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To cite this article: Mustofa *et al* 2019 *J. Phys.: Conf. Ser.* **1242** 012055

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Potential energy of photon passes through cold mirror on photovoltaic-thermoelectric generator with artificial lights radiation

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Abstract. The amount of photon energy becomes a key parameter that determines the release of electron bonds which is often called a band-gap in photovoltaic cells (PV) to generate electricity. This paper presents the results of measurements of photon energy from radiation sources of artificial light Halogen, Incandescent and Xenon which aims to adjust the bad gap type of solar cell material. Simulations of measuring 50 watts of bulb radiation were carried out repeatedly with the Spectrometer sensor and the application software Spectragryph 1.2.8 on each electron Volt the bulb light. The incoming radiation from the bulb is concentrated with a Polymethylmetacrylate (PMMA) Fresnel lens with an optimal light transmission capability of 92%. The results of this light transmission will be divided after illuminating at the Cold mirror (CM) spectrum splitter, partly reflected in the PV module and partially transmitted to the thermoelectric generator (TEG) in the PV-TEG hybrid. The measurement of photons leading to PV show values of 2.2 and 2.4 eV for Halogen with Cadmium Sulfide that match the band-gap for the photon's energy. While the Incandescent photon energy, it is more suitable with PV material in Silicon, Germanium and Indium nitride. For Xenon, it gives the effect of releasing electrons bond to Cadmium sulfide and band gap which is below 2.42 eV, such as CdSe, InN and Si. The maximum light intensity reflected by CM is emitted by a Xenon bulb, then Halogen and the lowest is Incandescent (50 > 40 > 36) a.u., respectively. Meanwhile, the energy of the photons transmitted to the TEG module illustrates a different trend, where the best Halogen is followed by the lowest then Xenon incandescent.

1. Introduction

In general, photovoltaic (PV) cells absorb up to 80% of the incident solar radiation. However, the proportion of converted incident energy into electricity depends of the conversion efficiency of the PV cell technology in terms of cells material. The remainder energy is dissipated as heat and the PV module can reach temperatures as high as 70°C above ambient [1]. This is due to the fact that PV cells convert a certain wavelength of the incoming irradiation that contributes to the direct conversion of light into electricity, while the rest is dissipated as heat [2]. This heat is more suitable for the need of thermoelectric generator to convert electric energy because there are hot and cold side of this module.

According to quantum theory, light can behave either as waves or as particles, depending upon the specific interaction of light with matter; this phenomenon is called the wave-particle duality of light.



In the particle description, light consists of discrete particle-like packets of energy called photons. Sunlight contains photons with energies that reflect the Sun's surface temperature; in energy units of electron volts (eV), the solar photons range in energy ($h\nu$) from about 3.5 eV (ultraviolet region) to 0.5 eV (infrared region). The energy of the visible region ranges from 3.0 eV (violet) to 1.8 eV (red); the peak power of the sun occurs in the yellow region of the visible region, at about 2.5 eV. At high noon on a cloudless day, the surface of the Earth receives 1,000 watts of solar power per square meter (1 kW/m²) [3].

In the case of the ability of solar cell materials to convert the incident light radiation into electricity, commonly termed band-gap cell material, while the energy of light radiation is often called the energy band-gap in units (eV). Therefore, to know more about the energy characteristics of band-gap light radiation source used artificial light in laboratory experiments, namely Halogen, Xenon and Incandescent light. The result will determine the semiconductor material group (III-V) that matches the radiation-band-gap energy that comes in contact with the solar cells [4] and [5]. Virtuani et al. [6] conducted simulation research on influence of fluorescent tube, halogen bulb with and without cold reflector, and the common incandescent lamp in low-irradiation in indoor environment on photovoltaic cell Cu(In,Ga)Se₂, particularly in the sensitivity range of the human eye (380–780 nm).

