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# A FLUORESCENT FIBRE SOLAR CONCENTRATOR (FFSC) DESIGN AND TRIAL RUN

WANG CHEN

FACULTY OF BUILT ENVIRONMENT
UNIVERSITY OF MALAYA
KUALA LUMPUR

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WANG CHEN

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Registration/Matric No: BHA060006

Name of Degree: PHD in Built Environment

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Designation: Associate Professor

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# ABSTRACT

This thesis presents the author's research work on a new concept development in the field of solar energy application for building illumination during his doctoral journey in Malaysia. As a considerable solution to the energy issues, solar energy is made widely available for daylighting and direct production of electricity. Various devices have been developed to collect, concentrate, transport, store, and convert solar irradiation, such as the light pipe, optical fibers, optical solar concentrators, and luminescent solar concentrators (LSC). Many limitations such as the strict dependence on beam irradiation and difficulties for wiring remain in these daylighting devices. This thesis introduces a new concept developed by the author and a new device designed and fabricated based on the concept in mitigating those limitations. The fabricated new device named "Fluorescent Fiber Solar Concentrator" (FFSC) is a 1200mm×1200mm solar concentrator consisting of 150 pieces of three-color 1m long fluorescent fibers with the diameter of 2mm. FFSC is mounted on the roof of a university building, and the concentrated light is transported to a remote dark room through 10m long 2mm diameter clear optical fibers. Outdoor testing for remote indoor daylighting and power production evaluation have been conducted for the fabricated new device FFSC. A 6-month monitored data from 24th May 2008 to 23rd Nov 2008 was analyzed. The radiation-to-radiation efficiency with a mean value of 0.057 and the lighting effect up to 114.1 lumens reveal FFSC a potential in remote indoor daylighting for the application in building integration. The wavelength test and the CIE color analysis present a satisfactory match in color between the FFSC light output and the natural light. Since the sun light is free, even though the luminous efficacy as 0.643lm/W is lower than the normal electrical light sources, FFSC does not consume any electricity when operating.

The light-to-light efficiency falls within the range 0.49% to 0.64% and it is expected to be raised by increasing the diameter of the fluorescent fibers embedded. FFSC systems could probably be applied for the illumination in underground areas of buildings or constructions such as the car park levels in shopping complexes, convention centers, and some office buildings. This system could also be applied to illuminate the inner areas in a building such as meeting rooms and corridors. Since electro circuits are not needed in the FFSC system, potentially FFSC systems are quite suitable for subaqueous and extremely moist operation environments when a durative illumination is needed during the daytime. Further, FFSC systems do not have any risk of fire caused by the electrical current in inflammable gas conditions.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| BIPV | Building Integrated Photovoltaic |
| CIE | Commission Internationale de l'Eclairage, the International Commission on Color |
| CTs | Current Transducers |
| EE | Energy Efficiency |
| EMI | Electromagnetic Interference |
| FFSC | Fluorescent Fiber Solar Concentrator |
| IR | Infra-red |
| LSC | Luminescent Solar Concentrator |
| OTDR | Optical Time Domain Reflectometry |
| PMMA | Poly Methyl Methacrylate |
| POF | Plastic Optical Fiber |
| QDs | Quantum Dots |
| LQE | Luminescence Quantum Efficiency |
| TDGS | Tubular Daylight Guidance Systems |
| UV | Ultra-violet |
| VT | Visible Transmittance |

# LIST OF SYMBOLS

(Symbols only used in this thesis)

| | |
|---|---|
| ε | unit for strain resolution |
| PY1 | light radiation monitored by Pyranometer 1 (Watt/m2) |
| PY2 | light radiation monitored by Pyranometer 2 (Watt/m2) |
| ηr | radiation-to-radiation efficiency of FFSC |
| ηl | light-to-light efficiency of FFSC |
| K | luminous efficacy of FFSC (lumen/Watt) |
| K0 | luminous efficacy of the sunlight (lumen/Watt) |
| ηr-avg | average radiation-to-radiation efficiency of FFSC |
| ηe | energy-to-energy efficiency of FFSC |
| ηe-avg | average energy-to-energy efficiency of FFSC |
| *F* | luminous flux yielding from a FFSC finishing end (lumen) |
| *F0* | luminous flux dropping on fluorescent fibers (lumen) |
| *Ev* | illuminance (LUX) |
| Shs | the half sphere's surface area radiated by a light source (m2) |
| Pout | energy output yielding from both finishing ends (Watt) |
| Psun | solar energy irradiated on the fluorescent fibers (Watt) |
| S0 | effective area of the FFSC plate (m2) |
| D | diameter of fluorescent fibers (m) |
| L | length of the fluorescent fibers (m) |
| n | number of piece for fluorescent fibers |
| Rf | radius of the finishing end (m) |
| λ | wave length of light (nm) |

# GLOSSARY

| | |
|---|---|
| CdSe | Cadmium Selenide (CdSe) is a solid, binary compound of cadmium and selenium. Common names for this compound are cadmium (II) selenide, cadmium selenide, and cadmoselite (a very rare mineral). Cadmium selenide is a semiconducting material, but has yet to find many applications in manufacturing. This material is transparent to infra-red (IR) light, and has seen limited use in windows for instruments utilizing IR light. Much current research on cadmium selenide has focused on nanoparticles. Researchers are concentrating on developing controlled syntheses of CdSe nano-particles. In addition to synthesis, scientists are working to understand the properties of cadmium selenide, as well as apply these materials in useful ways (Wikipedia, 2009a). |
| CdS | Cadmium Sulfide (CdS) is a chemical compound with the formula CdS. Cadmium sulfide is yellow in colour and is a semiconductor. It exists in nature as two different minerals, hexagonal greenockite and cubic hawleyite. Cadmium sulfide is a direct band gap semiconductor (gap 2.42 eV) and has many applications for example in light detectors. It forms thermally stable pigments and with the addition of e.g. CdTe, HgS colors ranging from deep red to yellow are formed (Wikipedia, 2009a). |
| GaAs | Gallium arsenide (GaAs) is a compound of two elements, gallium and arsenic. It is an important semiconductor and is used to make devices such as microwave frequency integrated circuits, infrared light-emitting diodes, laser diodes and solar cells (Wikipedia, 2009a). |
| Isotropy | Isotropy is uniformity in all directions. Precise definitions depend on the subject area. The word is made up from Greek ISO (equal) and TROPOS (direction). Exceptions, or inequalities, are frequently indicated by the prefix an, hence anisotropy. Anisotropy is also used to describe situations where properties vary systematically, dependent on direction. Isotropic radiation has the same intensity regardless of the direction of measurement, and an isotropic field exerts the same action regardless of how the test particle is oriented (Wikipedia, 2009a). |
| Pointolite | Point light source. A point light source is a single identifiable localized source of light. A point source has negligible extent, distinguishing it from other source geometries. Sources are called point sources because in mathematical modeling, these sources can usually be approximated as a mathematical point to simplify analysis. The actual source need not be physically small, if its size is negligible relative to other length scales in the problem. For example, in astronomy stars are routinely treated as point sources, even though they are in actuality much larger than the Earth (Wikipedia, 2009a). |
| Quantum yield | The quantum yield of a radiation-induced process is the number of times that a defined event occurs per photon absorbed by the system. Thus, the quantum yield is a measure of the efficiency with which absorbed light |

| | |
|---|---|
| | produces some effect. Quantum yield can be defined by the equation: $Q=$ photons emitted/photons absorbed. Quantum yield is essentially the emission efficiency of a given fluorochrome. For example, in a chemical photodegradation process, when a molecule falls apart after absorbing a light quantum, the quantum yield is the number of destroyed molecules divided by the number of photons absorbed by the system. Since not all photons are absorbed productively, the typical quantum yield will be less than 1 (Wikipedia, 2009a). |
| Sagnac interferometer | The Sagnac effect (also called Sagnac interference), named after French physicist Georges Sagnac, is a phenomenon encountered in interferometry that is elicited by rotation. The Sagnac effect manifests itself in a setup called ring interferometry. A beam of light is split and the two beams are made to follow a trajectory in opposite directions. To act as a ring the trajectory must enclose an area. On return to the point of entry the light is allowed to exit the apparatus in such a way that an interference pattern is obtained. The position of the interference fringes is dependent on the angular velocity of the setup. This arrangement is also called a Sagnac interferometer (Wikipedia, 2009a). |
| Snell's law | In optics and physics, Snell's law (also known as Descartes' law or the law of refraction), is a formula used to describe the relationship between the angles of incidence and refraction, when referring to light or other waves, passing through a boundary between two different isotropic media, such as water and glass. The law says that the ratio of the sines of the angles of incidence and of refraction is a constant that depends on the media (Wikipedia, 2009a). |
| Strain resolution | Strain is commonly specified in "micro inches per inch" or "micro-strain" which is in "microns per meter". Or course one could specify the length change in percentage if one preferred. The "resolution" to which it can make a measurement is limited by the noise superimposed on the signal. The two basic types of noise are shot noise, which is caused current flow flowing a resistance, and thermal noise, which is a function of the temperature of the input stage of the instrument amplifier, and the bandwidth of the amplifier (Wikipedia, 2009a). |

# Chapter 1

# Introduction

This thesis presents a research work on the solar energy application attempts conducted in Malaysia, where a new concept was developed by the author and a new device named "Fluorescent Fiber Solar Concentrator" (FFSC) was fabricated accordingly. The new device was fabricated, installed and instrumented, and it was monitored for a 6 month period. Testing results reveal FFSC a potential in remote indoor daylighting for the application in building integration.

## 1.1 Background of study

In the 21st century, the greatest challenge facing the world is the need for workable energy options (Robert & Ernest, 2006). As stated by Robert & Ernest (2006) in one of the Massachusetts Institute of Technology (MIT) energy research council report, researchers must work diligently to reach the need for the new global supplies of the affordable and sustainable energy to power the world. The acuteness of the challenge at this point in time results from the "perfect storm" of supply and demand, security, and environmental concerns, namely: a) a projected doubling of energy use and tripling of electricity demand within a half century, calling for a substantial increase in fossil fuel supplies or dramatic transformation of the fossil-fuel-based energy infrastructure; b) geological and geopolitical realities concerning the availability of oil and, to some extent, natural gas, specifically the concentration of resources and political instability in the Middle East, underlie major security concerns; and c) greenhouse gas emissions from fossil fuel combustion are increasingly at the center of decisions about how the global energy system evolves, one that carries on in the "business as usual" overwhelming dependence on fossil fuels or one that introduces technologies and policies that greatly improve efficiency, dramatically expand use of less carbon-intensive or "carbon free" energy, and implement large scale carbon dioxide capture and sequestration (Robert & Ernest, 2006).

In most of buildings, the energy consumption for lighting could be reduced by 30% to 50% through the application of renewable energy and better lighting design (EPA, 1999). More than 50% of the existing commercial buildings still use low efficient lighting systems. Efficient lighting designs are used in only a small minority of spaces, and the control systems that maximize the use of daylight are even less common (EPA, 1999).

As a considerable solution to the energy issues, solar energy is made widely available for daylighting and direct production of electricity. Various devices have been developed to collect, concentrate, transport, store, and convert solar irradiation, such as the light pipe, optical fibers, optical solar concentrators, and luminescent solar concentrators (LSC), and so on (Littlefair, 1996; Shao, Riffat, Yohannes, & Elmualim, 1998; Cariou, Martin & Dugas, 1982; Enedir & John, 2006; Ries, Zaibel, Dagan, & Karni, 1995; Beckman, Schlegel, Klein, Wood, & Muhs, 2003; Earp, Geoff, Jim, &

Paul, 2004). However, there are many limitations in such devices, such as the strict dependence on the beam irradiation and the difficulties for wiring (Enedir & John, 2006; Cariou et al., 1982).

### 1.2 Problem statement

Daylight has a disadvantage that it may not able to reach many areas such as storerooms, basements, and corridors. It also brings heat gain with the light (Bouchet & Fontoynont, 1996; Shao et al., 1998). Light pipes were designed to transport the daylight to the deeper parts in buildings. However, the light pipes have their difficulties for wiring so that daylight transportation through optical fibers is considered as the best approach so far (Enedir & John, 2006; Cariou et al., 1982). In building integration, one of the most important features of the remote light transportation is the wiring method, and the wiring method is expected to be as simple as that of electrical wires (Kaino, 1992; Nihei, Ishigure, Tanio, & Koike, 1997; Enedir & John, 2006; Cariou et al., 1982). Only optical fibers are suitable for this requirement. However, the optical fiber needs a pointolite for it to transport (Kaino, 1992; Nihei, et al., 1997; Cariou et al., 1982). The proposed design of FFSC is expected to solve this problem.

Solar concentrators have been designed using optical approaches such as using mirrors and/or lens because of the high price for PV cells. Since they are only sensitive for the beam irradiation, they function poorly in the cloudy weather and the diffuse light conditions, and a tracker is always needed (Compagnon, Scartezzini, & Paule, 1993; Page, Kaempf, & Scatrezzini, 2003). Luminescent solar concentrators (LSC) and some static solar concentrators were then designed as the diffuse light solution and the static solution respectively (Weber & Lambe, 1976; Goetzberger & Greubel, 1977; Rapp & Boling, 1978). Static concentrators always come with a poor concentration rate without a tracker, and the light concentrated by normal LSCs could not be transported by optical fibers to a remote place since the light produced by an LSC is not a pointolite (Compagnon, et al., 1993; Page, et al., 2003; Beckman et al., 2003; Kandilli, Ulgen, & Hepbasli, 2007). The proposed design of FFSC is expected to solve this problem as well.

A more detailed discussion on the working principles and the limitations for the above mentioned kinds of devices as well as the necessities of this study are provided in Chapters 2 and 4. A fluorescent fiber solar concentrator (FFSC) as an alternative solution in mitigating the limitations of present devices is designed by the author for remote indoor daylighting purposes.

## 1.3 Objectives and methodology

Three main objectives have been developed for this research, namely:

a) to identify the working principles and to extract the limitations of the present daylighting related devices, and

b) to develop a new concept to avoid or to mitigate the limitations of the present daylighting related devices and to fabricate a device based on the new concept, and

c) to assess the performance of the fabricated new device for remote indoor daylighting purposes through its trial run.

This research is a combination of the quantitative research and the qualitative research as discussed in Chapter 3. The first objective is achieved through literature reviews as presented in Chapter 2 and through the determination of the need for FFSC as presented in the first part of Chapter 4; the second objective is fulfilled through the concept development and the fabrication process as a qualitative process as described in Chapter 4; the last objective is achieved through the 6-month experimentations as a quantitative process as discussed in Chapters 5, 6, and 7. A conclusion of these objectives' achievements is summarized in Chapter 8. Chapter 8 also provides some potential applications of FFSC and the recommendations for future research.

### 1.4 Scope of research

In this study, only fluorescent fibers with the diameter of 2mm are embedded in the FFSC plate. This is due to the limitations in the availability of the fluorescent fiber market. There is no fluorescent fiber with larger diameters available with the supplier at that time. Since the reduction of the cross sectional area of the luminescent plate could increase the photon loss according to Richards (2006), Reisfeld (2001), Batchelder, Zewail, & Cole (1979), and Hammam, El-Mansy, El-Bashir, & El-Shaarawy (2007), if fluorescent fibers with a larger diameter could be embedded in FFSC, the performance parameters of FFSC such as the luminous efficacy and the light-to-light efficiency could be increased. This is recommended for future study.

Experimentations were conducted in a specially prepared dark and windowless storeroom in one of the University buildings. The building is located in Kuala Lumpur, Malaysia, which locates at latitude 3.7° North and longitude 101.33° East in the tropical region (Chia, Hamdan, & Dilshan, 2006). Malaysia has a yearly mean temperature of 26°C to 27°C throughout the year (Sabarinah, 2006). The findings would vary if the device is placed in a different regional or climatic condition, for example somewhere in the temperate zone or in the rigid zone. The radiation of sunshine, the rainfall, and the solar altitude in the temperate region or in the rigid region are different to that in the tropical region, so that the monitored data may vary accordingly. A critical review of the experimental limitations is presented in the latter part of Chapter 5.

## 1.5 Structure of the thesis

There are totally eight chapters in the thesis. Chapter 1 provides a brief introduction to the thesis, and Chapter 2 introduces the daylighting related devices as well as their principles of work, advantages and disadvantages. The common applications of fluorescent fibers have also been reviewed in Chapter 2. Chapter 3 discusses the research methodology. In the first part of Chapter 4, the author explains the needs for developing the new concept. A detailed description on the new concept development and the design of the new device named "fluorescent fiber solar concentrator" (FFSC) is provided in the latter part of Chapter 4. Chapter 5 discusses the approaches for data collection and data analysis as well as the experimentation procedures and instrumentation. Raw data restructuring and interpretation processes are explained in Chapter 6. Chapter 7 discussed the analysis results for the FFSC 6-month trial run. Finally, conclusions are drawn in Chapter 8. Some potential applications for FFSC system and the recommendations for future study are also presented in Chapter 8.

# Chapter 2

# Review of Daylighting Related Devices

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 (Mills & Orlando 2002). 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, daylighting, and direct production of electricity (Muhs, 2000; Reisfeld & Jorgensen, 1982).

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, Littlefair, Cooper, & McKennan, 1988; Lam & Chan,1995). The recent interest in energy efficiency and sustainability has led to the implementation of design strategies in buildings aiming at the achievement of the optimal utilization of daylight with minimum energy consumption for lighting and cooling (Hasdemir, 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 irradiation, 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 to substantially reduce energy costs.

## 2.1 Daylight for illumination

Lighting has a profound effect on the lives of people. It facilitates vision, which is the most important source of information on the world, and it affects the basic biological functioning through its effect on human "body clocks" as stated by Webb (2006). Electric lighting is one of the world's biggest end uses of electricity (Mills & Orlando, 2002). In developed nations, the electricity use for lighting ranges from 5% to 15% of total electrical energy use (Mills & Orlando, 2002). Because the energy for artificial lighting is often supplied by fossil fuel generation, it results in the large scale release of greenhouse gases (GHGs) according to Mills & Orlando (2002). Further, lighting is a major contributor to the peak demand for electrical power, which is often met by the the high-GHG generators.

Sunlight is the universal and free sources of renewable energy available throughout the earth. The survival of life and health as well as the conditions of environmental comfort and prosperity are dependent on their effective utilization of sunlight (Muhs, 2000). People can benefit directly from sunlight through active or passive daylighting systems besides the electrical generation and thermal gain from the sunlight. In an energy-efficient building design, it is always proper to reduce the energy consumption for artificial lighting (Muhs, 2000).

Solar energy utilization and specifically making use of the daylight in the buildings can be a very promising choice among the renewable energy options. Daylight is a kind of light source that most closely matches human visual response so that its quality is as high as to be the best for color rendering (Hasdemir, 1995). The luminous efficacy of sunlight is around 110 lm/W, while the luminous efficacy of fluorescent lamps and incandescent lamps are around 75 lm/W and 20 lm/W, respectively. Further, daylighting generates only 20% to 50% the heating that equivalent electric lighting does, significantly reducing the building cooling load (Hasdemir, 1995). A reduction of 65% of the total lighting energy consumption is achieved by active and passive systems that use daylight and control component (Hasdemir, 1995).

Electric lighting and daylight are compatible and complementary and should be used to bring out the best in the interior environment. Electric lighting can account for 25–40% of a commercial building's energy requirements so that the combined savings from reduced lighting and cooling loads can be substantial (Franzetti, Fraisse, & Achard, 2004). Franzetti et al. (2004) reports that energy saving could be as much as 52% along the window walls. The amount of daylight penetrating a building is mainly through window openings which provide the dual function not only of admitting light for indoor environment with a more attractive and pleasing atmosphere, but also allowing people to maintain visual contact with the outside world. People desire good natural lighting in their living environments (Chel, Tiwari, & Chandra, 2009).

Daylighting is an important issue in modern architecture because it affects the functional arrangement of spaces, visual and thermal comfort of occupants, structure, and energy use in building (Chel, Tiwari, & Chandra, 2009). Danny, Chris, & Joseph (2005) states that illumination levels on a bright sunlight may vary from 50,000 LUX to 100,000 LUX. According to Unver, Ozturk, Adiguzel, & Celik (2003), the first step of designing a building to utilize daylight for illuminating its interior is to acquire information on the amount of daylight available. However, the basic daylight illuminance data are not always readily obtainable in many regions of the world (Unver, et al., 2003).

Daylight has a significant positive impact on the people because it provides a sense of cheerfulness and brightness (Li & Lam, 2001). People spending the day in non-daylit buildings may therefore be in "biological darkness," causing reduced performance (Leslie, 2003). Accoring to Andre (2002), the most powerful impact of daylighting is on the building's occupants even though the potential for reducing energy costs and environmental emissions is substantial. However, the successful integration of such strategies requires data regarding daylight availability and illumination levels for every region in the world.

As reported by Aries & Newsham (2008), lighting has often been the target of energy efficiency initiatives because of its high-energy burden, and one of such initiative is daylight saving time. The principal reason for the application of daylight saving time was to shift human activity patterns to make better use of daylight, and thus reduce the amount of electric lighting necessary to support these activities. Daylight saving time impacts the changes to traffic fatalities and the commercial activities as well (Aries & Newsham, 2008).

The energy consumption of lighting in buildings is a major contributor to carbon emissions and the heat gains produced from such lighting have an important influence upon heating and cooling loads as reported by BRE (1997). With the aim of identifying how technological interventions might reduce emissions by 50% by the year 2030, a program is investigating the carbon emissions of UK buildings as reported by Peacock, Newborough, & Banfill (2005). This program was based on the estimations made with respect to technological and building improvements that, although not necessarily readily available in 2005, should be obtainable within the next 21 years until 2030. Several building categories such as domestic, office and retail are being investigated. Several different types of building are defined that are indicative of that category within each category. For the buildings under investigation in this program, electrical lighting accounts for a substantial proportion of carbon emissions as reported by Peacock et al. (2005).

The reduction of energy consumption is an important agenda in the world. There is an urgent need to search for renewable energy sources and modern technologies. A growing interest of illuminating engineers in the utilization of natural light is well recognized in last decades (Kocifaj, 2009). Paroncini, Calcagni, & Corvaro (2007) have summarized several reasons for preferring the natural light in designing the illumination systems, namely:

i) solar energy is free,

ii) the diffuse skylight is available for a whole day (also under overcast conditions),

iii) direct solar radiation is an extra supply, which increases the efficiency of light-guides dramatically, and,

iv) daylight is considered as the best source of light for good color rendering and it most closely matches human visual response.

Owing to an increasing awareness of the positive effects of daylight on the health and efficiency of humans, a wide range of daylighting systems was developed. Up to the year 2000, around 180 000 m2 of daylighting systems were installed in Europe (Koster, 2000).

Boyce (2009) claimed that the value of interior lighting means aesthetic, physiological and economic attributes. The aspect of environmental protection is always understood as a monetary term and analized in economics. The values of the aesthetic quality and the human well-being are difficult to quantify and they are only able to be estimated. As reported by Boyce (2009), to improve health and productivity of occupants, energy conservation and wider environmental benefits is the current interest in daylight. The health conditions of working environments can be improved by daylight through physiological responses such as regulation of the diurnal cycle of body activity. Since up to 85% of office costs are staff salaries and in comparison energy costs are tiny, small increases in staff productivity are equivalent to large savings in energy. The visual environment has an affect on wellbeing, personal satisfaction and mood, all of which influence office productivity, but attempts to measure the relationship between productivity and lighting directly have not been successful (Boyce, 2009).

Electricity generation is one of the largest sources of carbon dioxide (CO2), which comprises a significant amount of greenhouse gas emissions. The amount of CO2 released into the atmosphere depends on the fuel mix used in generation (Carbon Trust, 2009). A monetary value of £0.0043/kWh may be ascribed to this kind of pollution using the Climate Change Levy (CCL) and the tax on energy bills (Department of Environment, Farming and Rural Affairs, 2009).

The compliance to be based on a whole-building overall CO2 emission is implemented in the UK via the energy-related parts of the Building Regulations (2006), and it is required by the European Energy Performance of Buildings Directive. According ly, the requirements in building codes have been shifted towards the control of CO2 emissions (Carter, 2008). The provision of daylight within a building may influence CO2 emissions if daylight is used as a substitute for electric light. The Building Regulations (2006) define a daylit space as being either within 6m of a window wall, provided that the glazing area is at least 20% of the internal area of the window wall, or below roof-lights or similar provided that the glazing area is at least 10% of the floor area. No distinction is made in the regulations between roof-lights and daylight guidance. For thin roof constructions roof-lights and guides of similar aperture areas will deliver comparable amounts of light into a space, but for deeper roof constructions guides will generally have a superior performance. Smaller areas of external glazing may be needed using guides to produce a given daylight condition (Building Regulations, 2006). This may be beneficial in terms of the overall CO2 emission (Carter, 2008).

Martin (2002) classified the conventional daylighting systems into shading systems and optical systems. Shading systems have been designed primarily to block direct sun and admit diffuse light, but may address other daylighting issues as well, such as redirection of direct or diffuse sunlight. The use of conventional shading devices to prevent overheating or glare effects also reduces the use of daylight for visual tasks indoors. Shading systems that capable of redirecting diffuse light into the interior by rejecting or diffusing sunlight are developed to increase the use of daylight (Martin, 2002).

According to Martin (2002), optical systems are daylighting systems without shading, they include: diffuse light guiding systems, direct light guiding systems, scattering systems, and light transport systems, as discussed in below:

### *2.1.1 Diffuse light guiding systems.*

The overcast sky is much brighter in the zenithal area than in the horizontal part of the sky (Martin, 2002). The use of light guiding elements that redirect the light from these areas into the depth of the room allows an improved utilization of daylight. The zenith light is normally used near the window opening. Rooms are only well lit nearby the window because the high external obstructions shade the room against the diffuse skylight. This problem can be solved by diffuse light guiding elements, which include light shelf, anidolic integrated systems, anidolic ceiling, fish system, and zenith light guiding elements, and so on (Martin, 2002).

### *2.1.2 Direct light guiding systems.*

The direct light guiding systems include laser cut panel (LCP), prismatic panels, holographic optical elements in the skylight, and light guiding glass, and so on (Martin, 2002). When glare effects and overheating problems are avoided, rooms can be illuminated by direct sun light. Glare reduction needs the even distribution of light in the room without shadows and high contrasts in the working field. The avoidance of cooling loads can be realized by high efficient redirection and distribution of the sun light in a small part of the façade, while the rest of the facade is closed by conventional shading devices (Martin, 2002).

### *2.1.3 Scattering systems*

Scattering systems include light diffusing glass, capillary glass, and frosted glass, and so on (Martin, 2002). Scattering systems are used to realize an even lighting distribution. They are very useful in sky light openings in top-lit rooms. Attached in vertical openings they may produce huge glare problems. Their location has to be considered very carefully or they have to be shielded in some way to prevent glare problems.

The physical and optical properties of daylight emitters are heavily influenced by the transport system to which they are connected. Carter (2004) introduced daylight emitters as combined emitters and discreet emitters. In combined emitters, light is extracted continuously along its length. On the other hand, discreet emitters operate in a manner similar to conventional luminaries. Carter (2004) further classified daylight emitters into hollow prismatic emitters, slit light guides, and discrete emitters.

#### *a) Hollow prismatic emitters*

Light transport within hollow prismatic guides is by total internal reflection within the prismatic material (Whitehead, Nodwell, & Curzon, 1982). Imperfections in the prismatic structure and the presence of non-collimated light produce the emission. The loss is approximately two percent per 300mm of pipe length and the effect is to cause the pipe to glow. A number of devices are used to control the light output from the emitter. An extractor, a strip or wedge of diffusing material may be placed inside the guide-causing incident light to be scattered and escape through the walls. A reflective material may cover exterior surfaces of the guide that are not used as an emitter that redirects light inwards. Control of output along the length is achieved by varying the width and shape of the strip. Prismatic emitters have an appearance similar to large electrically powered diffusing area sources giving light with few shadows and little glare (Carter, 2004).

### *b) Slit light guides*

These are tubes made of elastic polyethlemephate film, which has a high reflectance up to 95% except for a slit running the length of the tube (Carter, 2004). The high reflectance is achieved through the internal coating and the light transmission along the guide is by mirror reflection. The material is fabricated, erected in situ, and air is pumped in under pressure to give the correct shape. However, light can be emitted through the transparent or diffusing slit (Aizenberg, Bukhman, & Pyatigorsky, 1975). The diameters for slit light guides range from 250 to 1200 mm and the angular size of the slit varies from 30 degree to 110 degree subtended by the axis (Aizenberg, et al., 1975).

### *c) Discrete emitters*

In daylight applications, many commercially available discrete emitters are incorporated at the ends of the light guides. The discrete emitters are made of opal or prismatic material of diameters corresponding to the light guides. They are generally circular flush, domed or square. For instance, a 600mm square emitter that fits into suspended ceiling systems is reported by Carter (2004). The square emitter is connected to a 500mm mirrored pipe via a transition box and the light is distributed within the building interior by either a diffuser or an array of Fresnel lenses as shown in Figure 2.1 (Carter, 2004).

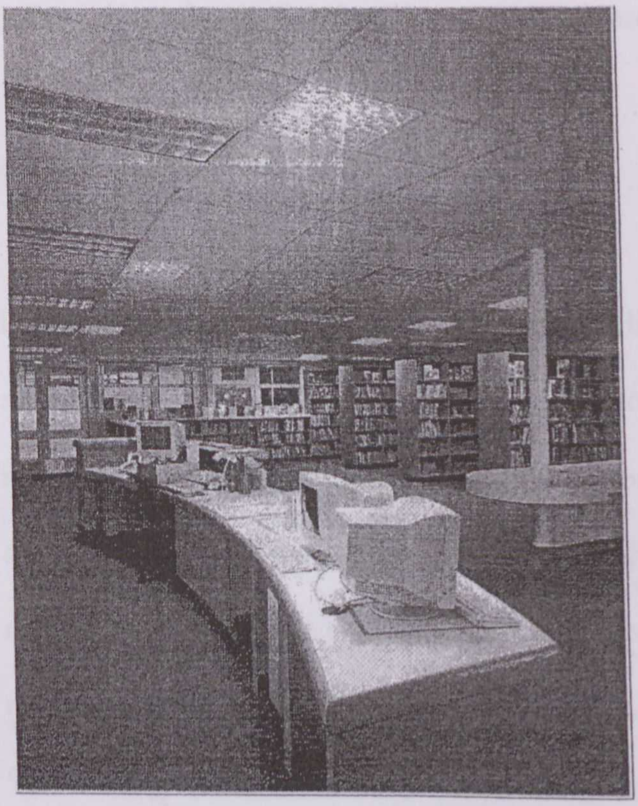

*Figure 2.1: interior lit using a square lens discrete emitter (Carter, 2004:223)*

### *2.1.4 Light transport systems*

Light transport is the feature that sets light pipes apart from other daylight redirection methods (Martin, 2002). Light transport systems such as light pipes and optical fibers allow daylight to be transported from outside by collating it and guiding it into the depth of the building. Transport elements deliver light from the collector to the point of exit and some devices have their own emitters. Daylight can be transported over long distances into floor areas or rooms without any window opening. At night time, artificial light could also be transported through this kind of systems (Hicks & Wright, 2000).

By considering a major factor of the availability for low-cost light redirection materials, four different transport methods, namely, beam/lens systems, hollow mirrored pipes, hollow prismatic pipes and solid core systems, are examined by Martin (2002).

### *a) Beam/lens systems*

In these systems, light from the collector is collimated by a lens and transported via an arrangement of lenses and mirrors. A physical 'guide' between the lenses is not necessary optically, but may provide protection. These systems have two drawbacks that limit practical application. First, light-redirecting equipment such as lenses and mirrors tend to be more expensive than the other methods. Second, there are high levels of light loss in the optical processes. Whilst a clear lens can transmit a maximum of 92% of light, losses increase with dirt deposition on surfaces. Efficiency is also dependent on accurate alignment, so that in systems consisting of several components, losses due to misalignment become significant (Martin, 2002).

The few examples of this type that have been realized are based on the work of Dugay & Edgar (1977). A building at the University of Minnesota, for example, uses heliostats on the roof to capture sunlight that is concentrated and collimated before being beamed through a vertical duct in the building containing lenses and mirrors to a working space 35m below ground. Thirteen optical processes give a maximum system efficiency of 28% in a clean state. The main advantage of this approach is that concentrated sunlight permits the use of smaller ducts than other transport methods delivering the same light flux. However, high capital and maintenance costs combined with low efficiencies suggest that these methods would almost certainly be uneconomic compared with other transport methods (Dugay & Edgar, 1977).

*b) Hollow mirrored guides*

These use multiple specula reflections at the inner wall surface to transmit light. Overall light transmission is a function of the surface reflectance, the input angles of the incident light and the proportions of the guide in terms of the ratio of length to diameter. If the light paths are long compared with the axial width of the pipe, the number of reflections is necessarily large (Martin, 2002).

Performance is particularly sensitive to reflectance of the mirror material with variations of as little as 0.1% causing noticeable changes. To attempt to minimize the number of reflections, light must enter the guide as a near collimated axial beam. Efficiency is as a function of both the ratio of effective length to diameter and the angle of incidence of the collimated incoming light. For the best case, efficiency was in excess of 50% for a length/diameter ratio of 40, corresponding to approximately 12m of light travel in a 300-mm diameter guide, but efficiency rapidly diminishes as the alignment of incident rays and guide axis diverges. In practice, dirt and component misalignment will mean that efficiencies are likely to be somewhat lower than those in laboratory measurement are (Hicks & Wright, 2000).

The recent introduction of visible mirror film, a reflecting material based on polymeric multiplayer optical stacks that has a specula reflectance of the order of 99%, in future will increase the economic light transport distance. The efficiency of a 12-m circular cross-section pipe of 300mm diameter would rise to 70% using this material (Hicks & Wright, 2000).

Aizenberg et al. (1975) described the slit lightguides, essentially a circular cross-section mirrored pipe with a transparent slit throughout its length that serves as a light emitter, in which light is totally reflected internally from a prismatic dielectric surface that traps the light and redirects it down the inside of the guide.

Incident light is totally reflected internally twice at the prismatic surface, thus operating like a mirror for certain angles of incidence. Unlike a mirror, however, the prismatic structure is transparent to light at higher angles of incidence. The main lighting applications use acrylic or polycarbonate materials having a 90-degree prismatic ridge structure on the exterior surface. The devices redirect light down the inside of the guide when the prisms are orientated parallel to the axis provided that the incident light does not exceed 27.5 degree to the axis of the pipe. Overall reflectance is of the order of 98%. In theory, all light would be reflected by this process, but irregularities in the film cause a small proportion of light to exceed the maximum angle and leak out of the pipe (Aizenberg et al., 1975).

### c) *Solid core systems*

The major lighting applications of solid core systems are optical fibers. These consist of two coaxial regions, an inner core that acts as the light transport medium and an outer cladding of lower refractive index that prevents leakage of from the core. The process of total internal reflection in an optical fiber is very efficient and light transport is essentially a function of length and not of diameter as in the case of mirrored or prismatic transport systems (Martin, 2002).

One of the very few examples of this technology in daylight guidance is the Himawari system as reported by Eben (1993). Sunlight is collected using a tracking Fresnel lens, self-powered by a solar cell, filtered and focused with a concentration of 1:10000 onto the ends of the optical fiber. A single 6 fiber 40mm-long cable (made up of six or nine optical fibers) delivers 1180 lumens from 98000 LUX of direct sunlight over a distance up to 200m from the collector, a distance far beyond the capabilities of the other transport methods. Notwithstanding this, these systems represent an extremely large capital investment that is unlikely to be justified for other than prestige buildings (Eben, 1993).

The huge number of different daylighting systems allows new and optimized ways of daylight utilization. But at least it has to be considered that the different systems have to be used in the right way and that the used system is adjusted to the building and matches the requirements of lighting for this special purpose. Otherwise, problems like overheating of rooms or glare may occur that would lead to refusal of the daylighting system and to stopgap solutions bringing the elements to a standstill to reduce these problems (Martin, 2002).

What makes daylighting a particularly challenging task is the permanent change of availability, brightness and angle of incidence due to weather conditions and the sun path. Other factors also play an important role, e.g. the reflectivity of nearby surfaces, the different levels of brightness due to the latitude, the different composition of direct and diffuse daylight due to air humidity, and the use of different glazing (Kischkoweit, 1998).

According to Kischkoweit (1998), daylight luminance ranges from 120000 Ev on a sunny day in the tropics to 5000 Ev with overcast sky in temperate climates even at high noon. The necessary average luminance level for most tasks in offices ranges from 500 Ev to 2000 Ev, and these levels are proposed for visually sensitive jobs such as designing. Owing to an ever-increasing amount of computer workplaces, the tolerance for higher or lower luminance, especially in office buildings, is limited. Veiling glare as well as disability glare has to be avoided.

Many options seem revolutionary: zero-energy houses are possible even under poor climate conditions. Energy gains can be obtained with active and passive solar facades. Visual comfort can be increased significantly by daylight guidance systems. Architectural concepts might be affected, e.g. the division of windows into a fanlight, especially equipped with three-dimensional daylight guidance systems for an optimized light distribution without glare and a sun-protected window at eye-level for visual contact with the outside world (Martin, 2002).

According to Laar & Friedrich (2002), an important issue to be considered for daylighting is the user's behavior. Daylighting systems are mainly considered for office buildings. Typically, the full depth of office space is used for working. However, office staffs are generally fully concentrated on their tasks and do not find time to adjust daylighting systems regularly. Therefore, systems with a high demand of user participation may be a problem, for example, once daylighting systems are adjusted to full protection, which means fully closed, they are rarely opened again. Lighting needs are then fully covered by artificial lighting. However, automatic systems adjust venetian blinds automatically. To avoid being overdriven or turned off by the user, these systems must be highly reliable and robust.

