A design of fluorescent fiber solar concentrator (FFSC) and outdoor testing for remote indoor day lighting and power producing evaluation for building integration

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Abstract

Different from the conventional luminescent solar concentrator (LSC), a 1200mm×1200mm solar concentrator consisting of 150 pieces of three-color 1m long, 2mm diameter fluorescent fibers (FFSC) has been designed and mounted on a University building roof and the concentrated light is transported to a remote dark room through 10m long, 2mm diameter clear optical fibers. Outdoor testing for remote indoor day lighting and power producing evaluation has been conducted. A 31-day monitored data from 24 May2008 to 23 June2008 has been presented and the results reveal that even though FFSC is not practical yet to replace the conventional BIPV approach for power producing, it has a pleasant potential in remote indoor day lighting for large amount application in building integration.

Keywords: Fluorescent Fiber Solar Concentrator (FFSC), Remote Indoor Day Lighting, Building Integrated Photovoltaic (BIPV)

Introduction

As a solution to the energy issues, solar energy is made widely available for day lighting and direct production of electricity. Various methods have been developed to collect, concentrate, transport, store and convert solar radiation such as the light pipe, optical fibers, optical solar concentrators, and luminescent solar concentrators (LSC), and so on (Littlefair, 1996; Shao et al., 1998; Cariou, Martin & Dugas, 1982; Enedir and John, 2006; Ries et al., 1995; Beckman et al., 2003; Alan, et. al, 2004; etc.). However, many limitations remain in such devices, such as strict dependence on beam irradiation and difficulties for wiring and so on. After providing a brief discussion on the working theory and limitations for those devices, a fluorescent fiber solar concentrator (FFSC) designed and used as a device for remote indoor day lighting and power producing, which is expected as an integration or evolution from earlier designed devices.

The 1200mm×1200mm fluorescent fiber solar concentrator (FFSC) consisting of 150 pieces of three-color 1m long, 2mm diameter is mounted on a university building roof and the concentrated light is transported to a remote dark room through 10m long, 2mm diameter clear optical fibers. Outdoor testing for remote indoor day lighting and power producing evaluation was conducted from 24 May2008 to 23 June2008.

Together with a description on the FFSC design and its outdoor experiments, analysis on the light to light efficiency (ηl), lighting effect, energy to energy efficiency (ηe), light efficacy (ηe-l), and the negative association between light to light efficiency (ηl) and solar irradiation for the FFSC have also been presented. Results reveal FFSC as a pleasant potential in remote indoor day lighting for large amount application in building integration.

The necessity to design FFSC: a journey in solar energy using

Solar energy as a solution to energy issues

Besides the rapidly rising price of petroleum, anthropogenic activities, especially the burning of fossil fuels, have released pollutants into the atmosphere increasing global warming and depleting the ozone layer. To improve the situation there needs to be a decrease in energy of which fossil fuel is used. As a result there has been an increased interest in renewable energy systems. Solar energy is made widely available for thermal applications, day lighting, and direct production of electricity.

Artificial lighting is one of the major sources of electrical energy costs in office buildings, both directly through lighting energy consumption and indirectly by production of significant heat gain, which increases cooling loads. Electric lighting represents up to 30% of building electricity consumption in commercial and office buildings (Crisp et al., 1988 and Lam,1995).

Sun light as a clean energy source could contribute considerably to a solution of the energy problem if appropriate methods were developed to collect, concentrate, store and convert solar radiation, which is diffuse and intrinsically intermittent (Reisfeld & Jorgensen, 1982). Daylight is an underused resource that has the potential to improve the quality of indoor lighting, as well as substantially reducing energy costs.

Day lighting, light pipe and optical fiber for light transportation

Increasing the use of day lighting in buildings can offer significant savings in energy consumption as well as improving

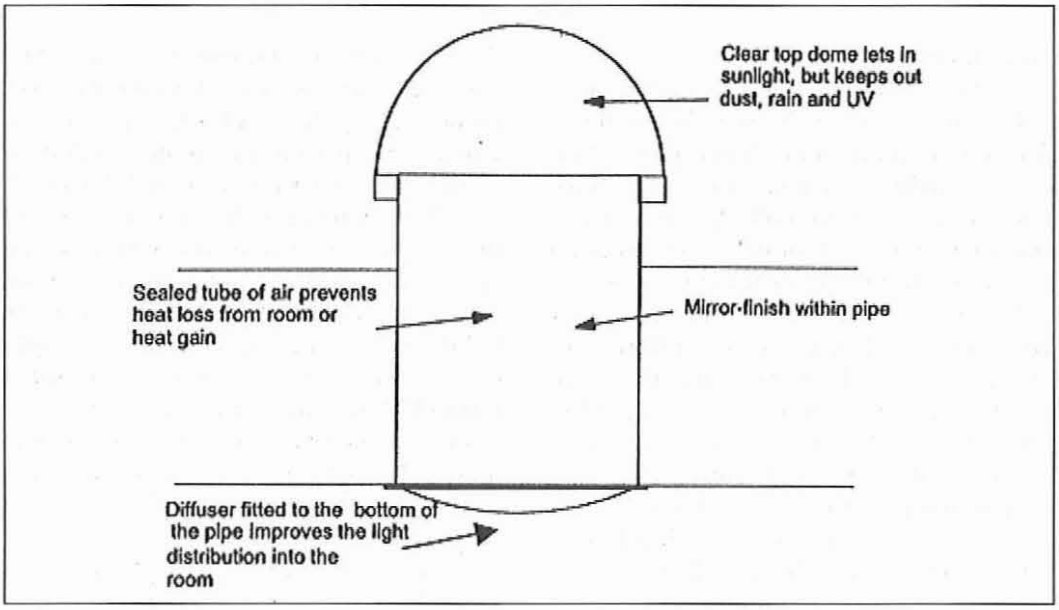


Figure1 : Schematic of a typical light pipe

the internal environment. For example, Bouchet and Fontoynont (1996) suggested that as little as 50 lux of daylight might provide significant relief from feelings of isolation for people working in underground spaces. However, there can be problems with glare and potential thermal discomfort due to direct solar gain with some daylighting systems. Natural light could be transported by light pipes and optical fibers in a building with little thermal effect.

Light pipes

As illustrated in Figure 1, light pipe systems have three components, namely: (i) an outside collector (usually on the roof), generally a clear dome that removes UV radiation and acts as a cap to prevent dust and water from entering the pipe; (ii) the light pipe itself; (iii) an emitter or luminaire that releases the light into the interior (Littlefair, 1996).

