Field Test for the Conversion Efficiency Determination of High Concentrating Solar Cells with Fresnel Lenses in a Tropical Location

Pattanapong Jumrusprasert, Nakhon Ratchasima Rajabhat University, Thailand

The North American Conference on Sustainability, Energy & the Environment 2014
Official Conference Proceedings

Abstract

Field test for the conversion efficiency determination of high concentrating solar cells with fresnel lenses in a tropical location was conducted at the top of NRRU Science Center Building, Nakhon Ratchasima, Thailand . The five of square shape of 5.5 mm x 5.5 mm. mutijunction solar cells were series connected to be a module. Each cell was fabricated with 100 suns silicon-glass fresnel lens for a concentrating purpose. We also determined the conversion efficiency of 160 watts peak monocrystalline silicon solar cell panel for a comparing purpose. All of solar cell module, solar cell panel, pyrheliometer, pyranometer and light sensor were set up on the dual axes sun tracker. Data were gathered every 2 minutes all day from November 2013 to May 2014 via the automatic data logging system. The results have presented that the average conversion efficiencies of high concentrating solar cell module with fresnel lenses and of the 160 watts peak monocrystalline solar cell panel were 20.36 % and 14.12 % respectively, while, the average output powers per unit area of them were 9,652.89 watt/m^2 and 78.43 watt/m^2 respectively. It is clearly seen that, in terms of conversion efficiency and output power per unit area, the advantage of high concentrating solar cell with fresnel lens module significantly better than the typical monocrystalline solar cell panel. Economical aspect, the dominant of high concentrating solar cell with fresnel lens module, it will be significantly reduce the land investment cost and also encouraging in use of solar cell in urban and rural in spite of under the tropical location of Thailand.

Keywords : concentrating solar cells, conversion efficiency, fresnel lens, tropical location

Introduction

Renewable energy sources are of increasing interest, especially with a combination of tightness in world oil supply and problems with global warming. Solar cells, in particular, have attracted much attention due to their relative simplicity of operation in converting solar energy directly to electrical energy (Green 1998). Commercially, three types of silicon solar cell were used: monocrystalline, polycrystalline and amorphous(Messenger and Ventre 2004) with the conversion efficiency under the STC condition reach to 25%, 19% and 6% respectively(Wikipedia 2014). However, under the outdoor condition, the conversion efficiency of these solar cells significantly drop. Individual solar cells combine to form a solar cell panel(Goswami, Kreith et al. 2000). Typically, to maximize the average solar energy incident onto solar cells for the whole year, solar cell panels are conventionally set up as fixed panels facing south for the northern hemisphere location. A latitude tilt angle ± 15° to 25° is widely used to maximize solar energy incident onto solar cells as the seasons change(D.Partain 1995). To enhance the conversion efficiency of these solar cells, the single axis or dual axis sun tracking system was employed to increase the conversion efficiency about 20%-30%(Markvart and Castaner 2003).

Recently, the high efficiency multijunction solar cell was reported on the conversion efficiency under the STC condition with non-concentrating system reach to over 30%. For only this conversion efficiency of the multijunction solar cell, it is not enough to compete to the typical solar cells due to the cost per efficiency ratio is greater(Wikipedia 2014). So, multijunction solar cells were used for incorporate to the concentrating system such as lens or mirror(Nilsson 2005) that attached to the dual axis tracker which concentrates the sunlight onto the cell(Luque and Andreev 2007), the most extreme conversion efficiency of the multijunction solar cell reach to 44.7% (under 297.3 suns) (Casey 2013). The conversion efficiency of multijunction solar cells vary as the concentration ratio (CR) of light onto the cell, cell temperature, optical of concentration system etc. The clear sky of most direct radiation and low temperature will give rise the high conversion efficiency such as in Spain, USA and Australia. Similar limitation to typical solar cells, under the outdoor condition, the conversion efficiency of multijunction solar cells drop due to many factors.