Another important aspect is maintenance. Mechanical systems, especially when applied on the facade, are problematic. While everybody is used to the idea of regular car maintenance, it is not necessarily the same for buildings. The high costs caused by neglecting this item started to lead to a change in this attitude, but it still depends strongly on the individual owner. In addition, a regular cleaning of relatively unprotected systems (outside and inside the building) is necessary to maintain the full efficiency of the applied system. Therefore, systems integrated into the vertical facade, protected by glass on each side, are clearly advantageous. Furthermore, the development of the daylighting systems was generally focused on the temperate climate instead of the tropic climate (Laar & Friedrich, 2002).

Increasing the use of daylighting in buildings can offer significant savings in energy consumption as well as improving the internal environment (Martin, 2002). For example, Bouchet & 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 (Bouchet & Fontoynont, 1996).

## 2.2 Light pipes for daylight transportation

Daylight guidance redirects natural light into buildings areas that cannot be lit by conventional glazing. The most commercially successful type is light pipes, also called tubular daylight guidance systems, which comprise a clear polycarbonate domed light collector that accepts sunlight and skylight from the whole sky, a light transport tube lined with highly reflective silvered or prismatic material, and a diffuser commonly made of opal or prismatic material light to distribute light in an interior (Carter, 2004).

The usage of cylindrical tubes for light guiding becomes one of very attractive approaches for delivery the natural light into the interior spaces (Al-Marwaee & Carter, 2006). New technologies support production of light tubes with satisfactory high reflectance of inner surfaces (Elmaualim, Smith, Riffat, & Shao, 1999). This minimizes energy losses during guiding the light.

The development of efficient reflective and refractive optical materials made possible the first light pipes in Australia and the US some two decades ago. The systems were initially aimed at the domestic building market, and subsequently at that for commercial buildings. More recently, light pipes were introduced into the European market where they have been the subject of heavy marketing based around manufacturers' claims of user appreciation of the delivered daylight and of potential energy savings (Carter, 2004).

As illustrated in Figure 2.2, 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 luminaries that releases the light into the interior (Oakley, Riffat, & Shao, 2000).

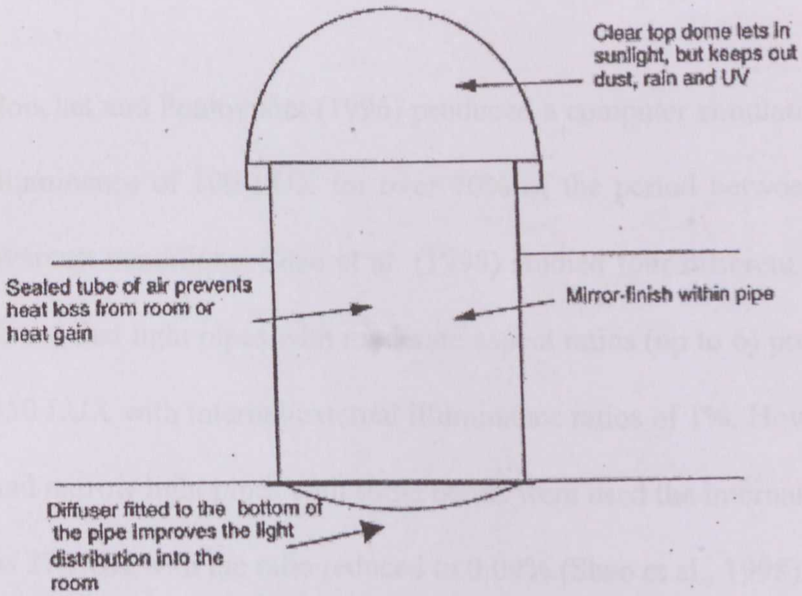

*Figure 2.2: schematic of a typical light pipe (Oakley, et al., 2000:91)*

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 anodized aluminum or coated plastic films such as Alcoa Everbrite and SilverLUX, which have reflectance 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, 1997). 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 ratios 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% (Shao et al., 1998).

Light pipes guide light which enters to the intended exit in the ceiling at the interior of the building. Illuminance from sunlight (and coincidental skylight) through the light pipe can complement that from side lighting especially for the space in the deep interior of a building. Light pipes are effective for a facade which faces the sun all year round and has been presented as an effective means to complement side lighting (Beltran, Lee, & Selkowitz, 1997).

For a tropical location, the sun may traverse in the northern or southern hemisphere depending on the day of the year. It is stated by Surapong, Siriwat, & Liu (2000) that the aperture of light pipes faces either east or west to utilize the sunlight in the morning or in the afternoon. For such a situation, sunlight is utilized only for a few hours for a facade each day, and for the rest of the time electric lighting will be used to supplement side lighting (Surapong et al., 2000).

Carter (2008) presents some photos of the uses of light pipes explored in actual buildings in UK as shown in Figure 2.3, 2.4 and 2.5. Exterior views of two installations are shown in Figure 2.3. Interior views of the same installations illustrated in Figure 2.4 show the circular opal diffuser, or square lens panel output devices. Figure 2.5 provides a general view of guides in roof space.

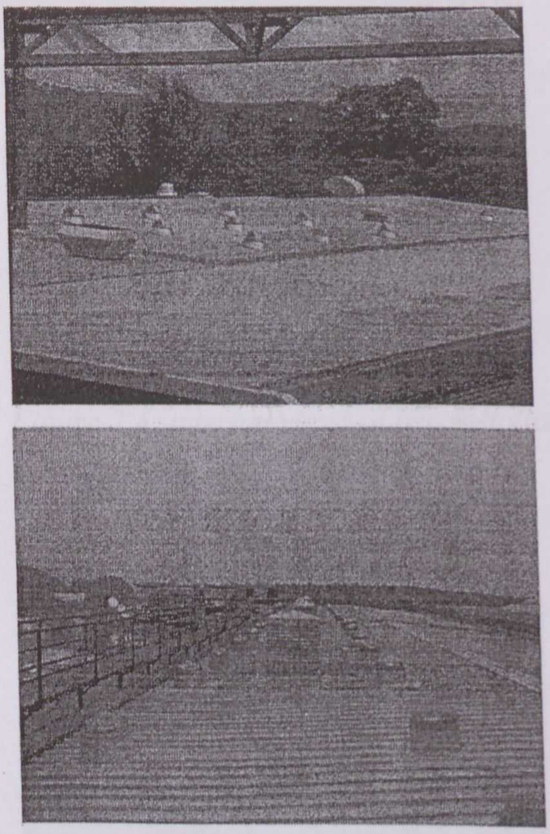

*Figure 2.3: external views of two installations (Carter, 2008:526)*

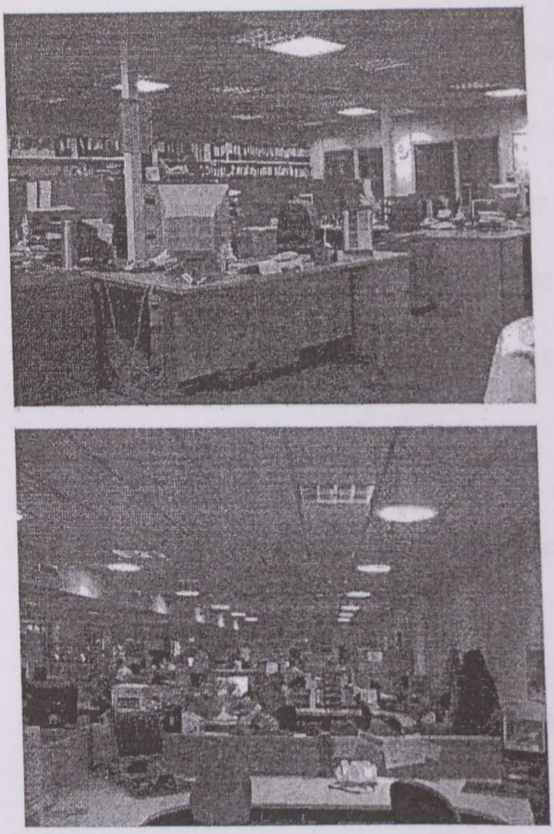

*Figure 2.4: internal views of two installations (Carter, 2008:526)*

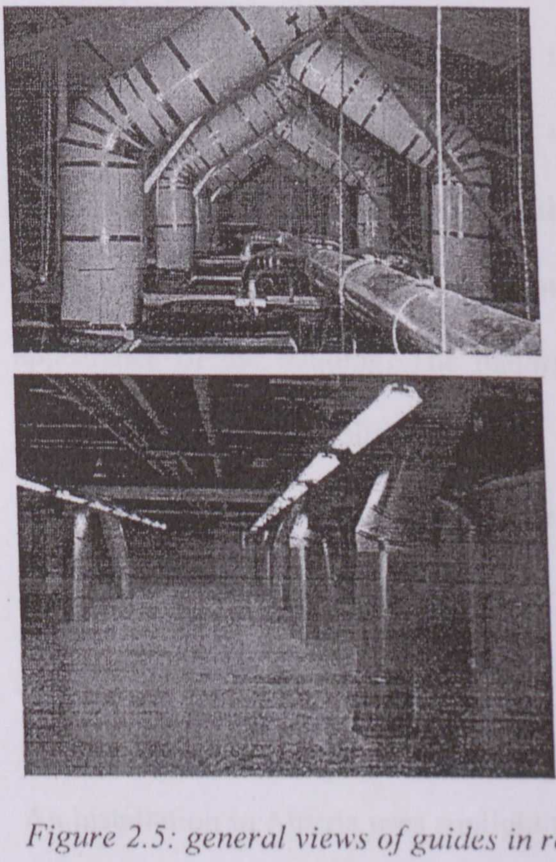

*Figure 2.5: general views of guides in roof space (Carter, 2008:526)*

Tubular light guidance systems are classified here by their light collection method by Carter (2004). The collector is usually located at roof level to gather light from the zenithal region of the sky and is either mechanical devices that actively focus direct daylight (usually sunlight) or are passive devices that accept sunlight and skylight from part or the whole sky hemisphere (Carter, 2004).

### *2.2.1 Zenithal systems with active collection*

A tracking mirror or Fresnel lens (heliostat) usually on a roof collects concentrates sunlight. A second mirror or lens directs a concentrated beam of sunlight into a light guide. Diffuse daylight is much less suitable as a light source since there are theoretical limits on the concentration achievable (Rabl, 1980). Collimated light is necessary to achieve the necessary concentration for efficient transport. The size of the tracking mirrors or lenses required can be large. It is estimated that a total mirror area of about 40m2, or a lens area of half this value, would be required to light a 1000m2 office to 500 LUX (Ngai, 1983). Collectors of this size would have high capital cost, require costly control systems and maintenance, and have implications for the external appearance of the building. The majority of light transport systems used for active collector systems are hollow mirrored or hollow prismatic pipes light pipes. Carter (2004) introduced two detailed examples of light pipes, namely: sun lighting system and Arthelio, as described in below:

*a) Sun lighting system*

An installation in Austria uses sunlight to provide lighting to an underground room with a size of 7.8m length, 4.5m width, and 2.4m height (Pohl & Anselm, 2001). A sun-tracking heliostat and a redirection mirror redirect light to a concentrator as shown in Figure 2.6.

*Figure 2.6 sun lighting system redirection mirror (Carter, 2004:224)*

Two adjustable Fresnel lenses increase the concentration of incoming sunlight by a factor of 35 for transport in a 300mm diameter tubular prismatic hollow guide (Figure 2.7). The emitter located in a windowless basement consists of two elements. A component similar to a mirrored louvered down light electric luminaries provides glare-free light to a task area. Diffuse ambient light is provided by light from the prismatic walls of the emitter. In addition, users can adjust a mirror to direct sunlight onto the task area thus creating a visual link to outside conditions. Supplementary fluorescent lamps are incorporated in the reflective optical component, which can be dimmed according to outside conditions and provide lighting after dark. The installation delivers glare-free light with working plane luminance between 100 and 1200 LUX given sunny conditions with a 30% overall system efficiency. Energy savings were measured by a combination of continuous monitoring of power consumption and simulation of the performance of the system located in various parts of Europe. The results indicated power savings of 40–60% compared with a conventional electric lighting system. The quoted capital cost of £225/m2 is of the order of ten times that of an electric lighting installation providing comparable lighting conditions. However, this kind of device is highly dependent on the direct sunlight and a tracker is always needed (Pohl & Anselm, 2001).

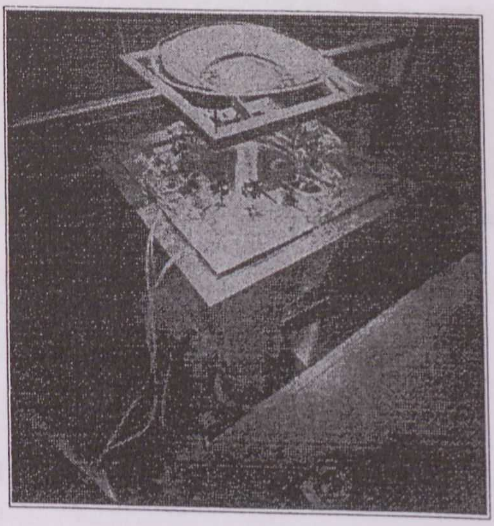

*Figure 2.7 sun lighting system concentrators (Carter, 2004:225)*

*b) Arthelio*

The Arthelio study developed systems combining daylight and electric light and culminated in the construction of two large installations: a staircase connecting three floors of an office building in Berlin and a working area of a single-storey warehouse in Milan (Mingozzi, Bottiglioni, & Casalone, 2001). The Berlin installation has a two-axis automatically controlled 6-m2 plane mirror directing sunlight horizontally toward four 1*1.4m Fresnel lenses, which concentrate the light by a factor of 100 and hence to a mixing box (Figure 2.8). The mixing box allows introduction of light from 1000W dimmable sulphur lamp to supplement and directs collimated light into two 12m long, 30-cm diameter hollow prismatic light guides with a specula reflectance of 97%. Light leakage from the guides is regulated by a series of white diffuse hollow tube extractors inside the guide (Mingozzi, et al., 2001).

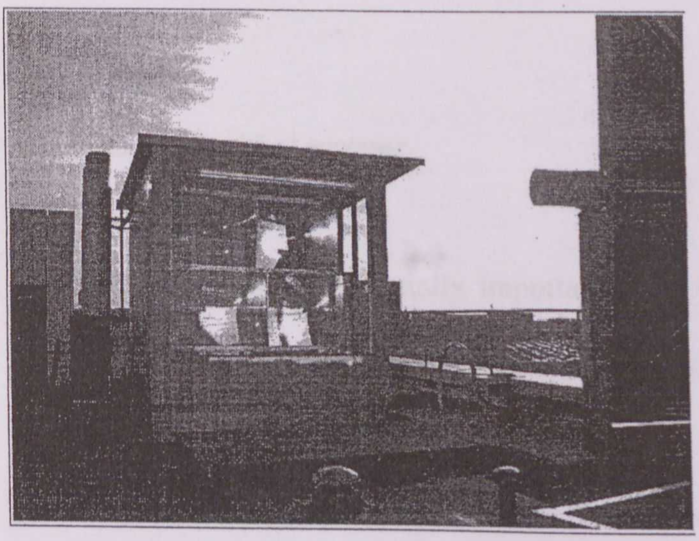

*Figure 2.8: ARTHELIO Fresnel lens (Mingozzi et al., 2001:16)*

The mixed light supply means that the appearance of the tubes varies with time of day and season. The Milan installation uses a single-axis light-capture head based on a Fresnel lens with an acceptance angle that enables sunlight to be collected from the majority of the sun path at the latitude of the installation. The sunlight is then reflected into a 13m long, 90cm diameter circular guide via an anidolic mirror. The guide is lined with prismatic material with a specula reflectance of 97%. A diffuser unit, shaped like a truncated cone and located at the end of the duct, distributes the light over some 14m2 of working area beneath the pipe. Connected to the diffuser unit are two horizontal prismatic light guides powered by 100W dimmable sulphur lamps. These provide a uniform luminance over the working area by a control system that tops up or replaces the daylight as necessary. The system delivers in the order of 200–250 LUX on the working plane and luminance beneath the diffuser is more than 2% of the external luminance from sunlight/ daylight and sunlight. The combination of dimming and the presence of a detection system give estimated savings of 67% over the fluorescent installation it replaced. No capital costs are quoted for either project (Mingozzi, et al., 2001)..

### 2.2.2 Passive zenithal systems

These are the most commercially important form of daylight guidance system. They consist of a light-transport section with, at the upper end, some device for collecting natural light whilst preventing ingress of wind and rain and, at the lower end, a means of distribution of light within the interior. The collector is usually a clear polycarbonate dome that may include a refractive redirection device. Modifications to the basic systems include: cutting the upper end of the tube at an oblique angle inclined toward the equator; laser-cut deflecting panels to redirect light in an axial direction; and reflectors known as ‘light scoops’ located outside or inside the collector dome to intercept direct sunlight, increasing the fLUX output under a clear sky plus sun, but having a negative effect under overcast conditions. The transport section is a rigid or flexible hollow mirrored or prismatic guide and may include bends or elbows (Carter, 2004).

Studies of achieved conditions and user views in buildings equipped with light pipes suggest that daylight guidance devices are recognized as sources of daylight, but are thought to be generally inferior to windows in the delivery of daylight (Ejhed, 2001; Al-Marwaee & Carter, 2006). Little authoritative work on either energy savings realized, or the general economic viability of light pipes, has been published. Fontoynont (2005) compared theoretical long-term costs of various methods of office lighting and concluded that whilst the costs of light pipes were similar in magnitude to electric lighting, they were more expensive than conventional windows or roof lights.

Muneer & Jenkins (2004) compared the costs of lighting a number of theoretical small rooms using light pipes. Their results suggested that light pipes may be an economic investment particularly if the economic value of daylight was included, but the limited nature of the study did not permit the viability of actual installations to be investigated.

The innovative nature of light pipes has posed two major problems for designers (Carter, 2008). The first is that there is little accumulated experience of how they are accommodated within a building. As conduits of daylight, light pipes penetrate the exterior envelope of a building but, unlike windows, may also pass through internal structural or construction elements. They thus make demands in terms of structural support and fire protection (fire compartments, fire stopping, and internal and external spread for flame) that other lighting systems do not. In this respect, they are akin to mechanical ventilation systems. In addition, the internal space required to accommodate light pipes components and associated ducts may affect building space planning and cause loss of rentable floor area (Carter, 2008).

The second problem relates to the availability of design guidance and data. Design guidance for conventional glazing sets out desirable window properties, room proportions and surface treatments, and allowable daylight levels and distributions to give satisfactory conditions for users. Similarly, electric lighting codes attempt to create comfortable conditions using recommended planar illuminance levels and limits on surface and source luminance. Little independent specialist design data have been developed for light pipes to date and manufacturers' websites are the main source.

These usually offer little more than output device spacing and installation advice. They are usually based on optimal conditions–the most favorable possible system configuration and assumed daylight resource, which are rarely found in practice. They also use a proliferation of methods of describing system performance, often incomplete, and with little indication of the source of that data. This means that evaluation of the range of alternatives on the market is at best very difficult and in some cases impossible. Indeed, unsubstantiated claims about system performance by a minority of daylight guidance manufacturers threaten to discredit the whole technology. This state of affairs sits uneasily in a lighting industry where standardized methods of design data production and exchange (e.g. utilization factors, luminous intensity tables, daylight factors and glare ratings) have existed for many years (Carter, 2008).

### 2.3 Optical fiber for light transportation

According to Enedir & 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, one example picture for light transportation through optical fibers is presented in Figure 2.9. 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.

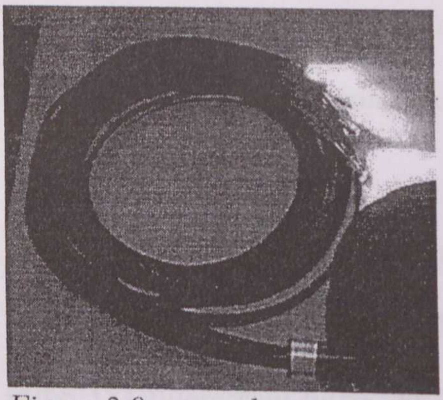

*Figure 2.9: example picture of light transmitted through optical fibers (Enedir & John, 2006: 1614)*

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, this 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 (Cariou, Martin & Dugas, 1980).

Wherever the remote lighting system has been introduced in an architectural project, it was mentioned clearly the practical advantages it breeds. In addition, the main light generators being put away at some distance, in a dry place, gives clear evidence about the safety higher degree of the system. Actually, in important projects where optical fibers take aim to satisfy more complex lighting design purposes, like illumination, safety is appreciated but is not certainly seen as the stimulus of the system choice. Additionally, the practical location of the effective light sources is valued but in terms of lower cost services. In fact, the main advantage aimed for while selecting a remote lighting system instead of an ordinary one, relates to some extent to the considerable cut down upon the effective running costs (Sala, Milanesi, Ceccherini, & NeW, 1993).

Under such circumstances is the Commercial Fair Tower in Franckfurt. This tall building is crowned by a pyramid previously enhanced by external lighting provided by some 353 fluorescent tubes. These have been now replaced by optical tubes supplied with the necessary light by only 76 metallic vapour lamps (250W). With this new lighting design scheme long term savings are to be realized not only upon the diminution of the effectively operating lamps but also upon the services as the generators are placed within the building (Djamila, 1996).

During the past 30 years a new type of optical fiber has been researched, namely the plastic optical fiber (POF). The situation of this transmission medium had remained rather stagnated for years because of its high attenuation and the lack of demand of specific commercial applications. However, since the development of the graded index plastic optical fibers in 1990 and the later attainment of the low-attenuation per fluorinated fibers in 1996, plastic optical fibers have received a lot of interest, which is expected to give rise to a great deal of applications in the next several years (Joseba & Jon, 2001).

Because of its high frequencies, the optical portion of the electromagnetic spectrum is currently being used by employing optical fibers as transmission media. Specifically, the well-known plastic optical fibers with PMMA core were introduced in the 1960s, although the first optical fibers that were used were made of glass. In the past several decades, concurrent with the successive improvements in glass fibers, POFs have become increasingly popular, owing to their growing utility (Kaino, 1992; Nihei, et al., 1997).

Although POFs have been available for some time, only quite recently have they found application as a high-capacity transmission medium, thanks to the successive improvements in their transparency and bandwidth (Murofushi, 1996). By the end of 20th century, they are advantageously replacing copper cables in short-haul communications links by offering the advantages intrinsic to any optical fiber in relation to transmission capacity, immunity to interference and small weight. In addition, POFs serve as a complement for glass fibers in short-haul communications links because they are easy to handle, flexible, and economical, although they are not used for very long distances because of their relatively high attenuation. These characteristics make them especially suitable as a means of connection between a large net of glass optical fiber and a residential area, where distances to cover are generally less than 1 km. An example would be Internet access from home or from an office. For this purpose, POFs allowing for increasingly better features regarding distance and transmission speed have been manufactured (Murofushi, 1996)

As that have already mentioned, POFs present some important advantages over their glass counterparts. Specifically, their large diameter typically 0.25-1mm, allows low precision plastic connectors to be used, which reduces the total cost of the system. In addition, POFs stand out for their greater flexibility and resistance to impacts and vibrations, as well as for the greater coupling of light from the light source to the fiber. Because of these merits, varied applications with POFs have been developed and commercialized, from their use as a simple light transmission guide in displays to their utilization (Joseba & Jon, 2001). The following paragraphs introduce a brief view on the mechanical properties, thermal properties, and chemical resistance for plastic optical fibers:

a) *Mechanical properties for plastic optical fibers*

Several authors have studied the mechanical properties of POFs. These studies have been focused on the attenuation induced by bends and tensile or torsion stresses (Blyler, 1999; Zubia, Arrue, & Mendioroz, 1997). In contrast to glass fibers, POFs are made of plastic materials. Another difference is that it is nearly two orders of magnitude lower than that of a silica fiber less than 2.1 Gpa for a PMMA POF (Blyler, 1999). For this reason, even a 1 mm diameter POF is sufficiently flexible to be installed according to typical fiber configurations. For the same reason, the minimum bend radius for POFs is smaller, since plastic is more ductile and much less stiff than silica. Similar results have been obtained for polycarbonate POFs, for which POF lies in the range between 1.55 and 2.55 Gpa (Guerrero, Guinea, & Zoido, 1998).

b) *Thermal properties for plastic optical fibers*

As POFs are made of polymer, they can operate at temperatures up to 80-100°C. Above this limit, POFs begin to lose their rigidity and transparency. The operation temperature can be increased up to 125°C or even to 135°C by using a jacket made of cross-linked polyethlylene or of a polyolefine elastomer (Koike, Ishigure, & Nihei, 1995)

On the other hand, the resistance of POFs to high temperatures strongly depends on the degree of moisture. This behavior is due to the strong OH⁻ absorption band in the visible range. Fluorinated fibers do not absorb water, so the attenuation rate through them is not mechanical properties, thermal properties, and chemical resistance for plastic optical fibers:

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*c) Chemical Resistance*

Most of the work on POFs' chemical resistance deals with the behavior of POFs when they are in contact with those liquids typically found in cars. For example, polycarbonate POFs without jacket only resist 5 minutes immersed in 85-octane petrol. However, these POFs are able to withstand oil and battery liquid for a long time (Guerrero, Zoido, Escudero, & Bernabeu, 1993). The polyethylene jacket of a fiber cord serves to protect the POF when it is dipped into chemical products. When using this jacket, PMMA POFs are protected against liquids such as water, NaOH, sulfuric acid (34.6%), or engine oil. In any of such liquids, the attenuation remains constant when the coated POF is dipped into the liquid at 50°C for 1000 h. Fluorinated POFs (CYTOP), do not show changes in their attenuation when they have been dipped for 1 week into chemical acids such as 50% HF, 44% NaOH, and 98% H2SO4 or organic solvents such as benzene, hexane, MEK, and CCL4 (Daum, Hoffman, & Strecker, 1994).

The continuous lighting industry progress and the perseverance of lighting designers have also allowed relying totally upon the remote lighting system to meet quantitative and qualitative lighting conditions within very spacious environments. A successful experiment has been carried out in the Congress Palace of Madrid (Djamila, 1996). Two auditoria (900 and 2000 seats) are exclusively lit by optical fibers scattered evenly in the ceilings and seeing to the standard of the design objectives required; an illumination level in accordance with the expected comfort lighting norms, a good color rendering, a uniform lighting and a pleasant luminous internal environment. Furthermore, heat output due to lamps is extracted in the generators and therefore nuisance caused by lighting appliances is not noticeable giving hence additional satisfaction with the adoption of this system (Djamila, 1996).

The use of concentrated solar energy and its transport in optical fibres is studied by Cariou et al. (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 might supply 2W with efficiency greater than 70 percent, whilst the concentration on the exit end of a 10m long fiber may exceed 3000. Such a device has been achieved and the experimental results are in good agreement with the preliminary study (Cariou et al., 1982).

## 2.4 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 daylighting aperture (Compagnon, et al., 1993; Page, et al., 2003). Recently, systems involving concentrating collectors (Beckman et al., 2003), heliostats (Pohl & Anslem, 2002), or mirror light pipes (Garcia-Hansen & 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). Figure 2.10 presents an example of the heliostats solar concentrator and light transmission through optical fibers developed by Kandilli, et al. (2007).

*Figure 2.10: one example of the heliostats solar concentrator and light transmission through optical fibers (Kandilli, et al., 2007:23)*

Solar concentrators were early brought into consideration as alternative ways to reduce the cost of photovoltaic electricity and solar heat due to the relatively high material and production costs of solar cells and solar thermal absorbers. One approach is to use concentrators that increase the irradiance on the modules or absorbers and thus the electricity or heat production per unit receiver area, which in turn reduces the area needed for a given output (Maria, Anna, Bjorn, Johan, & Arne, 2004).

Concentrating systems use lenses or reflectors to focus sunlight onto the solar cells or solar thermal absorbers. High concentration of solar radiation requires tracking of the sun around one axis or two axes, depending on the geometry of the system. The higher the concentration, the more concentrator material per unit area of solar cell or thermal absorber area is generally needed. It is therefore more appropriate to use lenses than reflectors in highly concentrating systems, because of their lower weight and material costs. Lenses, typically point-focus or linear-focus Fresnel lenses with concentration ratios of 10 - 500 are most often manufactured out of inexpensive plastic material with refracting features that direct light onto a small or narrow area of photovoltaic cells or on a linear thermal absorber. The cells are usually silicon cells. Single or mono-crystalline silicon approaches accounted for 93% of the annual cell production in 2002 (Schmela, 2003). Cells of GaAs and other compound materials have higher conversion efficiencies than silicon, and can operate at higher temperatures, but they are often substantially more expensive (Swanson, 2000). Concentrator module efficiencies range from 17% and upwards and concentrator cells have been designed with conversion efficiencies in excess of 30% (Yamaguchi & Luque, 1999; Fraas, Sundaram, Dinh, Davenport, & Yerkes, 1990). However, concentrator systems that utilize lenses are unable to focus scattered light, limiting their use to areas with mostly clear weather (Yamaguchi & Luque, 1999).

In areas with a lot of diffuse irradiation, as well as for moderate (5 - 20×) and low (less than 5×) concentration ratios, reflectors are often more cost-effective than lenses and therefore the most common type of concentrator. Below 5× concentration, it is possible to construct cost-effective static concentrators, both for photovoltaic and solar thermal systems (Whitfield, Bentley, & Burton, 1995; Hellstrom, Adsten, Nostell, Karlsson, & Wackelgard, 2003). These are mostly two-dimensional parabolic troughs or plane booster reflectors. Plane mirrors in front of the collector area increase the collected energy with 20 - 50% and reduce some of the diurnal variation (McDaniels, Lowndes, Mathew, Reynolds, & Gray, 1975). Reflectors for solar energy applications should fulfill a number of requirements (Maria et al., 2004):

* They should reflect as much as possible of the useful incident solar radiation onto the absorbers.

* The reflector material and its support structure should be inexpensive compared to the solar cells or thermal absorbers onto which the reflector concentrates radiation.

* The high reflectance should be maintained during the entire lifetime of the solar collector or photovoltaic module, which is often longer than 20 years.

* If cleaning is necessary, the surface should be easily cleaned without damaging its optical properties and the maintenance should not be expensive.

* The construction must be mechanically strong to resist hard winds, snow loads, vibrations, etc.

* The reflector should preferably be lightweight and easy to mount.

* The reflector material should be environmentally benign and should not contain any hazardous compounds.

* The visual appearance of the reflector should be aesthetical, since solar concentrators often are large and must be placed fully visible on open spaces so that the concentrator aperture is not shaded by objects in the surroundings.

The optical requirement that must be fulfilled for reflector materials in solar thermal applications is a high reflectance in the entire wavelength range of the solar spectrum (300 - 2500 nm). In lighting and photovoltaic applications, photons with lower energy than the band gap of the solar cell, which corresponds to wavelengths longer than about 1100 nm for a silicon cell, do not contribute to the photoelectric conversion but only to overheating. Hence, metals that are free electron-like are suitable as reflectors for solar thermal applications, but not optimal for lighting and photovoltaic applications. There are no known metals that combine a low reflectance in the near-infrared with a high reflectance in the ultraviolet and in the visible (Mwamburi & Roos, 2000).

Among the Drude metals, silver and aluminum are the best solar reflectors with a solar hemispherical reflectance of approximately 97% and 92%, respectively (Granqvist, 2003). Due to its lower cost, the material, which is most often used for solar reflectors today, is anodized aluminum. However, if the anodized aluminum is not protected, for example by a glazing, a plastic foil, or a lacquer, its optical performance degrades severely in only a couple of months (Bouquet, Helms, & Maag, 1987). The degradation of silver is essentially as rapid as that of aluminum (Czanderna, 1981). Due to the limited corrosion resistance of the free electron-like metals, they are often used in back surface mirrors, evaporated on the back of a glass or polymer substrate that protects the metal from oxidation. Among the state-of-the art in solar reflector materials are polymethylmethacrylate (PMMA) or back-surface-silvered low-iron glass (Schissel, Jorgensen, Kennedy, & Goggin, 1994). However, glass mirrors tend to be brittle and heavy. Front surface mirrors, on the other hand, are often bendable and of lightweight, but more susceptible to chemical attack (Roos, Ribbing, & Karlsson, 1989).

A solar reflector is not subject to the same high temperatures and thermal cycling as a solar absorber. Nevertheless, environmental conditions impose stringent demands on the material, whose surface will deteriorate more or less upon exposure to the environment. Loss of solar reflectivity can result from erosion or oxidation of the surface, dirt accumulation on the reflector, and action of cleaning agents (Duffie, 1962).

While degradation caused by accumulation of dust on the reflecting surface is essentially reversible, surface oxidation is not. The optical performance of solar reflectors thus depends on the mechanical and chemical properties of the surface and the protective coating, if such is present. For flexible reflective foils, a support of sheet metal may be necessary, while only a simple frame construction is needed if the reflector is self-supporting, which is the case for corrugated sheets. When installing booster reflectors, the cost of the reflector material, the frame and support construction, as well as mounting and installation of the reflector must be taken into account. Maintenance should also be included in lifecycle cost (Morris, 1980).

Mora, Jaramillo, Navaa, Taguena-Martinez, & Rio (2009) reported using porous silicon photonic mirrors (PSPM) as secondary reflectors in solar concentration systems. The PSPM were fabricated with nanostructured porous silicon to reflect light from the visible range to the near-infrared region (500–2500nm), although this range could be tuned for specific wavelength applications. The PSPM are multilayer of two alternated refractive indexes (1.5and2.0), where the condition of a quarter wavelengths in the optical path was imposed. The PSPM were exposed to high radiation in solar concentrator equipment as shown in Figure 2.11. As a result, it observed a significant degradation of the mirrors at an approximated temperature of 900°C. In order to analyze the origin of the degradation of PSPM, it was modeled the samples with a non-linear optical approach and study the effect of a temperature increase. It concluded that the main phenomenon involved in the breakdown of the photonic mirrors is of thermal origin, produced by heterogeneous expansion of each layer (Mora, et al., 2009).

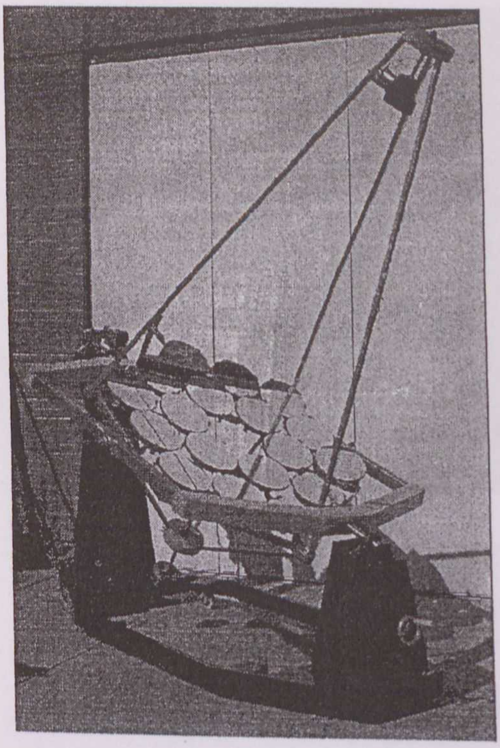


*Figure 2.11: DEFRAC-Spanish acronym of device for the study of highly concentrated radioactive fluxes (Estrada, Jaramillo, & Acosta, 2007: 1308)*

Poulek & Libra (2000) developed a tracking ridge concentrator using proven tracker hardware. This system combines simple low-cost tracker with flat booster mirrors but unlike V-trough concentrator (Klotz, 1995; Nann, 1991) by the new ridge concentrator the mirror has been eliminated as shown in Figure 2.12. On single axis trackers, both horizontal and polar, the mirrors have to be extended beyond PV panels to ensure uniform illumination of panels at seasonally variable elevation of the sun. On polar axis trackers with seasonally adjustable slope of the axle the extended mirror is not needed. Unlike V-trough concentrators, no additional mirror supporting structures are needed. However, it could only double solar energy gain of PV panels in comparison with fixed ones (Poulek & Libra, 2000).

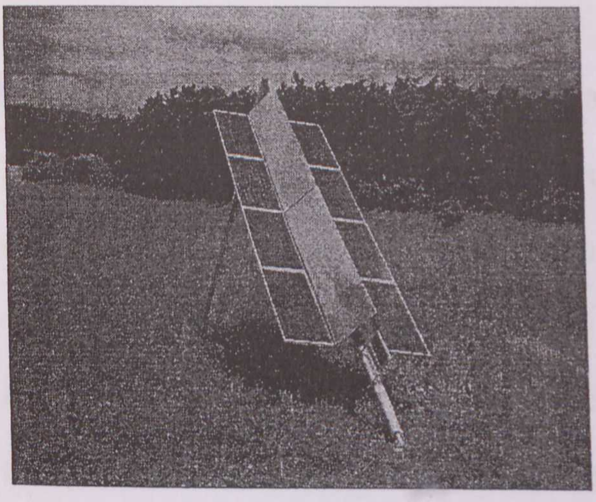


*Figure 2.12: photograph of the polar axis tracking ridge concentrator with 8*55 Wp PV panels (Poulek & Libra, 2000:201)*

To obtain cost-effective photovoltaic modules, Uematsu et al. (2001) have developed static prism-array concentrator modules consisting of prism concentrators about 4mm thick assembled unidirectional under a 3.2-mm-thick cover glass as shown in Figure 2.13. Calculating the optical collection efficiency for the annual solar irradiation in Tokyo, it found that the theoretical efficiency of the modules is 94.4% when the geometrical concentration ratio is 1.88 and that it is 89.1% when that ratio is 2.66, respectively. Fabricating prism-array-concentrator modules with a geometrical concentration ratio of 2.66, it only obtained a maximum optical collection efficiency of 82% with a flat reflector and 81.7% with a V-grooved reflector (Uematsu et al., 2001).