The term "band-gap" refers to the energy difference between the valence band peaks and the base of the conduction band, where electrons can move from one band to another. To allow electrons to move from the valence band to the conduction band, a certain amount of energy is required that corresponds to the solar cell gap in units (eV) of magnitude determined by the class of solar cell semiconductor material [7]. The magnitude of the semiconductor band-gap material lies between the band's conduction and valence band as depicted in figure 1. In general, the equation used to calculate the energy of a photon is:

$$E_{bg} = \frac{hc}{\lambda} \quad [\text{eV}] \quad (1)$$

where E_{bg} = energy of a photon (eV), 1 eV = 1.6x10⁻¹⁹ Joule, h = Plank's constant = 6.626069 x 10⁻³⁴ Joule second, c = speed of light in a vacuum = 3.0 x 10⁸ m/second, and λ = wavelength of light in nano meter (nm).

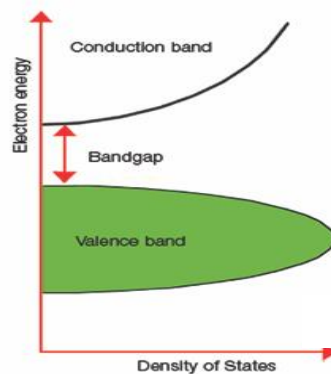


Figure 1. Band-gap [7]

For thermoelectric generator (TEG) materials, there are solid-state devices that can generate electricity from heat sources. Figure 2 schematically shows how the radiation source is focused by the solar concentrator before being passed to the TEG heat side. The expected TEG specification is to have high electronic conductivity simultaneously (σ), high thermoelectric power, and low thermal conductivity (κ). These properties determine the figure of merit $ZT = (S^2\sigma/\kappa) T$; where T is temperature. The $S^2\sigma$ products are often called power factors. The quantities $S^2\sigma$ and κ are the

number of transports and are therefore, determined by the details of the crystal and the electronic structure and the spread of the charge carrier [3].

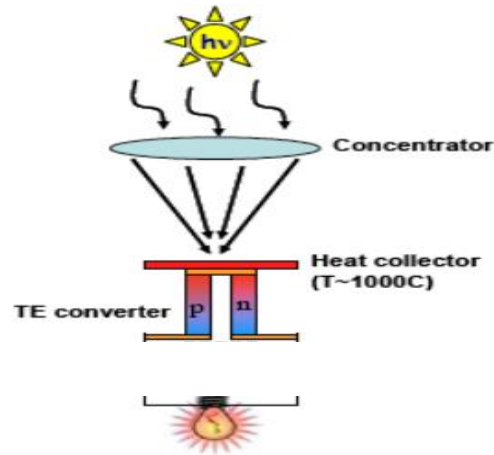


Figure 2 Illustration of a solar thermoelectric generator [3]

In the PV-TEG hybrid test conducted by Piarah et al. [8] has displayed a Halogen light spectrum configuration at 4 different measurement positions using both Hot and Cold Mirror (CM) spectrum splitters. The measurement results show a linear trend between spectrum proportions and the PV-TEG hybrid output power. Unfortunately, the suitability of photon energy emitted by the light spectrum of the bulb with the type of PV material is not displayed. The suitability of photon energy with the type of PV material is important to see whether the incoming energy radiation contains larger photons, smaller or equal to the band gap of PV material, so that the photon is able to release electron bonds in the PV cell and convert it to electricity. Therefore, this study will measure the photon energy of artificial light, both reflected and transmitted by the Cold mirror spectrum splitter. Cold mirror is chosen because the output power is slightly better than the results of Hot mirror [8].

The selection of artificial lights from Halogen, Incandescent and Xenon due to the spectrum of the bulb is close to the sunlight spectrum, as described by Doolittle [9] and described more fully the advantages light bulbs in the study [10-12] as follows.

1.1. Advantages of artificial lights

1.1.1 Halogen. Its form is like a balloon incandescent, a halogen balloon contains a halogen usually iodine that serves to increase the life of the bulb. The filament temperature is the same as the incandescent lamp. Therefore the halogen spectrum approaches the glow bulb and is suitable for PV and TEG requirements, This bulb was intensively tested in [10].