The majority of commercially available light pipes are simply empty tubes along which light can travel into the interior of a building or other dark spaces. They are available from a number of manufacturers and are versatile enough to be installed in straight or angled assemblies, enabling them to bring daylight into otherwise inaccessible rooms. The coating on the internal surface of the light pipe is composed of highly reflective materials such as anodised aluminium or coated plastic films such as Alcoa Everbrite and Silverlux, which have reflectances greater than 95% (Shao et al., 1998).

Light pipes use the principle of high efficiency reflection, and as a result straight light pipes perform better than angled ones as light energy decreases with increased reflections (Sweitzer, 1993). Each light pipe bend may reduce light output by approximately 8% (Monodraught, 200 8). The light pipe also transmits less solar heat than windows, preventing internal heat gains in summer, and heat loss in winter. Finally the diffuser distributes the light more evenly into the space the light pipe is illuminating.

Bouchet and Fontoynont (1996) produced a computer simulation predicting a minimum illuminance of 100 lux for over 70% of the period between 09:00 and 18:00 under overcast conditions. Shao et al. (1998) studied four different buildings in the UK, and found that light pipes with moderate aspect ratios (up to 6) produced illuminances up to 450 lux with internal/external illuminance rations of 1%. However, in cases where long and narrow light pipes with some bends were used the internal illuminance fell to as low as 27 lux with the ratio reduced to 0.09%.

Optical Fiber for light transportation

According to Enedir and John (2006), since the early 1990s, fiber optic cables using an artificial light source have been used in remote-source lighting systems. Using this technology, light travels from its source to one or more remote points through fiber optic cables. The technology has been used in many applications such as museums and retail displays and in architectural applications to emphasize the features of a building or to outline its exterior contours; other applications have involved lighting exit signs and aisles in theatres and aero planes etc. to name but a few.

The idea of concentrated solar energy transport by optical fibers was put forward in 1980 by a group of French investigators (Cariou, Martin & Dugas, 1980). Owing to the unavailability of high quality optical fibers and the high cost of their design, that project limited itself to theoretical analysis only. With the present day availability of fiber-optic techniques, solar energy can be transmitted by high-quality optical fibers of large core diameter and large numerical aperture. With flexible fiber optic solar energy transmission and concentration, a solar laser or any other light powered tool will be able to be moved out of its actual pumping position in the focusing area of the primary parabolic mirror and will find new applications.

The use of concentrated solar energy and its transport in optical fibres is studied by Cariou, Dugas & Martin (1982). Transmission properties of fibers as well as geometrical conditions of the association between fibers and concentrator were investigated. It was shown that modules where one fiber is associated with a small parabolic mirror may supply 2 W with efficiency greater than 70 per cent, whilst the concentration on the exit end of a 10-m long fiber may exceed 3000. Such a device has been achieved and the experimental results are in good agreement with the preliminary study.

Conventional Solar Concentrators

Sunlight holds considerable unrealized potential for application in energy efficient room lighting designs. There are currently few existing systems that efficiently utilize sunlight to provide sufficient room lighting to remote non-daylit rooms. Anidolic optics can be used for lighting of a room with an immediate day lighting aperture (Compagnon et al., 1993; Page et al., 2003). Recently, systems involving concentrating collectors (Beckman et al., 2003), heliostats (Pohl and Anslem, 2002), or mirror light pipes (Garcia-Hansen and Edmonds, 2003) have been developed for illumination of remote rooms. A fatal disadvantage of conventional solar concentrators is while systems using mirrors or lens may be advantageous for large-scale room lighting, they chiefly rely on beam solar irradiation and require tracking mechanisms to avoid astigmatism and other light losses experienced during collection of solar energy so that they lose their functions in cloudy and diffuse conditions (Ries et al., 1995).

In order to remove the tracker, a static solar concentrator is proposed by Masato and Toshiro (2005) to match the aesthetic features of towns. The concentrator consists of vertical plate solar cells and white/transparent switchable bottom plate, which is operated with external power. The bottom is switched to be a diffuse reflection white surface when the cell generates electric power, and switched to be a light transmissible transparent surface when the cell does not deliver power. The light collection of this concentrator was analyzed by using multiple total internal reflection model and ray tracing simulation. However, the results are not significantly satisfying for a static solution for solar concentration.

Luminescent Solar Concentrator (LSC)

Luminescent solar concentrators (LSCs) have attracted the attention of a large number of scientists and engineers since the first proposal by Weber and Lambe (1976). The operation of the LSC, which can be considered as a peculiar kind of light guide, is based on the following principles. One or more high quantum yield species are dissolved in a rigid highly transparent medium of high refractive index. Solar photons entering the plate are absorbed by the luminescent species and reemitted in random directions. Following Snell's law, a large fraction of the emitted photons will be trapped within the plate and transported by total internal reflections to the edge of the plate, as illustrated in Figure 2, where they will be converted by appropriate photovoltaic cells (Reisfeld, 2001; Batchelder. El, 1979)

It has been reported that thin luminescent concentrator films could be implemented in the form of integrated devices or as sensitive elements in the traditional four-detector differential position sensors (Evenson & Rawicz 1995; Melnik & Rawicz, 1997)

An LSC day lighting system has been produced by Alan, et al (2004), which transports sunlight to remote

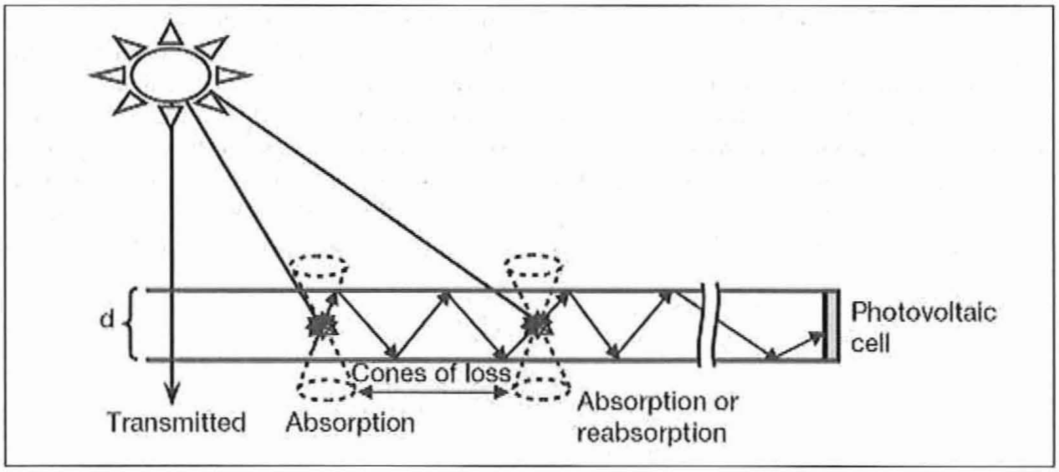


Figure 2 : Schematic representation of Luminescent solar concentrator (LSC)

areas of a building using a stack of pink, green and violet LSCs and clear PMMA light guides. In direct sun of intensity 100,000 lx, prototypes with collector area 1.2m*0.135m deliver 1000 lm of near-white light with a luminous efficacy of 311 lm/W and a light-to-light efficiency of 6%. Surface effects such as excess adhesive and variations in flatness are thought to be causing unnecessary light loss, which can be avoided by careful LSC production. A limitation in the wiring for long distance light transportation has emerged in this LSC system.