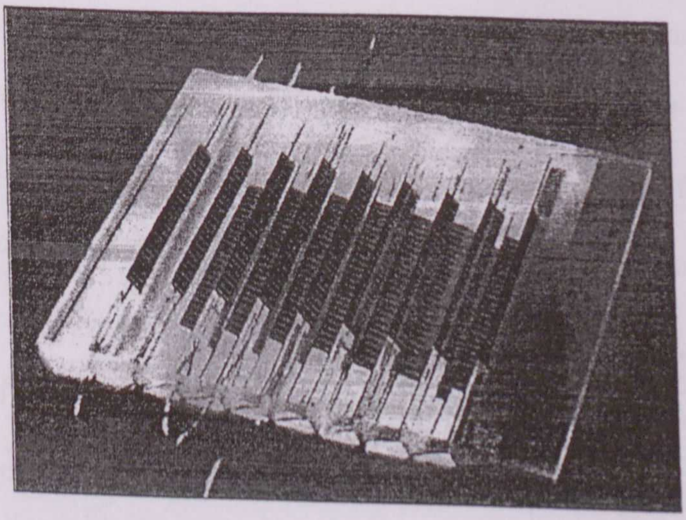


*Figure 2.13: photograph of a static prism-array concentrator module (Uematsu et al., 2001:420)*

In order to remove the trackers, a static solar concentrator is proposed by Masato & 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 (Masato & Toshiro, 2005).

## 2.5 Luminescent solar concentrator (LSC)

The luminescent planar solar concentrator was proposed in the late 1970s (Weber & Lambe, 1976; Goetzberger & Greubel, 1977; Rapp & Boling, 1978) consisting of a transparent plastic sheet doped with organic dyes. Sunlight is absorbed by the dye and then re-radiated isotropically, ideally with high quantum efficiency, and trapped in the sheet by internal reflection. A stack of sheets doped with different dyes can separate the light. Solar cells can be chosen to match the different luminescent wavelengths to convert the trapped light at the edge of the sheet (Goetzberger & Greubel, 1977).

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 2.14 and Figure 2.15, where they will be converted by appropriate photovoltaic cells (Richards, 2006; Reisfeld, 2001; Batchelder et al., 1979; Hammam et al., 2007)

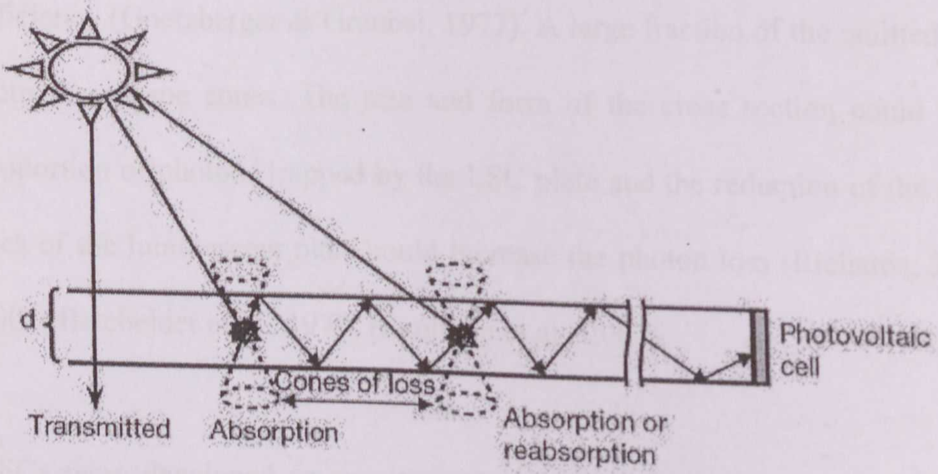


*Figure 2.14: schematic representation of luminescent solar concentrator (LSC) (Hammam et al., 2007:245)*

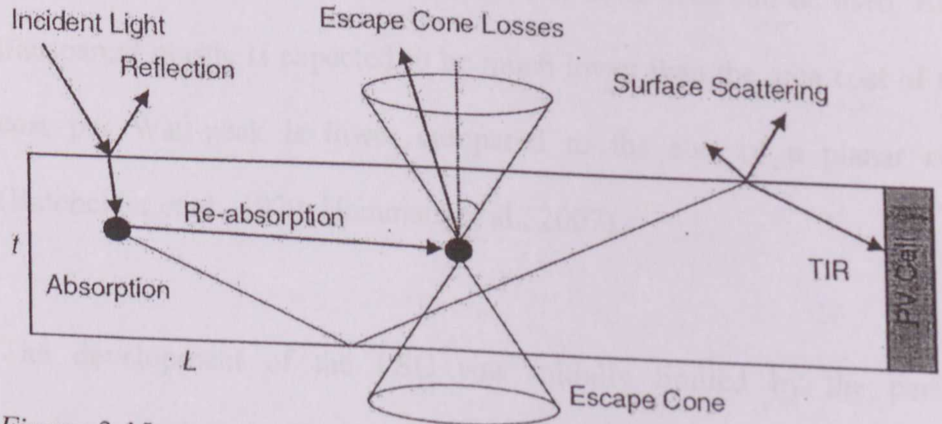


*Figure 2.15: more in detailed example of schematic representation of luminescent solar concentrator (LSC) (Richards, 2006:2335)*

Conversion of the incident solar spectrum to monochromatic light would greatly increase the efficiency of solar cells. Since LSC were proposed in 1970s, solar cells were attached to it. LSCs consist of a highly transparent plastic, in which luminescent species, originally organic dye molecules, are dispersed. These dyes absorb incident light and isotropically emit it at a red-shifted wavelength, with high quantum efficiency. Internal reflection ensures collection of part of the emitted light in the solar cells at the sides of the plastic body. The energy of the emitted photons ideally is only somewhat larger than the band gap of the attached solar cells, to ensure near-unity conversion efficiency (Goetzberger & Greubel, 1977). A large fraction of the emitted photons loses from the escape cones. The size and form of the cross section could impact on the proportion of photons trapped by the LSC plate and the reduction of the cross sectional area of the luminescent plate could increase the photon loss (Richards, 2006; Reisfeld, 2001; Batchelder et al., 1979; Hammam et al., 2007).

LSCs were developed as an alternative approach to lower the costs of PV. As both direct and diffuse light is concentrated by a factor of 5-10, without the need for expensive tracking, smaller silicon or other solar cells can be used. As the cost of the transparent plastic is expected to be much lower than the area cost of the solar cell the cost per Watt-peak is lower compared to the cost of a planar silicon solar cell (Batchelder et al., 1979; Hammam et al., 2007).

The development of the LSC was initially limited by the performance of the luminescent dyes available some decades ago. Nevertheless, efficiencies of up to 4% have been reported for a stack of two plates (40cm×40cm×0.3cm), one being coupled to a GaAs solar cell, and the other to a Si solar cell (Wittwer, Stahl, & Goetzberger, 1984). Particular problems were the poor stability of the dyes under solar irradiation and the large re-absorption losses owing to significant overlap of the absorption and emission. Within the fullspectrum project (Luque et al., 2005) the performance of both quantum dots and organic dyes are being evaluated as the luminescent species in the LSC. The important characteristics of organic dyes are that they: (i) can provide extremely high luminescence quantum efficiency (near unity), (ii) are available in a wide range of colours and, (iii) new molecular species are now available with better re-absorption properties that may also provide the necessary UV stability. quantum dots have advantages over dyes in that: (i) their absorption spectra are far broader, extending into the UV, (ii), their absorption properties may be tuned simply by the choice of nanocrystal size, and (iii) they are inherently more stable than organic dyes. Moreover, (iv) there is a further advantage in that the red-shift between absorption and luminescence is quantitatively related to the spread of quantum dot sizes, which may be determined during the growth process, providing an additional strategy for minimizing losses due to re-absorption (Barnham, Marques, Hassard, & Brien, 2000). However, as yet quantum dots can only provide reasonable luminescence quantum efficiency: luminescence quantum efficiency more than 0.8 has been reported for core-shell quantum dots (Peng, Schlamp, Kadavanich, & Alivisatos, 1997).

Advantages over geometric luminescent concentrators include that solar tracking is unnecessary and that both direct and diffuse radiation can be collected and, in addition, the sheets are inexpensive. However, the development of this promising concentrator was limited by the stringent requirements on the luminescent dyes, namely high quantum efficiency, suitable absorption spectra and red shifts and stability under illumination (Goetzberger, Stahl, & Wittwer, 1985; Wittwer, Goetzberger, Heidler, & Zastrow, 1981). Concentration ratios of 10× were achieved (Goetzberger et al., 1985; Wittwer et al., 1981). A typical measured electrical efficiency with a two-stack concentrator with GaAs solar cells was 4% (Goetzberger et al., 1985; Wittwer et al., 1981), whereas the original predictions were in the range 13 - 23% (Goetzberger & Greubel, 1977).

Barnham et al. (2000) have proposed a novel concentrator in which the dyes are replaced by quantum dots. The first advantage of the quantum dots over dyes is the ability to tune the absorption threshold simply by choice of dot diameter. For example, colloidal InP quantum dots, separated by dot size, have thresholds, which span the optical spectrum (Micic et al., 1997). Secondly, high luminescence quantum efficiency has been observed. CdSe/CdS hetero-structure dots have demonstrated luminescence quantum yields of above 80% at room temperature. Thirdly, since they are composed of crystalline semiconductor, the dots should be inherently more stable than dyes (Chattena, Barnhama, Buxtonb, Ekins-Daukesa, & Malik, 2003).

The disappointing results obtained with dye concentrators were probably mainly because of re-absorption, which was considered, but not modeled at the time of the original calculations (Goetzberger & Greubel, 1977). Barnham et al. (2000) have argued that there is a further advantage in that the red shift between absorption and luminescence is quantitatively related by the thermodynamic model to the spread of quantum dot sizes, which can be determined during the growth process. The ability to limit the overlap between the luminescence and absorption by the choice of quantum dot size distribution is a significant improvement compared to dye concentrators (Micic, Curtis, Jones, Nozik, & Sprague, 1994).

Goldschmidt et al. (2009) demonstrated how the collection efficiency of fluorescent concentrator systems is increased by two independent measures. One approach is to combine different dyes to enlarge the used spectral range. A system using the combination of two materials had an efficiency of 6.7%. The other approach is to increase the collection efficiency by the application of a photonic structure, which acts as a band stop reflection filter in the emission range of the dye. A relative efficiency increase of 20% with a commercially available filter was achieved. With the achieved efficiency of 3.1% and concentration ratio of 20, the realized fluorescent concentrator produces about 3.7 times more energy than that of the used GaInP solar cell produced on its own. Photonic structures are especially beneficial for larger systems. Goldschmidt et al. (2009) clarified the role of a white bottom reflector and its interaction with the photonic structure. The white bottom reflector increases the efficiency by two mechanisms. It increases the absorption of light in the fluorescent concentrator as it reflects non-absorbed light back into the fluorescent concentrator and it directly reflects light towards the solar cells. The second mechanism is especially important for small distances from the solar cell (Goldschmidt et al., 2009).

An LSC daylighting system has been produced by Earp, et al. (2004), which transports sunlight to remote areas of a building using a stack of pink, green and violet LSCs and clear PMMA (poly methyl methacrylate) light guides. In direct sun of intensity 100,000 LUX, prototypes with collector area of 1.2m×0.135m×0.002m deliver 1000 lumen of near-white light with a luminous efficacy of 311 lm/W and a light-to-light efficiency up to 6%. The light-to-light efficiency of the violet sheet is 0.29% and that of the green sheet is 5.8%. The light-to-light efficiency of the pink sheet is 1.5%. 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 (Earp, et al., 2004). A limitation in the wiring for long distance light transportation has emerged in this LSC system.

## 2.6 Fluorescent fiber and its usual applications

Although the fluorescent fiber have not experienced the dramatic commercial success for communications and lighting purposes, they have been continuously and enthusiastically studied. (Udd, 2002; Beller, 1998; Sorin, 1998). Fluorescent fibers are often used in radiation protection and measuring devices. Their working principle is similar as luminescent fibers. The fluorescent material absorbs high-energy alpha, beta and gamma radiation and converts that energy into forms that can be measured by conventional visible light detectors. Optical fiber sensors have unique advantages such as high sensitivity, immunity to electromagnetic interference (EMI), small size, lightweight, robustness, and the ability to provide multiplexed or distributed sensing (Peng & Chu, 2002). Since fluorescent fibers have not achieved a success in commercialization, there was hardly found any record for fluorescent fibers' application in remote indoor day-lighting purpose.

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).

Various ideas have been developed for applications (Yu & Yin, 2002; Grattan & Meggitt, 1998; Grattan & Meggitt, 1999; Othonos & Kalli, 1999; Marazuela & Moreno-Bondi, 2002). To date, some types of optical fiber sensors have been commercialized, but it is also true that, among the various techniques that have been studied, only a limited number of techniques and applications have been commercially successful. Optical fiber sensors have advantages such as immunity to EMI, lightweight, small size, high sensitivity, large bandwidth, and ease in signal light transmission. However, in many fields of application, optical fiber sensors should compete with other rather mature technologies such as electronic measurements. To appeal to users already accustomed to other mature technologies, the superiority of optical fiber sensors over other techniques needs to be clearly demonstrated. Typical users are not interested in specific techniques involved in measurement. They simply desire sensor systems having good performances with reasonable price except for very special uses. Hence, optical fiber sensor systems should be available in the form of complete systems including detecting and signal-processing electronics. In some cases such as electric protection relaying systems, the sensor systems are simply subsystems of rather larger systems. In some cases such as optical gyroscopes and optical current sensors, the optical fiber sensors should compete with other optical bulk sensors as well. Even with these difficulties, considerable efforts have been made to study of optical fiber sensors, and some of them are now nearing maturity (Yu & Yin, 2002; Grattan & Meggitt, 1998; Grattan & Meggitt, 1999; Othonos & Kalli, 1999; Marazuela & Moreno-Bondi, 2002). Some applications of optical fibers as fiber grating sensor, fiber-optic gyroscopes (FOGs), fiber-optic current sensors, and other sensors are briefly discussed below:

a) Fiber grating sensors

Although the formation of fiber gratings had been reported in 1978 (Hill, Fujii, Johnson, & Kawasaki, 1978), intensive study on fiber gratings began after a controllable and effective method for their fabrication was devised in 1989 (Meltz, Morey, & Glenn, 1989). Fiber gratings have been applied to add/drop filters, amplifier gain flattening filters, dispersion compensators, and fiber lasers and so on for optical communications.

studied, only a limited number of techniques and applications have been commercially successful. Optical fiber sensors have advantages such as immunity to EMI, lightweight, small size, high sensitivity, large bandwidth, and ease in signal light transmission. However, in many fields of application, optical fiber sensors should compete with other rather mature technologies such as electronic measurements. To appeal to users already accustomed to other mature technologies, the superiority of optical fiber sensors over other techniques needs to be clearly demonstrated. Typical users are not interested in specific techniques involved in measurement. They simply desire sensor systems having good performances with reasonable price except for very special uses. Hence, optical fiber sensor systems should be available in the form of complete systems including detecting and signal-processing electronics. In some cases such as electric protection relaying systems, the sensor systems are simply subsystems of rather larger systems. In some cases such as optical gyroscopes and optical current sensors, the optical fiber sensors should compete with other optical bulk sensors as well. Even with these difficulties, considerable efforts have been made to study of optical fiber sensors, and some of them are now nearing maturity (Yu & Yin, 2002; Grattan & Meggitt, 1998; Grattan & Meggitt, 1999; Othonos & Kalli, 1999; Marazuela & Moreno-Bondi, 2002). Some applications of optical fibers as fiber grating sensor, fiber-optic gyroscopes (FOGs), fiber-optic current sensors, and other sensors are briefly discussed below:

a) Fiber grating sensors

Although the formation of fiber gratings had been reported in 1978 (Hill, Fujii, Johnson, & Kawasaki, 1978), intensive study on fiber gratings began after a controllable and effective method for their fabrication was devised in 1989 (Meltz, Morey, & Glenn, 1989). Fiber gratings have been applied to add/drop filters, amplifier gain flattening filters, dispersion compensators, and fiber lasers and so on for optical communications.

Extensive studies have also been performed on fiber grating sensors and some of which have now reached commercialization stages (Othonos & Kalli, 1999).

b) Fiber-optic gyroscopes

It is generally recognized that the first demonstration of the FOG was achieved 33 years ago by Vali & Shorthill (1976), though there had been a few previous studies. The basic concept is based on the Sagnac interferometer and is quite simple. It is a good example of an application of special relativity. For a rotating optical fiber coil, two lights traveling in opposite directions in the coil experience different lengths, which results in different travel times and a phase difference in the two optical waves (Vali & Shorthill, 1976).

c) Fiber-optic current sensors

With the growth in the capacity of electric power systems, the role of protection relaying systems is becoming more important. Such a system can immediately recognize any sudden failures, such as a surge, and separate the failure parts from the power systems. These relaying systems require current sensors, referred to as current transformers or current transducers. Most current transducers currently in use are electromagnetic devices that suffer from magnetic saturation effects and residual field effects. Moreover, with the super increase in voltages (several hundred kV) in power distribution systems, the insulation of the current transducers becomes more difficult and expensive. Hence, optical current sensors that do not suffer from electromagnetic interference are good substitutes for conventional current transducers. In addition to protection relaying systems, the deregulation and growth of independent power producers and regional transmission companies have created a need for many new high voltage revenue-metering points (Sanders, Blake, Rose, Rahmatian, & Herdman, 2002).

In the transfer of power from a generation company to a regional transmission company, a 0.5% uncertainty in metering may result in an uncertainty of millions of dollars per year at a high power metering location. Hence the potential use of optical current transducers that provide high accuracy is promising (Sanders et al., 2002).

d) Others

Some other types of optical fiber sensors based on very simple concepts have been commercialized. Some examples include the displacement or pressure sensor based on the light coupling of two fibers, the liquid-level sensor based on frustrated total internal reflection, the pressure sensor using a wiggled (periodically bent) fiber, and the temperature sensor based on the detection of radiation from a heated sensor head (blackbody cavity) (Udd, 2002).

One of the most well-developed and commercialized in-line fiber sensors or diagnostic tools is Optical Time Domain Reflectometry (OTDR), which is based on the monitoring of the backscattering along the fiber. The concept is also quite old (Barnoski & Jensen, 1976) and the OTDR has become a standard technique for testing optical fiber links (Beller, 1998). It typically provides sub-meter spatial resolution but improved techniques can provide mm-order resolution. More complicated methods such as optical frequency domain reflectometry have been studied to achieve or sub-millimeter (~10 μm) spatial resolution (Sorin, 1998).

While OTDRs are generally aimed at monitoring optical fiber communication links, active research has also been done on distributed sensors for civil structure monitoring. One example is a distributed temperature sensor for monitoring concrete setting temperatures of a large dam (Thevenaz et al., 1999). The principle is based on the stimulated Brillouin scattering. An acoustic wave couples two counter-propagating beams, which are frequency-shifted by an amount that is dependent on temperature or strain. A commercialized distributed temperature and strain monitoring system shows the measurement range of up to 20 km with a spatial resolution of 0.8 m over 1 km (2–5 m at 10 km and 5–15 m at 20 km), a strain resolution of 20 μ ε (measurement range of up to 25 m ε ) and a temperature resolution of 1°C (Thevenaz et al., 1999).

Optical fiber acoustic sensors or optical fiber hydrophone systems have also been intensively studied and tested for marine or submarine applications (Peng & Chu, 2002). Fiber-optic low coherence interferometer has also been commercialized for civil applications (Inaudi & Casanova, 2002). The dynamic range of the commercialized deformation sensor using the method is of the order of a few tens of m ε for elongation (~5 m ε for shortening) (Thevenaz et al., 1999).

Cryogenic temperature sensing is also an attractive field for fiber-optic sensors (Lee & Lee, 2002). Fiber-optic chemical sensors or biosensors have been continuously studied. The principles are based on the monitoring of absorbance, reflectance, luminescence, reflective index change, or light scattering and aimed at the measurement of oxygen, pH, carbon dioxide, ammonia, detergents, biochemical oxygen demand, pesticides, and humidity (Marazuela & Moreno-Bondi, 2002; Orellana & Moreno-Bondi, 2002). In many cases optical fibers are simply used to guide light to the measurement point in the specimen. In some cases optical fibers are monitoring the response of a material deposited on the end of the fiber (Arregui, Galbarra, Matias, Cooper, & Claus, 2002). In some other cases well-developed sensor technologies such as FBG temperature sensors have been used for biological tests (Webb et al., 2000).

A good example of optical fiber chemical sensors in which the fiber itself plays a key role in the measurement is the use of LPGs (James, Rees, Tatam, & Ashwell, 2002; Allsop, Webb, & Bennion, 2002). An LPG can couple the core mode to a cladding mode. If the coating or jacket is removed from the optical fiber, the evanescent field of the cladding mode that exists outside the cladding experiences the refractive index change of the outside material. The sensitivity can be adjusted by fiber etching (Kim, Jeong, Kim, Kwon, Park, & Lee, 2000).

## 2.7 Summary

This chapter has introduced the dayligting related devices such as light pipes (or tubular daylight guidance systems), optical fibers for light transport, conventional solar concentrators, and luminescent solar concentrators (LSC). The common applications of fluorescent fibers have also been reviewed in this chapter since their application for remote indoor daylighting purpose has not been found in literatures. The principles of work, advantages and disadvantages for application of these daylighting related devices have been explained. Daylight has a disadvantage of not being able to reach deeper areas in a building such as storerooms, basements, and corridors, and it also brings the heat gain with the light. Light pipes and optical fibers were expected to transfer daylight to unreached areas, but light pipes have their difficulties in wiring and the optical fiber needs a pointolite for the light transportation. Solar concentrators are only sensitive for the beam radiation and they function poorly in overcast sky conditions. Even under a clear sky condition, trackers are always needed for conventional solar concentrators. Static concentrators always come with a poor concentration rate without a tracker, and the light concentrated by normal luminescent solar concentrators could not be transported by optical fibers to a remote place since the light produced by LSCs is not a pointolite.

The objectives of this research are determined based on the problems identified during the literature review as discussed in Chapter 3. The explaination on the need for FFSC as presented in Chapter 4 is based on the limitations of daylighting related devices as identified through the literature review. The next chapter, Chapter 3, provides a discussion on the research methodology of this study.

# Chapter 3

# Research Methodology

## 3.1 Overview of research process

In this chapter, the research methodology is discussed. This research starts with a literature review on daylighting related devices. The principles of work, advantages and disadvantages for application of these daylighting related devices have been studied. To seek for an alternative way in mitigating the limitations relevant in the studied devices, a new concept, which is to use fluorescent fibers for solar concentration and to use clear optical fiber bundles to transport the absorbed daylight into a target area for remote indoor daylighting purpose, is proposed and developed by the author. Accordingly, a new device named "fluorescent fiber solar concentrator" (FFSC) is designed and fabricated in this study based on the concept. The details about the design are explained in Chapter 4. To assess the performance of the fabricated new device for remote indoor daylighting purposes, the FFSC was mounted on a University building and a 6-month trial run was conducted for it. The detailed experimentation procedures and instrumentation are discussed in Chapter 5. Figure 3.1 illustrates the steps that have been made in the research.

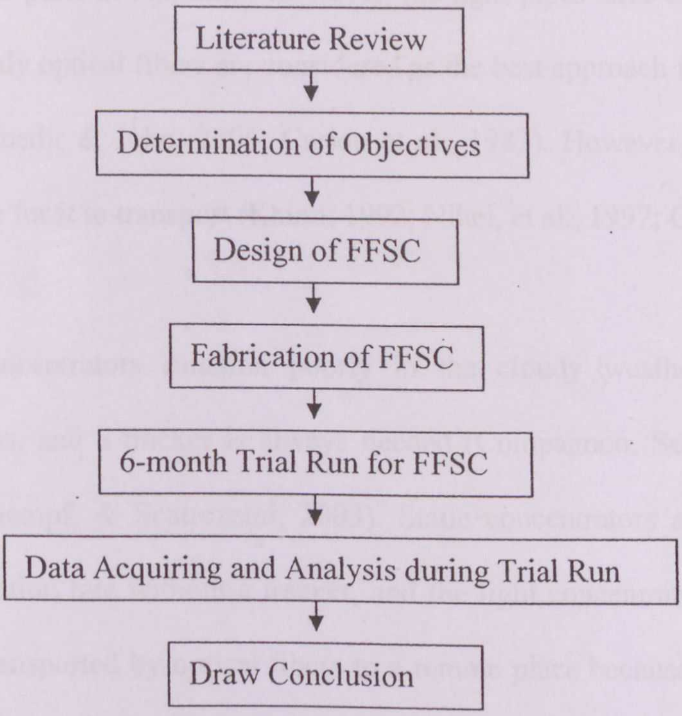


*Figure 3.1: overview of research process*

### 3.2 Determination of objectives

Objectives are the breakdown of the aim, which focuses on searching out or establishing certain issues, which will directly achieve the aim in the ultimate stage (Creswell, 1994; Fellows & Liu, 2003). Objectives of this research are raised based on the problems identified during the literature review. In solar energy applications, various methods have been developed to collect, concentrate, transport, store, and convert solar irradiation. However, there are many limitations relevant in such devices, such as the strict dependence on beam irradiation and the difficulties for wiring (Enedir & John, 2006; Cariou et al., 1982). Daylight may not able to reach many areas such as store rooms, basements, and corridors. It also brings heat gain with the light (Bouchet &

Fontoynont, 1996; Shao et al., 1998). Light pipes were designed to transport daylight to the deeper parts in buildings. However, the light pipes have their difficulties for wiring so that only optical fibers are considered as the best approach for daylight transportation so far (Enedir & John, 2006; Cariou et al., 1982). However, an optical fiber needs a pointolite for it to transport (Kaino, 1992; Nihei, et al., 1997; Cariou et al., 1982).

Solar concentrators function poorly in the cloudy weather and the diffuse light conditions, and a tracker is always needed (Compagnon, Scartezzini, & Paule, 1993; Page, Kaempf, & Scatrezzini, 2003). Static concentrators always come with a poor concentration rate without a tracker, and the light concentrated by normal LSCs could not be transported by optical fibers to a remote place because the light produced by an LSC is not a pointolite (Compagnon, et al., 1993; Page, et al., 2003; Beckman et al., 2003; Kandilli, Ulgen, & Hepbasli, 2007). An alternative way to mitigate the limitations inherited in the present daylighting related devices is needed to be proposed. Accordingly, the author proposed a new concept, which is to use fluorescent fibers for solar concentration and to use clear optical fiber bundles to transport the concentrated daylight into a target area for the remote indoor daylighting purpose. The objectives of this research are therefore determined as follows:

a) to identify the working principles and to extract the limitations of the present daylighting related devices, and

b) to develop a new concept to avoid or to mitigate the limitations of the present daylighting related devices and to fabricate a device based on the new concept, and

c) to assess the performance of the fabricated new device for remote indoor daylighting purposes through its trial run.

### 3.3 Qualitative and quantitative research

It is appropriate to define the classification of the approaches for obtaining data. Some commonly applied research strategies are proposed by Denscombe (1998), namely: survey, case study, experiment, and action research. The above-mentioned research strategies can be classified as the quantitative research and the qualitative research (Denscombe, 1998). Quantitative research has an enquiry arised based on the hypothesis tested or a theory variable. It is a measurable statistical approach to determine whether or not the particular theory holds true (Creswell, 1994; Melville, 1996). Creswell (1994) describes that the quantitative research deals with countable, tangible and solid data that can be recorded easily as documentation. In a quantitative research, the measurement must be objective, quantitative, and statistically valid, and it is about numbers and objective hard data (Creswell, 1994; Bouma, Atkinson & Dixon, 1995).

Likewise, qualitative research focuses more on one's professionalisms, knowledge, experiences and it is subjective in nature (Melville, 1996; Creswell, 1994). It requires a wide range of explanatory format of discussion in obtaining the descriptive data. Qualitative research is collecting, analyzing, and interpreting data by observing what people do and say. Whereas, quantitative research refers to counts and measures of things, but qualitative research refers to the meanings, concepts, definitions, characteristics, metaphors, symbols, and descriptions of things (Creswell, 1994).

Qualitative research is much more subjective than quantitative research and it uses very different methods of collecting information. The nature of this type of research is exploratory and open-ended (Melville, 1996; Neuman, 2003; Bouma et al., 1995).

Basically, quantitative research is objective and qualitative research is subjective. Quantitative research seeks explanatory laws; qualitative research aims at in-depth description. Qualitative research measures what it assumes to be a static reality in hopes of developing universal laws. Qualitative research is an exploration of what is assumed to be a dynamic reality. It does not claim that what is discovered in the process is universal, and thus, replicable (Creswell, 1994; Melville, 1996; Bouma et al., 1995).

In this research, both the qualitative approach and the quantitative approach are employed. The new concept development process is based on the author's professionalisms, knowledge, and experiences and it is subjective, exploratory and open-ended in nature. According to Creswell (1994) and Melville (1996), the new concept development is a process of qualitative research. The detailed description of the new concept development and the new device design is provided in Chapter 4.

After the new concept is developed, a device named FFSC is fabricated accordingly. A 6-month trial run is conduced to assess the performance of the fabricated device for remote indoor daylighting purposes. The data acquired during this process is countable, tangible and solid that can be recorded easily as documentation. According to Creswell (1994) and Melville (1996), the process of FFSC trial run is classified as quantitative research. Therefore, the research conducted by the author is a combination of the qualitative research and the quantitative research. The detailed explanation on the experimentation procedures and instrumentation is presented in Chapter 5.

There are four types of quantitative research classified by the goals, namely: the exploratory research, the descriptive research, explanatory research, and instrumental research (Eng, 2007; Neuman, 2003; Fellows & Liu, 2003). The definitions of these types were explained in below:

a) Exploratory Research

Become familiar with the basic facts, setting and concerns. Create a general mental picture of conditions. Formulate and focus questions for future research. Generate new ideas, conjectures, or hypotheses. Determine the feasibility of conducting research. Develop techniques for measuring and locating future data (Neuman, 2003:29).

b) Descriptive Research

Provide the detailed, highly accurate picture. Locate new data that contradict past data. Create a set of categories or classify types. Clarify a sequence of steps or stages. Document a causal process or mechanism. Report on the background or context of a situation (Neuman, 2003:29).

c) Explanatory Research

Test a theory's predictions or principle. Elaborate and enrich a theory's explanation. Extend a theory to new issues or topics. Support or refute and explanation or prediction. Link issues or topics with a general principle. Determine which of several explanations is best (Neuman, 2003:29).

d) Instrumental Research

Construct/Calibrate research instruments, whether physical measuring equipment or as tests/data collection. In such situations the construction of instruments and data measurement in terms of meaning which renders the activity of scientific research. The evaluation will be based on theory (Fellows & Liu, 2003:11).

The quantitative process conducted by the author in the research is a combination of the types (c) and (d). After the new concept is generated and a device named FFSC is fabricated based on the concept, a 6-month trial run is conduced to test the performance of the fabricated new device. Many instruments such as the pyranometers, the LUX sensor, the spectrometer, and the data logger are calibrated and employed during the trial run. According to Neuman (2003) and Fellows & Liu (2003), this is classified as both (c) explanatory research and (d) instrumental research.

According to Neuman (2003), the process of the 6-month trial run is neither an exploratory research nor descriptive research because there is no general mental picture of conditions created during the trial run, there is no new data located to contradict past data, and there are no categories created or new types classified. There is no sequence of steps or stages clarified. No causal process or mechanism is documented. No background or context of a situation is reported.

In sum, the research conducted by the author is a combination of the qualitative research and the quantitative research. During the quantitative process, it combines the explanatory research and the instrumental research.

# Chapter 4

# Design of Fluorescent Fiber Solar Concentrator (FFSC)

## 4.1 The need for fluorescent fiber solar concentrator (FFSC)

In building integration, one of the important features of remote light transportation is the wiring method, and the wiring method is expected to be as simple as that of electrical wires (Enedir & John, 2006; Cariou et al., 1982). As discussed in Chapter 2, only optical fibers are competent for this requirement. For instance, an LSC developed by Earp, et al. (2004) is transported by polymer sheets instead of the optical fibers because the light produced by the LSC is not a pointolite. The polymer sheets have a disadvantage in wiring, which brings difficulties in building integration. It is also not energy-efficient to further concentrate the rectangular light produced by the LSC into a pointolite for the transportation through optical fibers to a remote place in a building. Such a problem is expected to be solved by an alternative method, such as the developed FFSC system.

Figure 4.1 illustrates the needs to develop FFSC. In Figure 4.1, there are two groups of solutions that are practised in the building sector for general energy issues, namely: the building energy saving approaches and the renewable energy application approaches, which are presented in the left branch and the right branch, respectively.

According to the left branch shown in Figure 4.1, as an approach for energy saving, daylight has a disadvantage of not being able to reach many areas of a building such as store rooms, basements, and corridors, and it also brings heat gain with the light (Bouchet & Fontoynont, 1996; Shao et al., 1998). Light pipes were designed to transport daylight to unreached areas, but light pipes have their difficulties for wiring, so that optical fibers are considered as the best approach for the daylight transportation so far. However, the optical fiber needs a pointolite for the light transportation. An alternative device, such as the FFSC is designed to fulfill this requirement.

The right branch in Figure 4.1 shows various solar concentrators that were designed using optical approaches such as using mirrors or lens for the solar energy concentration. Since they are only sensitive for the beam irradiation, they function poorly in the cloudy weather and the diffuse light conditions, and even if they are under a clear sky condition, trackers are always needed. Luminescent solar concentrators (LSC) and some static solar concentrators were then designed as the diffuse light solution and the static solution, respectively. Static concentrators always come with a low concentration rate without a tracker, and the light concentrated by normal LSCs could not be transported by optical fibers to a remote place since the light produced by an LSC is not a pointolite. The FFSC is expected to solve this problem as well.

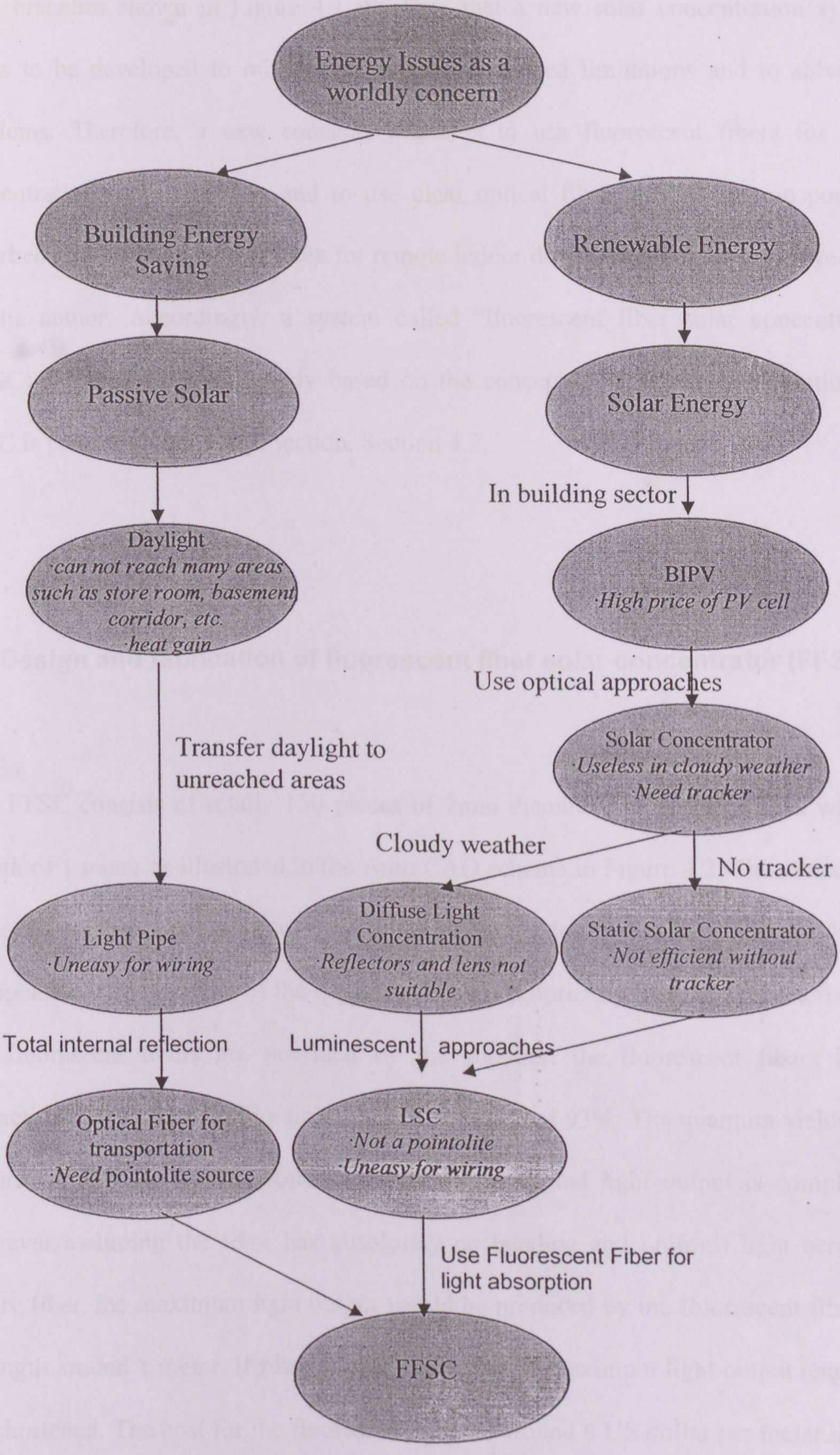


*Figure 4.1: from energy issues to solar applications: the needs for FFSC (concept developed by author)*

Both branches shown in Figure 4.1 illustrate that a new solar concentration system needs to be developed to mitigate the above-mentioned limitations and to solve the problems. Therefore, a new concept, which is to use fluorescent fibers for solar concentration and absorption and to use clear optical fiber bundles to transport the absorbed daylight into a target area for remote indoor daylighting purpose, is developed by the author. Accordingly, a system called "fluorescent fiber solar concentrator" (FFSC) is designed in this study based on the concept. The detailed description for FFSC is presented in the next section, Section 4.2.