Figure 3. Halogen bulb

1.1.2 Incandescent. A glowing bulb in the form of a glass balloon in which there is a filament heated at a high temperature with a Joule effect. This filament may be regarded as a radiator of a black body, in which the filament material is made of tungsten heated at a temperature of 2000 to 3000 K. The incandescent bulb complies with the Illuminant A standard as recommended by the International

Commission on Illumination (CIE) at the temperature standard $T = 2856$ K. capable of producing wavelengths of light between 300-830 nm [11].



Figure 4. Incandescent bulb

1.1.3. Xenon. The xenon bulb spectrum is good enough at the wavelength limit of 220 to 700 nm and continues to rise above 700 nm to 900 nm, so PV and TEG can make use of it. Coffas et al. [12] in a PV-TEG-STC hybrid experiment using a xenon bulb as its sun simulator that produces an illumination of 30 to 130 suns with a 14 kW bulb. The PV types used are InGaP 1.86eV multijunction 1.86eV, 1.40eV InGaAs, and 0.67eV Ge which are connected in series. There are 4 TEG modules with each dimension of 6x6x0.38 cm and 4x4x0.33 cm of type Bi₂Te₃ and copper plates with dimensions of 8x8 x1 cm in length, width and thickness.



Figure 5. Xenon bulb

2. Materials and Methods

In this PV-TEG combination, photovoltaic cell material is from polycrystalline silicon 0.14W, 0.5 V_{max} 0.28 I_{max} with dimension 52x19 mm mounted series. The dimensions of photovoltaic cells are adjusted to the cold mirror dimensions of 50x50 mm². Meanwhile the thermoelectric module specification is a ceramic material/Bismuth Telluride model SP1848-27145 with dimensions 40x40x3.4 mm and operating temperature -40-150°C. Meanwhile, to focus the artificial lights radiation used Fresnel lens from Polymethylmetacrylate (PMMA) material with dimension 112x73 mm and 110 mm focal length, 2 mm thick lens with 92% light transmittance.

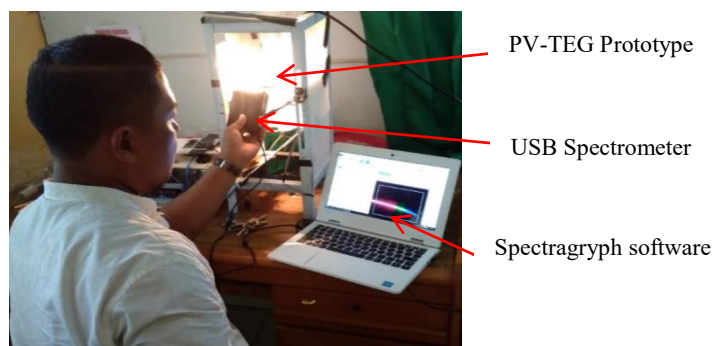


Figure 6. Photograph of the photon energy spectrometer on PV-TEG hybrid. The spectrometer is connected to Spectragryph application software on the computer to see its lights spectrum.

As for the experimental set-up as illustrated in figure 6, using a USB Mini Spectrometer hardware that is can capture the light that has been focused by the Fresnel lens which is then transmitted to the TEG and reflected to the PV. The light transmitted and reflected by Cold Mirror measured its spectrum with USB Spectrometer. The measurement results are recorded with the Spectragryph licensed application software version 1.2.8 created by Menges [13] that displays in the form of wavelength (nm) and/or band-gap energy (eV) on the X-axis and light intensity values in arbitrary unit (a.u) on the Y-axis.

