{on} = \dot{I}_{SC}\left(\frac{r_0}{r}\right)^2 = \dot{I}_{SC}E_0 \qquad (1)$$

For practicality, at solar zenith θz as shown in Figure 1, the irradiance on the horizontal surface can be written as

$$\dot{I}_0 = \dot{I}_{SC}\cos\theta_Z E_0 = \dot{I}_{SC}E_0\left(\sin\delta\,\sin\phi + \cos\delta\,\cos\phi\,\cos\omega\right) \qquad (2)$$

where, $\cos\theta_Z = \left(\sin\delta\,\sin\phi + \cos\delta\,\cos\phi\,\cos\omega\right)$, δ is solar declination, ϕ is the latitude of the site and ω is sunshine hour angle. For the given duration of time dt, solar irradiation is given by the relation

$$dI_0 = I_{SC}\,E_0(\sin\delta\,\sin\phi + \cos\delta\,\cos\phi\,\cos\omega)dt \qquad (3)$$

where dt is the time in hour and I_{SC} is the solar constant expressed in kilojoules per square meter per hour. For the sake of convenience, angular velocity for axial motion of the earth is

$$\frac{2\pi}{24\text{ hours}} = \frac{d\omega}{dt} \quad » \quad dt = \frac{12}{\pi} d\omega \qquad (4)$$

Daily extraterrestrial irradiation

Extraterrestrial irradiation during a day *i.e.*, from sunrise (sr) to sunset (ss) is

$$H_0 = \int_{sr}^{ss} I_0 dt = 2\int_{0}^{ss} I_0 dt \qquad (5)$$

$$H_0 = \frac{24}{À} I_{SC} E_0 \left[\frac{À}{180} \omega_s \left(\sin\delta \ \sin\phi \right) + \left(\cos\delta \ \cos\phi \ \sin\omega_s \right) \right] \qquad (6)$$

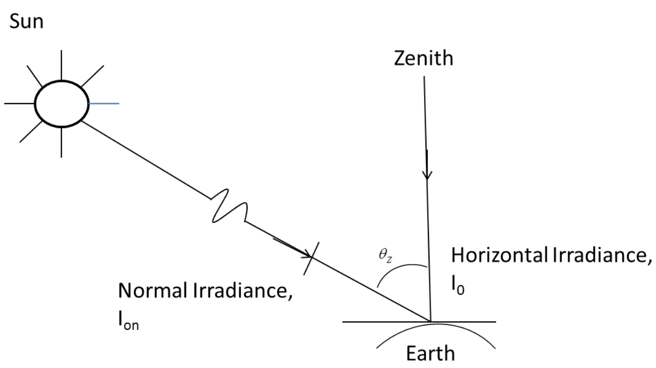

Figure 1: Normal and Horizontal irradiance on the earth

The monthly mean extraterrestrial daily irradiation on a horizontal surface can be defined as

$$\bar{H}_0 = \frac{1}{(n_1 - n_2)} \sum_{n_1}^{n_2} H_o \qquad (7)$$

where n_1 and n_2 are as defined in the hourly radiation case.

Attenuation of direct solar radiation

Attenuation of a beam of light undertaken due to scattering and absorption, as passing through an optically homogeneous and transparent medium, was first explained by Pierre Bouguer and therefore is called Bouguer law given by (Kondratyev 1969, Iqbal 1983)

$$\dot{I}_{n\lambda} = \dot{I}_{on\lambda} \exp(-k_\lambda m) \qquad (8)$$

where $\dot{I}_{on\lambda}$ is the incident monochromatic flux on a homogeneous medium, $\dot{I}_{n\lambda}$ is the solar irradiance received by the earth surface after traversing a distance m, k_λ is the monochromatic attenuation coefficient, and $k_\lambda m$ is the monochromatic extinction optical thickness.

Solar cells' related theories

The SCAPS solves the following three fundamental equations, based on (Fonash, 2012) and modified by Niemegeers et al. (2014), to acquire the desirable output (short circuit current, fill factor and power conversion efficiency):

$$\frac{d}{dx}\left((\varepsilon_0\mu_r\frac{d\psi}{dx}\right)=-e\left[p-n+N_D^+-N_A^-+\frac{P_{def}}{e}\right] \quad \textbf{(Poisson's equation)} \quad (9)$$

where ψ is electrostatic potential, ε_r is dielectric constant, e is electronic charge, n(p) are carrier concentrations, $N_{D(A)}$ dopant concentrations and ρ_{def} is defect charge density.