The advantages and necessity of FFSC

In building integration, one of the most important features of remote light transportation is the wiring method and the wiring must be as easy as electrical wires. As discussed in earlier section, only optical fibers are competent for this requirement.

However, the light concentrated by Alan, et al's (2004) LSC is transported by polymer sheets instead of optical fibers because the light produced by the LSC is not a pointolite. The polymer sheets have fatal disadvantage in wiring, which therefore makes it impossible for building integration. It is also not energy efficient to further concentrate the sheety light produced by the LSC into a pointolite in order to transport it through optical fibers to a remote place in a building. This problem is expected to be solved in the designed FFSC system.

As a summary for sections above, Figure 3 illustrates the necessities to design FFSC. In Figure 3, there are two groups of solutions able to be practiced in the building sector for energy issues namely: building energy saving and renewable energy using, which are presented in the left branch and the right branch, respectively.

According to the left branch shown in Figure 3, as an approach for energy saving, day lighting has a disadvantage that it may not able to reach many areas such as store room, basement, hallway, and it also brings heat gain with the light (Bouchet & Fontoynont, 1996; Shao et al., 1998). Light pipes were designed to transfer day light to unreached areas. However, the light pipes have their limitation for difficulties in wiring so that day light transportation through optical fibers is considered as the best approach so far. However, the optical fiber needs a pointolite for it to transport.

The FFSC is designed targeting on this requirement.

The right branch in Figure 3 show various solar concentrators that were designed using optical approaches such as mirrors or lens because of the high price for PV cells as a solution to solar energy using. Since they are only sensitive for beam irradiation, they do not function well in cloudy weather and diffuse conditions and a tracker is always needed. Luminescent solar concentrators (LSC) and some static solar concentrators were then designed as a diffuse light solution and a static solution respectively. Static concentrators always come with a disappointing concentration

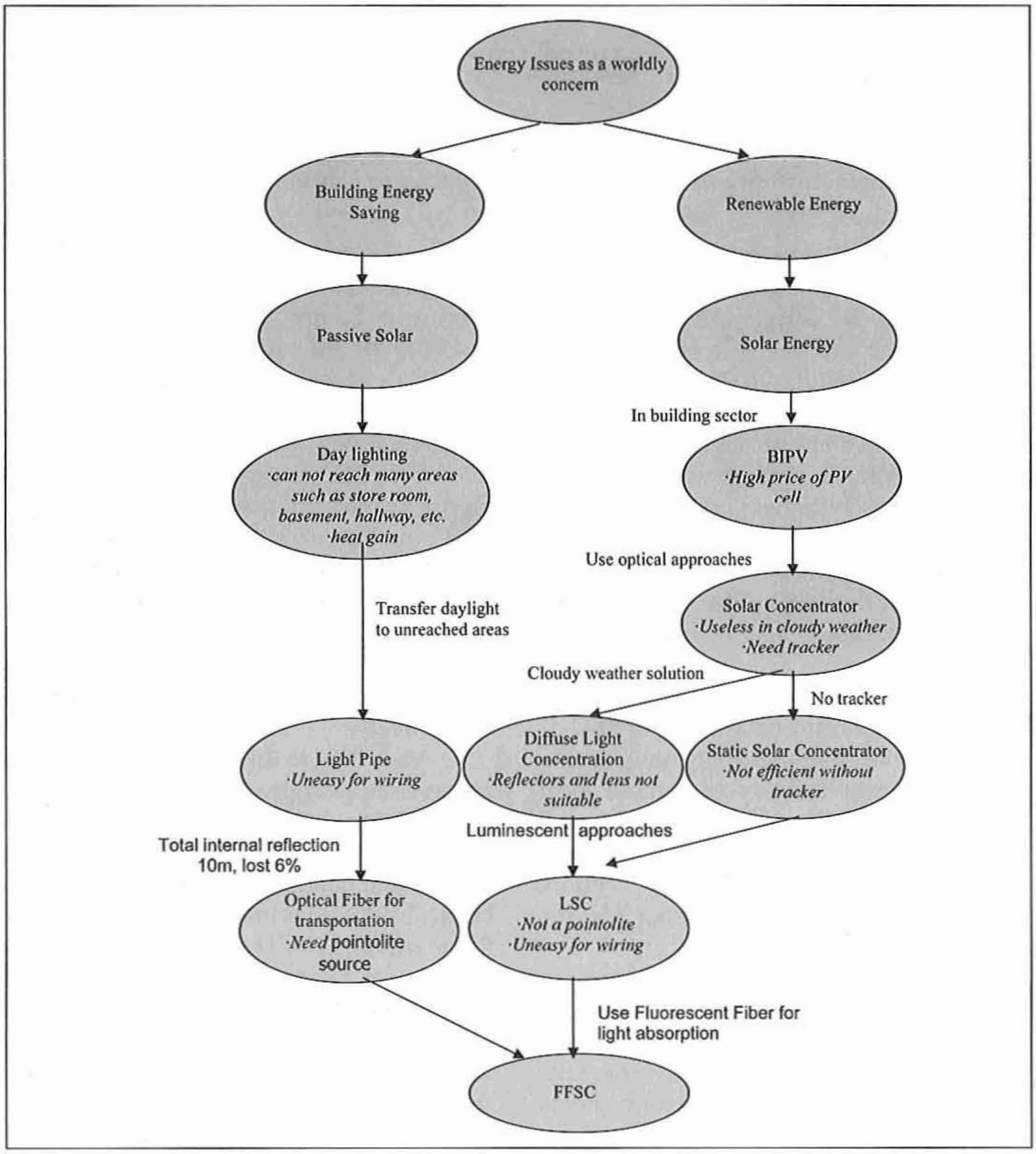


Figure 3 : From energy issue to solar using: the necessity of FFSC (Concept developed by Wang Chen, 2008)

rate without a tracker and the light concentrated by normal LSC could not be transported by optical fibers to a remote place since the light produced by LSC is not a pointolite. The FFSC is expected to solve this problem as well.