3. Result and Discussions

3.1. Photon energy of the halogen radiation (reflection and transmitted)

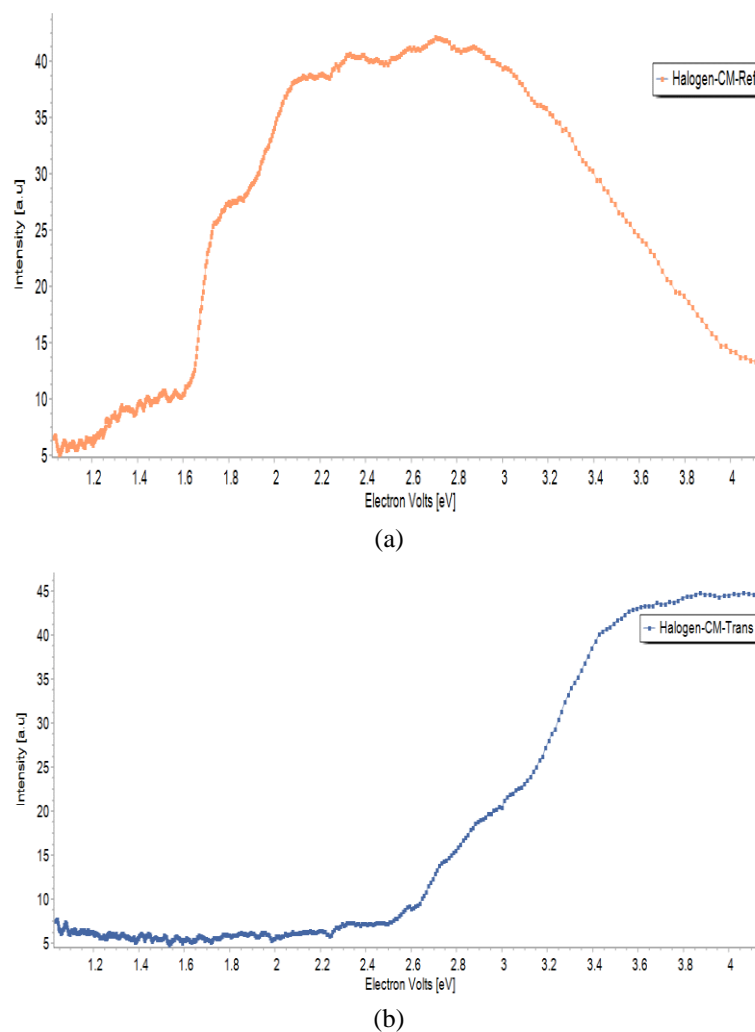


Figure 7. Band gap energy of halogen; (a) reflection light to to PV module
(b) transmitted light to TEG module

In figure 7 (a) shows the halogen spectrum spectrum energy (eV) band gap graph transmitted and reflected by Hot Mirror spectrum splitter. The trend is in the band gap energy between 1.8-3 eV (E_f) at high light intensity. For example in figure 7 (b), the intensity of the light is 45 a.u and band energy apporoximetally 2.4 eV. This means that the photon energy is more suitable with PV material in material group II-VI CdS ($E_g < E_f$) as written in table 1. The energy of the photons form

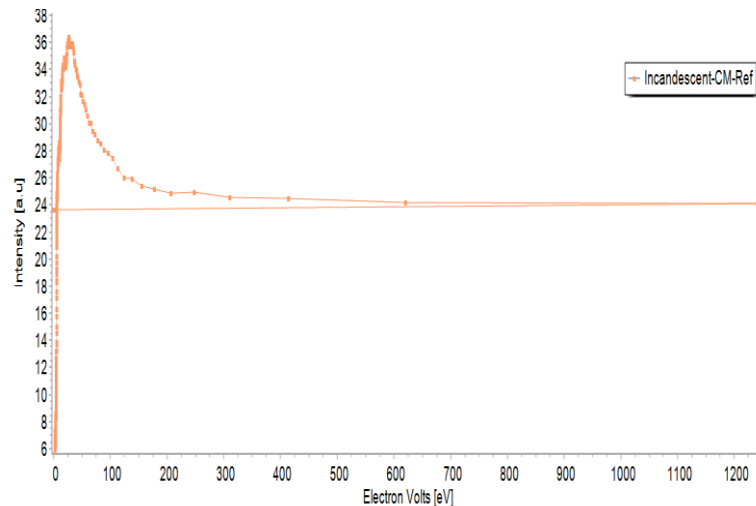
halogen light (E_f) and illuminate the surface of the PV module must be close to or greater than the band gap (E_g) of the module [14]. While figure 7 (b) indicates that the photon energy produced is only suitable for PV at the beginning of the band gap (2.2-2.4) eV. Referring to table 1, this indicates that the spectrum produced by a Halogen bulb matches the PV material of Cadmium Sulfide in the band gap 2.42 eV [15-16]. In terms of PV temperature, the maximum upper surface temperature is 39°C, while the maximum temperature of the hot side of the TEG on the test is 37.5°C and the cold side is 36.1°C.