## 4.2 Design and fabrication of fluorescent fiber solar concentrator (FFSC)

The FFSC consists of totally 150 pieces of 2mm diameter fluorescent fibers with the length of 1 meter as illustrated in the Auto CAD schema in Figure 4.2. The material for these fluorescent fibers is acrylic with quantum dots seeded in them. Detailed composition and structure of the quantum dots are proprietary, but the characteristics of the fluorescent fibers are provided by the supplier: the fluorescent fibers have a refractive index of 1.49 and a light transmission rate of 93%. The quantum yields of all colors range from 0.8-1.0. Relation between length and light output is complicated, however assuming the fiber has absolutely no bending and uniform light across the entire fiber, the maximum light output would be produced by the fluorescent fiber with a length around 1 meter. If fiber is coiled or bent, the maximum light output length will be shortened. The cost for the fluorescent fiber is around 6 US dollar per meter in 2007. The cost for the clear fiber is around 1 US dollar per meter in 2007.

The 150 pieces of fluorescent fibers consist of three colors (green, red, and yellow) as shown in Figure 4.3. There are 50 pieces for each color. The total 150 pieces of fluorescent fibers are symmetrically embedded in a 1200mm×1200mm Poly Methyl Methacrylate (PMMA) plate with a space of 2mm between each two pieces of fibers. The Auto CAD schema of FFSC is provided in Figure 4.2. The detail drawing of "Detail 1" in Figure 4.2 is illustrated in Figure 4.2a. The section view of "A-A" is shown in Figure 4.2b. The scaled drawings of FFSC are provided in APPENDIX C.

At both edges of the FFSC plate, each fluorescent fiber is connected with a 10m long 2mm diameter PMMA clear optical fiber by an aluminum bushing and fixed by a type of UV glue as shown in Figure 4.2a. The light absorbed by the fluorescent fibers is therefore transported by these clear fibers to a remote place for lighting or power production purposes.

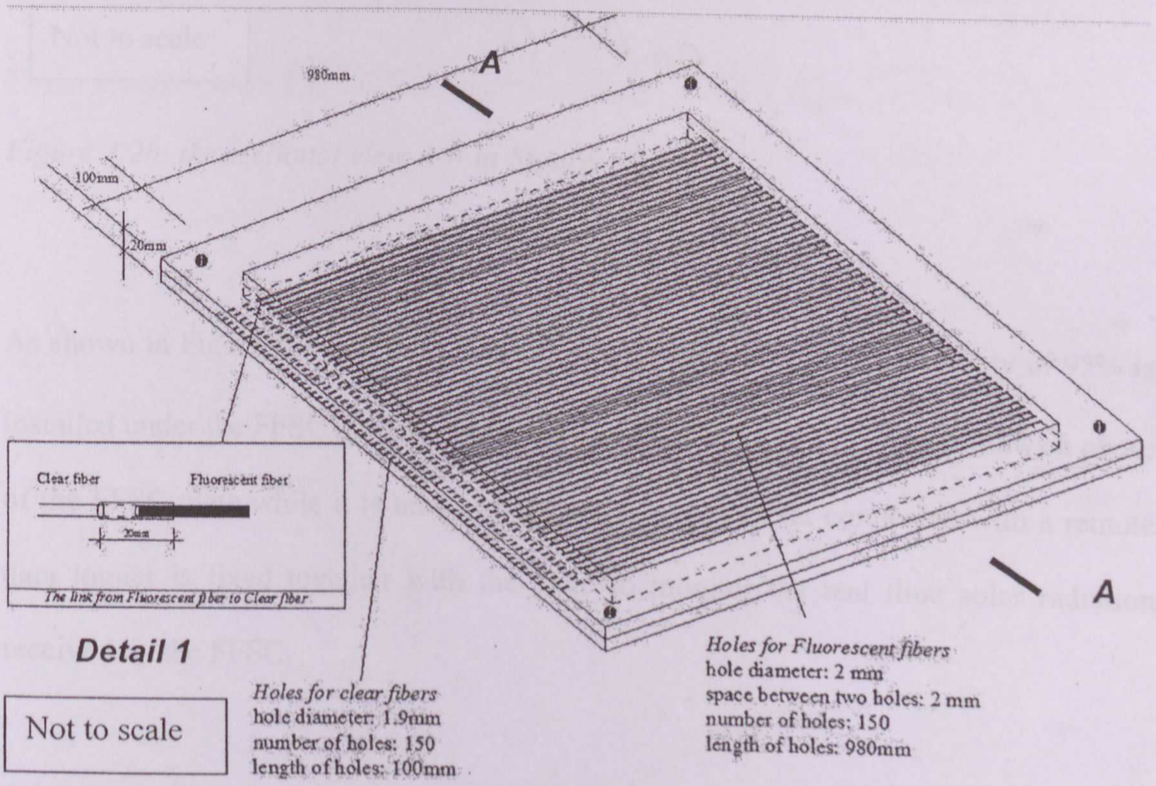


*Figure 4.2: Auto CAD schema of FFSC (concept developed by author)*

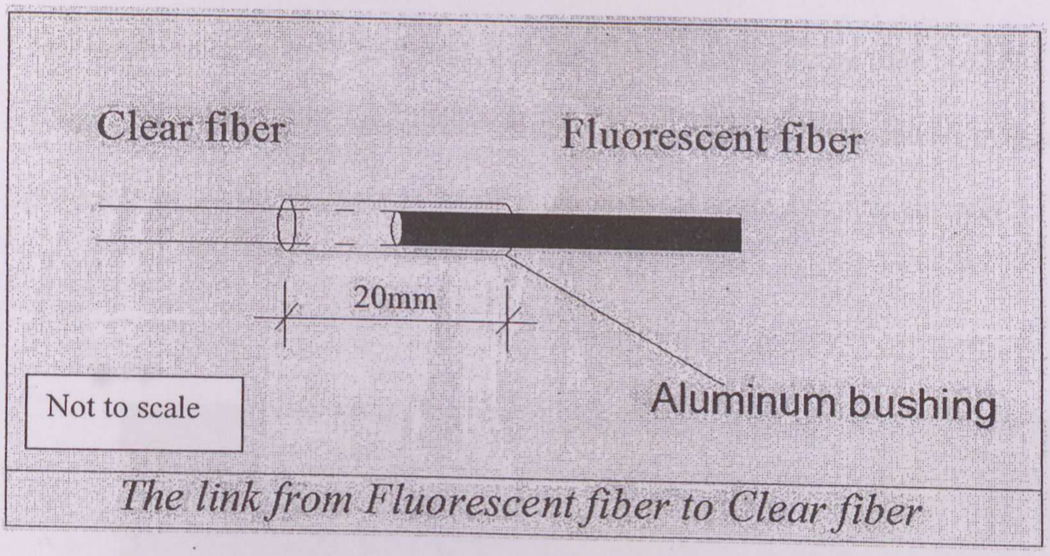


*Figure 4.2a: Detail 1 in Figure 4.2, the link from fluorescent fiber to clear fiber*

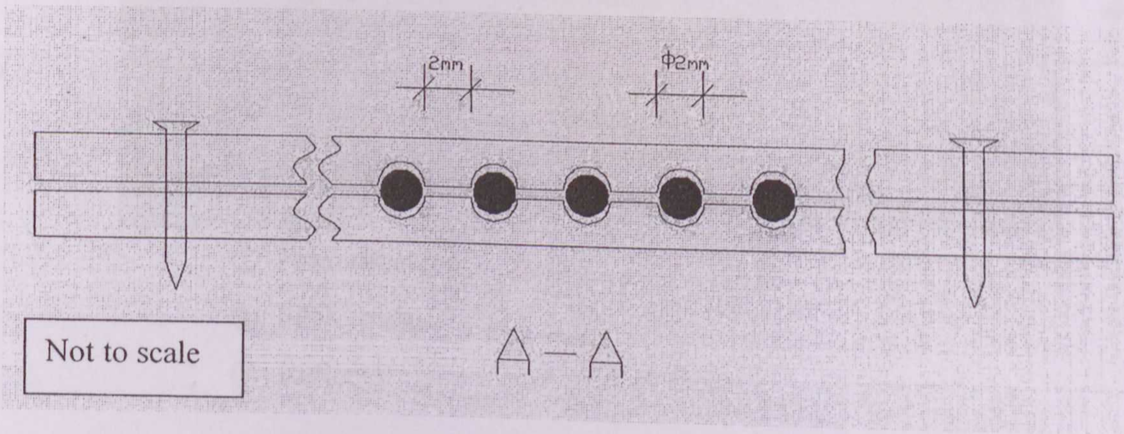


*Figure 4.2b: the sectional view A-A in Figure 4.2,*

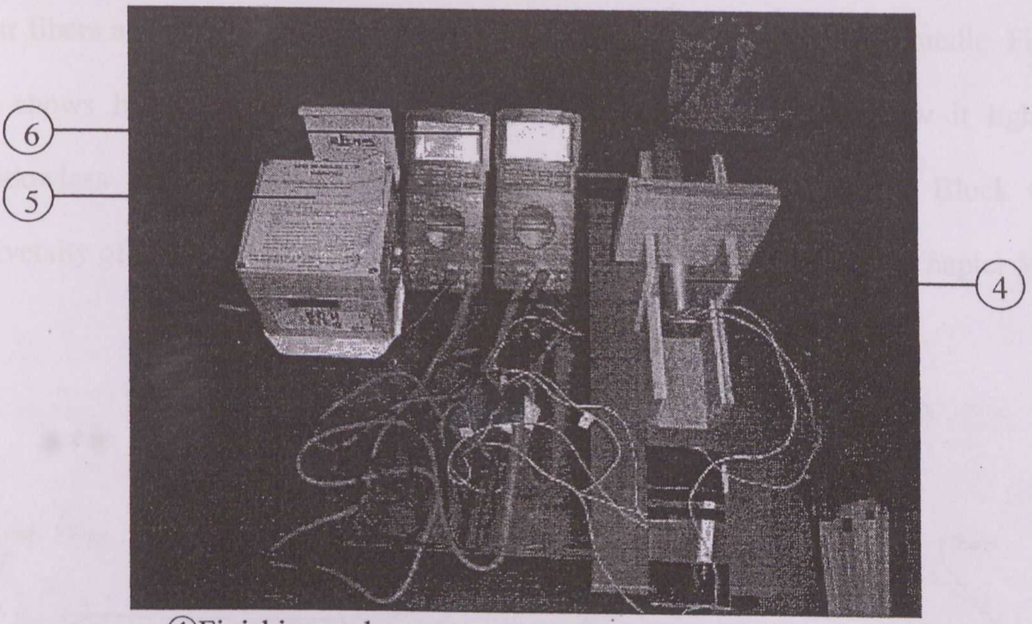
As shown in Figure 4.3, a 1.3m×1.3m silver-gilt reflector with a reflectivity of 95% is installed under the FFSC plate to increase the light absorption. Figure 4.3 shows a photo of the FFSC plate while it is under operation. A pyranometer connected with a remote data logger is fixed together with the plate to monitor the real time solar radiation received by the FFSC.

One reason for using fibers in three colors is trying to cover the full spectrum band (Earp, et al., 2004). Another reason for using three color fibers is because the transported light coming out of the finishing end could considerably mix into a near-white color light by self-scattering for illumination purpose (Yoshi, 2000; Schiler, 1992). The mixed light was observed as yellow-white light by naked eyes and was proved to match the daylight by a CIE color analysis as discussed in Chapter 7.

① Pyranometer 1
② FFSC plate
③ Reflector

*Figure 4.3: FFSC installed on the building roof (concept developed by author)*

The light concentrated by FFSC is transported by two clear fiber bundles with a diameter of 30mm for each, which is reasonably easy for wiring in the building integration. Each finishing end of the fiber bundles has an diameter of only 30mm, as shown in Figure 4.4 marked by serial number ④.



④Finishing end
⑤Data logger
⑥Multimeters

*Figure 4.4: equipments used for testing*

## 4.3 The principle of FFSC

The FFSC designed in this study consists of transparent acrylic fibers doped with appropriate quantum dyes. In brief, sunlight is absorbed by the fibers and then re-radiated isotropically by the quantum dots, ideally with high quantum efficiency, and trapped in the fibers by internal reflection. The micro operation of the FFSC is similar as that for luminescent solar concentrators that has been discussed by Weber & Lambe (1976), Goetzberger & Greubel (1977), and Rapp & Boling (1978). As elaborated in Figure 4.5, quantum yield species are dissolved in rigid highly transparent acrylic fibers of high refractive index. Solar photons entering the FFSC plate are absorbed by the luminescent species and reemitted in random directions. Following Snell's law, a large fraction of the emitted photons are trapped within the fibers and transported by total internal reflections to the edge of the fluorescent fibers, where they enter the edge of the clear fibers and are transported to the dark room through the clear fiber bundle. Figure 4.6 shows how the FFSC is mounted on the building roof and how it lights a windowless dark storeroom on the fourth floor of the building, the Block G22, University of Malaya. The building for FFSC installation is introduced in Chapter 5.

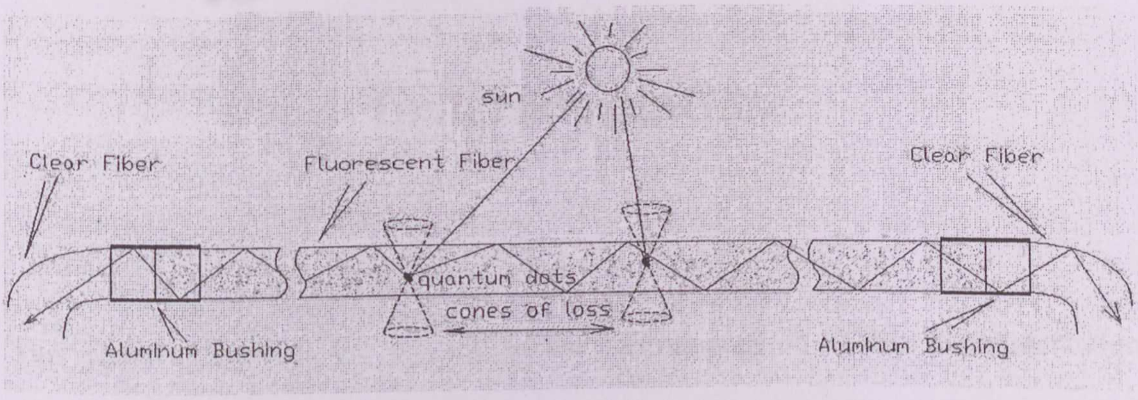


*Figure 4.5: principle of work for fluorescent fiber (drawn by the author)*

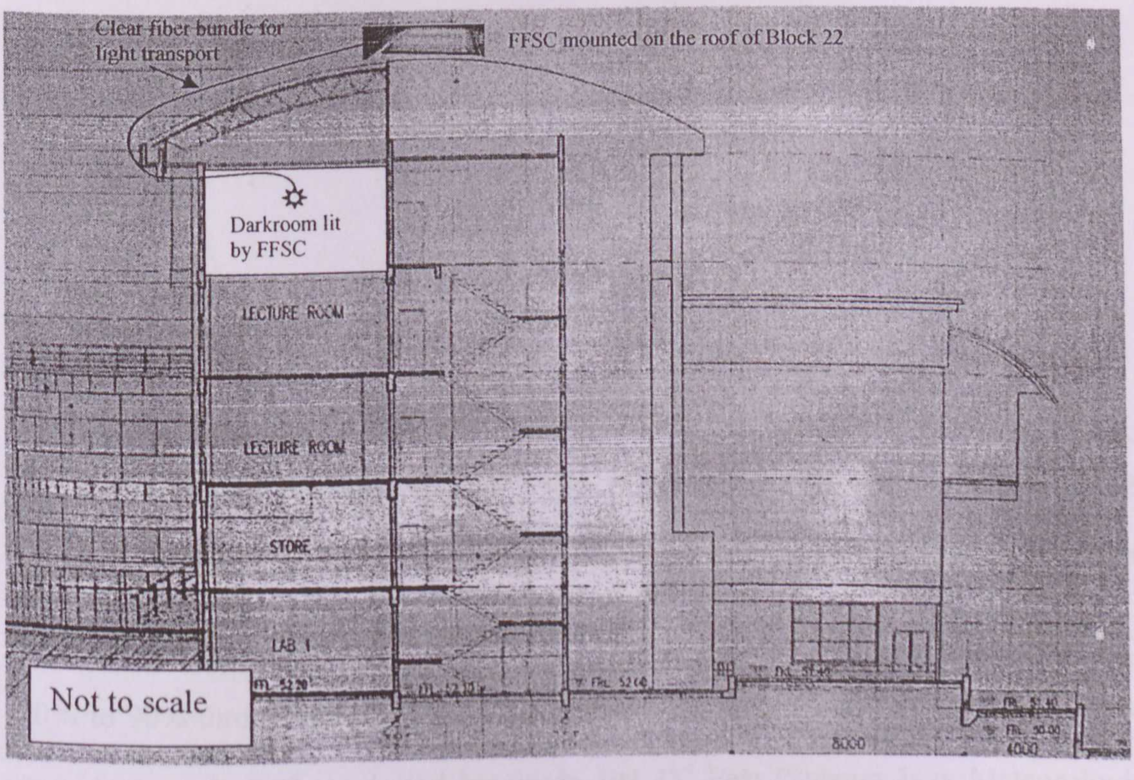


*Figure 4.6: working principle of FFSC that mounted on the roof of Block G22, University of Malaya (drawn by the author)*

# Chapter 5

# Experimentation Procedures and Instrumentation

This chapter describes the procedures and instrumentation of the experimentation, starting with a discussion on the Malaysian climate and the experimentation duration and followed by the explanation on the data collection approaches, apparatus, building context of the experimentations, data analysis approaches, and a critical discussion on experimentation limitations.

## 5.1 Malaysian climate and experimentation duration

The building used for the experimentation is located in the city of Kuala Lumpur, latitude 3.7° North and longitude 101.33° East in the tropical region (Chia, et al., 2006). Malaysia has a yearly mean temperature of 26°C to 27°C and relative humidity (RH) of 70% to 90% throughout the year (Sabarinah, 2006). Records of hourly solar radiation data for latitude 3.7° North and longitude 101.33° East (Subang Jaya Meteorological Station, Malaysia) received an annual maximum of more than 1000W/m2 on horizontal surface and about 850W/m2 on vertical surface for east and west facing surfaces. This is about 75% to 80% of the solar radiation outside the earth's atmosphere. (Dilshan, Hamdan, & Nor, 2006).

Malaysia is located in the tropical region. The climate is governed by the regime of the North-east and South-West monsoons, which blows alternatively during the course of the year. The north-west monsoon blows from approximately October until March, and the south-west monsoon blows between May and September. The period of change between the two monsoons is being marked by heavy rainfall. The period of south-west monsoon is a drier period. Hence, heavy rainfall, constantly high temperature and relative humidity characterize the Malaysia climate. Much of the precipitation occurs as thunderstorms and the normal pattern is one of heavy falls within a short period. Generally, chances of rain falling in the afternoon or early evening are high compared with that in the morning (Kamaruzzaman, 2006). The country experiences more than 170 rainy days per year; however, an area may have a greater number of rainy days and yet receive a lesser amount of rain in a year than another area with smaller number of rainy days but receiving its rain in heavy spells. Ambient temperature remains uniformly high over the country throughout the year.

The intensity of solar radiation in hot humid climates such as Malaysia is generally high and uniform throughout the year (Dilshan et al., 2006). Therefore, the duration from 24th May 2008 to 23rd November 2008, all together 6 months, which covers both the north-east monsoon and south monsoons, has been chosen for data monitoring. Since the daily intensity of sunshine in Malaysia is remarkably stable through a year according to Kamaruzzaman (2006) and Dilshan et al. (2006), the data in a random week from 2nd June 2008 to 8th June 2008 (Monday to Sunday) has been chosen for the hourly data analysis.

## 5.2 Experimentation for FFSC: data collection

The fabricated new device called Fluorescent Fiber Solar Concentrator (FFSC) is mounted horizontally (with a low gradient of around 3° to the horizontal to lead the rainwater out of the surface, the effect caused by the small gradient was not considered in the analysis) on the roof of a building roof and the concentrated light is transported by two 10m long clear fiber bundles into a remote windowless dark room. One pyranometer, which is denoted as Pyranometer 1 in the thesis, is installed with the FFSC plate to detect the solar radiation. The light radiation yielding out of a finishing end is measured by another pyranometer denoted as Pyranometer 2. The values measured by the Pyranometer 1 and Pyranometer 2 are marked as PY1 and PY2 respectively, and are recorded by a remote data logger at an interval of 10 minutes for 24 hours a day. The units for both PY1 and PY2 are W/m2.

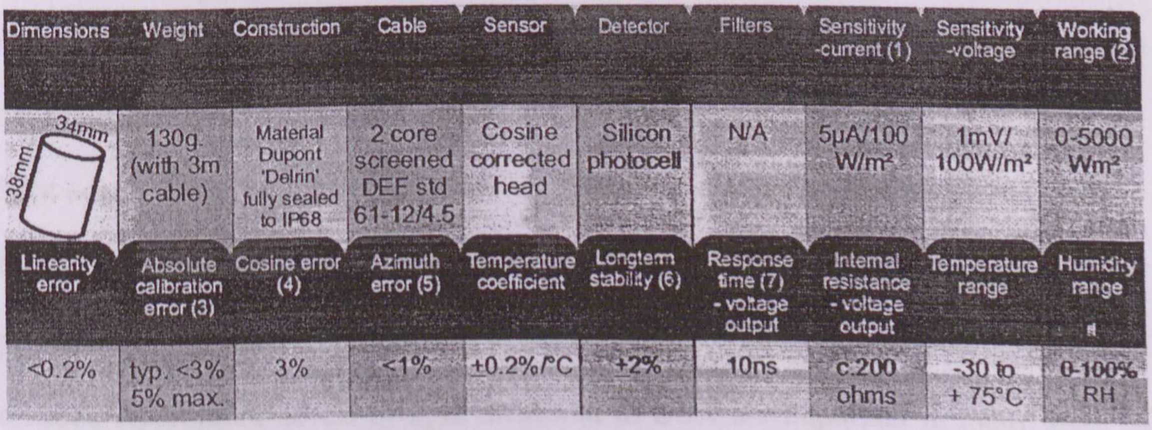
Another finishing end is installed upon a LUX sensor at a distance of 100mm. The values measured by the LUX sensor are marked as Ev and they are recorded by the remote data logger at an interval of 10 minutes for 24 hours a day. The unit for Ev is LUX. In addition, it should be noted that the direct display from the LUX sensor uses a unit of kLUX. In the analysis, the unit of Ev is converted from kLUX to LUX to be inline with the international common practice.

PY1 and PY2 were recorded from 24th May 2008 to 23rd November 2008, all together 6 months. Ev was recorded from 24th May 2008 to 12th June 2008, all together 20 days, because the finishing end used for the LUX sensor since 13th June 2008 had been used for other testing purposes until 23rd November, say, for wavelength monitoring and CIE (Commission Internationale de l'Eclairage, the International Commission on Color) color analysis.

## 5.3 Experimentation for FFSC: instrumentation

### *5.3.1 The pyranometers*

The SKS1110 Pyranometer sensor has been chosen in the experimentation because it is the widest selling unit in the Skye instruments' range of sensors. It gives much greater output than thermopile instruments, which, with its better temperature stability, makes it easier to use. The sensors are calibrated against precision reference thermopile pyranometers in natural light conditions. The specifications of SKS1110 pyranometer are shown in Figure 5.1 and its responding range is from 400nm to 1100nm as shown in Figure 5.2. The calibration files are enclosed in APPENDIX E.



| Dimensions | Weight | Construction | Cable | Sensor | Detector | Filters | Sensitivity -current (1) | Sensitivity -voltage | Working range (2) |
|---|---|---|---|---|---|---|---|---|---|
| 34mm<br>38mm | 130g. (with 3m cable) | Material Dupont 'Delrin' fully sealed to IP68 | 2 core screened DEF std 61-12/4.5 | Cosine corrected head | Silicon photocell | N/A | 5μA/100 W/m² | 1mV/ 100W/m² | 0-5000 Wm² |

| Linearity error | Absolute calibration error (3) | Cosine error (4) | Azimuth error (5) | Temperature coefficient | Longterm stability (6) | Response time (7) - voltage output | Internal resistance - voltage output | Temperature range | Humidity range |
|---|---|---|---|---|---|---|---|---|---|
| <0.2% | typ. <3%<br>5% max. | 3% | <1% | ±0.2%/°C | ±2% | 10ns | c.200 ohms | -30 to + 75°C | 0-100% RH |

*Figure 5.1: specifications of SKS1110 pyranometer (provided by supplier)*

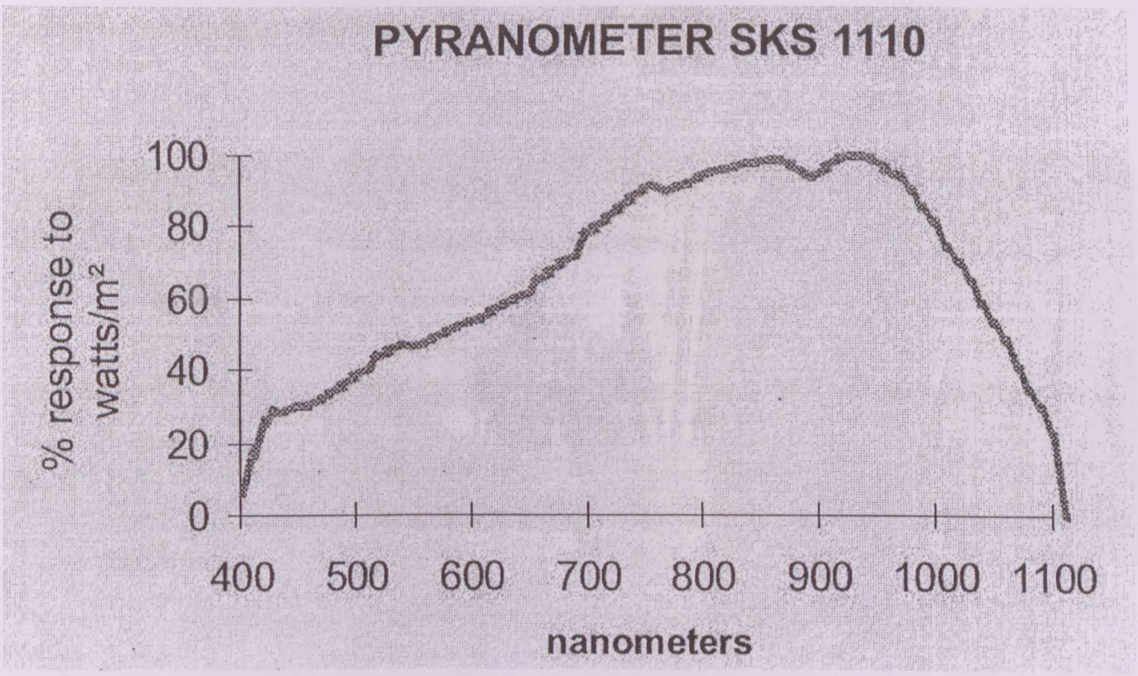
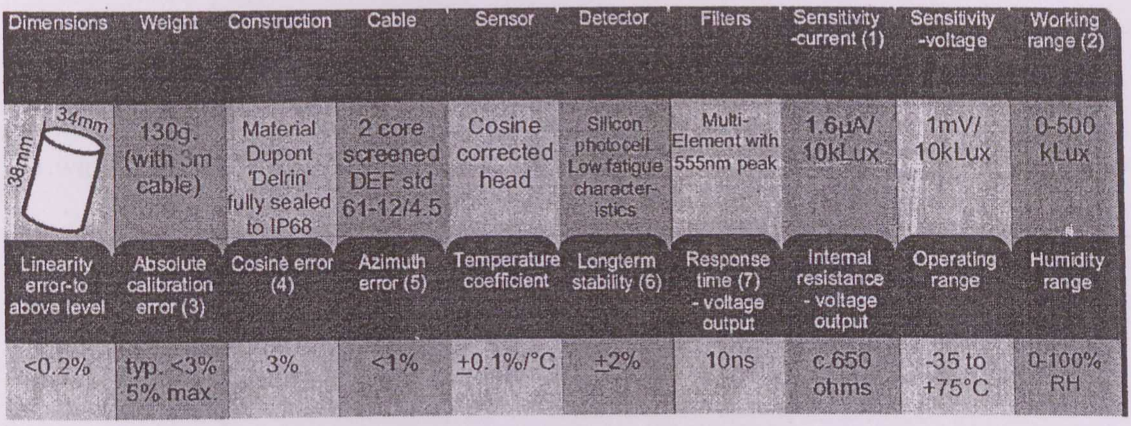


*Figure 5.2: response range of SKS1110 pyranometer (provided by supplier)*

### *5.3.2 LUX sensor*

The LUX sensor SKL 310 was chosen since its responding range from 350nm to 750nm is sufficient for the experimentation. Its specification is shown in Figure 5.3 and its responding range graph is shown in Figure 5.4. Visible light can be defined as the part of the wavelength spectrum perceived by the human vision in a manner similar to the eyes. This response to the human eyes to light can be expressed as a spectral response curve which has the form shown on reverse. There is a peak sensitivity at 555nm for the light adapted eye. This curve is known as the photopic curve or CIE Standard Observer Curve. The response curve for this filtered sensor is almost indistinguishable from the photopic curve shown on the reverse. Light falling within the curve is measured in LUX sensors. Appropriate levels of light measured in LUX are important in many areas of human activity such as close fieldwork, general reading, and relaxation and can have important psychological effects. The calibration files are enclosed in APPENDIX E.



| Dimensions | Weight | Construction | Cable | Sensor | Detector | Filters | Sensitivity -current (1) | Sensitivity -voltage | Working range (2) |
|---|---|---|---|---|---|---|---|---|---|
| 34mm<br>38mm | 130g. (with 3m cable) | Material Dupont 'Delrin' fully sealed to IP68 | 2 core screened DEF std 61-12/4.5 | Cosine corrected head | Silicon photocell. Low fatigue characteristics | Multi-Element with 555nm peak | 1.6μA/ 10kLux | 1mV/ 10kLux | 0-500 kLux |
| **Linearity error-to above level** | **Absolute calibration error (3)** | **Cosine error (4)** | **Azimuth error (5)** | **Temperature coefficient** | **Longterm stability (6)** | **Response time (7) - voltage output** | **Internal resistance - voltage output** | **Operating range** | **Humidity range** |
| <0.2% | typ. <3%<br>5% max. | 3% | <1% | ±0.1%/°C | ±2% | 10ns | c.650 ohms | -35 to +75°C | 0-100% RH |

*Figure 5.3: specifications of SKL310 LUX sensor (provided by supplier)*

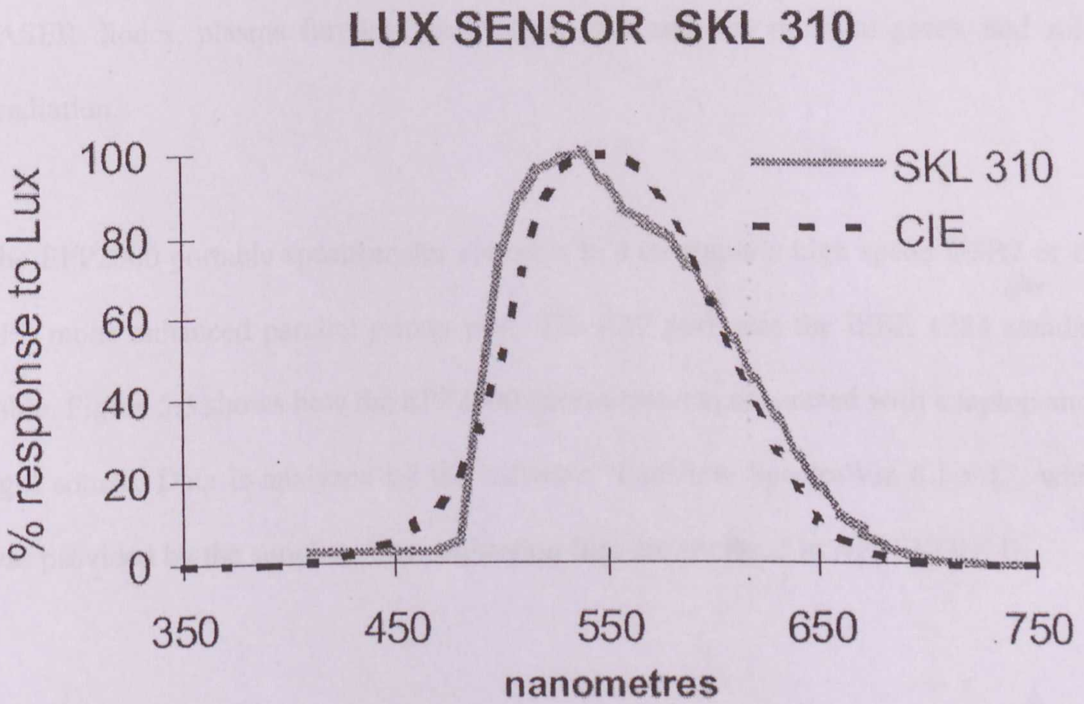


*Figure 5.4: response range of SKL310 LUX sensor (provided by supplier)*

### *5.3.3 Spectrometer*

The EPP2000 (portable) spectrometer is employed in the 6-month experimentation for the wavelength testing and the CIE color analysis. Table 5.1 briefs some information about this model. The EPP2000 spectrometer is a compact, fiber optic spectrometer instrument. It is used to make various types of spectral measurements in the UV-VIS-NIR ranges from 190-2200nm. When it is used for spectroscopy applications, the instrument provides wavelength information for compute sample absorbance, transmittance, reflectance and emittance (such as fluorescence, plasma, laser induced breakdown and Raman spectroscopy). The spectrometer could be used to measure spectral emissions from various light sources such as LED's (Light Emitting Diodes), LASER diodes, plasma furnaces, arc lamps, high and low pressure gases, and solar irradiation.

The EPP2000 portable spectrometer connects to a computer's high speed USB2 or the EPP mode enhanced parallel printer port. The EPP port uses the IEEE 1284 standard cable. Figure 5.5 shows how the EPP2000 spectrometer is connected with a laptop and a light source. Data is analyzed by the software "LabView SpectraWiz 6.1 v.1", which was provided by the supplier. The calibration files are enclosed in APPENDIX E.

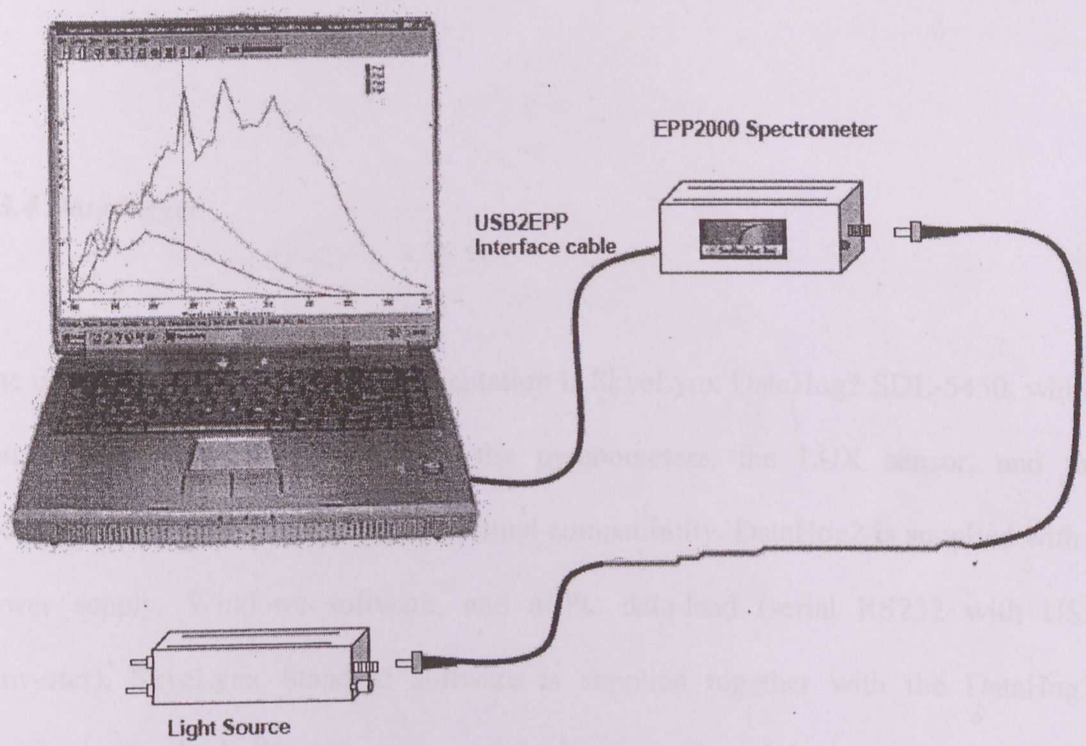


*Figure 5.5: EPP2000 Spectrometer connected with laptop and light source*

**Table 5.1: information of the spectrometer used in experimentation (provided by supplier)**

| | |
|---|---|
| Product name: | Miniature Fiber Optic Spectrometer |
| Product type: | Spectrum Analyzer |
| Product models: | EPP2000 |
| Safety: | EN61010-1, EN61010-2-031, IEC61010-3-1 |
| EMC: | EN61326 + A1 |
| Supplementary information: | The product complies with the requirements of the Low Voltage Directive 73/23/EEC-93/68/EEC, and the EMC Directive 89/336/EEC-92/31/EEC and 93/68/EEC. |

### *5.3.4 Data logger*

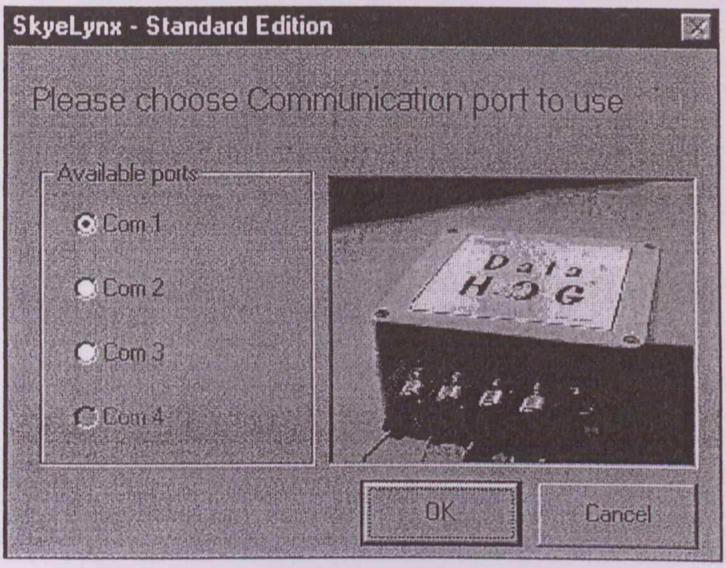
The data logger used in this experimentation is SkyeLynx DataHog2 SDL-5450, which comes from the same supplier of the pyranometers, the LUX sensor, and the spectrometer, for the purpose of the optimal compatibility. DataHog2 is supplied with a power supply, Windows software, and a PC data-lead (serial RS232 with USB converter). SkyeLynx Standard software is supplied together with the DataHog2. SkyeLynx Standard allows the setup and the configuration of the logger or meter, plus the downloading of the data stored in the instrument's memory. Data can be transferred to a PC hard drive in an ASCII numerical format compatible with the word processors and spreadsheets such as Microsoft Word and EXCEL. The software version "SkyeLynx Standard v2.6" provided by the supplier is used for the data analysis during the FFSC trial run.