Both branches in Figure 3 illustrate that a new solar concentration system is necessary to be designed targeting on the above mentioned problems. Therefore, a system called FFSC is designed in this study and the detailed description for it is presented in the next section.

The design of FFSC

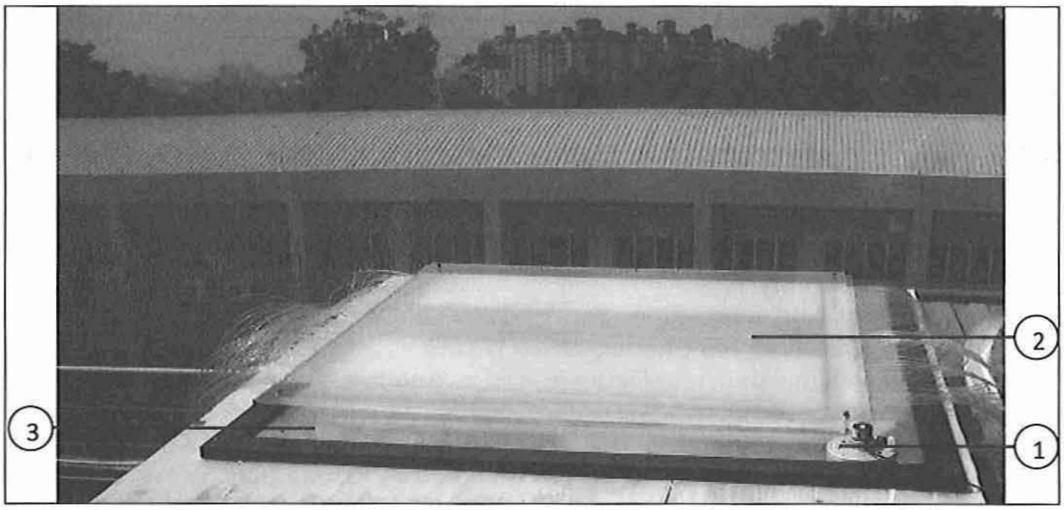
The FFSC consists of totally 150 pieces of 1m long 2mm diameter fluorescent fibers. The material for these fluorescent fibers is acrylic with quantum dots seeded in them. Detailed composition and structure of the quantum dots are proprietary.

The 150 pieces of fluorescent fibers consist of three colors (green, red, and yellow) as shown in Figure 4. There are 50 pieces for each color. The totally 150 pieces of fluorescent fibers are symmetrically embedded in a 1200mm□1200mm polymethyl methacrylate (PMMA) plate with a space of 2mm between each two pieces of fibers.

At both edges of the FFSC plate, each fluorescent fiber is connected with a 10m long, 2mm diameter PMMA clear optical fiber by a aluminum bushing and fixed by a type of UV glue. The light absorbed by the fluorescent fibers is therefore transported by these clear fibers to a remote place for lighting or power producing purpose.

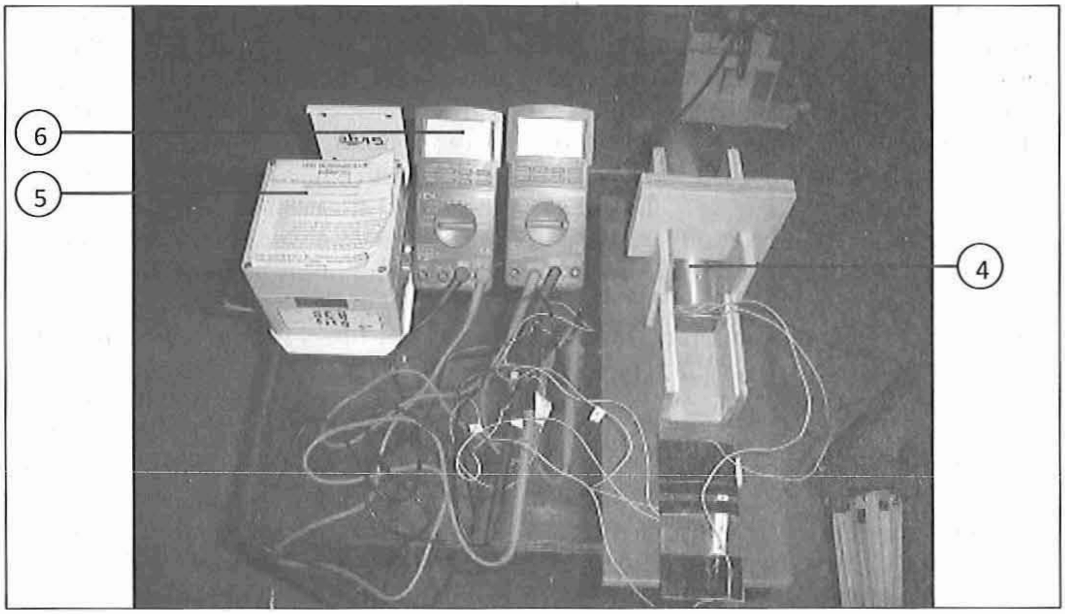
As shown in Figure 4, a 1300m□1300m reflector is installed under the FFSC plate to increase the light absorption. A pyranometer connected with a remote data logger is fixed together with the plate to monitor the real time solar irradiation received by the FFSC.

One reason for using three color fibers is trying to cover a full spectrum band (Alan, et al., 2004). Another reason for using three color fibers is because the transported light coming out of the



① Pyranometer 1
② FFSC plate
③ Mirror

Figure 4 : FFSC installed on the building roof (Concept developed by Wang Chen, 2008)



④ Finishing end
⑤ Data logger
⑥ Multimeters (not used for testing in this report)

Figure 5 : Equipments used for testing

finishing end could considerably mix into white color light by self-scattering for illumination purpose. The mixed white light was proved by naked eye observation and a wavelength testing for the mixed light is under analysis, but the wavelength discussion is not reported here.

The light concentrated by the FFSC is transported by two 30mm diameter clear fiber bundles, which are reasonably easy for wiring in building integration. Each finishing end of the fiber bundles has an only 30mm diameter as shown in Figure 5 marked by serial number ④, which is even smaller than a normal light bulb.

The experimentation: equipments and data collection approaches

The FFSC is mounted on a building roof and the light concentrated is transported by two 10m long clear fiber bundles into a remote windowless dark room. One pyranometer, which is called Pyranometer 1, is installed with the FFSC plate to detect the solar irradiation. The light density coming out of a finishing end is measured by another pyranometer called Pyranometer 2. The values measured by the Pyranometer 1 and Pyranometer 2 are marked as PY1 and PY2 respectively, which are recorded by a remote data logger at an interval of 10 minutes for 24 hours a day. The unit for PY1 and PY2 is W/m2.