In spite of the cloudy sky of most diffuse radiation and high temperature that will drop down the conversion efficiency of the cells such as in Thailand, Malaysia and Vietnam, there were rarely outdoor researchs that reported on the conversion efficiency of multijunction solar cells with concentrating system. In contrast, instead of typical solar cells using, the use of high efficiency multijunction solar cell incorporate to concentrating system should be boost the conversion efficiency of cells to compensate the disadvantages of the cloudy sky and high temperature. The most dominant of this high concentrating solar cell system is the reduction on the land use due to its has a very small size cell that need very small area to install compare with the typical solar cell system. So, I have decided to do the field test research to determine the conversion efficiency of multijunction solar cell incorporate to concentrating system (under 100 suns) via fresnel lens and dual axis tracker to justify or make a decision on using this system in a tropical location like in Thailand.

Background

Multijunction solar cells

Typical, commercially, solar cells made of one p-n junction silicon that have a specific band gap to capture specific photon energy. So, most of photon energy from the sun are lost. Then, it effects to the conversion efficiency limitation. To capture photon energy from the sun as much as possible, multijunction solar cells were designed and fabricated. The different type of III-V materials which have different band gap were layered from high band gap energy to low band gap energy from top to bottom of each multijunction solar cell respectively as shown in figure1. The reason for this is that the excess photon energy from the top layer penetrates to the middle and then to the bottom of multijunction solar cell. The consequent is of dominantly increase the conversion efficiency of multijunction solar cells compare with typical solar cells. However, to date, the cost-efficiency ratio of multijunction solar cells is too high compare with typical solar cells. So, economically, multijunction solar cells were suggested to work with concentration system and dual sun tracker for enhancing the maximum performance. To date, the conversion efficiency of the multijunction solar cell reaches to 44.7% (under 297.3 suns) (Casey 2013).

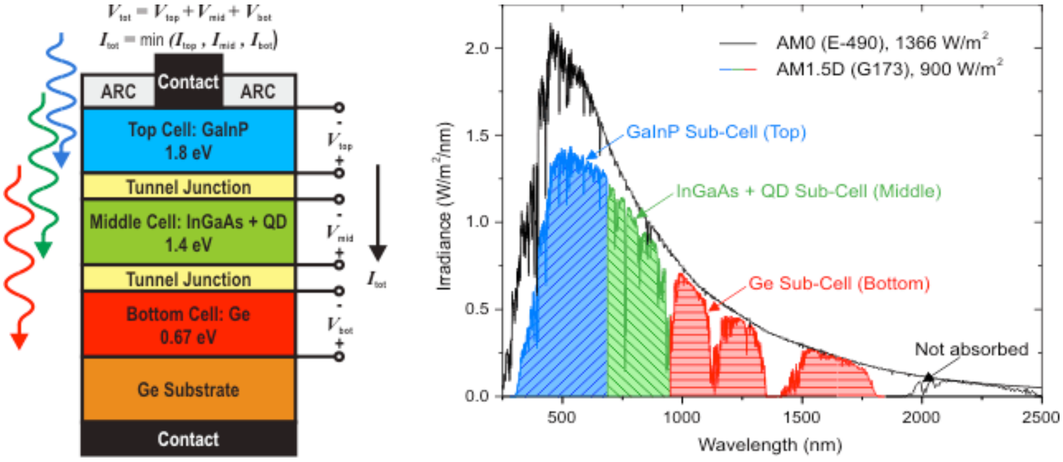
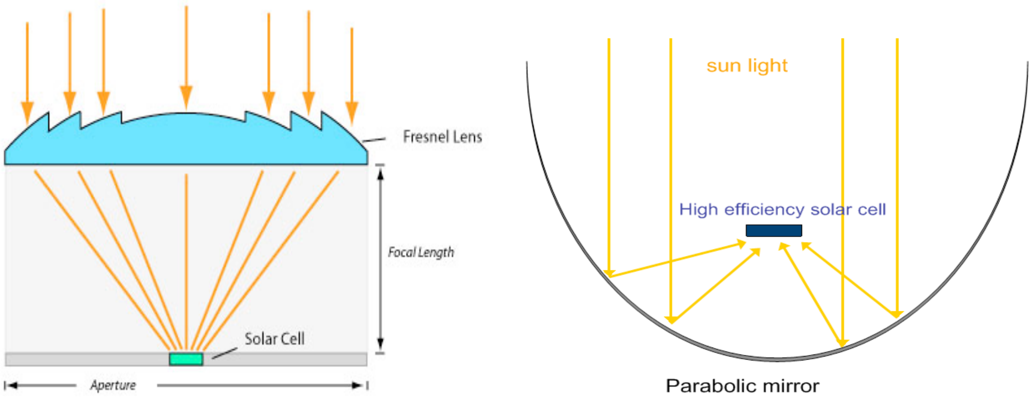