Table 1. List of materials semiconductor [4]

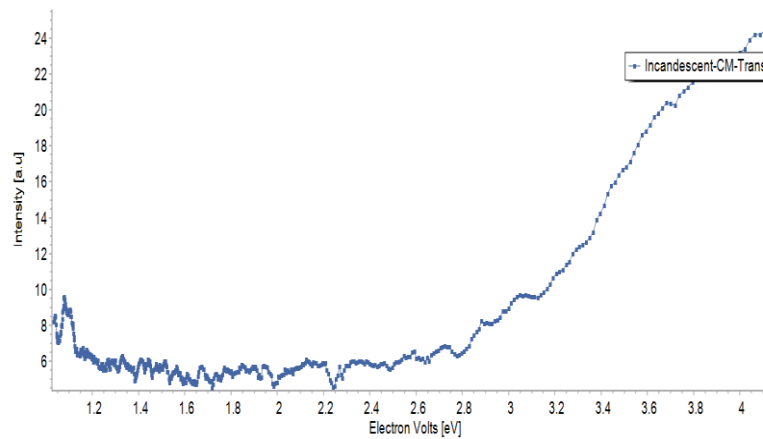
Group	Element	Material	Formula	Band gap (eV)	Gap type	Description
IV	1	Silicon	Si	1.12	Indirect	Used in conventional <u>crystalline silicon (c-Si) solar cells</u> , and in its amorphous form as <u>amorphous silicon (a-Si) in thin film solar cells</u> . Most common semiconductor material in <u>photovoltaics</u> ; dominates worldwide PV market; easy to fabricate; good electrical and mechanical properties
IV	1	Germanium	Ge	0.67	Indirect	A substrate for high-efficiency <u>multijunction photovoltaic cells</u>
III-IV	2	Indium nitride	InN	1.35	Direct	Possible use in solar cells, but p-type doping difficult. Used frequently as alloys
II-VI	2	Cadmium selenide	CdSe	1.74	Direct	Tested for high-efficiency solar cells.
II-VI	2	Cadmium sulfide	CdS	2.42	Direct	CdS/Cu ₂ S, Cd Te for PV
II-VI	2	Cadmium telluride	CdTe	1.49	Direct	CdS, digunakan dalam thin film PV, kurang efisien dibandingkan crystalline silicon
I-VI	2	Copper sulfide	Cu ₂ S	1.2	Indirect	p-type, Cu ₂ S/CdS was the first efficient thin film solar cell
IV-VI	2	Lead telluride PbTe	PbTe	0.32		Low thermal conductivity, good thermoelectric material at elevated temperature for thermoelectric generators.
IV-VI	2	Tin sulfide	SnS	1.3/1.0	Direct/indirect	Tin sulfide (SnS) is a semiconductor with direct optical band gap of 1.3 eV and absorption coefficient above 10 ⁴ cm ⁻¹ for photon energies above 1.3 eV. It is a p-type semiconductor whose electrical properties can be tailored by doping and structural modification and has emerged as one of the simple, non-toxic and affordable material for thin films solar cells since a decade.

3.2. Photon energy of the incandescent radiation (reflection and transmitted)

Compared with the intensity of the emitted halogen bulb, the incandescent bulb is lower than that of halogen bulb depicted in figure 8(a) at each peak of its intensity. The different is the energy value of the photon to the PV module, which is around 1.4 eV in the incandescent, while about 2.2 eV in the halogen. The value of this photon will determine the right type of material of the PV semiconductor material. Because the photon energy of the light reflected by the incandescent bulb must be greater or at least the same [15-16], then the corresponding PV material is Si, Germanium and Indium nitride which is less band gap than of the bulb light.