Measurements direct from the DataHog2 and sensors can be viewed using the SkyeLynx Standard software. These measurements are stored using the "Log on Demand" function. A system check of the logger battery and memory status can be performed on screen. All these functions are accessed via the logging meter's own display.

All files are created in ASCII space delimited format. Each file contains an instrument identifier. Each measurement has a real time and date stamp. DataHog2 uses the

"Off-Load" button for automatic fast data downloading or use the software main menu "Offload data" option and "Capture File" feature.

When the program SkyeLynx Standard starts to run, firstly the choice of Com Ports are made. The "Com 1" of the computer is selected as the required port for this experimentation, as shown in Figure 5.6.



SkyeLynx - Standard Edition

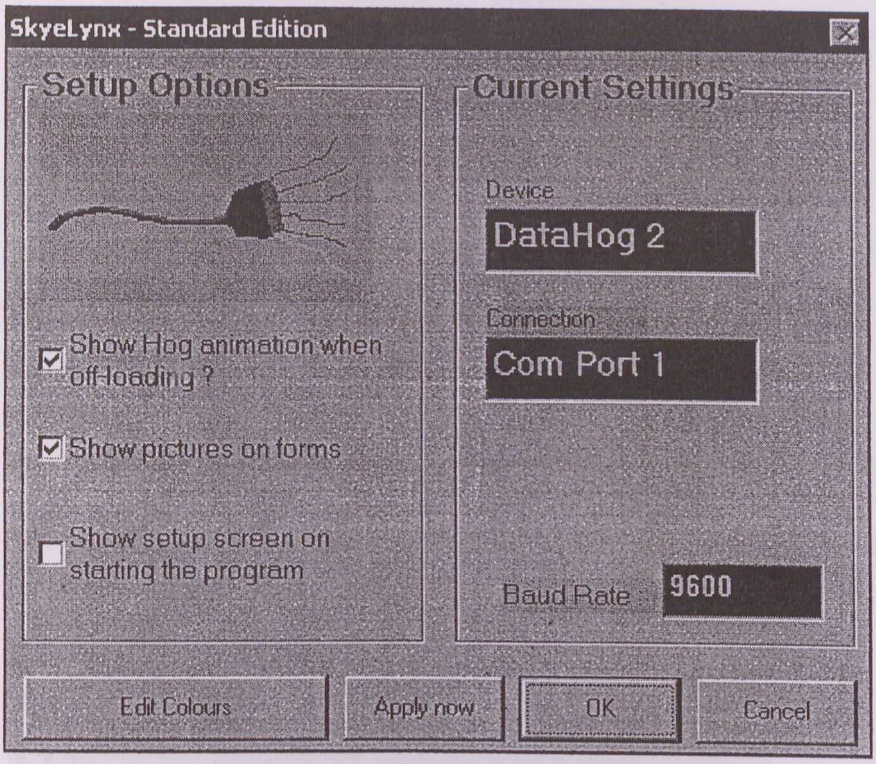
Please choose Communication port to use

Available ports

● Com 1
○ Com 2
○ Com 3
○ Com 4

*Figure 5.6: "Com 1" was configured to DataHog2*

After that, the screen colors, and the options to see pictures and animations in the program are also specified as shown in Figure 5.7.


SkyeLynx - Standard Edition

Setup Options

☑ Show Hog animation when off-loading ?

☑ Show pictures on forms

☐ Show setup screen on starting the program

Current Settings

Device: DataHog 2

Connection: Com Port 1

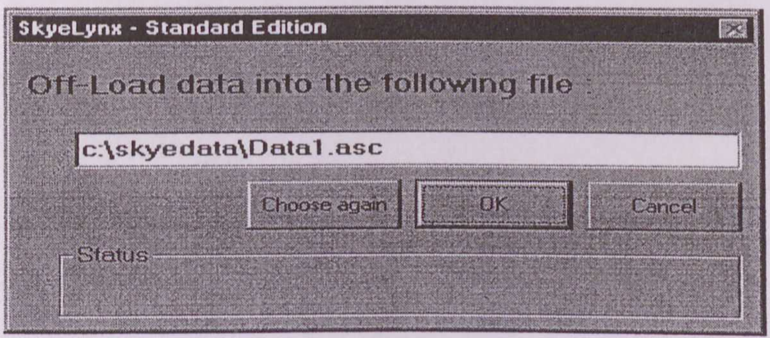
Baud Rate: 9600

*Figure 5.7: pictures and animations options are selected*

The settings for channel configurations and logging intervals are done before it starts working. The Channel 1 is configured for Pyranometer1 and the Channel 2 for Pyranometer2. The Channel 3 is configured for the LUX sensor. All intervals are set into 10 minutes.

In the 6-month experimentation for FFSC, data are captured and stored directly in Microsoft EXCEL files for analysis. The function of "Capture File" is often used. Everything displayed in the main screen after the file is opened are written into the file. This is a useful way of recording details from the logger. For instance, if a capture file is opened, then through various menus on the SkyeLynx Standard program, all sorts of details for later viewing are record. This method is used for off-loading data. The capture file is closed before anything else in the program could be done. If the file already exists, it will be asked if it wish to append to the end of the existing file, or to overwrite it. During the experimentation, the options “append” are always selected so that any new data off-loaded are added to the end of the existing file. Sometimes the data file is getting very big so that the computer process may take a long time because of the groups of new data inserted. Therefore, a new capture file is always created for each 4 or 5 days’ period.

Data off-loading allows DataHog2 to download the data into a file on a PC. A fast Off-Load response box is shown in Figure 5.8. This is where the data is read from the logger in the binary mode, and then decoded on a PC.


SkyeLynx - Standard Edition

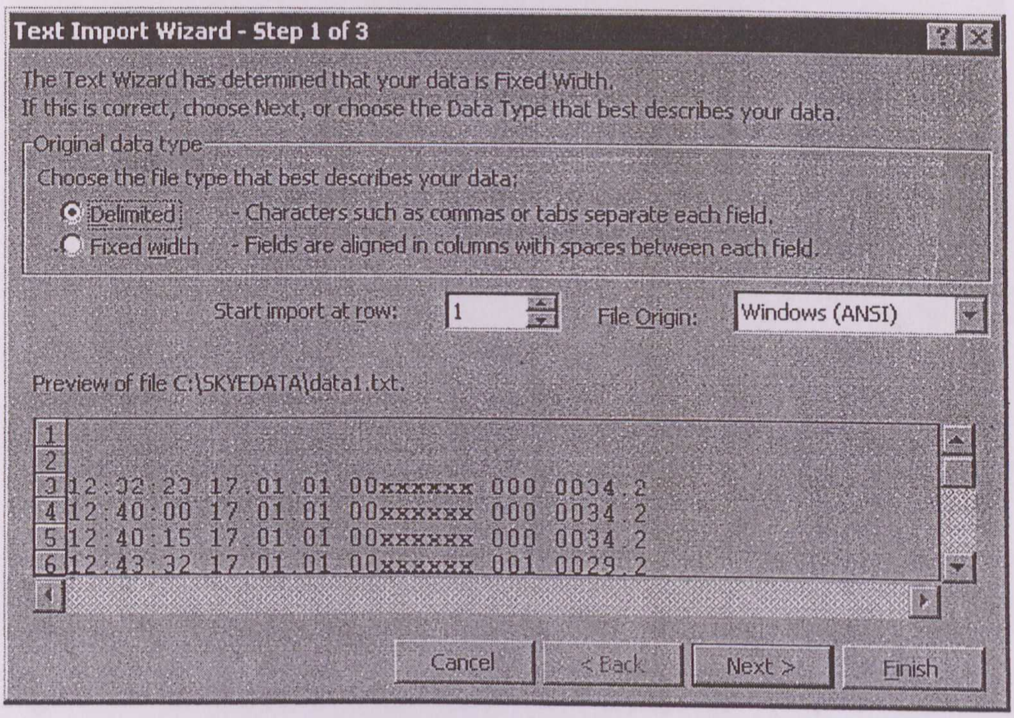
Off-Load data into the following file :

c:\skyedata\Data1.asc

*Figure 5.8: data offloading dialogue box in DataHog2*

After each time data off-loading, the DataHog2 is returned to the logging mode manually. This allows the device to return to its logging state, where it is recording data. The logger is always left in this mode; otherwise, it will not record any new information.

The off-loaded data from the DataHog2 are imported into Microsoft EXCEL for manipulating. Firstly, the offloaded ASCII data file are captured in EXCEL as a space delimited file and then are transferred manually into a workable format through 3 steps as demonstrated in Figure 5.9. Figure 5.10, and Figure 5.11. This brings the data into a spreadsheet as shown in Figure 5.12. Data in this format are then workable for the analysis purpose.



Text Import Wizard - Step 1 of 3

The Text Wizard has determined that your data is Fixed Width.
If this is correct, choose Next, or choose the Data Type that best describes your data.

Original data type

Choose the file type that best describes your data:

● Delimited - Characters such as commas or tabs separate each field.
○ Fixed width - Fields are aligned in columns with spaces between each field.

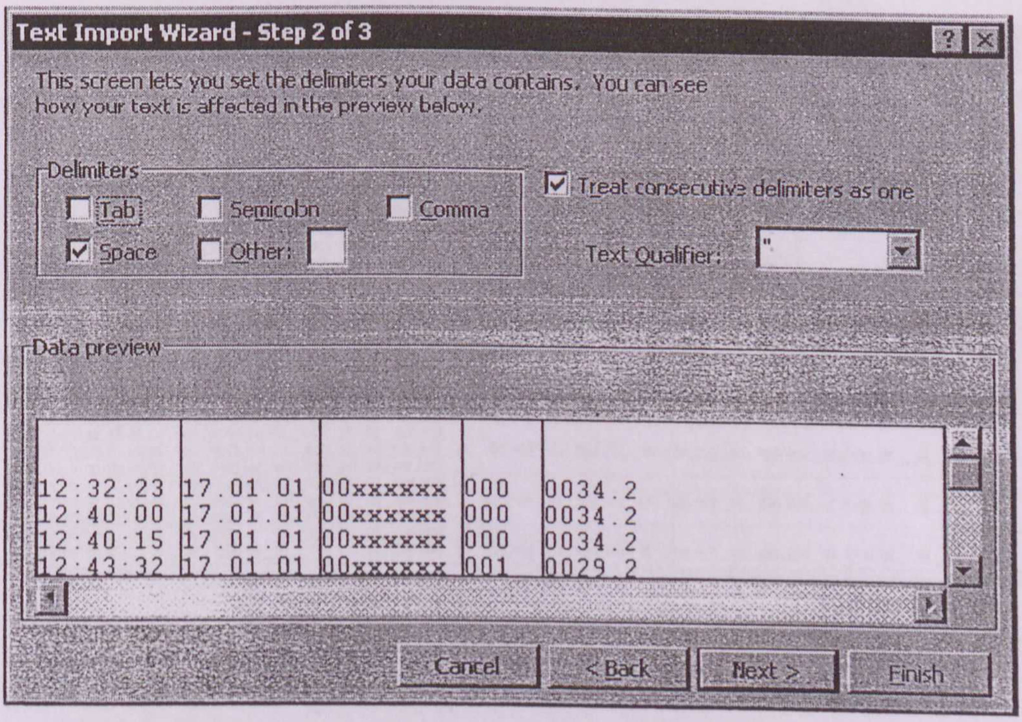
Start import at row: 1

File Origin: Windows (ANSI)

Preview of file C:\SKYEDATA\data1.txt.

```
1
2
3 12:32:23 17.01.01 00xxxxxx 000 0034.2
4 12:40:00 17.01.01 00xxxxxx 000 0034.2
5 12:40:15 17.01.01 00xxxxxx 000 0034.2
6 12:43:32 17.01.01 00xxxxxx 001 0029.2
```

*Figure 5.9: data export into Microsoft EXCEL, Step1 of 3 (displayed data only for demonstration)*



Text Import Wizard - Step 2 of 3

This screen lets you set the delimiters your data contains. You can see how your text is affected in the preview below.

Delimiters

☐ Tab ☐ Semicolon ☐ Comma
☑ Space ☐ Other:

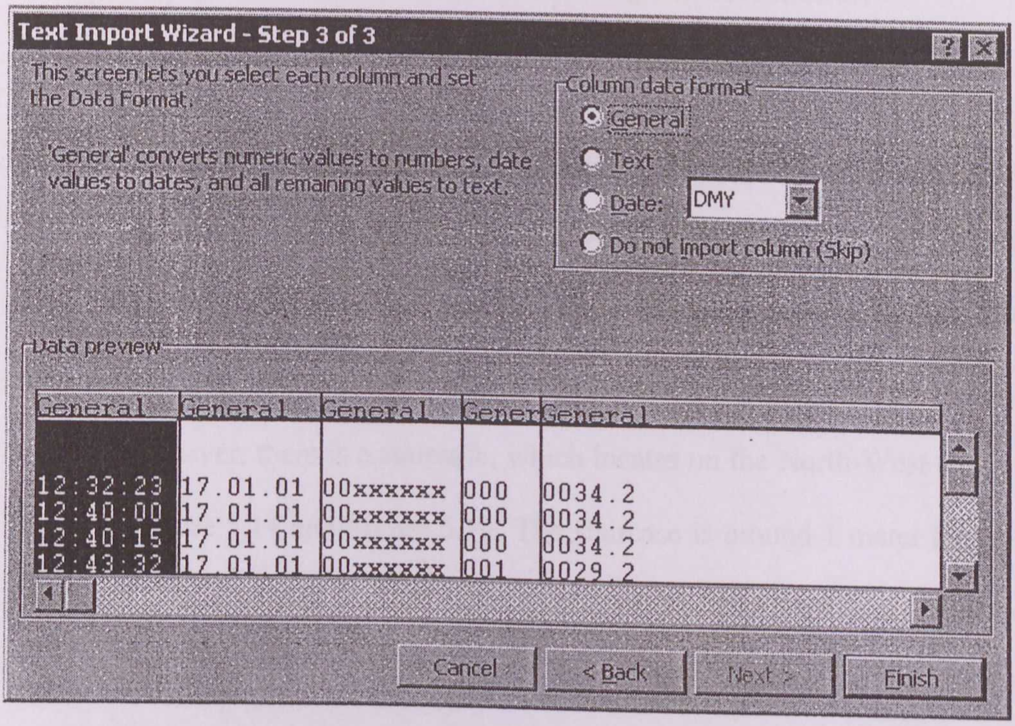
☑ Treat consecutive delimiters as one

Text Qualifier: "

Data preview

```
12:32:23 17.01.01 00xxxxxx 000 0034.2
12:40:00 17.01.01 00xxxxxx 000 0034.2
12:40:15 17.01.01 00xxxxxx 000 0034.2
12:43:32 17.01.01 00xxxxxx 001 0029.2
```

*Figure 5.10: data export into Microsoft EXCEL, Step2 of 3 (displayed data only for demonstration)*


**Text Import Wizard - Step 3 of 3**

This screen lets you select each column and set the Data Format.

'General' converts numeric values to numbers, date values to dates, and all remaining values to text.

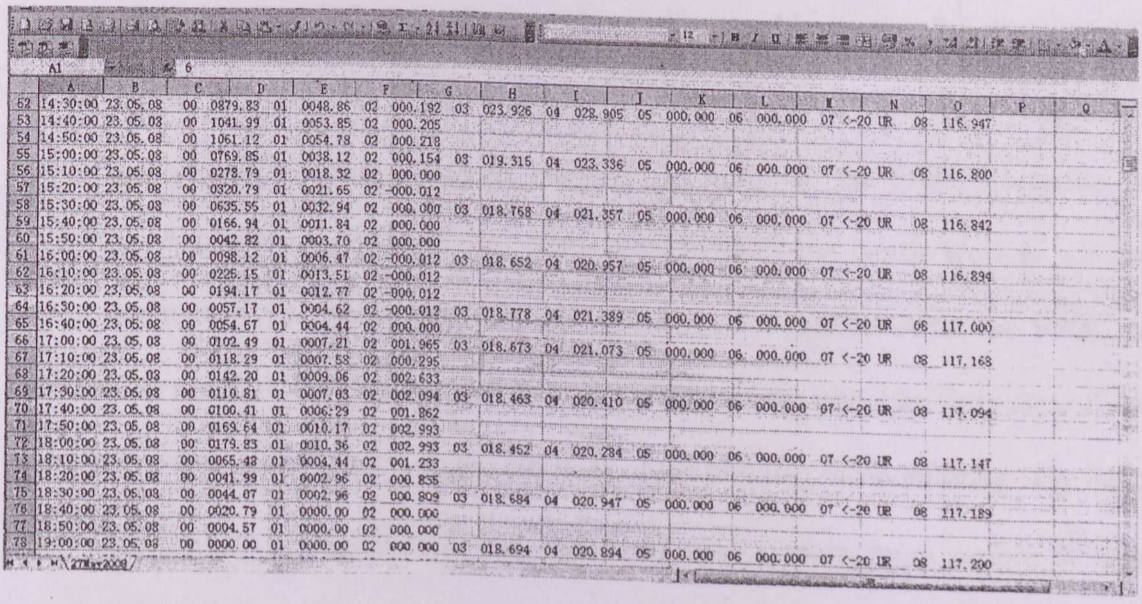
Column data format

● General
○ Text
○ Date: DMY
○ Do not import column (Skip)

Data preview

| General | General | General | Gener | General |
|---|---|---|---|---|
| | | | | |
| 12:32:23 | 17.01.01 | 00xxxxxx | 000 | 0034.2 |
| 12:40:00 | 17.01.01 | 00xxxxxx | 000 | 0034.2 |
| 12:40:15 | 17.01.01 | 00xxxxxx | 000 | 0034.2 |
| 12:43:32 | 17.01.01 | 00xxxxxx | 001 | 0029.2 |

*Figure 5.11: data export into Microsoft EXCEL, Step 3 of 3 (displayed data only for demonstration)*


A1 6

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 52 | 14:30:00 | 23.05.08 | 00 | 0879.83 | 01 | 0048.86 | 02 | 000.192 | 03 | 023.926 | 04 | 028.905 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 116.947 |
| 53 | 14:40:00 | 23.05.08 | 00 | 1041.99 | 01 | 0053.85 | 02 | 000.205 | | | | | | | | | | | | |
| 54 | 14:50:00 | 23.05.08 | 00 | 1061.12 | 01 | 0054.78 | 02 | 000.218 | | | | | | | | | | | | |
| 55 | 15:00:00 | 23.05.08 | 00 | 0769.85 | 01 | 0038.12 | 02 | 000.154 | 03 | 019.315 | 04 | 023.336 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 116.800 |
| 56 | 15:10:00 | 23.05.08 | 00 | 0278.79 | 01 | 0018.32 | 02 | 000.000 | | | | | | | | | | | | |
| 57 | 15:20:00 | 23.05.08 | 00 | 0320.79 | 01 | 0021.65 | 02 | -000.012 | | | | | | | | | | | | |
| 58 | 15:30:00 | 23.05.08 | 00 | 0635.55 | 01 | 0032.94 | 02 | 000.000 | 03 | 018.768 | 04 | 021.357 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 116.842 |
| 59 | 15:40:00 | 23.05.08 | 00 | 0166.94 | 01 | 0011.84 | 02 | 000.000 | | | | | | | | | | | | |
| 60 | 15:50:00 | 23.05.08 | 00 | 0042.82 | 01 | 0003.70 | 02 | 000.000 | | | | | | | | | | | | |
| 61 | 16:00:00 | 23.05.08 | 00 | 0098.12 | 01 | 0006.47 | 02 | -000.012 | 03 | 018.652 | 04 | 020.957 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 116.894 |
| 62 | 16:10:00 | 23.05.08 | 00 | 0225.15 | 01 | 0013.51 | 02 | -000.012 | | | | | | | | | | | | |
| 63 | 16:20:00 | 23.05.08 | 00 | 0194.17 | 01 | 0012.77 | 02 | -000.012 | | | | | | | | | | | | |
| 64 | 16:30:00 | 23.05.08 | 00 | 0057.17 | 01 | 0004.62 | 02 | -000.012 | 03 | 018.778 | 04 | 021.389 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 117.000 |
| 65 | 16:40:00 | 23.05.08 | 00 | 0054.67 | 01 | 0004.44 | 02 | 000.000 | | | | | | | | | | | | |
| 66 | 17:00:00 | 23.05.08 | 00 | 0102.49 | 01 | 0007.21 | 02 | 001.965 | 03 | 018.673 | 04 | 021.073 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 117.168 |
| 67 | 17:10:00 | 23.05.08 | 00 | 0118.29 | 01 | 0007.58 | 02 | 000.295 | | | | | | | | | | | | |
| 68 | 17:20:00 | 23.05.08 | 00 | 0142.20 | 01 | 0009.06 | 02 | 002.633 | | | | | | | | | | | | |
| 69 | 17:30:00 | 23.05.08 | 00 | 0110.81 | 01 | 0007.03 | 02 | 002.094 | 03 | 018.463 | 04 | 020.410 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 117.094 |
| 70 | 17:40:00 | 23.05.08 | 00 | 0100.41 | 01 | 0006.29 | 02 | 001.862 | | | | | | | | | | | | |
| 71 | 17:50:00 | 23.05.08 | 00 | 0169.64 | 01 | 0010.17 | 02 | 002.993 | | | | | | | | | | | | |
| 72 | 18:00:00 | 23.05.08 | 00 | 0179.83 | 01 | 0010.36 | 02 | 002.993 | 03 | 018.452 | 04 | 020.284 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 117.147 |
| 73 | 18:10:00 | 23.05.08 | 00 | 0065.48 | 01 | 0004.44 | 02 | 001.233 | | | | | | | | | | | | |
| 74 | 18:20:00 | 23.05.08 | 00 | 0041.99 | 01 | 0002.96 | 02 | 000.835 | | | | | | | | | | | | |
| 75 | 18:30:00 | 23.05.08 | 00 | 0044.07 | 01 | 0002.96 | 02 | 000.809 | 03 | 018.684 | 04 | 020.947 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 117.189 |
| 76 | 18:40:00 | 23.05.08 | 00 | 0020.79 | 01 | 0000.00 | 02 | 000.000 | | | | | | | | | | | | |
| 77 | 18:50:00 | 23.05.08 | 00 | 0004.57 | 01 | 0000.00 | 02 | 000.000 | | | | | | | | | | | | |
| 78 | 19:00:00 | 23.05.08 | 00 | 0000.00 | 01 | 0000.00 | 02 | 000.000 | 03 | 018.694 | 04 | 020.894 | 05 | 000.000 | 06 | 000.000 | 07 | <-20 UR | 08 | 117.200 |

*Figure 5.12: data export into Microsoft EXCEL, the workable spreadsheet (displayed data only for demonstration)*

## 5.4 Experimentation for FFSC: the building for installation

The University building, Block G22, was chosen as the building for FFSC's installation because its roof and the roof of its next building, Block G21, have the same height of 23.1m, and they are the tallest building roofs amongst the surrounding 500 square meters. There is no any other building or tree causing shading on the FFSC plate during daytime. However, there is a staircase, which locates on the North-West to the FFSC as shown in Figure 5.14 and Figure 5.16. The staircase is around 1 meter higher than the FFSC plate. Even though, according to Dilshan et al. (2006) and Kamaruzzaman et al. (2006), since Kuala Lumpur is located in the northern hemisphere and the beam solar irradiation comes only from the South and Top, the staircase does not cause any shading for beam solar irradiation but probably some negligible diffuse irradiation on FFSC. However, the light reflected from the staircase's South-East surface may considerably counteract the blocked diffuse irradiation. This is discussed in Section 5.5. Figure 5.13 shows the orientation of this building and it also shows where FFSC was mounted on. The A-A section view is provided in Figure 5.14, in which the FFSC's location is illustrated. A photo for Block 22 has been taken towards the North-West facade as shown in Figure 5.15, where the staircase appears in the middle. After the FFSC is mounted on the roof, the concentrated light is transported through 10m long clear fiber bundles to a dark room located on the 4th floor of the building for monitoring. The dark room (width3.15m × length6.50m × height3.30m) was a store room before it was employed for this experimentation. The layout of the 4th floor is presented in Figure 5.17.

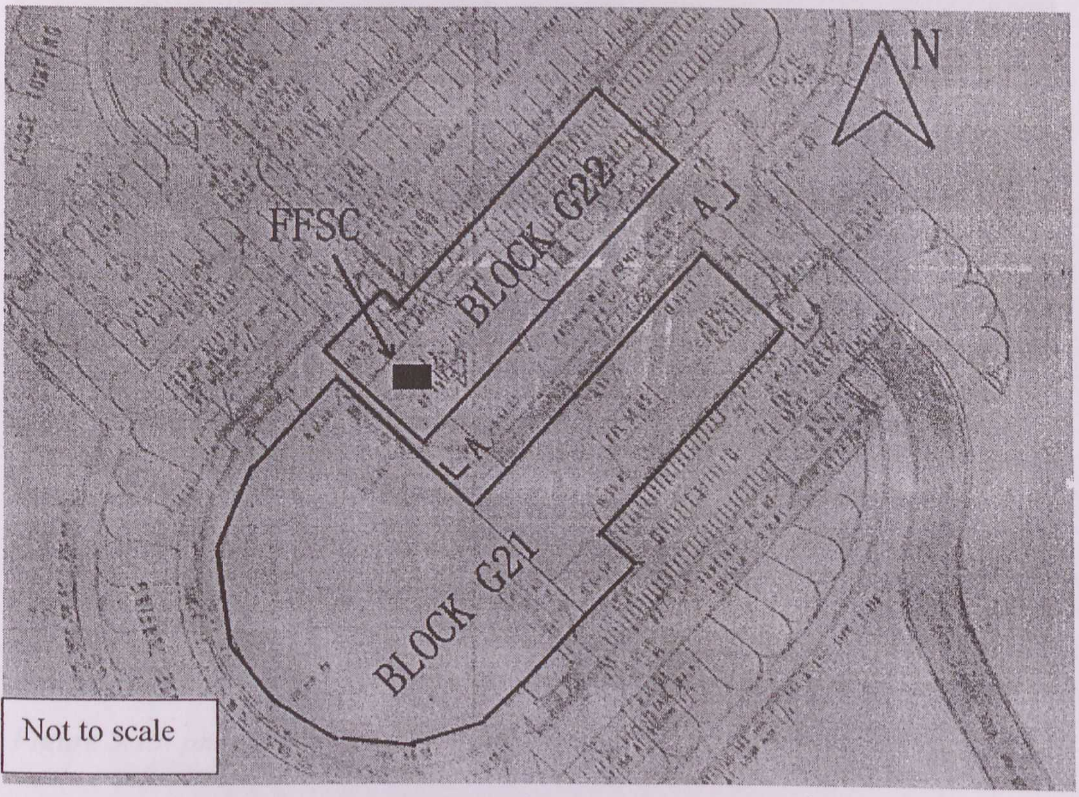


*Figure 5.13: Block G22, where FFSC was mounted on*

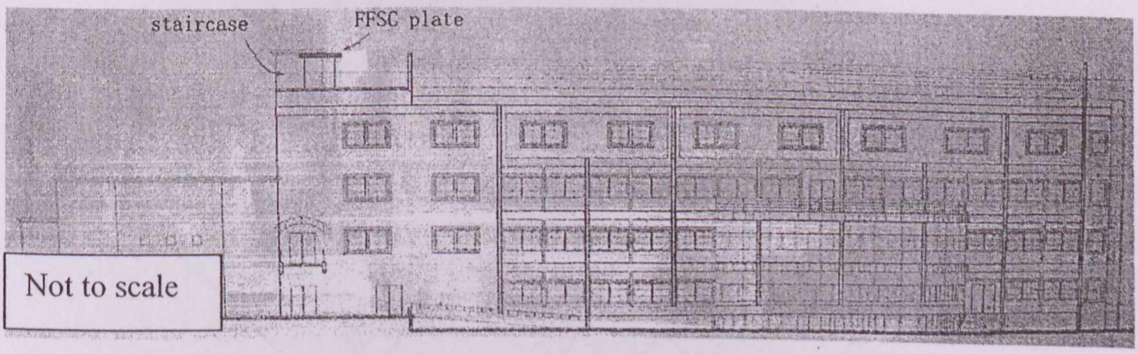


*Figure 5.14: A-A section view for Block G22 and where FFSC installed*

*Figure 5.15: photo for Block G22*

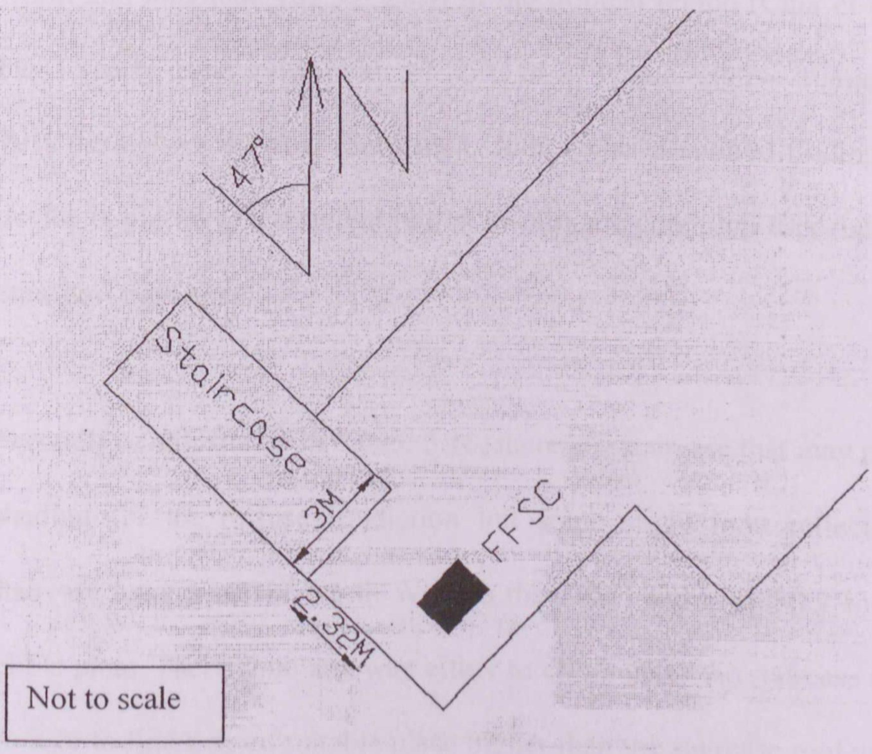


*Figure 5.16: the staircase that close to FFSC*

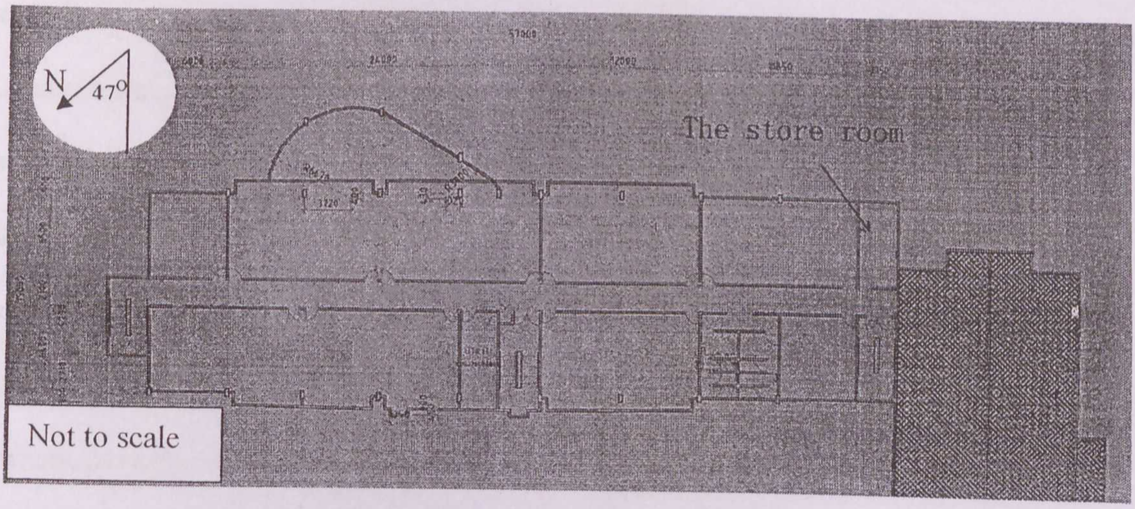


*Figure 5.17: layout of the 4th floor*

## 5.5 Critical review of experimental limitations

In general, experimentations were conducted in Kuala Lumpur, Malaysia (latitude 3.7° North and longitude 101.33° East) in the tropical region (Chia et al., 2006). Malaysia has a yearly mean temperature of 26°C to 27°C and relative humidity (RH) of 70% to 90% throughout the year (Sabarinah, 2006). The monitored findings would vary if the device is placed in a different region or climatic condition especially for the temperate zone and rigid zone.

Secondly, as illustrated in Figure 5.16, there is a staircase that may probably cause some shading for the diffuse irradiation but some slight light reflection on FFSC. The staircase locates on the North-West to the FFSC and is about 1 meter higher than the FFSC plate. There is no any way either to climb up to the staircase roof to install FFSC on it or to find a more suitable place higher than the staircase roof according to the field limitation. However, the staircase does not cause any shading for beam solar irradiation since that Kuala Lumpur is located in the northern hemisphere and the beam solar irradiation only comes from the South and Top according to Dilshan et al. (2006) and Kamaruzzaman et al. (2006). Therefore, the impact caused by the staircase was not experimentally studied because it was considered as insignificant and negligible as mentioned above.

Finally, the limitations in the availability of the fluorescent fiber market also bring limitations to the study. In this research, only fluorescent fibers with a diameter of 2mm are supplied. There is no fluorescent fiber with a larger diameter available with the supplier at that time. According to Richards (2006), Reisfeld (2001), Batchelder et al. (1979) and Hammam et al. (2007), the size and the form of the cross sectional area could impact on the proportion of photons trapped by the luminescent plate and the reduction of the cross sectional area of the luminescent plate could remarkably increase the photon loss. Accordingly, if fluorescent fibers with a larger diameter could be embedded in FFSC, say 10mm diameter, the performance parameters of FFSC such as the luminous efficacy and the light-to-light efficiency could increase. Experimentation for fluorescent fibers with larger diameters is recommended in future study as mentioned in Chapter 8.

## 5.6 Experimentation for FFSC: parameters analyzed

The time system used in this research is the 24-hour system. The daily data recorded for FFSC from 6:00 to 20:00 were selected for every day, because there was no any significant response from all the light meters during the rest hours of a day when it was during nighttime. The following analysis has been conducted for the FFSC system, namely: radiation-to-radiation efficiency (ηr), lighting effect, energy-to-energy efficiency (ηe), luminous efficacy (K), light-to-light efficiency (ηl), wavelength test, CIE color analysis, and the negative trend between radiation-to-radiation efficiency (ηr) and solar radiation (PY1), and so on, which are discussed in Chapter 6 and Chapter 7. The statistic methods such as correlation and linear test are employed. The program "Statistical Package for Social Science (SPSS) program for Windows98/XP" is employed for the statistic analysis.