Figure1. Multijunction solar cell structure and spectral irradiance-wavelength graph (Solar PV, 2014)

Concentration system

Concentration sunlight via some optics such as fresnel lens or parabolic mirror onto a small area solar cell is popularly called concentrated photovoltaic (CPV). CPV can significantly increase the conversion efficiency of multijunction solar cells(44.7%) compare to non-concentrated multijunction solar cells(over 30%)(Wikipedia 2014) and conventional silicon solar cells(25%) due to its photon fluxes are more consolidated. The dominant benefit of CPV is of using only small amount materials to fabricate very small solar cells compare to conventional solar cells. So, CPV can save the environment, land cost, installing cost, labor cost etc. However, CPV needs the multijunction solar cell, lens or parabolic mirror, direct sunlight, cell cooling, sun tracker that increasing in overall cost compare to conventional solar cells. For competition, CPV must be enhanced the performance on increasing conversion efficiency of multijunction solar cell and lower its cost as soon as possible. We can be categorized the CPV type based on the level of sunlight concentration (unit: suns) in to 3 types: low concentration (sunlight concentration 2-100 suns) that no need to active cool and active sun tracker, medium concentration (sunlight concentration 100-300 suns) that need to active or passive cool and dual sun tracker. The last one: high concentration (sunlight concentration 1,000 suns or more) that need to active cool and active dual sun tracker. Figure2. was shown about some examples of CPV optics. The more lower or higher concentrations and the more higher temperature can be make low conversion efficiency of multijunction solar cell. The optimum concentration is around 500 suns as shown in figure3.



(a) (b)

Figure2. Concentration by lens(a) (Concentrated Photovoltaic Technology, 2014) and concentration by parabolic mirror (b)(Liang, 2010)

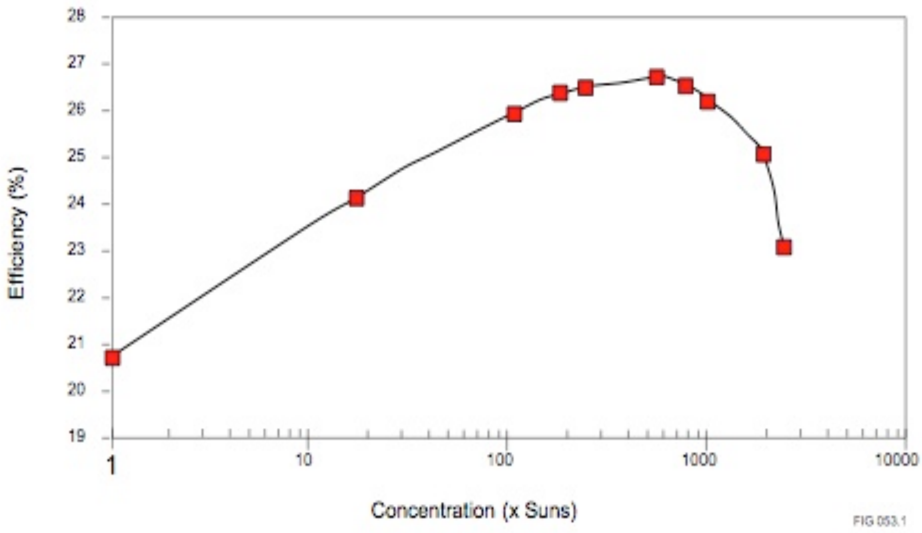


Figure3. Effect of concentration ratio on conversion efficiency of solar cell (McConnell and Fthenakis, 2012)

Performance and economical analyses of the system

1) Conversion efficiency of solar cell (η)

The average conversion efficiency for each solar cell module can be determined by equations 1 to 2. Note that we define both Δt and dt as time intervals between data points. Economically, we favorite high conversion efficiency from solar cell.