Another finishing end is installed upon a Lux sensor at a distance of 10cm. The values read by the Lux sensor are marked as Lx and they are also recorded by the remote data logger with an interval of 10 minutes for 24 hours a day. The unit for Lx is lux.

PY1 and PY2 were recorded from 24 May 2008 to 23 June 2008, all together 31days. Lx was recorded from 24 May

2008 to 12 June 2008, all together 20 days, because the finishing end used for the Lux sensor since 13 June 2008 had been used for other testing purposes which is not presented in this report.

The data recorded from 6:00 to 20:00 every day were selected. Various analysis has been conducted for the FFSC system, namely: light to light efficiency (ηl), lighting effect, Energy to energy efficiency (ηe), Light Efficacy (ηe-l) of the finishing end, and the negative association between light to light efficiency (ηl) and solar radiation (PY1), and so on, which are discussed in the following section.

Results from monitoring

The solar irradiation (PY1) and FFSC output (PY2)

As mentioned in the above section, the light density monitored by Pyranometer 1 that installed on the building roof is defined as PY1, and the light density monitored by Pyranometer 2 that installed with the fiber bundle finishing end is defined as PY2.

The mean values for PY1 and PY2 in these 31 days are 308.65 W/m2 and 17.08 W/m2 respectively. The maximum value for PY1 and PY2 in these 31 days are both at 13:00 on 14 June 2008, which are 1308.31 W/m2 and 64.77 W/m2 respectively.

PY1 and PY2 in one particular day

The hour to hour values of PY1 and PY2 on a particular day 24 May 2008 are presented in Figure 6. The peak values of PY1 and PY2 both appeared at 13:00, which are 1151.76W/m2 and 60.89W/m2 respectively. Both PY1 and PY2 values are negligible before 7:00 and after 19:00 on a typical day.

The linearity between PY1 and PY2

To make it more presentable, the value of 10×PY2 is used here instead of PY2 to compare with the PY1 value since the magnifying coefficient 10 is a constant.

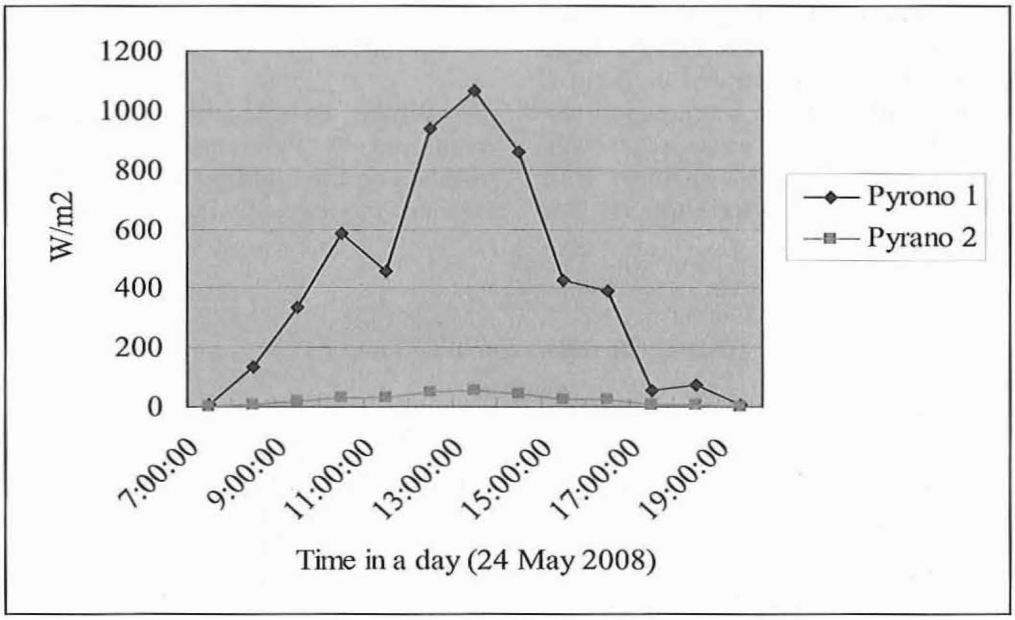


Figure 6 : PY1 and PY2 in a particular day

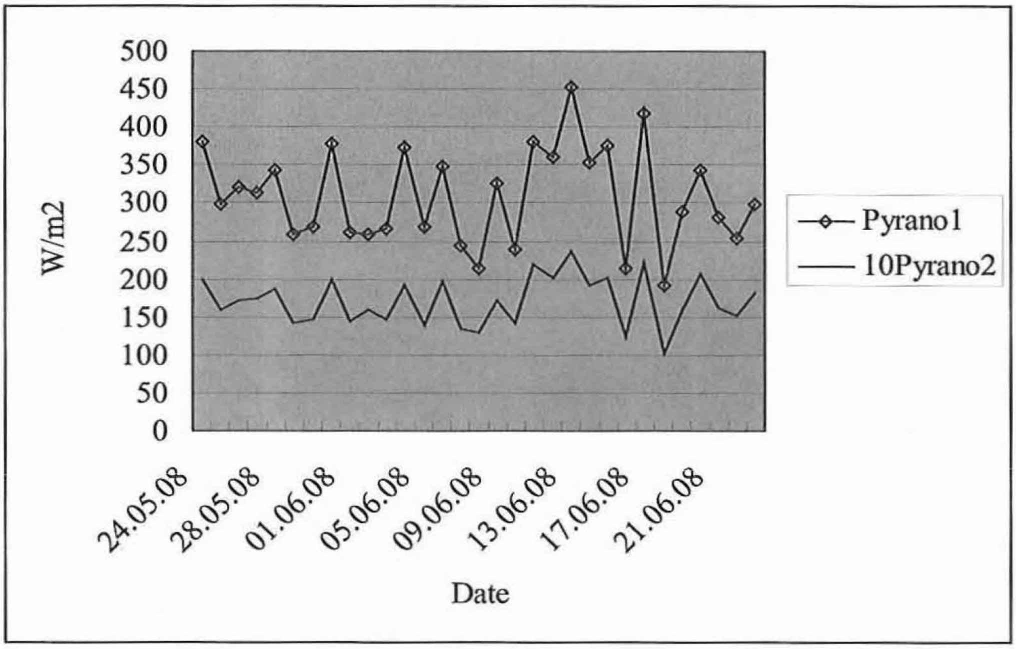


Figure 7 : 31-DAY daily mean value of PY1 and 10×PY2

Figure 7 shows that the PY1 value and 10×PY2 value have very similar curves, from which it may assume that PY1 and PY2 are linear. This is proved by the analysis results as illustrated in the Table 1 and Figure 8. As illustrated in Table 1, the significant value on a regression test between PY1 and PY2 is under a 0.05 level, which indicates that PY2 is linear with the PY1. Figure 8 further supports this finding.