# Chapter 6

# Data Restructuring and Interpretation

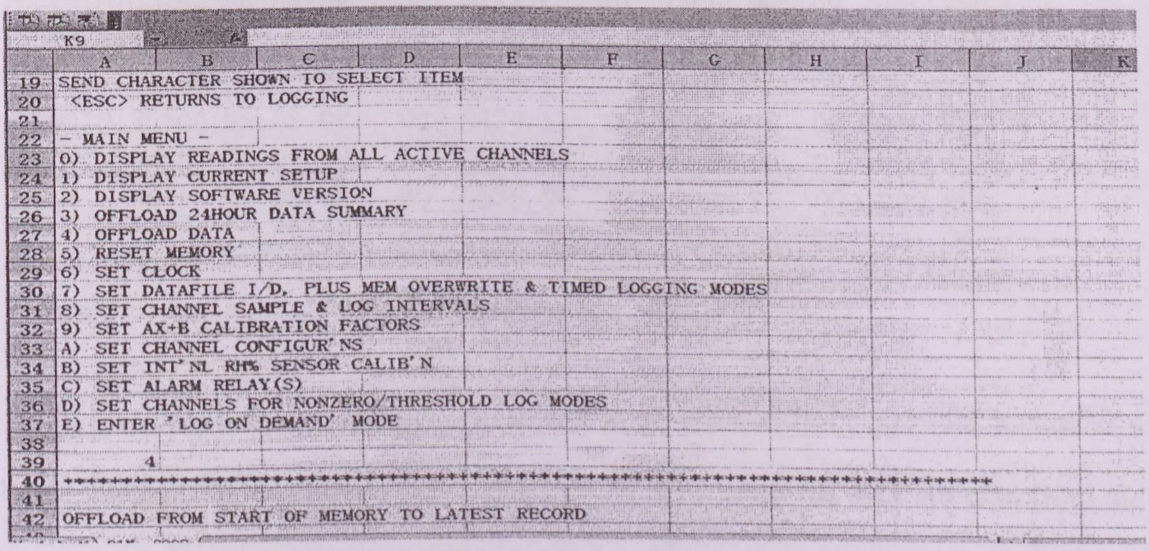
Data used for the analysis were mainly acquired through the DataHog2 and the EPP2000 spectrometer. The DataHog2 was linked with the Pyranometer1, the Pyranometer2, and the LUX sensor, and it transferred the data measured from all these meters to a computer for the recording and the analysis purposes. The EPP2000 spectrometer has its own built-in data logger and it was linked to the computer directly without connecting to the DataHog2. The following sections explain how the data measured by various meters were restructured and interpreted into an analyzable format.

## 6.1 Data acquired from DataHog2

The DataHog2 is able to record data using its built-in memory for around 1 week without off-loading to a computer hard disk until its built-in memory is full. The program "SkyeLynx Standard v2.6" is used for data acquiring for DataHog2. The following main menu is displayed on the screen for operation as shown in Figure 6.1. The calibration results for DataHog2 are attached in APPENDIX E.

By selecting the option "SET CHANNEL CONFIGUR'NS" as shown in Figure 6.1, all together 8 channels in the DataHog2 are configured to various meters. In this experimentation, there are three channels configured for light meters. Channel 1 is configured to Pyranometer1, and Channel 2 is configured to Pyranometer2. Channel 3 is for the LUX sensor. Channels 4 to Channel 8 are not configured and they are not used in the experimentation, so that the values appeared under these channels do not make any sense and they are not analyzed.

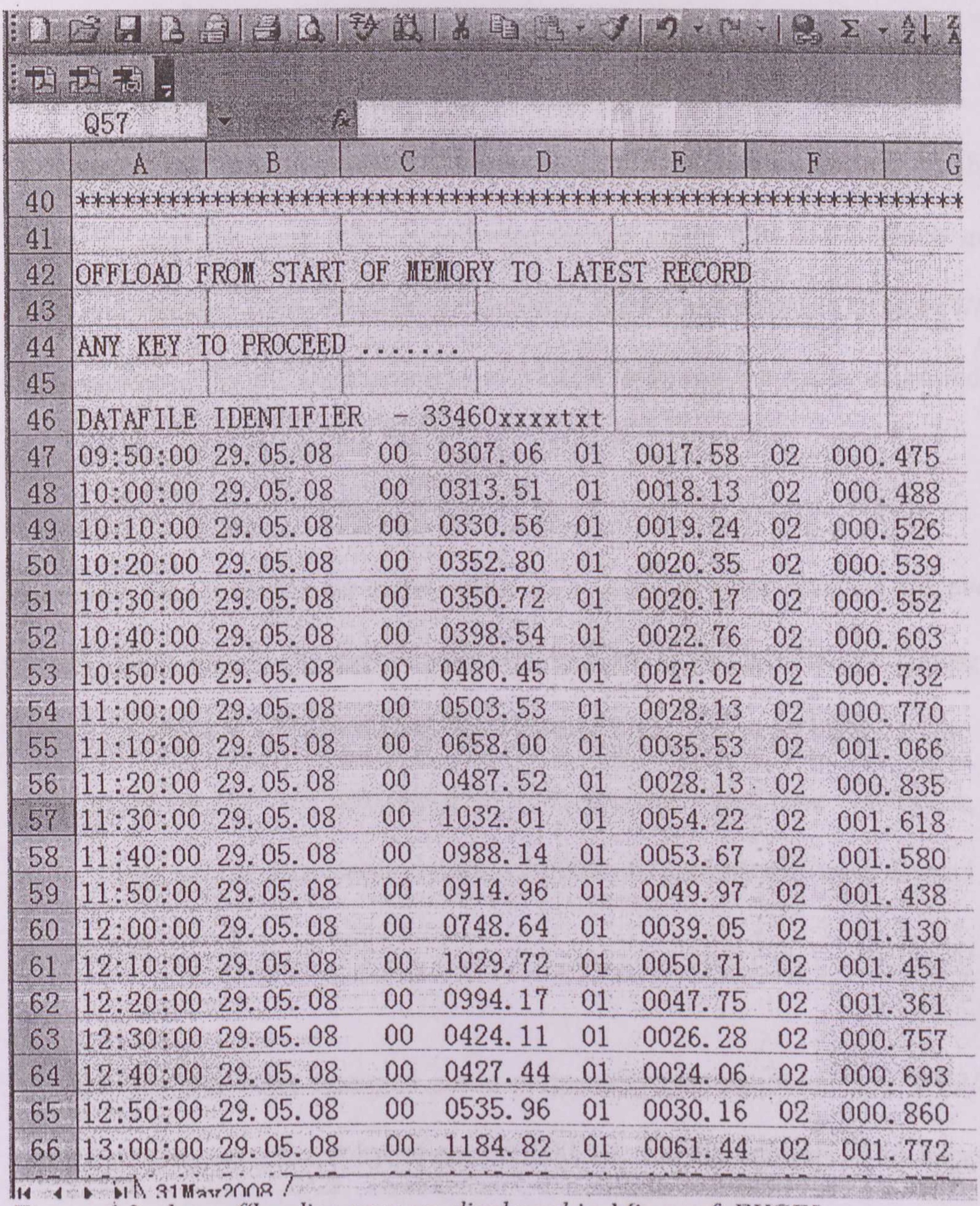
By selecting the option "SET CHANNEL SAMPLE & LOG INTERVALS", Channel 1 is coded as "00"; Channel 2 is coded as "01", and Channel 3 is coded as "02". For the intervals, there are two types of intervals to be set, namely: sampling intervals and logging intervals. The sampling interval is where a reading is taken from the associated channel and stored in the temporary memory. On the other hand, at the chosen logging interval, the sampled readings are divided by the number of samples and the single averaged measurement stored in memory with the appropriate time and date. If the sample time and the log times are equal, the averaging process is irrelevant, and readings are stored directly. During the 6-month monitoring, both the sampling interval and logging interval are set at 10 minutes as decided by the research group.



```
19 SEND CHARACTER SHOWN TO SELECT ITEM
20  <ESC> RETURNS TO LOGGING
21
22 - MAIN MENU -
23 0) DISPLAY READINGS FROM ALL ACTIVE CHANNELS
24 1) DISPLAY CURRENT SETUP
25 2) DISPLAY SOFTWARE VERSION
26 3) OFFLOAD 24HOUR DATA SUMMARY
27 4) OFFLOAD DATA
28 5) RESET MEMORY
29 6) SET CLOCK
30 7) SET DATAFILE I/D, PLUS MEM OVERWRITE & TIMED LOGGING MODES
31 8) SET CHANNEL SAMPLE & LOG INTERVALS
32 9) SET AX+B CALIBRATION FACTORS
33 A) SET CHANNEL CONFIGUR'NS
34 B) SET INT'NL RH% SENSOR CALIB'N
35 C) SET ALARM RELAY(S)
36 D) SET CHANNELS FOR NONZERO/THRESHOLD LOG MODES
37 E) ENTER 'LOG ON DEMAND' MODE
38
39          4
40 ****************************************************************
41
42 OFFLOAD FROM START OF MEMORY TO LATEST RECORD
```

*Figure 6.1: main menu displayed in "SkyeLynx Standard v2.6"*

A Microsoft EXCEL file is opened for the data capturing and recording before the data is off-loaded. By selecting the option "OFFLOAD DATA", data are displayed in the Microsoft EXCEL spreadsheet as shown in Figure 6.2.



```
40 ****************************************************************
41
42 OFFLOAD FROM START OF MEMORY TO LATEST RECORD
43
44 ANY KEY TO PROCEED .......
45
46 DATAFILE IDENTIFIER   - 33460xxxxtxt
47 09:50:00 29.05.08   00  0307.06  01  0017.58  02  000.475
48 10:00:00 29.05.08   00  0313.51  01  0018.13  02  000.488
49 10:10:00 29.05.08   00  0330.56  01  0019.24  02  000.526
50 10:20:00 29.05.08   00  0352.80  01  0020.35  02  000.539
51 10:30:00 29.05.08   00  0350.72  01  0020.17  02  000.552
52 10:40:00 29.05.08   00  0398.54  01  0022.76  02  000.603
53 10:50:00 29.05.08   00  0480.45  01  0027.02  02  000.732
54 11:00:00 29.05.08   00  0503.53  01  0028.13  02  000.770
55 11:10:00 29.05.08   00  0658.00  01  0035.53  02  001.066
56 11:20:00 29.05.08   00  0487.52  01  0028.13  02  000.835
57 11:30:00 29.05.08   00  1032.01  01  0054.22  02  001.618
58 11:40:00 29.05.08   00  0988.14  01  0053.67  02  001.580
59 11:50:00 29.05.08   00  0914.96  01  0049.97  02  001.438
60 12:00:00 29.05.08   00  0748.64  01  0039.05  02  001.130
61 12:10:00 29.05.08   00  1029.72  01  0050.71  02  001.451
62 12:20:00 29.05.08   00  0994.17  01  0047.75  02  001.361
63 12:30:00 29.05.08   00  0424.11  01  0026.28  02  000.757
64 12:40:00 29.05.08   00  0427.44  01  0024.06  02  000.693
65 12:50:00 29.05.08   00  0535.96  01  0030.16  02  000.860
66 13:00:00 29.05.08   00  1184.82  01  0061.44  02  001.772
```

*Figure 6.2: data offloading process displayed in Microsoft EXCEL*

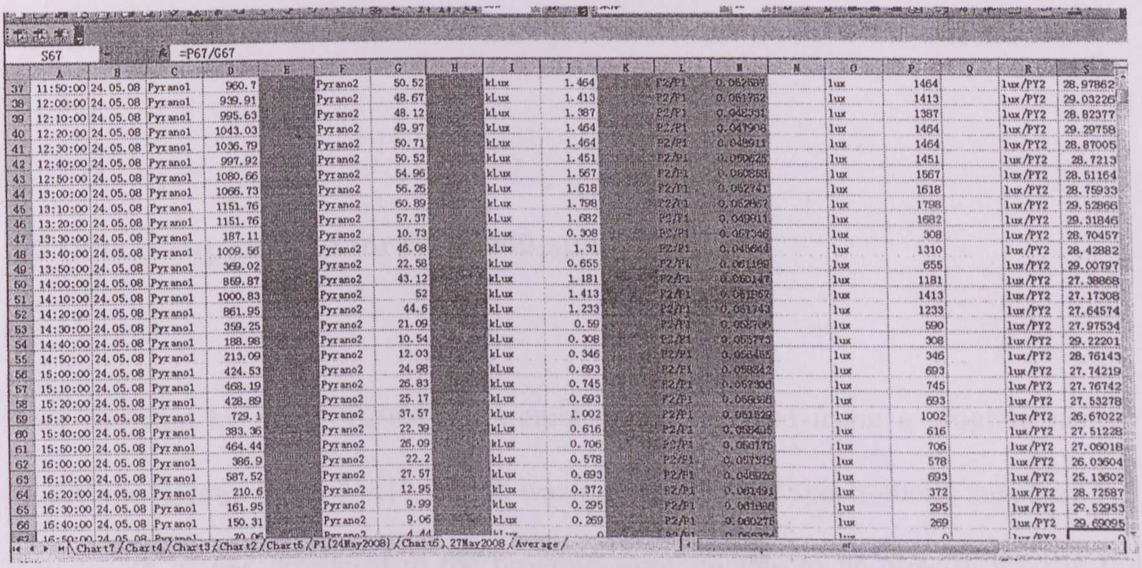
In Figure 6.2, each row displays a group of data acquired from different meters at a same moment. In the column "A" it displays the time when the data are read from the meters and in the column "B" it displays the date. For instance, in the row number "57", the time "11:30:00" is shown in column "A" and the date "29.05.08" is shown in column "B", which means the data in the whole row number "57" were measured at 11:30 on 29th May 2008.

The mark "00" displayed in column "C" is the code for Pyranometer1, followed by the value measured by the Pyranometer1. The mark "01" is for Pyrannometer2 and "02" for the LUX sensor. For the same instance in the row number "57", the mark "00" is followed by the value "1032.01"; the mark "01" in this row is followed by the value "0054.22", and the mark "02" is followed by the value "001.618", which means at 11:30 on 29th May 2008, the value measured by the Pyranometer1 is 1032.01W/m2, the value measured by the Pyranometer2 is 54.22W/m2, and the value measured by the LUX sensor is 1.618 kLUX.

The daily data recorded for FFSC from 6:00 to 20:00 were selected for every day, because there was no any significant response from all the light meters during the rest hours of a day when it was during night time. All the measured values in the duration from 20:00 to 6:00 are zero since it is during the night time. Therefore, in data restructuring, all the data captured during 20:00 to 6:00 every day were deleted from the spreadsheet.

The selected data were arranged and a preparatory calculation such as PY2/PY1 and LUX/PY2 were conducted by Microsoft EXCEL for the analysis. The interval of 10 minutes remains. The light radiation monitored by Pyranometer1 that installed on the building roof is denoted as PY1, and the light radiation monitored by Pyranometer2 that installed with the finishing end is denoted as PY2. Figure 6.3 demonstrates one of the screens for data restructuring and the preparatory calculation conducted by Microsoft

EXCEL, where data were sorted by “Pyrano1”, “Pyrano2”, “LUX”, “P2/P1”, and “LUX/PY2” in various columns. “Pyrano1” or “P1” presents the values for Pyranometer1 and they are equal as PY1. “Pyrano2” or “P2” presents the values for Pyranometer2 and they are equal as PY2. However, these different symbols were only employed to ease the data restructuring process. Therefore, in the discussion of the analysis results as presented in Chapter 7, only the symbols as PY1 and PY2 are employed to indicate the values measured by the pyranometers.



S67 =P67/G67

|  | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 37 | 11:50:00 | 24.05.08 | Pyrano1 | 960.7 |  | Pyrano2 | 50.52 |  | kLux | 1.464 |  | P2/P1 | 0.052587 |  | lux | 1464 |  | lux/PY2 | 28.97862 |
| 38 | 12:00:00 | 24.05.08 | Pyrano1 | 939.91 |  | Pyrano2 | 48.67 |  | kLux | 1.413 |  | P2/P1 | 0.051782 |  | lux | 1413 |  | lux/PY2 | 29.03226 |
| 39 | 12:10:00 | 24.05.08 | Pyrano1 | 995.63 |  | Pyrano2 | 48.12 |  | kLux | 1.387 |  | P2/P1 | 0.048331 |  | lux | 1387 |  | lux/PY2 | 28.82377 |
| 40 | 12:20:00 | 24.05.08 | Pyrano1 | 1043.03 |  | Pyrano2 | 49.97 |  | kLux | 1.464 |  | P2/P1 | 0.047908 |  | lux | 1464 |  | lux/PY2 | 29.29758 |
| 41 | 12:30:00 | 24.05.08 | Pyrano1 | 1036.79 |  | Pyrano2 | 50.71 |  | kLux | 1.464 |  | P2/P1 | 0.048911 |  | lux | 1464 |  | lux/PY2 | 28.87005 |
| 42 | 12:40:00 | 24.05.08 | Pyrano1 | 997.92 |  | Pyrano2 | 50.52 |  | kLux | 1.451 |  | P2/P1 | 0.050625 |  | lux | 1451 |  | lux/PY2 | 28.7213 |
| 43 | 12:50:00 | 24.05.08 | Pyrano1 | 1080.66 |  | Pyrano2 | 54.96 |  | kLux | 1.567 |  | P2/P1 | 0.050858 |  | lux | 1567 |  | lux/PY2 | 28.51164 |
| 44 | 13:00:00 | 24.05.08 | Pyrano1 | 1066.73 |  | Pyrano2 | 56.25 |  | kLux | 1.618 |  | P2/P1 | 0.052731 |  | lux | 1618 |  | lux/PY2 | 28.75933 |
| 45 | 13:10:00 | 24.05.08 | Pyrano1 | 1151.76 |  | Pyrano2 | 60.89 |  | kLux | 1.798 |  | P2/P1 | 0.052867 |  | lux | 1798 |  | lux/PY2 | 29.52866 |
| 46 | 13:20:00 | 24.05.08 | Pyrano1 | 1151.76 |  | Pyrano2 | 57.37 |  | kLux | 1.682 |  | P2/P1 | 0.049811 |  | lux | 1682 |  | lux/PY2 | 29.31846 |
| 47 | 13:30:00 | 24.05.08 | Pyrano1 | 187.11 |  | Pyrano2 | 10.73 |  | kLux | 0.308 |  | P2/P1 | 0.057346 |  | lux | 308 |  | lux/PY2 | 28.70457 |
| 48 | 13:40:00 | 24.05.08 | Pyrano1 | 1009.56 |  | Pyrano2 | 46.08 |  | kLux | 1.31 |  | P2/P1 | 0.045644 |  | lux | 1310 |  | lux/PY2 | 28.42882 |
| 49 | 13:50:00 | 24.05.08 | Pyrano1 | 369.02 |  | Pyrano2 | 22.58 |  | kLux | 0.655 |  | P2/P1 | 0.061189 |  | lux | 655 |  | lux/PY2 | 29.00797 |
| 50 | 14:00:00 | 24.05.08 | Pyrano1 | 859.87 |  | Pyrano2 | 43.12 |  | kLux | 1.181 |  | P2/P1 | 0.050147 |  | lux | 1181 |  | lux/PY2 | 27.38868 |
| 51 | 14:10:00 | 24.05.08 | Pyrano1 | 1000.83 |  | Pyrano2 | 52 |  | kLux | 1.413 |  | P2/P1 | 0.051957 |  | lux | 1413 |  | lux/PY2 | 27.17308 |
| 52 | 14:20:00 | 24.05.08 | Pyrano1 | 861.95 |  | Pyrano2 | 44.6 |  | kLux | 1.233 |  | P2/P1 | 0.051743 |  | lux | 1233 |  | lux/PY2 | 27.64574 |
| 53 | 14:30:00 | 24.05.08 | Pyrano1 | 359.25 |  | Pyrano2 | 21.09 |  | kLux | 0.59 |  | P2/P1 | 0.058706 |  | lux | 590 |  | lux/PY2 | 27.97534 |
| 54 | 14:40:00 | 24.05.08 | Pyrano1 | 188.98 |  | Pyrano2 | 10.54 |  | kLux | 0.308 |  | P2/P1 | 0.055773 |  | lux | 308 |  | lux/PY2 | 29.22201 |
| 55 | 14:50:00 | 24.05.08 | Pyrano1 | 213.09 |  | Pyrano2 | 12.03 |  | kLux | 0.346 |  | P2/P1 | 0.056455 |  | lux | 346 |  | lux/PY2 | 28.76143 |
| 56 | 15:00:00 | 24.05.08 | Pyrano1 | 424.53 |  | Pyrano2 | 24.98 |  | kLux | 0.693 |  | P2/P1 | 0.058842 |  | lux | 693 |  | lux/PY2 | 27.74219 |
| 57 | 15:10:00 | 24.05.08 | Pyrano1 | 468.19 |  | Pyrano2 | 26.83 |  | kLux | 0.745 |  | P2/P1 | 0.057306 |  | lux | 745 |  | lux/PY2 | 27.76742 |
| 58 | 15:20:00 | 24.05.08 | Pyrano1 | 428.89 |  | Pyrano2 | 25.17 |  | kLux | 0.693 |  | P2/P1 | 0.058686 |  | lux | 693 |  | lux/PY2 | 27.53278 |
| 59 | 15:30:00 | 24.05.08 | Pyrano1 | 729.1 |  | Pyrano2 | 37.57 |  | kLux | 1.002 |  | P2/P1 | 0.051529 |  | lux | 1002 |  | lux/PY2 | 26.67022 |
| 60 | 15:40:00 | 24.05.08 | Pyrano1 | 383.36 |  | Pyrano2 | 22.39 |  | kLux | 0.616 |  | P2/P1 | 0.058405 |  | lux | 616 |  | lux/PY2 | 27.51228 |
| 61 | 15:50:00 | 24.05.08 | Pyrano1 | 464.44 |  | Pyrano2 | 26.09 |  | kLux | 0.706 |  | P2/P1 | 0.056175 |  | lux | 706 |  | lux/PY2 | 27.06018 |
| 62 | 16:00:00 | 24.05.08 | Pyrano1 | 386.9 |  | Pyrano2 | 22.2 |  | kLux | 0.578 |  | P2/P1 | 0.057379 |  | lux | 578 |  | lux/PY2 | 26.03604 |
| 63 | 16:10:00 | 24.05.08 | Pyrano1 | 587.52 |  | Pyrano2 | 27.57 |  | kLux | 0.693 |  | P2/P1 | 0.046926 |  | lux | 693 |  | lux/PY2 | 25.13602 |
| 64 | 16:20:00 | 24.05.08 | Pyrano1 | 210.6 |  | Pyrano2 | 12.95 |  | kLux | 0.372 |  | P2/P1 | 0.061491 |  | lux | 372 |  | lux/PY2 | 28.72587 |
| 65 | 16:30:00 | 24.05.08 | Pyrano1 | 161.95 |  | Pyrano2 | 9.99 |  | kLux | 0.295 |  | P2/P1 | 0.061686 |  | lux | 295 |  | lux/PY2 | 29.52953 |
| 66 | 16:40:00 | 24.05.08 | Pyrano1 | 150.31 |  | Pyrano2 | 9.06 |  | kLux | 0.269 |  | P2/P1 | 0.060276 |  | lux | 269 |  | lux/PY2 | 29.69095 |
| 67 | 16:50:00 | 24.05.08 | Pyrano1 | 70.06 |  | Pyrano2 | 4.44 |  | kLux | 0 |  | P2/P1 | [illegible] |  | lux | 0 |  | lux/PY2 |  |

*Figure 6.3: data restructure and preparatory calculation conducted by EXCEL*

Daily mean values for “Pyrano1”, “Pyrano2”, “LUX”, “P2/P1”, and “LUX/PY2” were also calculated by Microsoft EXCEL as demonstrated in Figure 6.4. Advanced analysis such as the linear test and the correlation test in radiation-to-radiation efficiency (ηr), lighting effect, energy-to-energy efficiency (ηe), luminous efficacy (K), and the negative trend between radiation-to-radiation efficiency (ηr) and solar radiation (PY1) were conducted in the “Statistical Package for Social Science (SPSS) program for Windows98/XP” as discussed in Chapter 7.

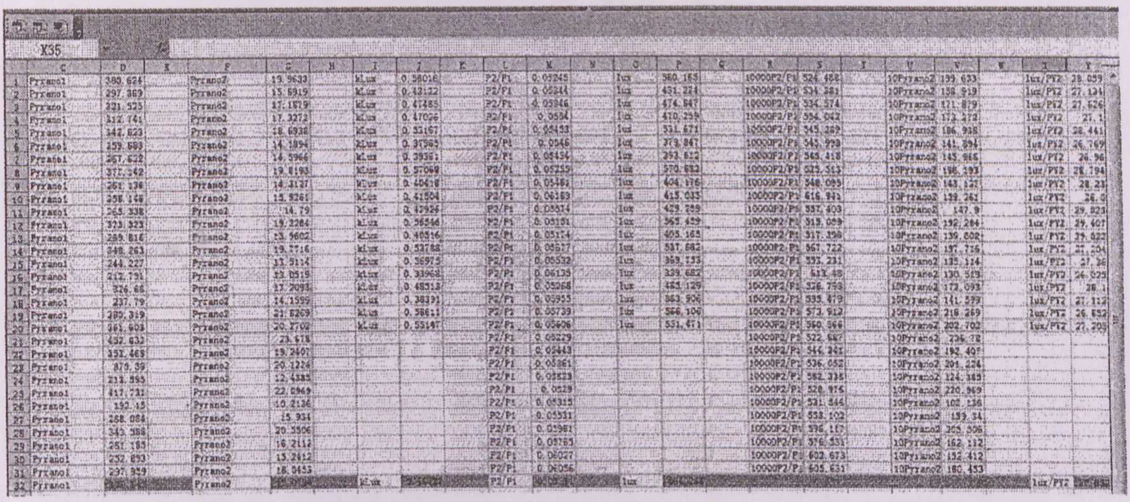


*Figure 6.4: daily mean value for restructured data*

## 6.2 Data interpretation for EPP2000 spectrometer

Data acquired by the EPP2000 spectrometer was analyzed using a program named "LabView SpectraWiz 6.1 v.1", which was provided by the spectrometer supplier. The wavelength graphs displayed in the program were suitable to be directly used in the analysis as shown in Figure 6.5, which presents a wavelength screen in the scope mode at 12.47pm on 16th Oct 2008 at a distance of 80cm from the FFSC finishing end to the light detector. It indicates on the top of the screen that the centroid is 653.59nm. Since the scales on the Y dimension do not really make sense for this particular analysis purpose, they are not discussed in the research findings.

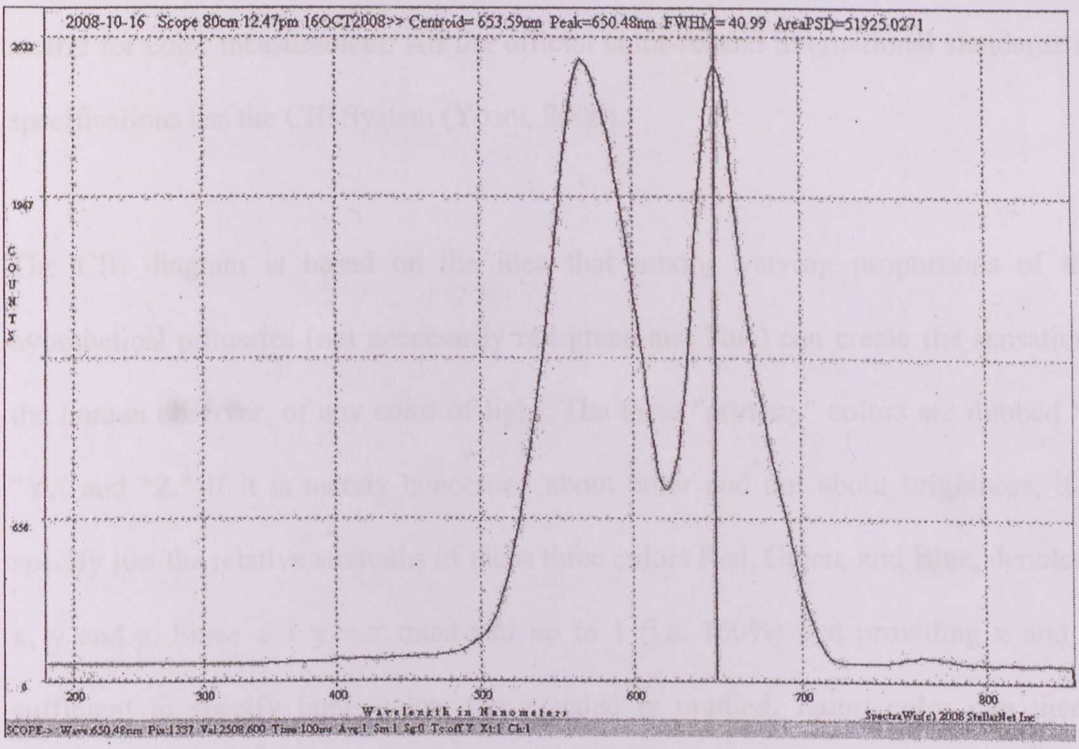


*Figure 6.5: wavelength display in "LabView SpectraWiz 6.1 v.1"*

In order to analyze the color of the FFSC light output, a CIE (Commission Internationale de l'Eclairage, the International Commission on Color) color analysis is conducted under the irradiant mode. The term "color" is used with different meanings in different technologies. To lamp engineers, color refers to a property of light sources. To graphics art engineers, color is a property of an object's surface (under a given illumination). In each case, color must be physically measured in order to record it and reproduce the same color. The perception of color is a psychophysical phenomenon, and the measurement of color must be defined in such a way that the results correlate accurately with what the visual sensation of color is to a normal human observer (Wyszecki & Stiles, 1982). Colorimetry is the science and technology used to quantify and describe physically the human color perception. The basis for colorimetry was established by CIE in 1931 based on visual experiments. Even though limitations are well recognized, the CIE system of colorimetry remains the only internationally agreed metric for color measurement. All the official color-related international standards and specifications use the CIE System (Yoshi, 2000).

The CIE diagram is based on the idea that mixing varying proportions of three hypothetical primaries (not necessarily red green and blue) can create the sensation in the human observer, of any color of light. The three "primary" colors are dubbed "X," "Y," and "Z." If it is merely concerned about color and not about brightness, it can specify just the relative strengths of these three colors Red, Green, and Blue, denoted by x, y and z. Since x + y + z must add up to 1 (i.e. 100%) just providing x and y is sufficient to specify lamp color; the z value is implied. Lamp color can then be represented on a two-dimensional plot of x and y. All possible colors then fall under a "guitar-pick" shaped triangle in which the perimeter encompasses spectrally pure colors (seen in nature only in rainbows and prisms) ranging from red to blue. Moving toward the center "dilutes" the color until it ultimately becomes "white". Specifying the x,y coordinates locates a color on the color triangle (ISO/CIE10526, 1991).

The color points traversed by an incandescent object as its temperature is raised can be plotted on the CIE Chromaticity diagram as the "Blackbody curve" and occupies the central white region. Two lamps whose x, y co-ordinates fall one above the Blackbody curve and one below could have the same correlated color temperature (CCT). However, the one above will appear slightly greener, and the one below slightly pinker. This is why two lamps having the same color temperature can still show differences in color as seen by the human eye. Color is complex; attempting to describe the lamp color with just one number (or even with two numbers) does not provide total information on how different materials will appear under that light (CIE Publication, 1986).

The CIE graph in the program "LabView SpectraWiz 6.1 v.1" is displayed in color screen with a black background as shown in Figure 6.6, which is not suitable for the monochrome printing purpose since the colors are not able to be recognized in the black and white mode. All the CIE graphs captured from the program "LabView SpectraWiz 6.1 v.1" were transformed into grayscale mode using the program "Adobe Photoshop v7.0". Annotations such as "Green", "Yellow", "Orange", "Red", "Violet", and "Blue" were added in the modified CIE graphs and the dimensional values of "x" and "y" were also annotated below the graphs as demonstrated in Figure 6.7.

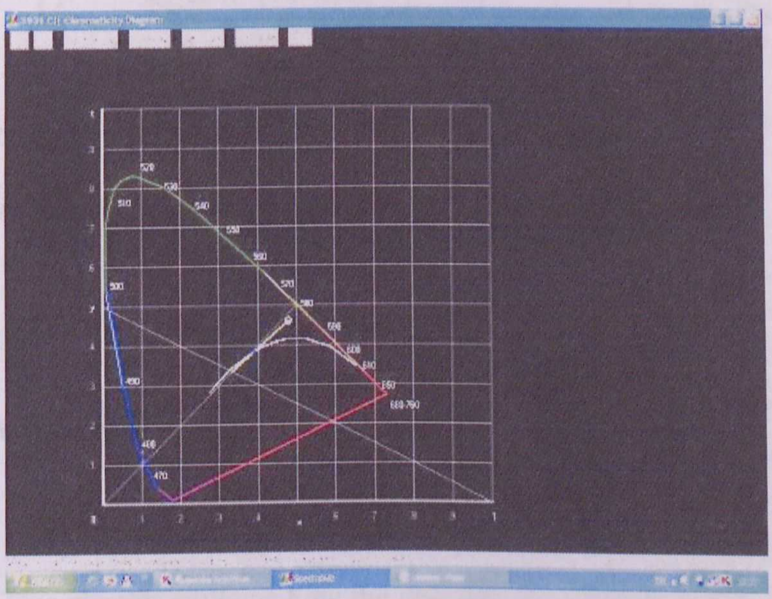
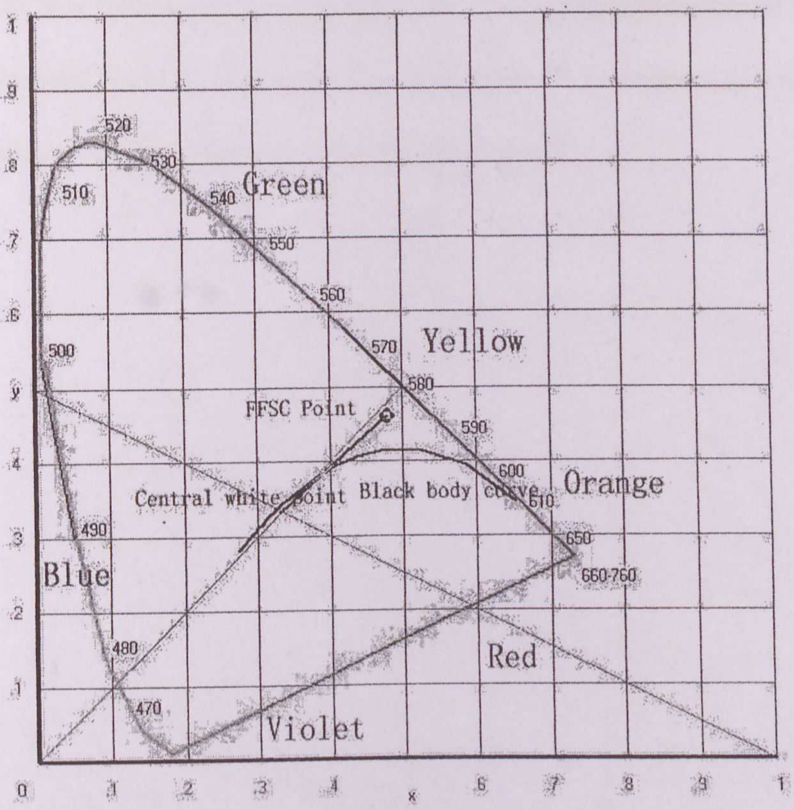


*Figure 6.6: CIE graph displayed in "LabView SpectraWiz 6.1 v.1"*



Note: x=0.479 and y=0.460

*Figure 6.7: CIE graph modified by "Adobe Photoshop v7.0"*

## 6.3 Summary

This chapter explains how the raw data acquired from the DataHog2 and the EPP2000 spectrometer were restructured and interpreted. Some captured screen and data segments are presented for the explanation. The programs "SkyeLynx Standard v2.6", "Microsoft EXCEL", and "Statistical Package for Social Science (SPSS)" were used in analyzing the data acquired from the DataHog2. Data acquired from the EPP2000 spectrometer was analyzed using the program "LabView SpectraWiz 6.1 v.1" provided by the same supplier. This chapter has interpreted the wavelength graphs and the CIE graphs displayed in the program "LabView SpectraWiz 6.1 v.1", and it has introduced that how the graphs were restructured into a presentable format by the program "Adobe Photoshop v7.0". The next chapter, Chapter 7, provides a detailed discussion about the research findings through the in-depth analysis.

# Chapter 7

# Results of Analysis

## 7.1 The solar radiation (PY1) and FFSC output (PY2)

As mentioned in Chapter 5, the radiation monitored by Pyranometer 1 that installed on the building roof is denoted as PY1 (W/m2), and the radiation monitored by Pyranometer 2 that installed with the fiber bundle finishing end is denoted as PY2 (W/m2).

The mean values for PY1 and PY2 in these 6 months are 307.73 W/m2 and 17.02 W/m2, respectively. The maximum values for PY1 and PY2 in these 6 months are both at 13:00 on 14th June 2008, which are 1308.31 W/m2 and 64.77 W/m2, respectively. The hourly diagram of PY1 and PY2 for seven days in a random week from 2nd June 2008 to 8th June 2008 is presented in Figure 7.1 and Figure 7.2, respectively. The precise values of PY1 and PY2 for these seven days at an interval of 10 minutes are provided in APPENDIX D.