$$\text{Efficiency}_{\text{av}} = \frac{\text{Total Energy Output in time T}}{\text{Total Energy Input in time T}} \text{ x } 100\% \qquad (1)$$

Thus,

$$\text{Efficiency}_{\text{av}} = \frac{\int_0^T \text{Power Output}_{\text{ins}}\, dt}{\int_0^T \text{Power Intput}_{\text{ins}}\, dt} \text{ x } 100\% \qquad (2)$$

where Efficiency$_{\text{ins}}$ = instantaneous conversion efficiency for each solar cells module.

Power Output $_{\text{ins}}$ (W) = instantaneous electric power output from the solar cell module.

Power Input $_{\text{ins}}$ (W) = instantaneous power incident on solar cell module.

Efficiency $_{\text{av}}$ = average conversion efficiency for each solar cell module over an extend time interval T.

2) Concentration ratio (CR)

The parameter used to quantify the amount of refractive area of lens or reflective area of mirror that receive sunlight energy flux input onto each aperture(A) per a small area of each solar cell is called the concentration ratio. It is determined using equation 3(Nilsson 2005). The more concentration ratio of solar cell system the more of solar flux intensity onto solar cell.

$$CR = A/a \qquad (3)$$

3) Cost-efficiency ratio (CE)

This parameter used to quantify the cost of investment in solar cell system (C) per conversion efficiency (η) of solar cell. It is determined using equation 4. The lower cost-efficiency ratio of the solar cell system the more benefit of that solar cell system.

$$CE = C/\eta \qquad (4)$$

4) Payback period (PP)

Payback period is the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment. It is one of the simplest investment appraisal techniques. It is determined using equation 5. The lower payback period the more benefit of that solar cell system.

$$\text{Payback Period} = \frac{\text{Initial Investment Cash}}{\text{Inflow per Period}} \qquad (5)$$

When cash inflows are uneven, we need to calculate the cumulative net cash flow for each period and then use the following formula for payback period:

$$\text{Payback Period} = A + \frac{B}{C}$$

In the above formula,
A is the last period with a negative cumulative cash flow;
B is the absolute value of cumulative cash flow at the end of the period A;
C is the total cash flow during the period after A

Climate conditions of the experimental site

The experimental site was located in Nakhon Ratchasima, a northeastern province of Thailand. Thailand is located between latitude 5º 37' N and 20º 27' N, and between longitude 97º 22' E and 105º 37' E. Thailand is geographically divided into 4 regions: Northern, Northeastern, Central and Southern regions. A map of Thailand and neighbouring countries is shown in Figure4.

Figure4. Map of Thailand. (Google 2014)

Thailand has 3 seasons: rainy (from mid-May to mid-October), winter (from mid-October to mid-February) and summer (from mid-February to mid-May). The climate of Thailand, a tropical country, is mainly affected by the two monsoon winds: the Southwest and Northeast. The Southwest monsoon comes from the Indian Ocean in May. As a result, clouds and rains spread widely around the country until the end of the rainy season in October. The Northeast monsoon comes from the mainland of China in October. Consequently, dry and cold weather with a clear sky widely appears around the country until the end of winter in February. However, the east coast of the Southern region experiences heavy rain at this time due to moisture from the Gulf of Thailand. A period of the transition of the monsoons, from the Northeast to the Southwest occurs in February. The weather then becomes hot and humid around the country until the end of summer in May. The hottest months of the year are from March to May. There are many climate parameters which characterise the general weather for each season in Thailand, such as cloudiness, surface wind, surface temperature, rainfall, relative humidity etc. (TMD 2014)

Table 1. Climatological information of Nakhon Ratchasima, Thailand (WMO 2014)