FFSC light to light efficiency (ηl)

System light to light efficiency is defined by the following equation

$$\eta l = PY2/PY1$$

Where PY1 is the light density monitored by Pyranometer 1, the one installed on the building roof, and PY2 is the value monitored by Pyranometer 2 that

Table 1: The regression of PY1 and PY2

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	291.779	1	291.779	458.973	.000[a]
	Residual	18.436	29	.636		
	Total	310.215	30			

a. Predictors: (Constant), Pyranometer1

b. Dependent Variable: Pyranometer2

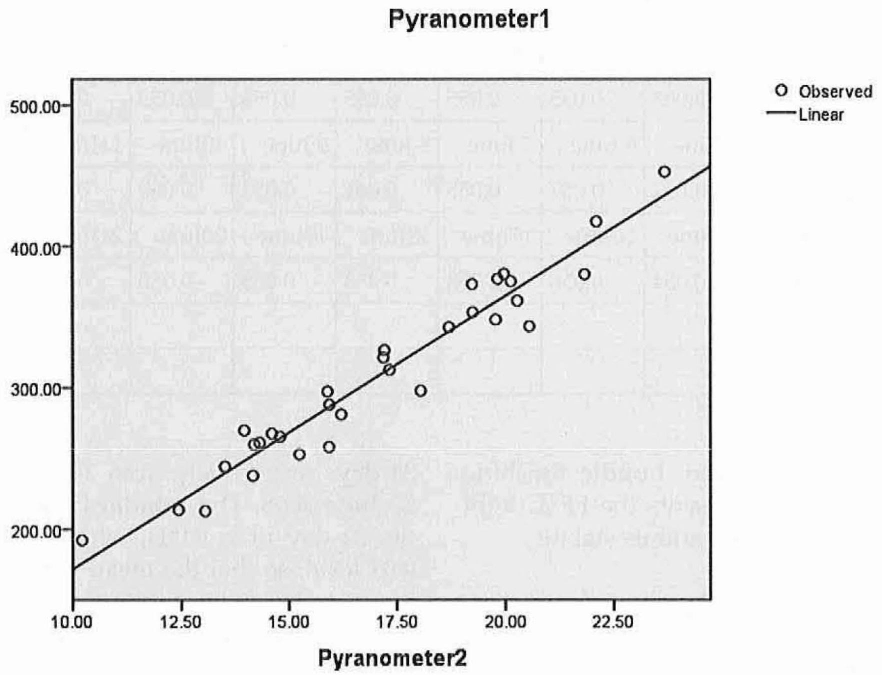


Figure 8 : The linear test of PY1 and PY2

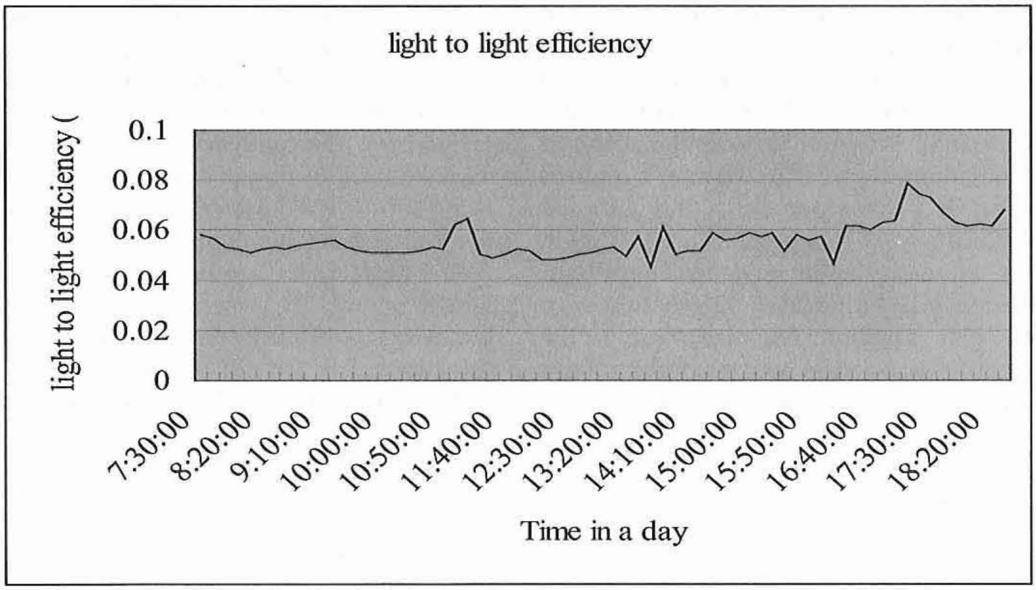


Figure 9 : Daily curve of light to light efficiency (ηl) on 24 May 2008

Table 2: 31-DAY daily mean value of ηl

24May	25May	26May	27May	28May	29May	30May	31May	1 June	2 June
0.052	0.053	0.053	0.055	0.055	0.055	0.055	0.053	0.055	0.062
3 June	4 June	5 June	6 June	7 June	8 June	9 June	10June	11June	12June
0.056	0.052	0.052	0.057	0.055	0.061	0.053	0.060	0.057	0.056
13June	14June	15June	16June	17June	18June	19June	20June	21June	22June
0.052	0.054	0.054	0.058	0.053	0.053	0.055	0.060	0.058	0.060
23June									
0.061									

installed with the fiber bundle finishing end. This section presents the FFSC light to light efficiency (ηl) and its stability.

ηl in one particular day

In one typical day on 24 May 2008, the maximum value of ηl is 0.079 (17:20) and the minimum value is 0.046 (13:40). The mean value of ηl on that day is 0.052. The standard deviation is 0.0095 which is under a 0.01 level, so that the mean value of 0.052 is significantly representative for that day. Figure 9 presents the curve of the light to light efficiency ηl from 7:30 to 18:30 on 24 May 2008.

Notice that the maximum value of ηl 0.079 appears at 17:20 when the solar irradiation is much weaker than that at 13:40 when the solar irradiation supposes to be at peak value on a day but the minimum ηl 0.046 appears. An assumption has therefore risen that the light-light efficiency has a negative association with the solar radiation. The discussion on the negative association between light to light efficiency (ηl) and solar radiation (PY1) will be presented in later section.

ηl in a 31-day monitoring

The 31-day mean value of the ηl is 0.056. Table 2 presents the daily mean value of light to light efficiency ηl on these 31 days respectively from 24 May 2008 to 23 June 2008. The standard deviation for the 31-day ηl is 0.003, which is under a 0.01 level, so that the mean value of 0.056 is concluded to be significantly stable and representative for these 31 days.