The carriers flux ($J_{n(p)}$) in thermal equilibrium and the continuity equations are

$$J_n=-\frac{\mu_n n}{e}\frac{dE_{Fn}}{dx} \quad \text{and} \quad J_p=+\frac{\mu_p p}{e}\frac{dE_{Fp}}{dx} \quad \textbf{(Transport equation)} \quad (10)$$

$$\frac{dn}{dt}=-\frac{dJ_n}{dx}+G-\Re_n \quad \text{and} \quad \frac{dp}{dt}=-\frac{dJ_p}{dx}+G-\Re_p \quad \textbf{(Continuity equations)} \quad (11)$$

where $\mu_{n(p)}$ are mobility of carriers, $E_{Fn(p)}$ quasi Fermi levels, $\Re^R+\Re^L+\Re^A=\Re$ is the total recombination, and G is rate of generation of charge carriers due to the solar energy.

The solar cells convert the fraction of incident power into useful electricity or output power under illumination. The ratio is the **power conversion efficiency** (η). It is given by

$$\eta=\frac{P_{out}}{P_{in}}=\frac{FF\times V_{OC}J_{SC}}{P_{in}} \quad (12)$$

$\mathbf{J_{SC}}$ is associated with the Quantum efficiency (QE), incident photon and wavelength as

$$J_{SC}=e\int QE(\lambda)\,\Phi(\lambda)\,d\lambda \quad (13)$$

where $\Phi(\lambda)$ is flux of photon impinge on the solar cell. The **fill factor (FF)** is defined by

$$FF = \frac{J_{mp}V_{mp}}{J_{sc}V_{oc}} = \frac{P_{max}}{J_{sc}V_{oc}} = \frac{P_{out}}{J_{sc}V_{oc}} \qquad (14)$$

RESULTS AND DISCUSSIONS

Potential of global solar radiation (GSR) and other meteorological data

The analysis of the data is carried out using the ground based measurements as available from the DHM/GoN and SAHR IOE/TU for the years 2000 to 2014 whereas the data summary for Biratnagar (BRT), Kathmandu (KTM), Pokhara (PKR) and Jumla (JML) is illustrated in Table 1. It shows that the average of yearly mean daily relative humidity (RH) was observed to be maximum in Kathmandu, after that, Pokhara, Biratnagar, and the least value was found to be in Jumla.

The mean of yearly sum GSR was found to be maximum in Jumla and minimum in KTM. And the yearly mean daily GSR was found to be 19.28±0.53, 16.33±1.37, 13.82±1.65 and 13.98±1.72 MJ/m^2/day for JML, PKR, KTM and BRT respectively. Likewise, the yearly mean daily sunshine duration for JML, PKR, KTM and BRT were 7.30, 6.58, 6.48 and 6.76 hrs respectively. These data average out to be 6.78 hrs/day; it is found to be similar to the national mean sunshine hours 6.8 hrs/day. JML is the place where the sunshine duration was observed maximum whereas KTM has minimum sunshine duration due to its valley effect and high particulate in the atmosphere.

Table 1: Summary of meteorological data from 2000-2014

Descriptions/Sites	BRT	KTM	PKR	JML	National average
Average of yearly means daily RH (%)	84.14	86.14	84.97	72.17	
Mean of yearly sum GSR (MJ/m^2)	5117.22	5057.95	5967.23	7044.23	
Yearly mean daily GSR (MJ/m^2/day)	13.98± 1.72	13.82± 1.65	16.33± 1.37	19.28± 0.53	16.7
Mean of daily SSHs (hrs)	6.76	6.48	6.58	7.30	6.80

With 95% confidence level, the interval for the mean of a normal distribution of the GSR for BRT, KTM, PKR and JML are derived to be

±1.72, ±1.65, ±1.37 and ±0.53 MJ/m^2/day respectively as illustrated in Table 1.

Daily variation of solar radiation

A plot of daily variation for four, four, five and three years mean of daily Global Solar Radiation (GSR) for Biratnagar, Kathmandu, Pokhara and Jumla respectively is shown in figure 2.