Month	Mean Daily Minimum Temperature (°C)	Mean Daily Maximum Temperature (°C)	Mean Total Rainfall (mm)	Mean Number of Rain Days
Jan	**17.9**	**30.9**	**5.9**	**0.9**
Feb	**20.5**	**33.6**	**17.8**	**2.2**
Mar	**22.8**	**35.8**	**37.1**	**5.1**
Apr	**24.5**	**36.6**	**63.5**	**7.7**
May	**24.7**	**35.1**	**140.5**	**13.8**
Jun	**24.8**	**34.4**	**108.3**	**13.3**
Jul	**24.3**	**33.9**	**113.7**	**13.5**
Aug	**24.2**	**33.2**	**146.2**	**16.4**
Sep	**23.7**	**32.2**	**221.6**	**18.1**
Oct	**22.9**	**30.9**	**143.4**	**12.2**
Nov	**20.5**	**29.7**	**27.3**	**4**
Dec	**17.6**	**29.1**	**2.8**	**0.7**

Methods

The methods for this research were done as following steps;

1. Series connected the five 5.5 cm x 5.5 cm multijunction solar cells together (with built in heat ventilation substrate that further attach to the heat sink for each cell).
2. Fabricated each multijunction solar cell to receive the expected 100 suns concentrated sunlight from each fresnel lens.
3. Installed the module which composes of a set of multijunction solar cell and a set of fresnel lens onto the rack of dual axis sun tracker.
4. Installed a 160 watts monocrystalline solar cell panel as a comparative cell onto the rack of dual axis sun tracker.
6. Installed the pyrheliometer and pyranometer onto the rack of dual axis sun tracker to measure the direct and diffuse solar fluxes incident onto these solar cells.
7. Installed the light sensor on the dual axis sun tracker to sense and control for a precision tracking.
8. Connected wires from all of the system to the data loggers for data gathering

purpose.

9. Set up the data loggers to collect the data every 2 minutes for 6 months.
10. Collected data were calculated to determine the average conversion efficiency and average output power per unit area of a set of multijunction solar cell module and a comparative monocrystalline solar cell panel.

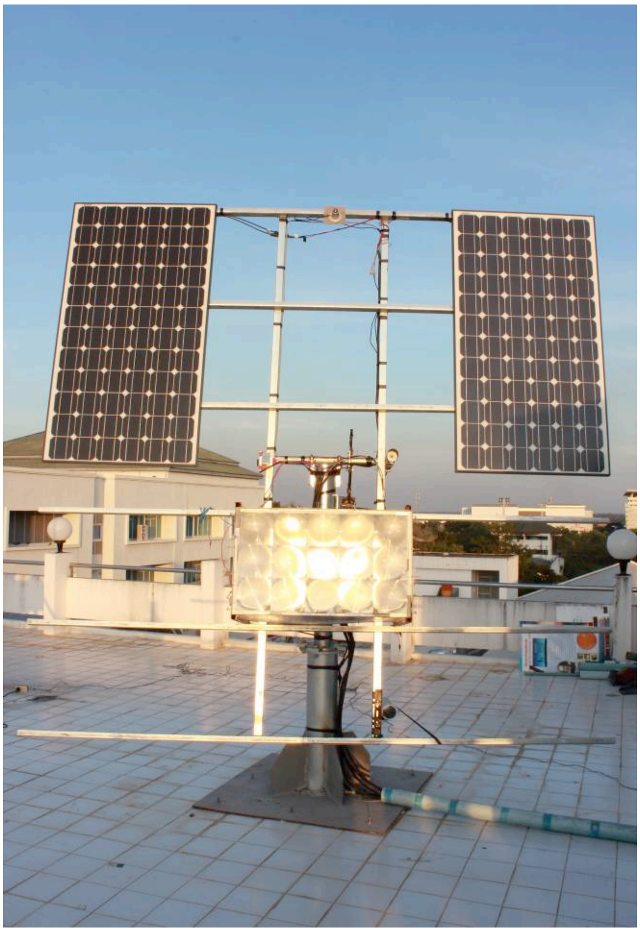
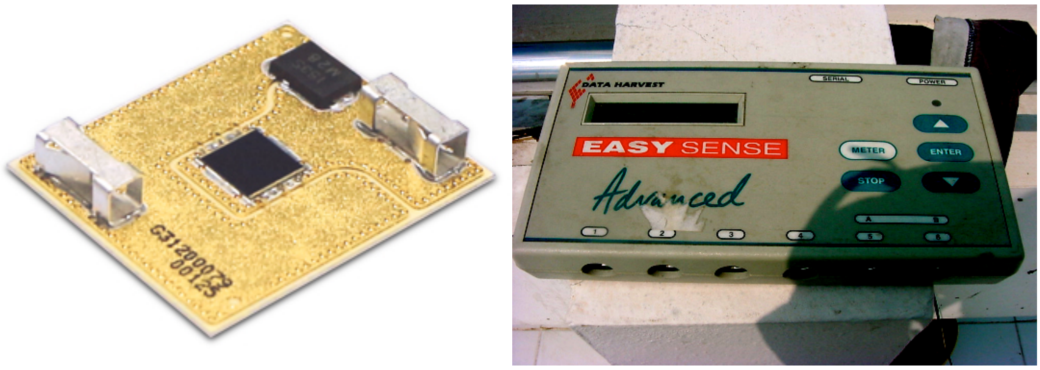