System lighting effect

Calculate luminous flux (ϕ) from lux (Lx)

As described by Schiler (1992), the lux takes into account the area over which the luminous flux is spread. If a light source emits one candela of luminous intensity uniformly across a solid angle of one steradian, its total luminous flux emitted into that angle is one lumen. Alternatively, an isotropic one-candela light source emits a total luminous flux of exactly 4π lumens. If the source were partially covered by an ideal absorbing hemisphere, that system would radiate half as much luminous flux, which is only 2π lumens. The luminous intensity would still be one candela in those directions that are not obscured (Schilar, 1992). The luminous flux (ϕ) is therefore calculated in the following equation:

$$\phi = Lx \times Shs$$

Where the Lx is the values detected by the Lux sensor and the Shs is the half sphere's surface area radiated by a light

Table 3: Converting lumen of Typical Incandescent lamps to FFSC 0.1m lux

Watt of Lamps	lm	Convert to FFSC 0.1m lux
5W	25	397
15W	110	1746
25W	200	3175

source. The distance between the finishing end and the Lux sensor is 0.1m. So that the radiated half sphere's surface area is calculated as below:

$Shs=2\pi Rl\times Rl=2\times 3.14\times 0.1\times 0.1=0.063m^2$

So that the luminous flux (ϕ) from one finishing end is

$\phi=Lx\times Shs=0.063Lx$

Comparison of Light Effect between FFSC and Typical Incandescent Lamps

The luminous flux of typical incandescent lamps (Egan, 1983) is illustrated in the first two columns in Table 3. By using the equation from the preceding section, the lumens of their relative lamps are converted into the lux value produced by the FFSC from a 0.1m distance, which is shown in the last column of Table 3.

As shown in Figure 10, the light effect provide by one of the FFSC finishing end is above 400 lux (equal to a 5W incandescent lamp) from 8:30 to 16:30, which almost covers the whole office hours on a day.

The monitored maximum Lx provided by one FFSC finishing end in these 20 days is 1811 lux, which is at 13:00 31st of May 2008, when it is even brighter than a 15W incandescent lamp according to Table 3.

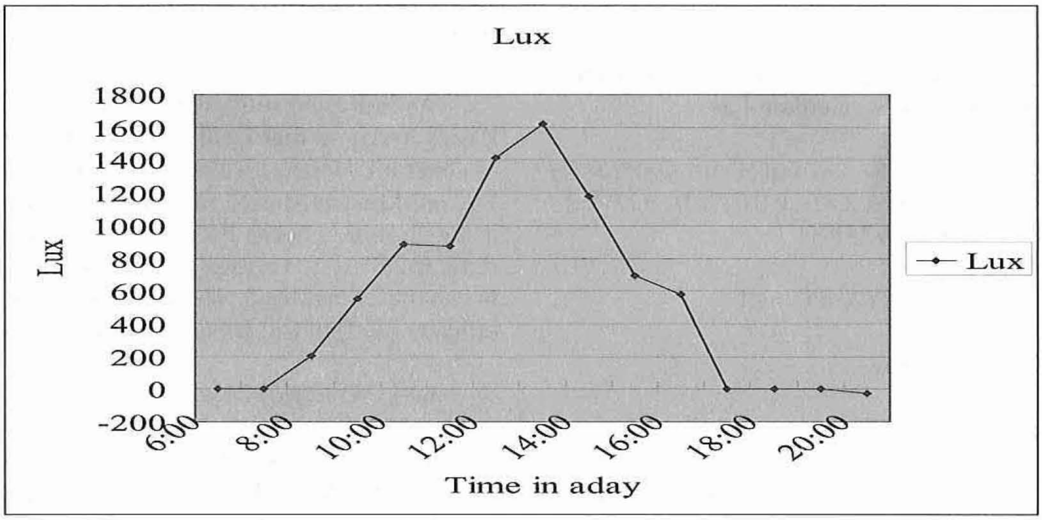


Figure 10 : Lux values in a particular day 24 May 2008

Energy to energy efficiency (ηe)

The energy to energy efficiency ηe is defined as the ratio of total energy output yielding from both finishing ends divided by the solar energy irradiated on the fluorescent fibers, which is illustrated by the following equation:

$$\eta e = Pout/Psun$$

The effective area of the FFSC plate is

$$S0=\Phi\times L\times n=0.002\times 1\times 150=0.3m^2$$

Where Φ and L are the diameter and the length of the fluorescent fibers respectively. The variable n is the number of piece for fluorescent fibers, which is 150.

The effective area of one finishing end is

$$Sf=\pi\times Rf\times Rf=3.14\times 0.015\times 0.015=0.0007\ m^2$$

Where Rf is the radius of the finishing end.

Therefore, the energy to energy efficiency ηe is calculated as

$$\eta e=Pout/Psun=2\times PY2\times Sf/(PY1\times S0)=(2\times 0.0007/0.3)PY2/PY1=0.0047PY2/PY1$$

Where $PY2/PY1=\eta l$,

Therefore,

$$\eta e=0.0047\eta l$$

The average light to light efficiency in these 31 days is

$$\eta l\text{-}avg=0.056$$

So that the average light to energy efficiency in these 31 days is

$$\eta e\text{-}avg=0.0047\times\eta l\text{-}avg=0.0047\times 0.056=0.000263$$

The mean value of energy to energy efficiency as low as 0.000263 reveals that FFSC currently is not yet suitable to replace the conventional PV cell for power producing.

Light Efficacy (ηe-l) of the finishing end

The light efficacy (ηe-l) for one of the finishing end as a light source is defined as below

$$\eta e\text{-}l=\phi/0.5Pout$$

Where ϕ is the luminous flux irradiated by a finishing end, and the 0.5Pout is the solar energy reaching one finishing end.