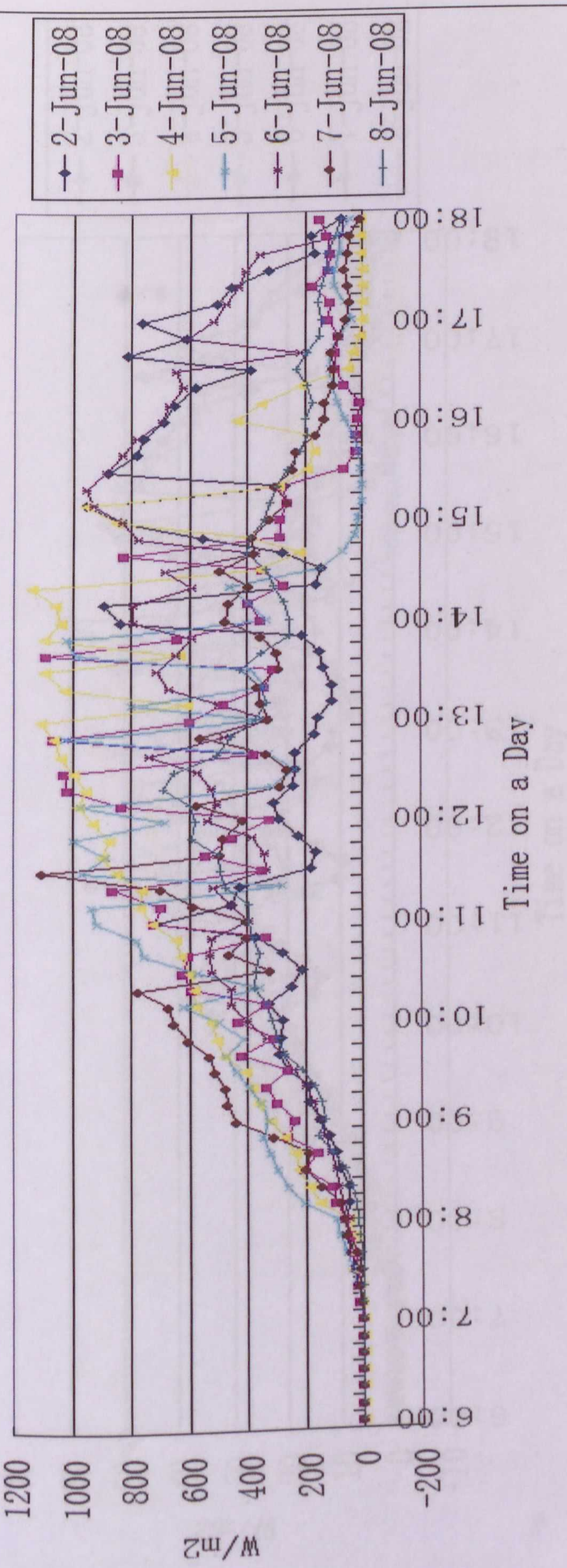


*Figure 7.1: hourly PY1 for a random week*

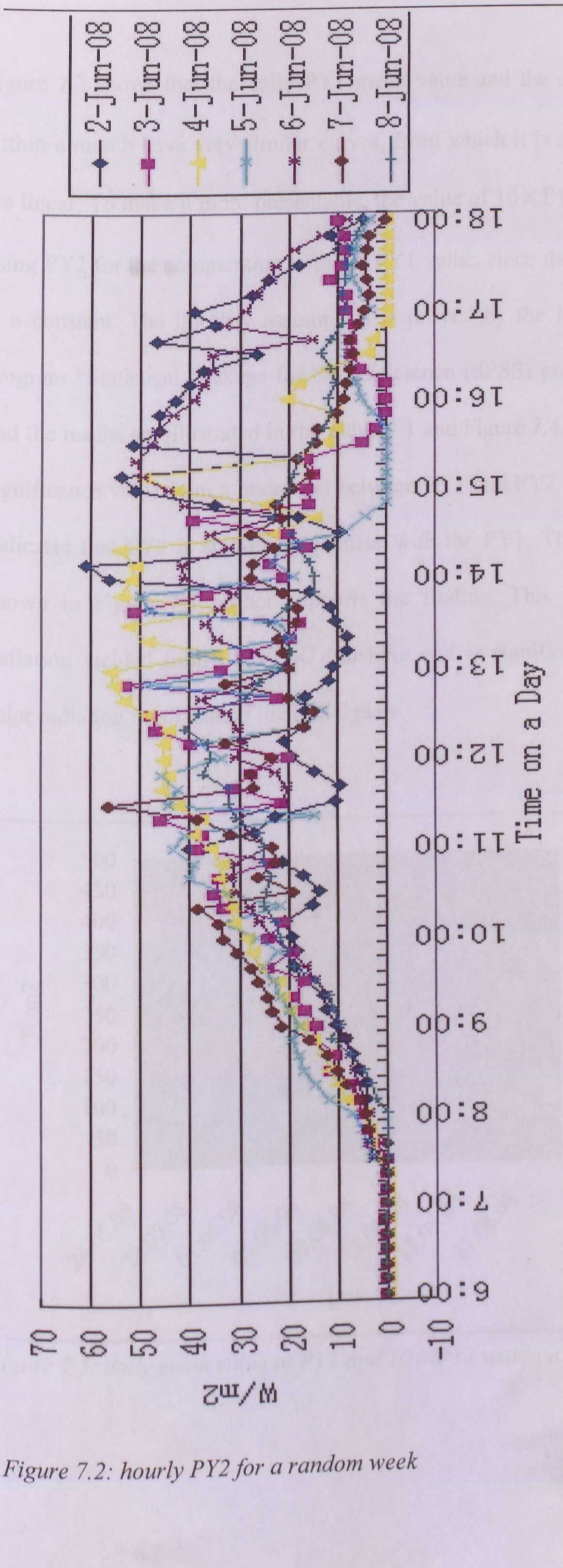


*Figure 7.2: hourly PY2 for a random week*

Figure 7.3 shows that the daily PY1 mean value and the daily 10×PY2 mean value within a month have very similar curves, from which it is assumed that PY1 and PY2 are linear. To make it more presentable, the value of 10×PY2 is plotted here instead of using PY2 for the comparation with the PY1 value, since the magnifying coefficient 10 is a constant. The linearity assumption is proved by the linear test conducted in the program "Statistical Package for Social Science (SPSS) program for Windows98/XP" and the results are illustrated in the Table 7.1 and Figure 7.4. As shown in Table 7.1, the significance value from a linear test between PY1 and PY2 is under a 0.05 level, which indicates that PY2 is significantly linear with the PY1. The linearity-testing graph as shown in Figure 7.4 further supports the finding. This finding concludes that the radiation yielded from the FFSC finishing end is significantly proportional with the solar radiation irradiated on the FFSC plate.

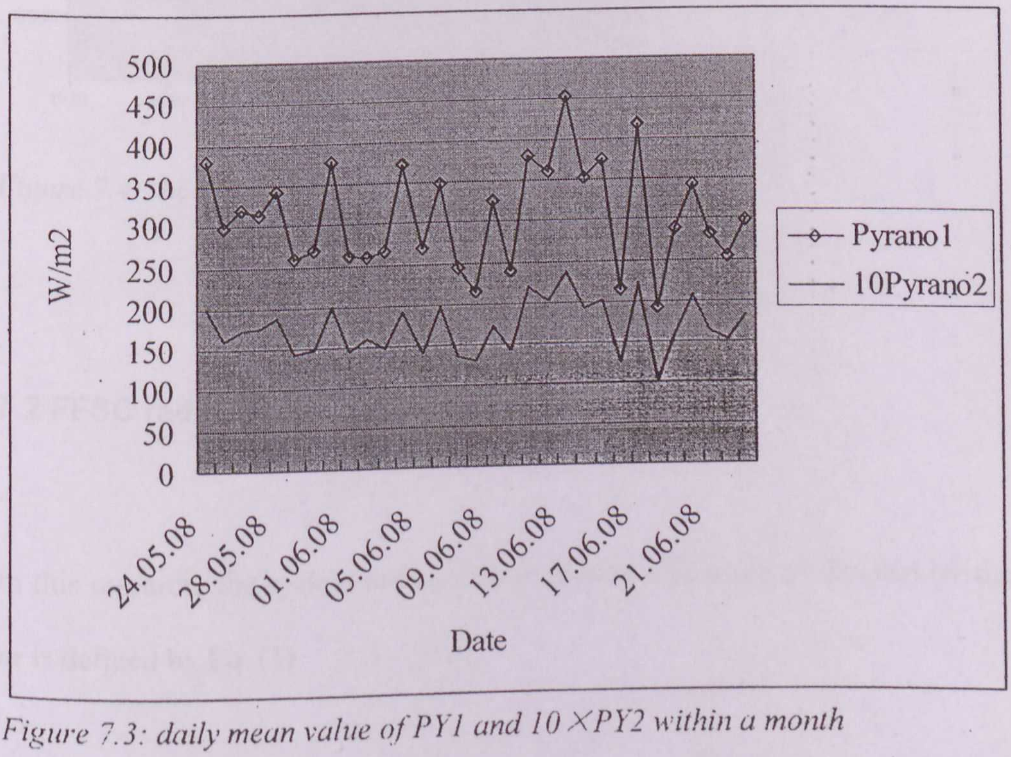


*Figure 7.3: daily mean value of PY1 and 10×PY2 within a month*

**Table 7.1: the regression test 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

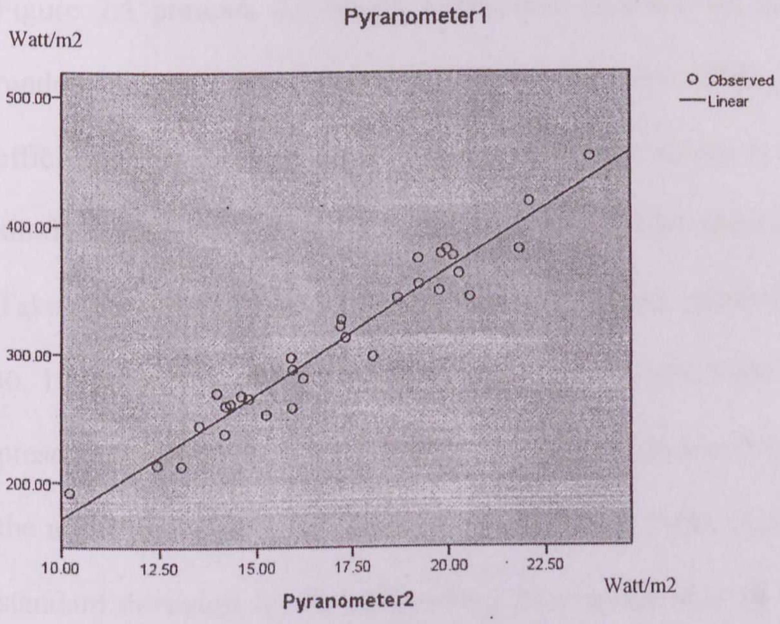


*Figure 7.4: the linear test of PY1 and PY2*

## 7.2 FFSC radiation-to-radiation efficiency (ηr)

In this research, the system radiation-to-radiation efficiency as denoted by the variable ηr is defined by Eq. (1).

$$\eta r = PY2/PY1 \tag{1}$$

Where PY1 is the light radiation monitored by Pyranometer 1 and PY2 is the light radiation monitored by Pyranometer 2. This section presents the FFSC radiation-to-radiation efficiency (ηr) and discusses the hourly and monthly stability of ηr.

### *7.2.1 Hourly radiation-to-radiation efficiency*

Figure 7.5 presents the hourly radiation-to-radiation efficiency for seven days in a random week, from 2nd June 2008 to 8th June 2008. The radiation-to-radiation efficiency from 9:00 to 16:00 appears stable. The curves of these seven days appear a similar trend. The peak values appear at around 7:30 when the sun light is very weak. Taken from Figure 7.5, the curve of the radiation-to-radiation efficiency (ηr) from 7:00 to 17:00 on a random day 4th June 2008 is illustrated in Figure 7.6 for better presentation. On the day 4th June 2008, the maximum value of ηr is 0.11 (at 7:50) and the minimum value is 0.046 (at 17:00). The mean value of ηr on that day is 0.056. The standard deviation for the values on a 10 minutes interval is 0.012, which is under a 0.05 level, so that the radiation-to-radiation efficiency mean value of 0.056 is significantly representative for that day.

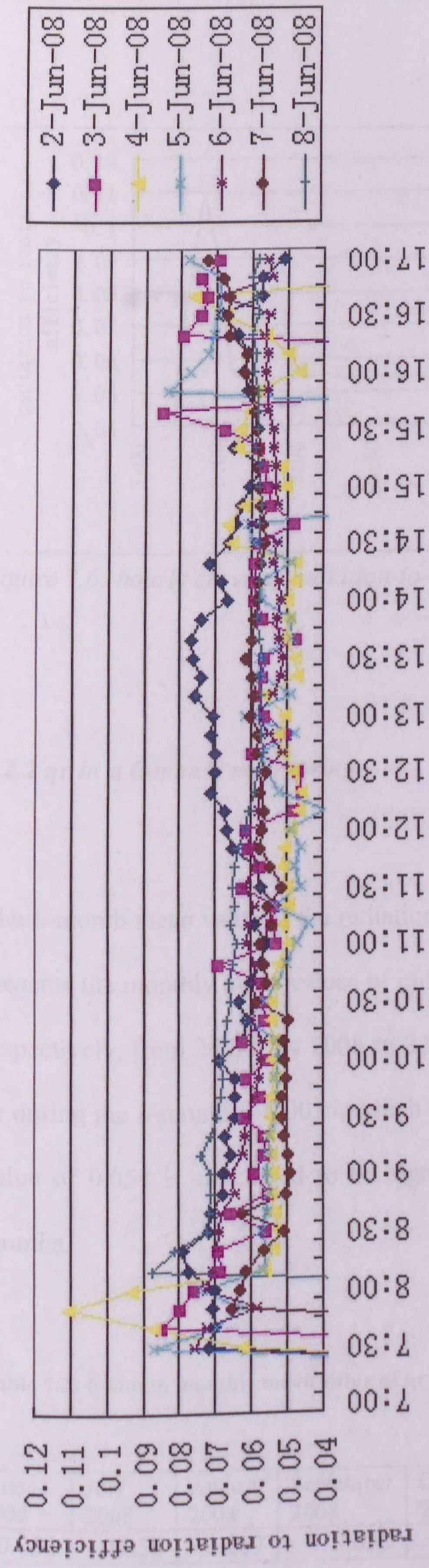


*Figure 7.5: hourly curve of radiation-to-radiation efficiency (ηr) in a random week*

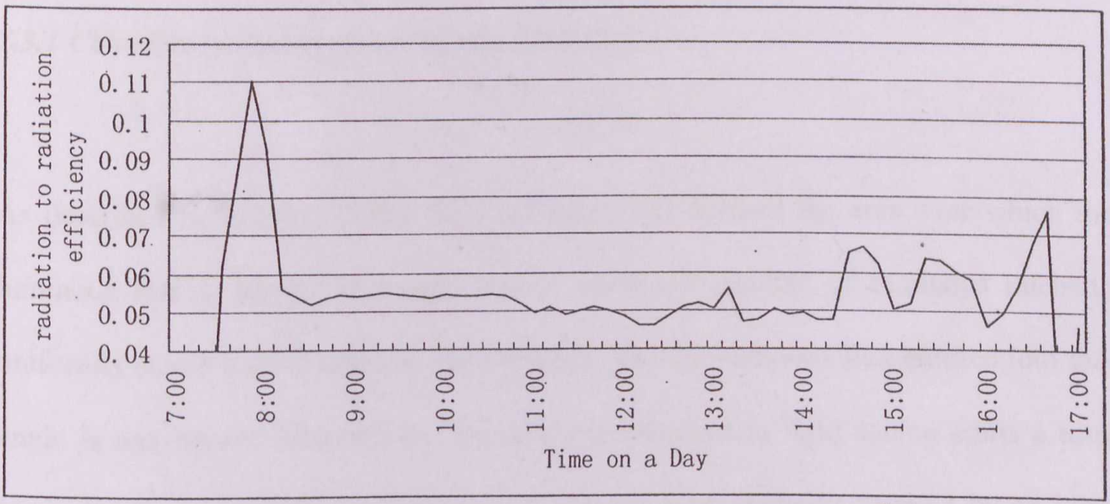


*Figure 7.6: hourly curve of radiation-to-radiation efficiency (ηr) on 4$^{th}$ June 2008*

### *7.2.2 ηr in a 6-month monitoring*

The 6-month mean value of the radiation-to-radiation efficiency (ηr) is 0.057. Table 7.2 presents the monthly mean values of radiation-to-radiation efficiency in these 6 months respectively, from 24th May 2008 to 23rd November 2008. The standard deviation for ηr during the 6-month is 0.0015, which is under a 0.01 level, so that the monthly mean value of 0.057 is concluded to be significantly stable and representative for these 6 months.

**Table 7.2: 6-month monthly mean value of ηr**

| June 2008 | July 2008 | August 2008 | September 2008 | October 2008 | November 2008 |
|---|---|---|---|---|---|
| 0.056 | 0.058 | 0.057 | 0.059 | 0.055 | 0.056 |

## 7.3 System lighting effect

### *7.3.1 Calculate luminous flux (F) from LUX (Ev)*

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 $4\pi$ lumens. If the source were partially covered by an ideal absorbing hemisphere, that system would radiate half as much luminous flux, which is only $2\pi$ lumens. The luminous intensity would still be one candela in those directions that are not obscured (Schiler, 1992). The luminous flux (*F*) for one FFSC finishing end in this research is therefore calculated in Eq. (2):

$$F = Ev \times Shs \tag{2}$$

Where the Ev is the values detected by the LUX sensor and the Shs is the half sphere's surface area radiated by the light source, the FFSC finishing end. The distance between the finishing end and the LUX sensor as denoted by Rl is 0.1m. So that the radiated half sphere's surface area is calculated in Eq. (3) as below:

$$Shs = 2\pi Rl \times Rl = 2 \times 3.14 \times 0.1 \times 0.1 = 0.063m2 \tag{3}$$

Therefore, the luminous flux (*F*) of one finishing end is calculated as shown in Eq. (4):

$$F = Ev \times Shs = 0.063Ev \quad (4)$$

Where Ev is the illuminance values detected by the LUX sensor.

Eq. (4) indicates that the luminous flux (*F*) of one FFSC finishing end is proportional to the illuminance values. By using Eq. (4), the luminous flux (*F*) of one FFSC finishing end is calculated in Table 7.3.

**Table 7.3: conversion from LUX to luminous flux**

| Illuminance (LUX) | luminous flux (*lumen*) |
|---|---|
| 400 | 25.2 |
| 600 | 37.8 |
| 800 | 50.4 |
| 1000 | 63.0 |
| 1200 | 75.6 |
| 1400 | 88.2 |
| 1600 | 100.8 |
| 1800 | 113.4 |
| 2000 | 126.0 |

Figure 7.7 presents the hourly illuminance (LUX) for seven days in a random week, from 2nd June 2008 to 8th June 2008 (Monday to Sunday). The precise values of the illuminance (LUX) for these seven days at an interval of 10 minutes are provided in APPENDIX D. As shown in Figure 7.7, for most of the time in the duration from 9:00 to 16:00, which almost covers the main office hours on a day, the lighting effect provided by one of the FFSC finishing end is above 400 LUX (equals to a luminous flux of 25.2 lumens). By using Eq. (4) and Table 7.3, the seven-day hourly luminous flux of one FFSC finishing end is calculated and illustrated in Figure 7.8. As presented in Figure 7.8, one FFSC finishing end could provide a luminous flux of from 20 lumens to 110 lumens during the office hour from 9:00 to 17:00.

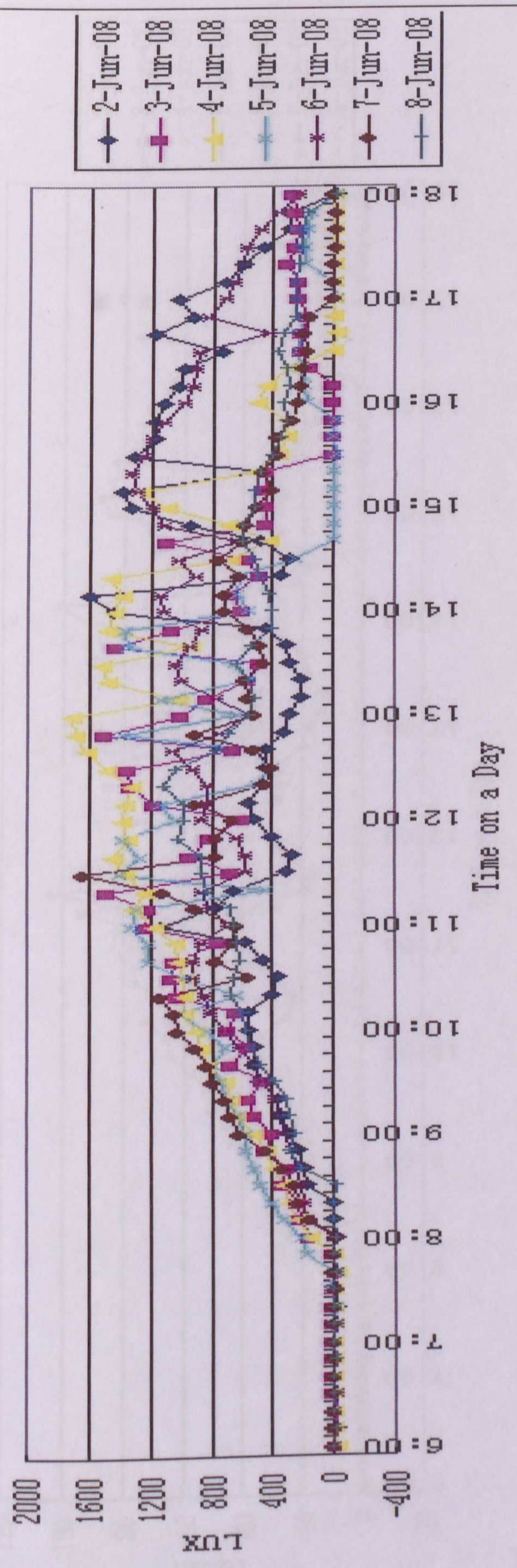


*Figure 7.7: hourly LUX values in a random week*

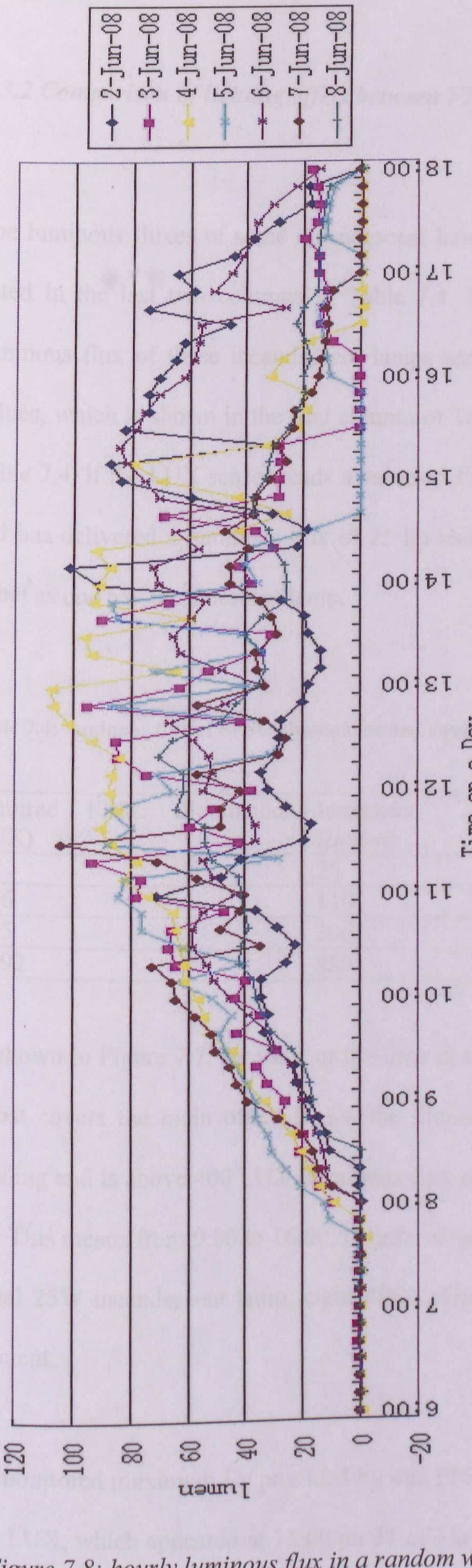


Figure 7.8: hourly luminous flux in a random week

### *7.3.2 Comparison of lighting effect between FFSC and incandescent lamps*

The luminous fluxes of some incandescent lamps (Egan, 1983; Wikipedia, 2009b) are listed in the last two columns in Table 7.4. Through calculation using Eq. (4), the luminous flux of these incandescent lamps are converted into the FFSC illuminance values, which is shown in the first column of Table 7.4. For instance in the first row in Table 7.4, if the LUX sensor reads a value of 397 LUX, that means the FFSC finishing end has delivered a luminous flux of 25 lm and it has achieved an equivalent lighting effect as one 5W incandescent lamp.

**Table 7.4: luminous flux of FFSC illuminance and equivalent incandescent lamps**

| Required FFSC illuminance (LUX) | luminous flux (*lumen*) | Watt of equivalent Lamps |
|---|---|---|
| 397 | 25 | 5W |
| 1746 | 110 | 15W |
| 3175. | 200 | 25W |
| 13492 | 850 | 60W |

As shown in Figure 7.7, for most of the time in the duration from 9:00 to 16:00, which almost covers the main office hours, the illuminance provided by one of the FFSC finishing end is above 400 LUX (luminous flux equals to 25 lumens according to Table 7.4). This means from 9:00 to 16:00, in order to provide 200 lumens that equivalent to a typical 25W incandescent lamp, eight FFSC finishing ends or four FFSC systems are sufficient.

The monitored maximum Ev provided by one FFSC finishing end in these 20 days was 1811 LUX, which appeared at 13:00 on 31 of May 2008, when the solar radiation PY1 was 1156.13W/m2. The luminous flux (F) of a finishing end at that time equals to 114.1 lumens as calculated by Eq. (4). It is higher than that of a 15W incandescent lamp (110 lumens) according to Table 7.4. However, a typical room normally requires a 60W bulb (850 lumens), which means totally eight FFSC finishing ends or four FFSC systems are required to deliver a equivalent lighting effect.

## 7.4 Energy-to-energy efficiency (ηe)

The energy-to-energy efficiency denoted by ηe in this research 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 Eq. (5):

$$\eta e = Pout/Psun \quad (5)$$

Where Pout is the total energy output yielding from both finishing ends and Psun is the solar energy irradiated on the fluorescent fibers. The effective area of the FFSC plate is calculated in Eq. (6) as follows:

$$S0 = D \times L \times n = 0.002 \times 1 \times 150 = 0.3m2 \quad (6)$$

Where D and L are the diameter and the length of the fluorescent fibers respectively. The variable n is the number of piece for the fluorescent fibers, which is 150. The effective area of one finishing end is calculated as shown in Eq. (7):

$$Sf = \pi \times Rf \times Rf = 3.14 \times 0.015 \times 0.015 = 0.0007m2 \quad (7)$$

Where Rf is the radius of the finishing end.

Therefore, the energy-to-energy efficiency ηe is calculated as shown in Eq. (8):

$$\begin{aligned} \eta e &= Pout/Psun \\ &= 2\times PY2\times Sf/(PY1\times S0) \\ &= (2\times 0.0007/0.3)PY2/PY1 = 0.0047PY2/PY1 \end{aligned} \tag{8}$$

Where PY2/PY1= ηr as defined by Eq. (1),

Therefore,

$$\eta e = 0.0047\eta r \tag{9}$$

The average radiation-to-radiation efficiency denoted by ηr-avg in these 6 months is 0.057 as mentioned in Section 7.2.2, which is shown in Eq. (10):

$$\eta r\text{-}avg = 0.057 \tag{10}$$

So that the average energy-to-energy efficiency in these 6 months is calculated in Eq. (11):

$$\eta e\text{-}avg = 0.0047\times \eta r\text{-}avg = 0.0047\times 0.057 = 0.000268 \tag{11}$$

The mean value of energy-to-energy efficiency is low at 0.000268. This reveals that FFSC currently is not suitable to replace the conventional PV cells for power production as present.

## 7.5 Luminous efficacy (*K*) of FFSC

Luminous efficacy is a figure of merit for light sources. It is the ratio of luminous flux (in lumens) to power (usually measured in watts). As most commonly used, it is the ratio of luminous flux emitted from a light source to the power consumed by the source, and thus describes how well the source provides visible light from a given amount of energy (Yoshi, 2004). Accordingly, the luminous efficacy (*K*) for FFSC is defined by Eq. (12):

$$K=2F/\mathrm{Psun} \tag{12}$$

Where *F* is the luminous flux produced by one finishing end, and Psun is the solar energy irradiated on the fluorescent fibers. Since there are two finishing ends equally sharing the irradiation from the fluorescent fibers, the coefficient "2" is used here in Eq. (12). Therefore, the luminous efficacy (*K*) is calculated as shown in Eq. (13):

$$K=2F/\mathrm{Psun}=2\times0.063\mathrm{Ev}/(\mathrm{PY1}\times\mathrm{S0})=2\times0.063\mathrm{Ev}/(\mathrm{PY1}\times0.3)=0.42\mathrm{Ev}/\mathrm{PY1} \tag{13}$$

A significant value of 0.01 as shown in Table 7.5 in the linear test conducted for Ev and PY1 indicates that the values of Ev and PY1 are linear so that Ev/PY1 is considered here as a comparatively stable value. Hence, an average ratio of Ev/PY1 could be used in the above equation as a constant in general. From the monitored data, the monthly mean value of Ev/PY1 is calculated as 1.53. Therefore, the luminous efficacy (*K*) of the FFSC finishing end is shown in Eq. (14):

$$K = 0.42 \times Ev/PY1 = 0.42 \times 1.53 = 0.643 \mathrm{lm/W} \tag{14}$$

**Table 7.5: linear test for Ev and PY1**

Coefficients(a)

| Model | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|
| | B | Std. Error | Beta | | |
| 1 (Constant) | -8.389 | 3.234 | | -2.594 | .010 |
| LUX | .657 | .005 | .987 | 136.389 | .000 |

a Dependent Variable: PY1

The value of FFSC luminous efficacy is below that of the natural daylight, which generally falls within the range 100lm/W to 130lm/W (Lam & Li, 1996). When compared to standard artificial light sources (Lam & Li, 1996) such as incandescent light bulbs (16 – 40 lm/W) and fluorescent lamps (50 – 80 lm/W), the FFSC luminous efficacy as 0.643lm/W is considered low. However, it is higher than the luminous efficacy of a combusting candle at 0.3 lm/W according to Wapedia (2009). Furthermore, since the sun light is free, different from all the electrical light sources, the low luminous efficacy of FFSC does not mean any electricity consumption when it is under operation.

## 7.6 Light-to-light efficiency (ηl) evaluation

Light-to-light efficiency is the ratio of output luminous flux to the input luminous flux (Earp et al., 2004; Yoshi, 2004). Evaluation is conducted to calculate the ratio of the luminous flux yielding from the two FFSC finishing ends to the luminous flux dropping on the fluorescent fibers and it is defined here as the light-to-light efficiency (ηl). The luminous flux yielding from a FFSC finishing end is denoted as *F*, and it has been calculated in Eq. (4). The luminous flux dropping on the fluorescent fibers is denoted as *F0,* and the luminous flux is from the solar irradiation. Accordingly, the light-to-light efficiency (ηl) is defined by Eq. (15):

$$\eta l = 2F/F0 \tag{15}$$

The value of *F0* could be calculated from either the illuminance (LUX) or the radiation (W/m2) (Yoshi, 2004; Schiler, 1992). Since in this experimentation only a Pyranometer instead of a LUX sensor is installed to measure the solar irradiation, the values of *F0* are calculated from the solar radiation PY1 (W/m2). The luminous flux is the product of the irradiation energy and the luminous efficacy of the irradiation (Yoshi, 2004; Schiler, 1992). Therefore, the luminous flux dropping on the fluorescent fibers is calculated in Eq. (16):

$$F0 = (\mathrm{PY1} \times \mathrm{S0}) \times \mathrm{K0} \tag{16}$$

Where S0 is the total effective area of the fluorescent fibers on the FFSC plate and it is calculated as 0.3 $m^2$ by Eq. (6). K0 is the luminous efficacy of the sunlight. According to Lam & Li (1996), the luminous efficacy of the sunlight K0 is remarkably stable and it generally falls within the range 100lm/W to 130lm/W.

By synthesizing Eq. (4), Eq. (15) and Eq. (16), the FFSC light-to-light efficiency (ηl) is calculated as shown in Eq. (17):

$$\eta l = 2F/F0 = 2 \times 0.063Ev/(PY1 \times 0.3 \times K0) = (0.42/K0) \times (Ev/PY1) \quad (17)$$

From the monitored data, the monthly mean value of Ev/PY1 is stable and is calculated as 1.53 as mentioned in Section 7.5. The Eq. (17) is therefore transformed into Eq. (18):

$$\eta l = (0.42/K0) \times (Ev/PY1) = (0.42/K0) \times 1.53 = 0.64/K0 \quad (18)$$

According to Lam & Li (1996), the luminous efficacy of the sunlight K0 generally falls within the range 100lm/W to 130lm/W. By substituting this range into Eq. (18), the evaluated FFSC light-to-light efficiency (ηl) falls within the range 0.49% to 0.64%.

Comparing to the light-to-light efficiency of the LSC produced by Earp et al. (2004) as 6%, the FFSC light-to-light efficiency is low. This is because of the small cross sectional area of the fluorescent fibers in FFSC. However, there is no comparability between FFSC and Earp et al.'s LSC because the size and the form of these two types of cross sections are greatly different. The cross sectional area of the fluorescent fiber in FFSC is only 12.56 mm2 but the cross sectional area of the Earp et al.'s (2004) LSC is 270mm2. The cross section of the LSC produced by Earp et al. (2004) is a 2mm× 135mm rectangular section. Since solar photons entering the FFSC plate are absorbed by the luminescent species and reemitted in random directions, a large fraction of the emitted photons lose from the escape cones. The size and the form of the cross section could impact on the proportion of photons trapped by the LSC plate and the reduction of the cross sectional area of the luminescent plate could increase the photon loss (Richards, 2006; Reisfeld, 2001; Batchelder et al., 1979; Hammam et al., 2007). Accordingly, the light-to-light efficiency of the FFSC could be raised by increasing the diameter of the fluorescent fibers embedded. Therefore, in future study, the fluorescent fibers with a large diameter, say 10mm diameter, is recommended for the testing in FFSC system. This is expected to increase the light-to-light efficiency of FFSC and it will not bring extra difficulties for wiring. Moreover, a study on the relationship between the diameter and the light-to-light efficiency for fluorescent fibers is also recommended. Even though the light-to-light efficiency of FFSC appears lower than the LSC produced by Earp et al. (2004), FFSC has a greater advantage in wiring as it is designed to be, because the light transportation media of FFSC are optical fibers but this is difficult for the LSC produced by Earp et al. (2004) to achieve.

## 7.7 The negative trend between radiation-to-radiation efficiency (ηr) and solar radiation (PY1)

Based on the monitored 10167 sets of effective data in the 6 months from 6:00 to 20:00 at an interval of 10 minutes, the system radiation-to-radiation efficiency (ηr) presents a holistic negative trend with the solar radiation PY1. As shown in Figure 7.9, all these 10167 sets of data are symmetrically sorted by the radiation-to-radiation efficiency (ηr) in an ascending order while the corresponding values of the solar radiation (PY1) present a descending trend.

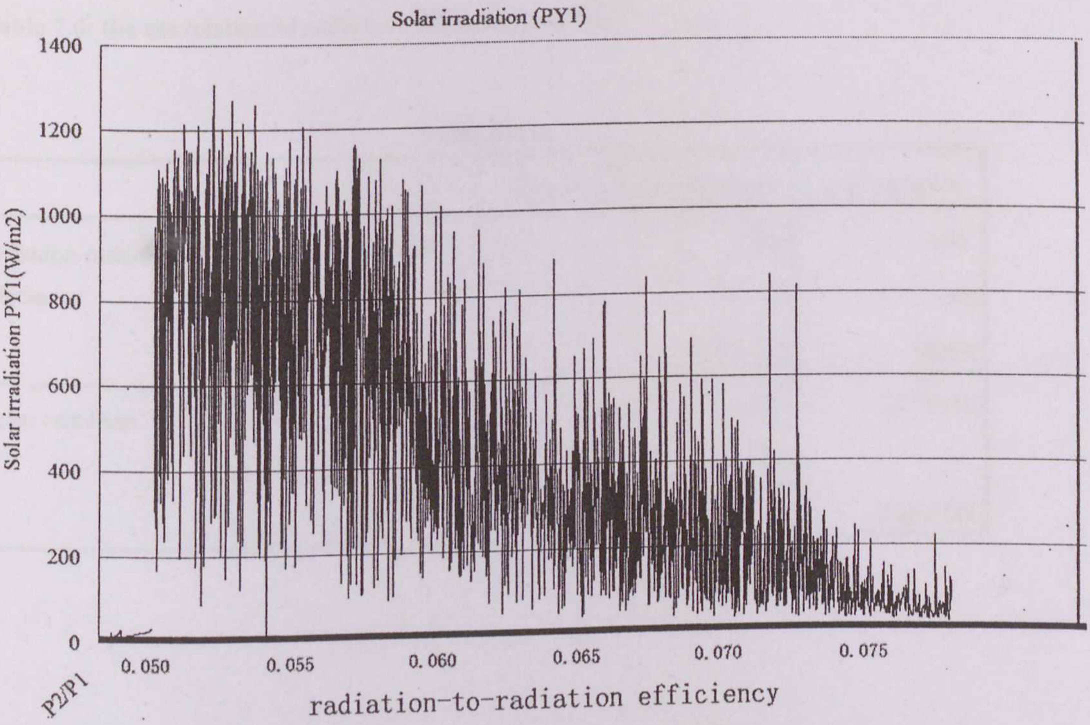


*Figure 7.9: negative trend between radiation efficiency and PY1*

There is a negative correlation coefficient (-0.643) in Table 7.6 between the radiation-to-radiation efficiency and the solar radiation, indicating that the relationship between these two variables is that the values of one variable decrease as the other increases. However, this kind of negative trend does not indicate a strictly negative association, for the negative correlation coefficient (-0.643) is not significantly under a 0.01 level. The reason for the negative trend between the radiation-to-radiation efficiency (ηr) and the solar radiation (PY1) is not discussed here because it may beyond the researchers' specialized knowledge and it is recommended in the future study.

**Table 7.6: the correlation of radiation efficiency and PY1**

Correlations

| | | radiation-radiation efficiency | solar radiation |
|---|---|---|---|
| radiation-radiation efficiency | Pearson Correlation | 1.000 | -.643** |
| | Sig. (2-tailed) | | .000 |
| | N | 10167.000 | 10167 |
| solar radiation | Pearson Correlation | -.643** | 1.000 |
| | Sig. (2-tailed) | .000 | |
| | N | 10167 | 10167.000 |

## 7.8 Matching the natural light: CIE color analysis and wavelength ( λ ) test

The CIE color analysis and wavelength test for the artificial light produced by the FFSC were conducted on a random day 16th Oct 2008 from 9:00 to 15:00. The weather on that day was sunny with a clear sky from 9:00 to 11:00, while from 11:30 to 13:30 it was sunny with little clouds. Since 14:00, it was overcast and raining until the evening.