Figure5. System set up and installation

(a) (b)

Figure6. The SK01-D pyranometer (a) and DN5-E pyrheliometer (b) set up



(a) (b)

Figure7. The 5.5 cm x 5.5 cm CTJ multijunction solar cell (a) (Suncore 2014) and data
logger (b)

Result and discussion

Conversion efficiency

1) Overall average conversion efficiency

The result for overall average conversion efficiency of multijunction solar cell module (100 suns) and a comparative monocrystalline silicon solar cell panel (160 watts) were 20.36% and 14.12% respectively. We clearly seen that the performance of 100 suns concentrated of sunlight via fresnel lenses onto multijunction solar cells significantly greater than monocrystalline silicon solar cell panel. In spite of a cloudy and overcast sky in a tropical location site, the CPV system was still shown a good performance although it has lower performance than in the clear sky, dry weather and cool temperature location. To increase the performance of multijunction solar cells module, the increment of concentration ratio for the system is recommended.

2) Monthly average conversion efficiency

The result for monthly average conversion efficiency of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel was presented in figure8. We found that, every month except for in April 2014, the performance of 100 suns concentrated of sunlight via fresnel lenses onto multijunction solar cells greater than monocrystalline silicon solar cell panel. Especially, in winter (from November to February), the performance of 100 suns concentrated of sunlight via fresnel lenses onto multijunction solar cells dominantly greater than monocrystalline silicon solar cell panel. The average conversion efficiency in winter of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 20.94% and 13.31% respectively. The low temperature incorporate to the very clear sky in winter must be influent in both of solar cells performance. The average conversion efficiency in summer of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 16.48% and 15.19% respectively. Critically, we have seen that the average conversion efficiency in summer of multijunction solar cell module a few more than a comparative monocrystalline silicon solar cell panel. The high temperature incorporate to the cloudy and overcast sky in summer must be influent in both of solar cells performance.