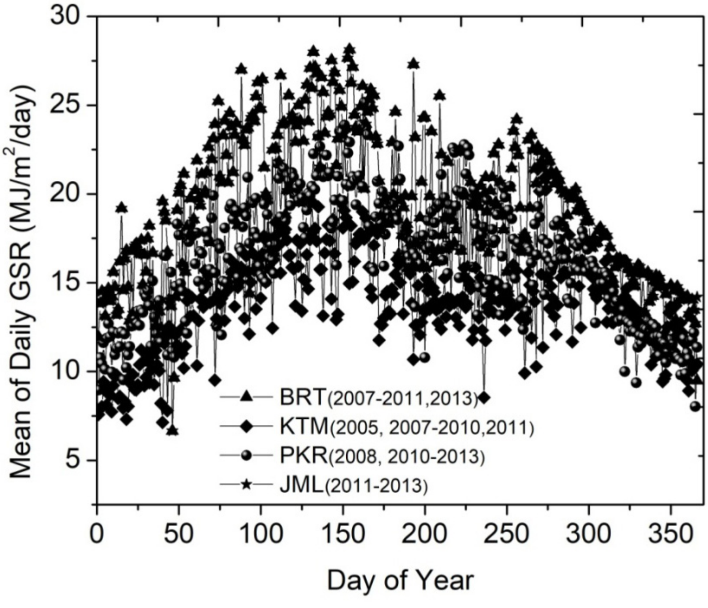

Figure 2: Variation of GSR for four sites in Nepal (2005-2013)

The GSR for all the sites increased from January to April/May. It was found fluctuating from April/May to September and it appeared to decrease from September to December *i.e.*, the similar trend of variation was observed. The fluctuation of the insolation from April-May to September can be attributed to the presence of clouds in the sky, pre-monsoon season and traces of precipitation. In April, the presence of aerosol particulates might also be the cause to decrease the solar radiation reaching the earth surface.

The insolation was found a higher value of 19.28±0.453 MJ/m^2/day for Jumla and the least value of 13.82±1.65 MJ/m^2/day for Kathmandu with single value of standard deviation. This shows that the solar insolation at a place depends upon altitude of the site, day of the year, the earth-sun distance and the condition of the sky at the site of interest. Thus, the outcomes of the device using the solar energy will also vary with altitude, day of the year, the earth-sun distance and condition of the sky.

Performance of the solar cells at different sites of Nepal

The yearly mean daily irradiance for BRT, KTM, PKR and JML were found to be 574.46±70.67, 594.25±71.80, 691.48±46.57 and 733.64.±41.47 W/m^2 respectively with 95% confidence level for the mean of a normal distribution (Adhikari, 2017). Using these data on the simulation work, the PCE of the perovskite-based solar cells was found to be 22.67±0.06, 22.69±0.06, 22.77±0.04 and 22.80±0.03% in BRT, KTM, PKR and JML respectively which is similar to the laboratory fabrication value 20.1% under 1 Sun as reported by (Green et al. 2015). These values illustrate the not significant variation in PCE of the solar cells with the location in Nepal. Moreover, speaking precisely, a solar cell performs better in JML than the other places. After that, Pokhara, Kathmandu and Biratnagar took the second, third and fourth place respectively. Thus, the outcomes of the device using the solar energy will also vary with altitude, day of the year, the earth-sun distance and condition of the sky.

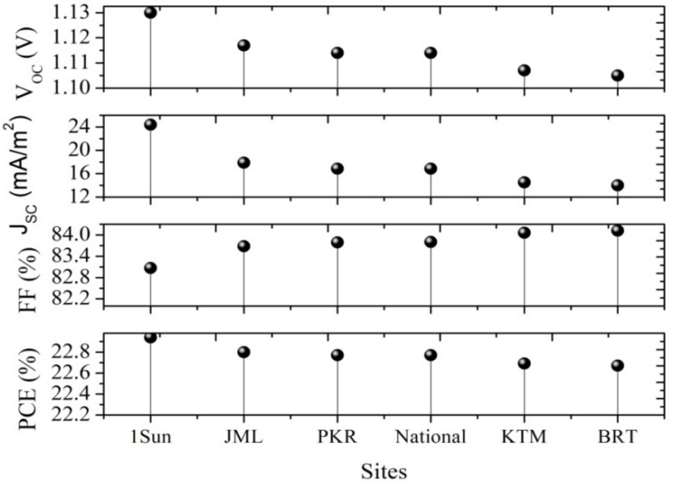

Figure 3: Performance of SC at different sites of Nepal

Higher values of current and voltage were obtained at the place having greater solar irradiance according to the equations (13) and (14) that yield the better PCE. At higher irradiance, the fill factor was found to be decreased which may be due to the increase in resistance due to the higher irradiance and hence the higher temperature.

CONCLUSION

This study has concluded that there is a high potential for solar energy in Nepal. The national average annually mean daily global solar radiation in Nepal is found to be 16.7 $MJ/m^2/day$ which is greater than that in Laos but smaller than that in Egypt. This value of global solar radiation in Nepal can be harnessed by using the solar PV of high power conversion efficiency.

Moreover, the performance of the perovskite-based solar cells has been examined at Biratnagar, Kathmandu, Pokhara and Jumla of Nepal where PCE was found to be approximately the same. Jumla is found to be the place where the performance of the solar cell can be maximum owing to the maximum solar irradiance.

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