(a)

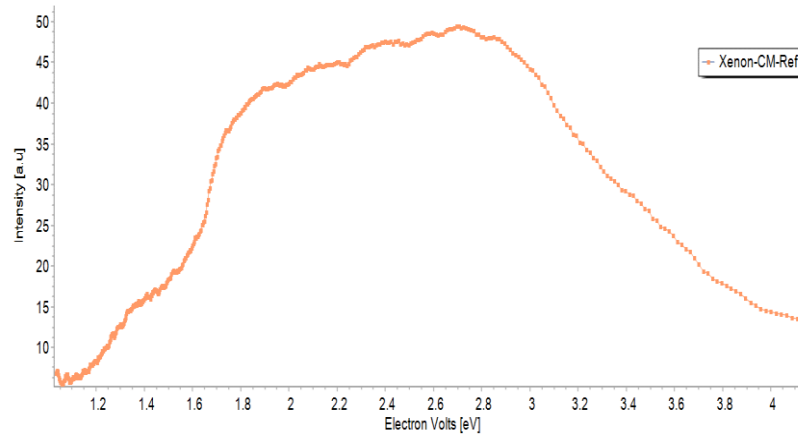


(b)

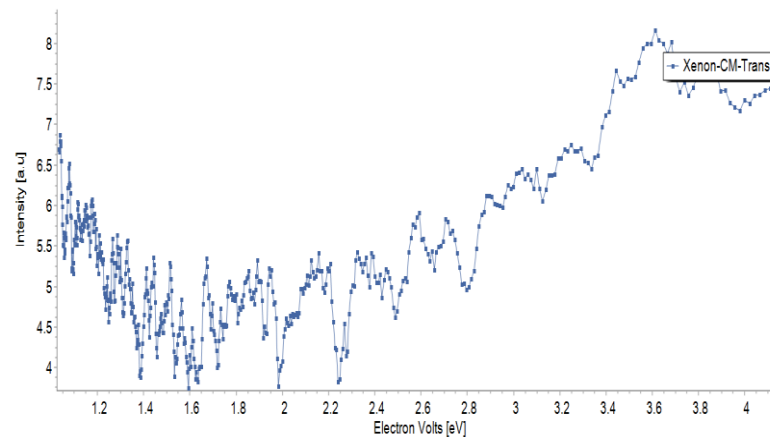
Figure 8. Band gap energy of incandescent; (a) reflection light to PV module (b) transmitted light to TEG module

3.3. Photon energy of the xenon radiation (reflection and transmitted)

The interesting test was shown in xenon light bulb. The distribution of intensity graph and photon energy reaches peak intensity at the middle of the 2.7 eV with the light intensity close to 50 a.u. as depicted in figure 9. Unfortunately, energy photons leading to the TEG module do not help much to influence the temperature difference between the hot side (38.3°C) and the cold side (36.9°C) of the material.



(a)



(b)

Figure 9. Intensity vs electron Volts of xenon; (a) incident xenon light to PV cell (b) to TEG module

From figure 7-9 of the photon energy reflected by CM into the PV module, it appears that the Xenon bulb emits the highest energy intensity (approximately 50 a.u), followed by Halogen (around 40 a.u) and the lowest is incandescent (36 a.u). While photon energy that meets potentially useful criteria for TEG is not significant, it can be ignored with Xenon as the lowest photon emission. That is, the energy of CM-transmitted photons is still useful for PV, although from experiments [16] the energy of photons below 1.4 eV is still useful for TEG. Furthermore, the measurement of photon/band gap energy needs to be compared with the Hot Mirror spectrum splitter in further research to provide comprehensive parameters between Hot and Cold mirrors because the spectrum of light has only been measured by Piarah et al. [8] and Mustofa et al. [17].

4. Conclusions

The energy potential of photons emitted by light bulbs (Halogen, Incandescent and Xenon) is significant enough to release electron bonds in PV material by seeing the compatibility between photon energy and the gap band criteria for PV material. Xenon light displays the best potential photon energy for PV and Halogen in TEG module by using light spectrum splitter Cold mirror. The potential of photon energy from the bulb will be more significant if the next research is to vary the power of the bulb that is greater than 100 to 500 Watts.

Acknowledgments

We would like to thank the University of Hasanuddin and the University of Tadulako for hosting this research. We also would like to thank Irwan Mahmudi is the head of fundamental electric and measurement in the Electrical Engineering Laboratory of Universitas Tadulako, Indonesia for his setting up the experiments.

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