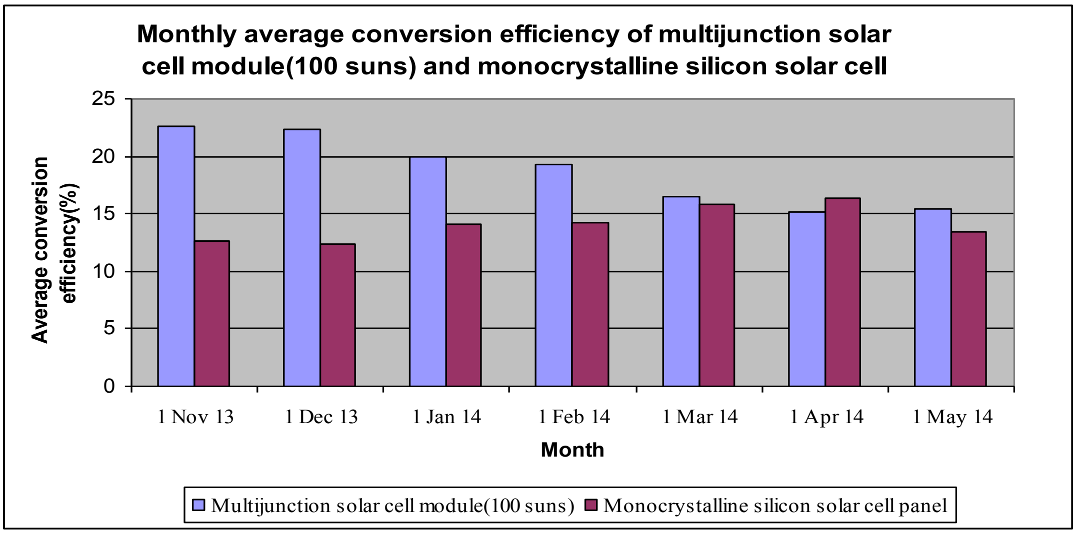


Figure8. Monthly average conversion efficiency of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel

3) Average output power per unit area

The average output powers per unit area of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 9,652.89 watt/m^2 and 78.43 watt/m^2 respectively. Economical aspect, the dominant of high concentrating solar cell with fresnel lens concentrating system module, it will be significantly reduce the land investment cost and also encouraging in use of solar cell in urban and rural in spite of under the tropical location of Thailand and neighbouring.

Conclusion

The field test for the conversion efficiency determination of 100 suns concentrated via fresnel lenses onto the multijunction solar cells in Nakhon Ratchasima, Thailand as a tropical location was shown the satisfactory result. The average conversion efficiency of multijunction solar cell module was significant greater than a comparative monocrystalline silicon solar cell panel with the 20.36% and 14.12% performances respectively. Especially, the performances of both solar cells were better in winter than in summer because of sky condition and temperature. The average output powers per unit area of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 9,652.89 watt/m^2 and 78.43 watt/m^2 respectively. The result was presented the possibility to use concentrating solar cell system via fresnel lens in the tropical area although lesser performance than the clear sky and low temperature location. To increase the performance of multijunction solar cells module, the increment of concentration ratio for the system is recommended.

Acknowledgements

I would like to thank for the Higher Education Research Promotion (HERP) of Thailand as a sponsorship and financial support. Thank for Nakhon Ratchasima Rajabhat University as a project site and equipment support. As well, very thank for Mr.Tanawat Rungsungnern and Mr.Kajondet Weangsong from Physics and General Science Program and NRRU Science Center who dedicated their time with a hard working for me.

References

Casey, T. (2013). "Cost Of Solar Set To Plummet With New 44.7% Efficiency Record." Retrieved 15 June, 2014, from http://cleantechnica.com/2013/09/24/new-solar-cell-efficiency-record-of-44-7-set/.

D.Partain, L., Ed. (1995). Solar Cells and Their Applications. Concentrator Modules Using Multijunction Cells. New York, A Wiley-Interscienc Publication.

Google (2014). Map of Thailand

Goswami, D. Y., F. Kreith, et al. (2000). Priciples of Solar Engineering. Philadelphia, Taylor&Francis.

Green, M. A. (1998). Solar Cells. New South Wales, The University of New South Wales.

Luque, A. L. and V. M. Andreev, Eds. (2007). Concentrator Photovoltaics. Multijunction Concentrator Solar Cells. Heidelberg, Springer.

Markvart, T. and L. Castaner, Eds. (2003). Practical Handbook of Photovoltaics: Fundamentals and Applications High-efficiency concentrator silicon solar cells. Oxford, Elsevier Advanced Technology.

Messenger, R. A. and J. Ventre (2004). Photovoltaic Systems Engineering. Florida, CRC Press.

Nilsson, J. (2005). Optical Design and Characterization of Solar Concentrators for Photovoltaics. Lund, KFS KB.

Suncore. (2014). "CPV Technology." Retrieved 20 July, 2014, from http://www.suncorepv.com/index.php?m=content&c=index&a=lists&catid=82.

TMD. (2014). "Weather." Retrieved 6 May, 2014, from http://www.tmd.go.th/index.php.

Wikipedia. (2014). "Multijunction photovoltaic cell." Retrieved 18 August, 2014, from http://en.wikipedia.org/wiki/Multijunction_photovoltaic_cell.

WMO. (2014). "Climatological Information of Nakhon Ratchasima, Thailand " Retrieved 3 July, 2014, from https://www.wmo.int/pages/index_en.html.

Contact email: pattanapong@mail.com