Therefore, the light efficacy (ηe-l) is calculated as

$$\eta e\text{-}l=\phi/0.5Pout=0.063Lx/(PY2\times Sf)=0.063Lx/(PY2\times 0.0007)=90Lx/PY2$$

As indicated in Figure 11, the Lx and PY2 is linear so that Lx/PY2 is considered as constant. Hence, an average ratio of Lx/PY2 could be used in the above equation as a constant in general. From the monitored data, the 31-day average value of Lx/PY2 is calculated as 27.63. Therefore, the light efficacy (ηe-l) of the FFSC finishing end is

$$\eta e\text{-}l=90\times 27.63=2486.7lm/W$$

The value of luminous efficacy by far exceeds that of natural daylight, which generally falls within the range 100lm/W to 130lm/W (Lam & Li, 1996). When compared to standard artificial light sources such as incandescent light bulbs

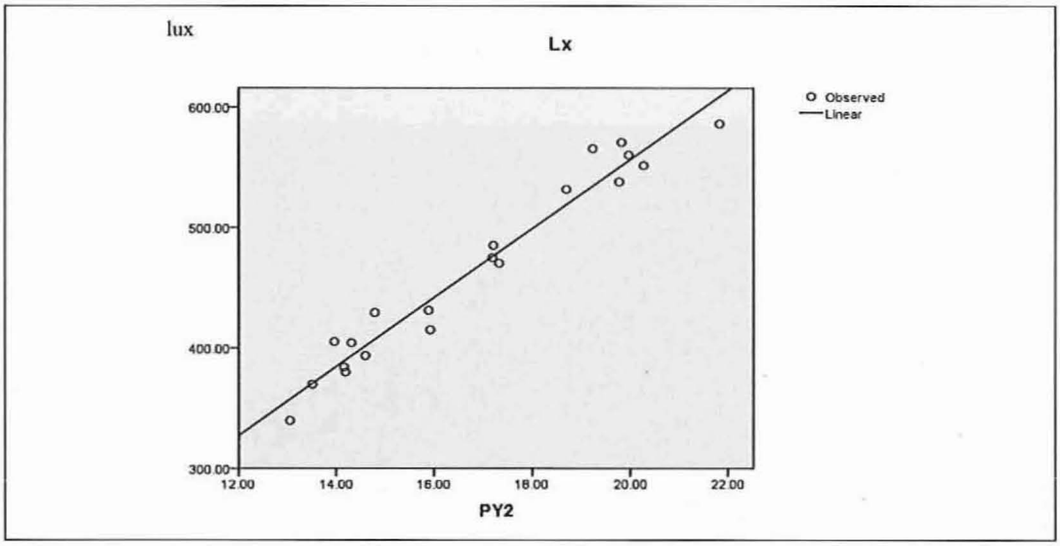


Figure 11 The linear test of Lx and PY2

(16–40 lm/W) and fluorescent lamps (50–80 lm/W), it is clear that the output of the FFSC finishing end is remarkably more energy efficient.

The negative association between light to light efficiency (ηl) and solar radiation (PY1)

Base on the monitored 1696 sets of effective data in the 31 days from 6:00 to 20:00 with an interval of 10 minutes, the system light to light efficiency (ηl) presents a negative association with the solar radiation PY1. As shown in Figure 12, all these 1696 sets of data are symmetrically sorted by the light to light efficiency (ηl) in an ascending order while the corresponding values of the solar radiation (PY1) present a descending trend.

It is proved in Table 4 that there is a statistically significant ($p < .001$) negative correlation coefficient (-0.646) for the association between light-light efficiency and solar irradiation, indicating that the linear relationship between these two variables is that that the values of one variable decrease as the other increases. The negative association between light to light efficiency (ηl) and solar radiation (PY1) is therefore concluded.

Conclusions and recommendations for future research

A 1200mm×1200mm solar concentrator consisting of 150 pieces of three-color 1m long 2mm diameter fluorescent fibers (FFSC) has been designed and mounted on a university building roof and the concentrated light is transported to a remote dark room through 10m long 2mm diameter clear optical fibers. Outdoor testing for remote indoor day lighting and power producing evaluation has been conducted from 24 May2008 to 23 June2008. The negative association between light to light efficiency (ηl) and solar irradiation is detected and analyzed for the first time. The low energy to energy efficiency value of 0.000263 proves that FFSC is not practical yet to replace the conventional BIPV approach for power producing. However, the reasonable light to light efficiency with a mean value of 0.056, the acceptable lighting effect up to

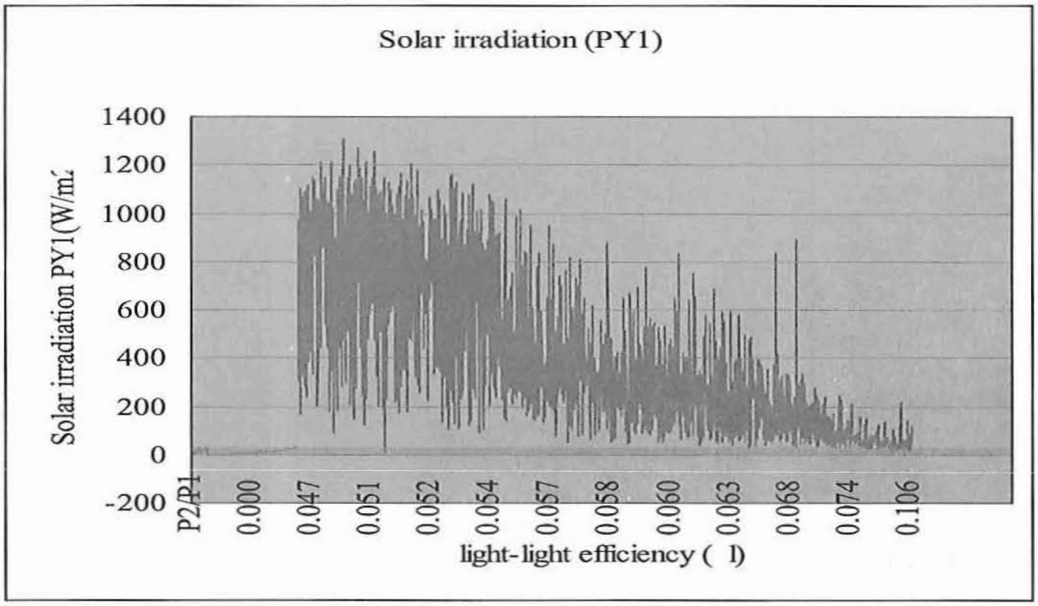


Figure 12: Negative association between ηl and PY1

Table 4: The correlation of ηl and PY1

Correlations

		light-light efficiency	solar irradiation
light-light efficiency	Pearson Correlation	1.000	-.646**
	Sig. (2-tailed)		.000
	N	1696.000	1696
solar irradiation	Pearson Correlation	-.646**	1.000
	Sig. (2-tailed)	.000	
	N	1696	1696.000

**. Correlation is significant at the 0.01 level (2-tailed).

110 lumens, and the high light efficacy 2486.7lm/W reveal FFSC a pleasant potential in remote indoor day lighting for large amount application in building integration. Moreover, comparing to the conventional artificial lighting powered by PV cells which is converting light to electricity and then back to light again which lost a lot of efficiency in multi converting, the idea of FFSC as a shortcut light-light conversion is considered to have a more efficient future. For future study, wavelength testing and cost evaluations are recommended for commercializing purpose.

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