The device used for the CIE color analysis and the wavelength test is the EPP2000&ISA2000 spectrometer as introduced in Chapter 5, the responding range for which is from 190nm to 2200nm. Since the visible light waveband drops between 400nm to 700nm (Geoffrey, 2004), and according to Geoffrey (2004) and Earp et al. (2004), the average wavelength for the white light is around 555nm, therefore, this device is suitable for the test described in this section.

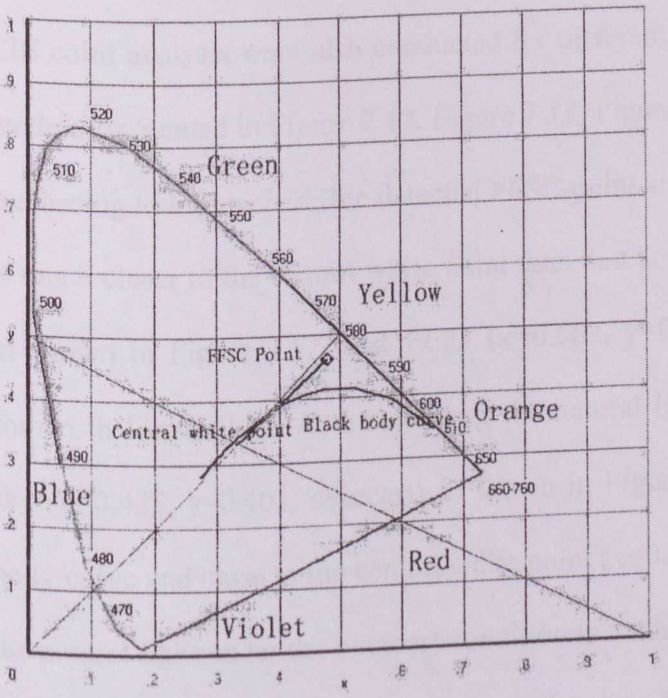
The detector of the spectrometer was placed towards the FFSC finishing end at the distances of 10cm, 20cm, 30cm, 40cm, 50cmm, 80cm, and 100cm, respectively. The reason for using these various distances is to prove that the light yielding out of the finishing end could considerably mix into a white color light through a short distance by self-scattering.

In order to find out the relationship between the output color and the various sky conditions, a same group of tests was repeated three times on 16th Oct 2008. The first group of tests was conducted at around 10:00 (clear sky), and it was repeated at around 12:30 (sunny with little clouds). The last group of tests was conducted at around 14:30 (overcast).

### *7.8.1 CIE color analysis*

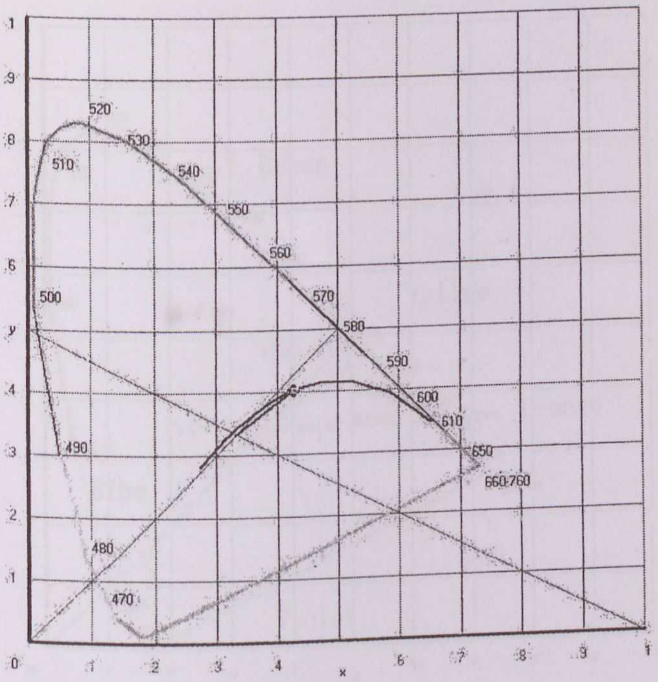
A CIE color analysis was conducted under the irradiant mode at around 12:30 (sunny with little clouds) on a random day on 16th Oct 2008. Figure 7.10 presents the screen of the detected data. As indicated in Figure 7.10, the solid curve in the right of the diagram is the black body curve. There are two diagonals forming a cross in the central area and the cross point is indicated as "central white point" in the diagram, where x=0.333, y=0.333. Any detected point drops on or near this central white point is considered as white color (Yoshi, 2000). The FFSC point in the diagram drops between the central white point and the yellow area, where x=0.479 and y=0.460, indicating that the FFSC light output at a 10cm distance to the light detector leans a bit towards the yellow area comparing to the absolutely white light. Referring to the CIE diagram for the direct sun light (x=0.427, y=0.401) shown in Figure 7.11, the FFSC point (x=0.479 and y=0.460) appears a great match to the direct sun light. Therefore, it concludes that the FFSC light output under a sunny sky is a kind of yellow-white color light and its color has a good match to that of the direct sunlight. According to Yoshi (2000) and Schiler (1992), a yellow-white color light is comforting to human eyes.

It is noticed that as the distance between the detector and the finishing end increases from 10cm to 100cm, the FFSC points in CIE diagrams are getting closer to the yellow area and getter apart from the white color region around the cross point (central white point) in the middle of the diagram, as indicated in from Figure B1 to Figure B8 as enclosed in APPENDIX B.



Note: x=0.479, y=0.460

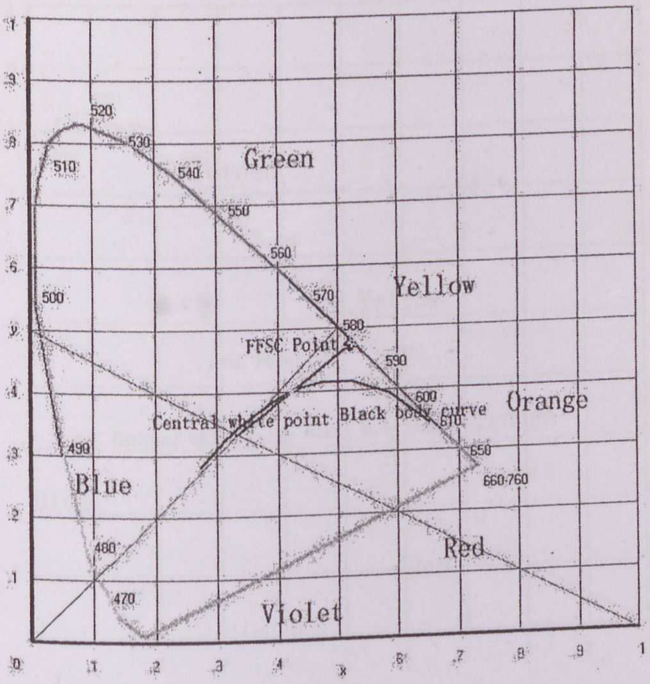
*Figure 7.10: CIE color analysis 10cm 12:27, 16OCT2008*



Note: x=0.427, y=0.401

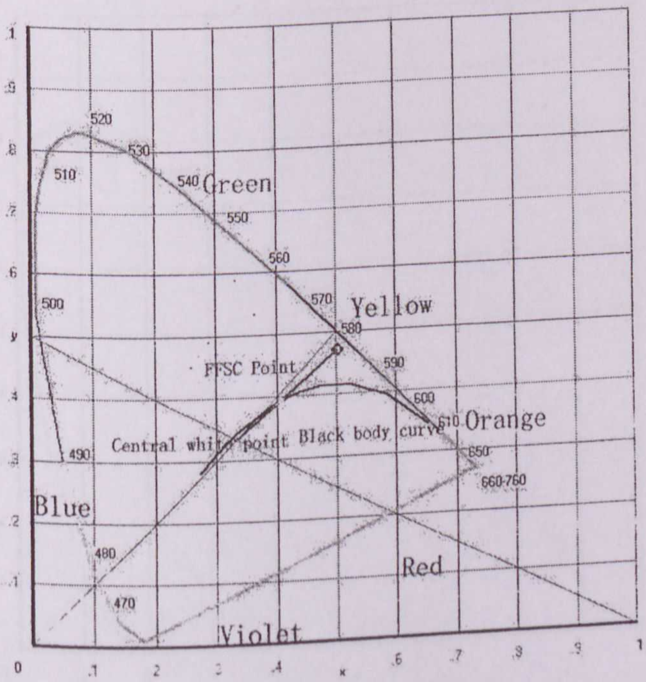
*Figure 7.11: CIE color analysis for direct sun light 11:33, 12Nov2008*

CIE color analysis were also conducted for different sky conditions under the irradiant mode as presented in Figure 7.12, Figure 7.13, Figure 7.14, and Figure 15, respectively. According to Figure 7.14, the detected FFSC point at 14:36 (x=0.481, y=0.449, overcast) is much closer to the central white point than that at 9:50 (x=0.520, y=0.471, clear sky) as shown in Figure 7.12, and 12:33 (x=0.502, y=0.470, sunny with little clouds) as shown in Figure 7.13. As a reference, the natural light color point under the overcast sky (x=0.425, y=0.403, overcast) as shown in Figure 7.15 is just located on the black body curve and close to the central white point (x=0.333, y=0.333), which indicates that the natural light under the overcast condition is a white light. Therefore, the light output of FFSC in all the sky conditions is proved to be a kind of yellow-white color light. In addition, under the overcast sky, the FFSC light color is whiter than that under the clear sky condition.



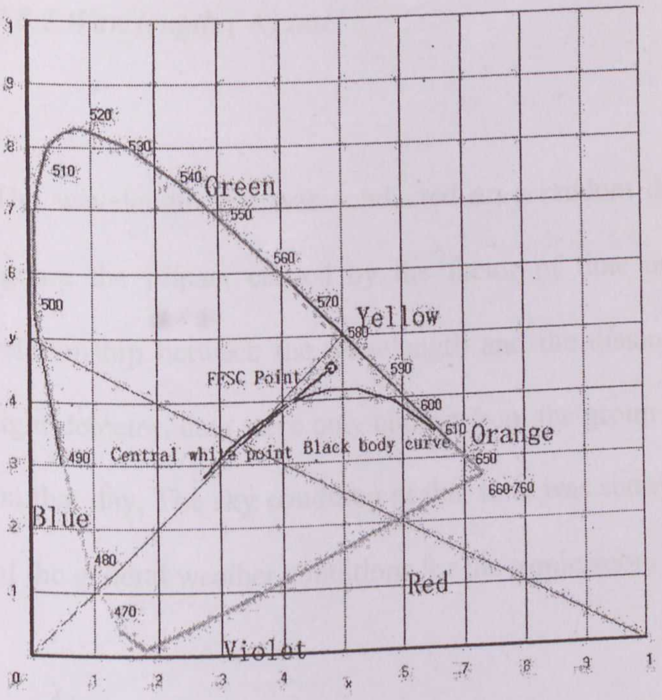
Note: x=0.520, y=0.471

*Figure 7.12: CIE color analysis 9:50, 16OCT2008 (clear sky)*



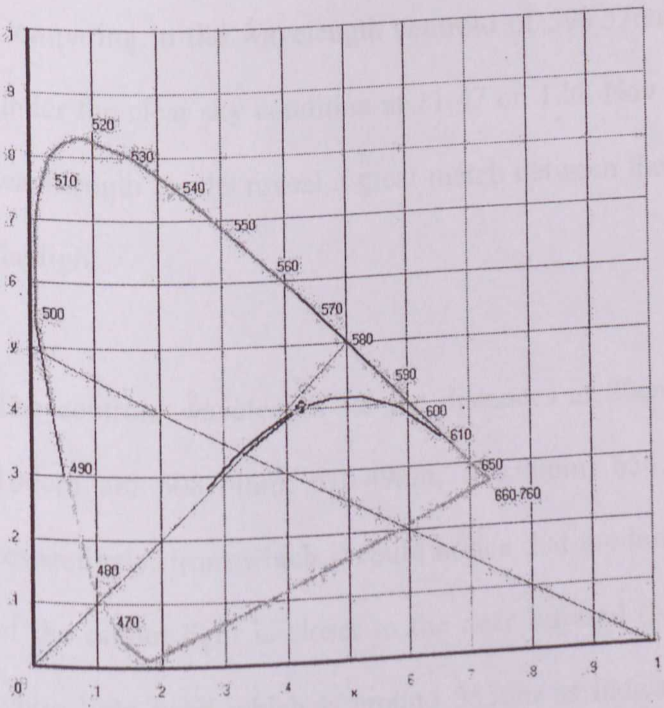
Note: x=0.502, y=0.470

*Figure 7.13: CIE color analysis 12:33, 16OCT2008 (sunny with little clouds)*



Note: x=0.481, y=0.449

*Figure 7.14: CIE color analysis 14:36, 16OCT2008 (overcast)*



Note: x=0.425, y=0.403

*Figure 7.15: CIE color analysis natural daylight overcast 2nd Nov 2008*

### *7.8.2 Wavelength ( $\lambda$ ) test*

The wavelength test was conducted on a random day on 16th Oct 2008. In order to ignore the impact caused by the factor of time and the weather, in analyzing the relationship between the wavelength and the distances from the finishing end to the light detector, data were only chosen from the group of tests conducted at around 12:30 on that day. The sky condition at that time was sunny with little clouds, which was one of the general weather conditions for the tropic zoon.

Figure 7.16 presents a wavelength screen in the scope mode at 12:23 on 16th Oct 2008 at a distance of 10cm from the FFSC finishing end to the detector, from which it indicates on the top of the screen that the centroid is 607.31nm. The wave band as 607.31nm is not far from the average band for the white light, which is 555nm. Comparing to the wavelength centroid of 598.57nm captured for the natural daylight under the clear sky condition at 11:47 on 12th Nov 2008 as shown in Figure 7.17, the wavelength results reveal a great match between the FFSC light output and the natural daylight.

The centroid wavelength for the distances at 20cm, 30cm, 40cm, 50cm, 80cm, and 100cm are 608.74nm, 610.49nm, 610.00nm, 654.29nm, 653.59nm, and 653.52nm, respectively, from which it could notice that the longer the distance is, the wavelength of the output light is closer to the near infrared (NIR) area and more apart from the white light band which is around 555nm as indicated in Figure A1 to Figure A8 in APPENDIX A as enclosed.

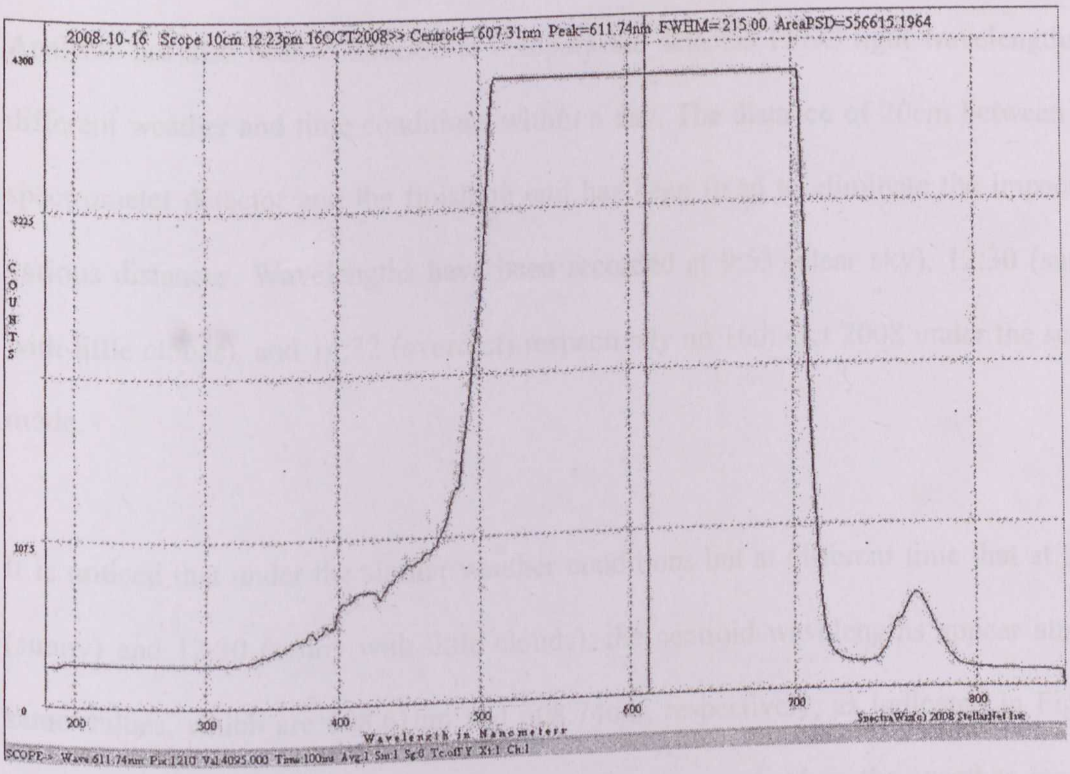


*Figure 7.16: wavelength Scope mode 10cm 12:23, 16OCT2008*

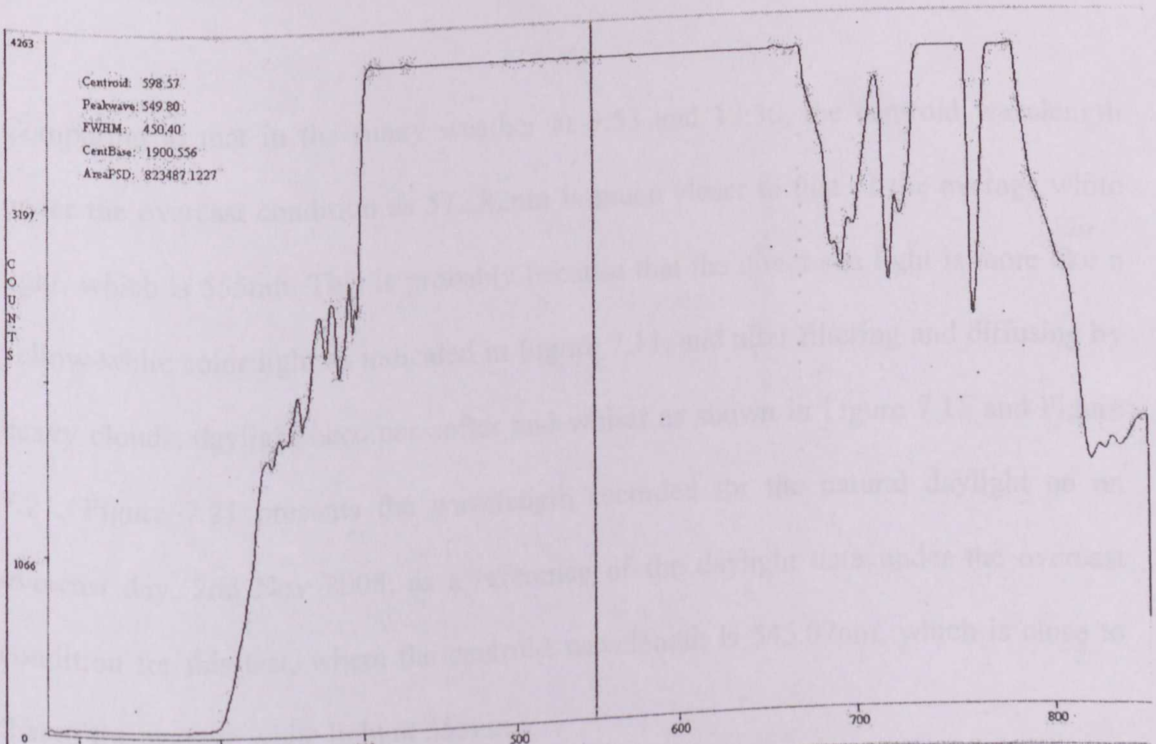


*Figure 7.17: wavelength Scope mode natural light at sunny condition 11:47, 12Nov2008*

Analysis has also been conducted to compare the detected FFSC light wavelengths in different weather and time conditions within a day. The distance of 20cm between the spectrometer detector and the finishing end has been fixed to eliminate the impact of various distances. Wavelengths have been recorded at 9:53 (clear sky), 12:30 (sunny with little clouds), and 14:32 (overcast) respectively on 16th Oct 2008 under the scope mode.

It is noticed that under the similar weather conditions but at different time that at 9:53 (sunny) and 12:30 (sunny with little clouds), the centroid wavelengths appear almost same values, which are 608.61nm and 608.74nm, respectively, as indicated in Figure 7.18 and Figure 7.19. However, differences has emerged when the weather rapidly changed into the overcast condition at 14:32 on that day, when the centroid wavelength dramatically moved into 572.82nm as indicated in Figure 7.20.

Comparing to that in the sunny weather at 9:53 and 12:30, the centroid wavelength under the overcast condition as 572.82nm is much closer to that of the average white light, which is 555nm. This is probably because that the direct sun light is more like a yellow-white color light as indicated in Figure 7.11, and after filtering and diffusing by heavy clouds, daylight becomes softer and whiter as shown in Figure 7.15 and Figure 7.21. Figure 7.21 presents the wavelength recorded for the natural daylight on an overcast day, 2nd Nov 2008, as a reference of the daylight data under the overcast condition for this test, where the centroid wavelength is 545.07nm, which is close to that of the average white light at 555nm.

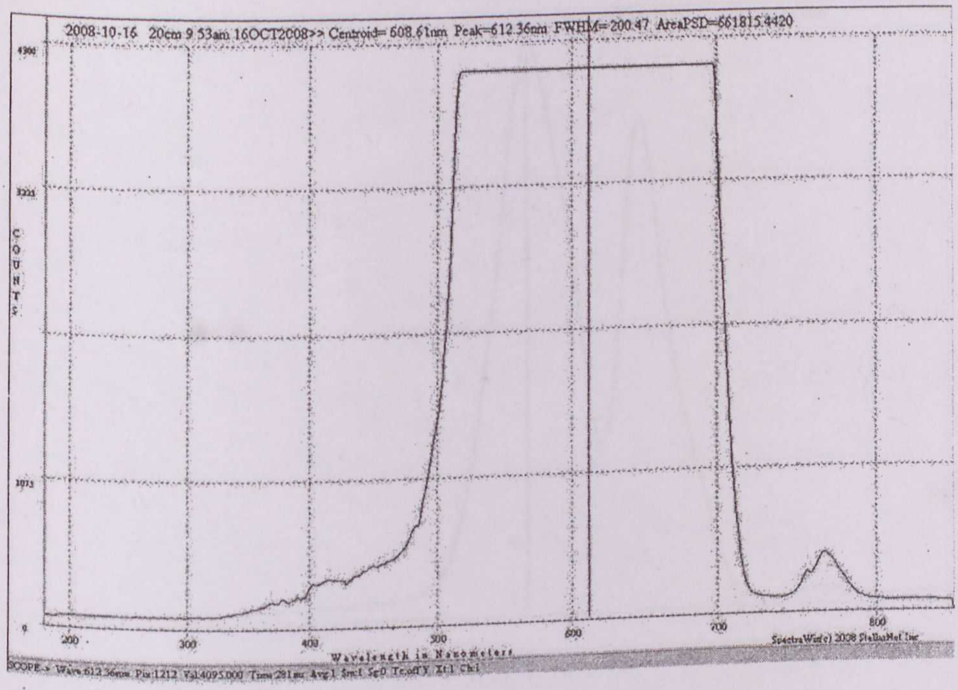


*Figure 7.18: wavelength Scope mode 20cm 9:53, 16OCT2008*

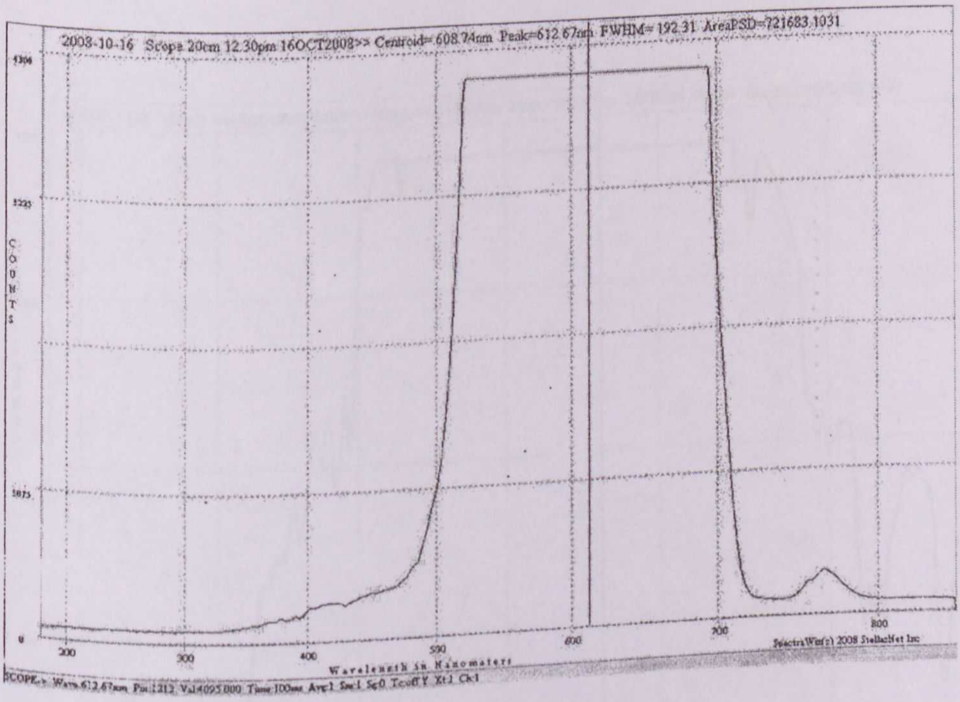


*Figure 7.19: wavelength Scope mode 20cm 12:30, 16OCT2008*

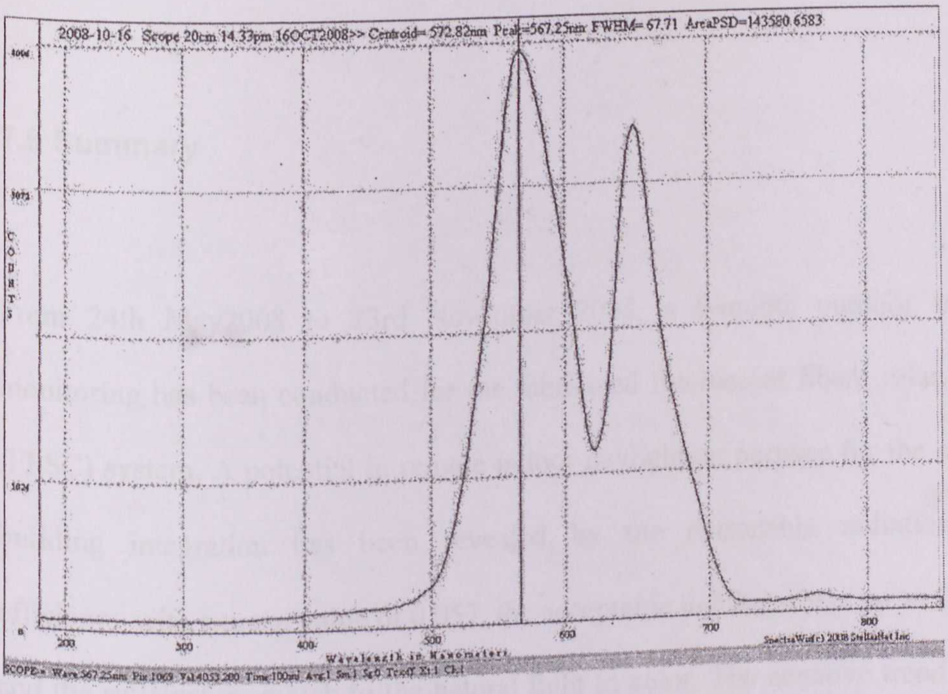


*Figure 7.20: wavelength Scope mode 20cm 14:32, 16OCT2008*

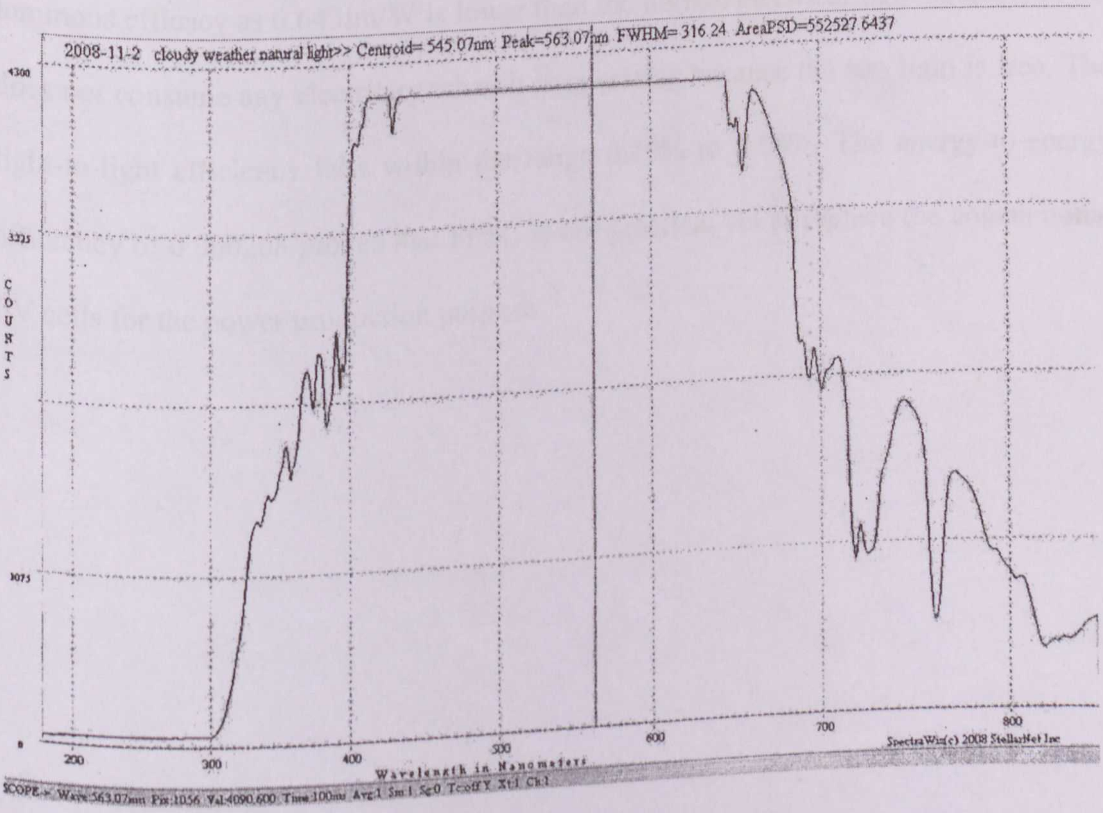


*Figure 7.21: Scope mode natural daylight overcast 2nd Nov 2008*

## 7.9 Summary

From 24th May2008 to 23rd November 2008, a 6-month outdoor trial run and monitoring has been conducted for the fabricated fluorescent fibers solar concentrator (FFSC) system. A potential in remote indoor daylighting purpose for the application in building integration has been revealed by the reasonable radiation-to-radiation efficiency with a mean value of 0.057, the acceptable lighting effect up to 114.1 lumens, and the satisfactory match to the natural light in color. The negative trend between the radiation-to-radiation efficiency (ηr) and the solar radiation is detected. The wavelength tests and the CIE color analysis reveal that the FFSC light output has a satisfactory match to the natural light, and it is comforting to human eyes. Even though the luminous efficacy as 0.643lm/W is lower than the normal electrical light sources, FFSC does not consume any electricity when it is operating because the sun light is free. The light-to-light efficiency falls within the range 0.49% to 0.64%. The energy-to-energy efficiency of 0.000268 proves that FFSC is not practical yet to replace the conventional PV cells for the power production purpose.

# Chapter 8

# Conclusions and Recommendations

## 8.1 Conclusions

In conclusion, the three main objectives have been fully achieved in this research. The three main objectives of this research are:

a) to identify the working principles and to extract the limitations of the present daylighting related devices, and

b) to develop a new concept to avoid or to mitigate the limitations of the present daylighting related devices and to fabricate a device based on the new concept, and

c) to assess the performance of the fabricated new device for remote indoor daylighting purposes through its trial run.

The 1st objective is achieved through literature reviews on the natural lighting related devices as presented in Chapter 2 as well as through the discussions on the necessity of FFSC as presented in the first section of Chapter 4. Daylight has a disadvantage of not being able to reach deeper areas in a building such as storerooms, basements, and corridors, and it brings the heat gain with the light. Light pipes and optical fibers were expected to transfer daylight to unreached areas, but light pipes have their difficulties in wiring and the optical fiber needs a pointolite for the light transportation. Solar concentrators are only sensitive for the beam radiation and they function poorly in overcast sky conditions. Even under a clear sky condition, trackers are always needed for conventional solar concentrators. Static concentrators always come with a poor concentration rate without a tracker, and the light concentrated by normal luminescent solar concentrators could not be transported by optical fibers to a remote place since the light produced by LSCs is not a pointolite.

The 2nd objective is achieved through the concept design and the fabrication process as described in Chapter 4. A new concept, which is to use fluorescent fibers for solar concentration and to use clear optical fiber bundles to transport the absorbed daylight into a target area for remote indoor daylighting purposes, has been developed by the author. Accordingly, a new device named "fluorescent fiber solar concentrator" (FFSC) is designed and fabricated in this study based on the concept.

The last objective is to monitor the performance of the fabricated new device in remote indoor daylighting purposes through its trial run, and this is fulfilled through a 6-month experimentation as discussed in Chapters 5, 6, and 7. Through the 6-month experimentation, the fabricated 1200mm × 1200mm solar concentrator (FFSC) consisting of 150 pieces of three-color 1m long fluorescent fibers with the diameter of 2mm has been mounted on the roof of a University building, and the concentrated light is transported to a remote dark room through the 10m long, 2mm diameter clear optical fiber bundles. Outdoor testing for remote indoor daylighting and power production evaluation has been conducted from 24th May2008 to 23rd November 2008.

The negative trend between the radiation-to-radiation efficiency and the solar radiation is detected and analyzed. The low energy-to-energy efficiency value of 0.000268 indicates that FFSC is not practical yet to replace the conventional PV cells for power production. However, the reasonable radiation-to-radiation efficiency with a mean value of 0.057 and the acceptable lighting effect up to 114.1 lumens reveal FFSC a potential in remote indoor daylighting for the application in building integration. The wavelength test and the CIE color analysis reveal that the FFSC light output has a satisfactory match to the natural light in color. Since the sun light is free, even though the luminous efficacy as 0.643lm/W is lower than the normal electrical light sources, FFSC does not consume any electricity when it is operating. The light-to-light efficiency falls within the range 0.49% to 0.64% and it is expected to be raised by increasing the diameter of the fluorescent fibers embedded in FFSC. Even though the light-to-light efficiency of FFSC appears lower than that of the LSC produced by Earp et al. (2004), there is no comparability between FFSC and Earp et al.'s LSC because the cross section of the fluorescent fiber in FFSC is a 12.56m2 circular section while that of the Earp et al.'s LSC is a 270m2 rectangular section, and the size and form of the cross section could impact on the proportion of photons trapped. FFSC has a greater advantage in wiring as it is designed for, because its media for light transportation are optical fibers, which is difficult for the LSC produced by Earp et al. (2004) to achieve. Moreover, comparing to the conventional artificial lighting devices powered by PV cells, which convert light to electricity and then convert it back to light again losing a lot of efficiency in multi-converting, the idea of FFSC as a shortcut light-to-light conversion is considered to have a more efficient future.

## 8.2 Potential applications of FFSC

In light of the revealed potentials in remote indoor daylighting for the application in building integration, and dependent on the potential dramatic commercial success of fluorescent fibers in the future, FFSC systems could probably be applied for the illumination in underground areas of buildings or constructions during the daytime. Since the FFSC plate does not rely on only beam irradiation, it could be placed anywhere there is sufficient light, no matter the light source is the beam irradiation or the diffuse irradiation or even the electrical light. For example, the FFSC plate can be placed vertically in the south facade of a building in the northern hemisphere. The proposed underground areas to be illuminated by FFSC systems could be the car park levels in shopping complexes, convention centers, and some office buildings.

FFSC system could also be applied to illuminate the inner areas in a building. Where there is insufficient daylight, an artificial light source is always needed during the daytime. Illumination produced by FFSC could complement the side lighting (e.g. light from windows), especially for the space in the deep interior of a building. These inner areas include such as meeting rooms, corridors, and so on.

Since electro circuits are not needed in the FFSC system, there is no any risk for short circuits while this system is operating. Hence. potentially FFSC systems are quite suitable for subaqueous illumination during the daytime, especially for the underwater areas where the sunlight is not able to penetrate through effectively. Because of this kind of attribute, some extremely moist operation environments are also suitable for FFSC systems to be applied in when a durative illumination is needed during the daytime. Also becasue there is no electro circuit needed, FFSC systems do not have any risk of fire caused by the electrical current in inflammable gas conditions.

## 8.3 Recommendations for Future Research

The following areas are recommended for future study:

Firstly, in future study, the fluorescent fibers with a large diameter, say 10mm diameter, are recommended in the FFSC system. This will increase the light-to-light efficiency of FFSC and it does not bring extra difficulties in wiring. A study on the relationship between the diameters and the light-to-light efficiency of fluorescent fibers is recommended.

Secondly, cost evaluations for the fluorescent fiber solar concentrator (FFSC) or for other types of new designed fluorescent solar concentrators could probably be conducted in the future for the commercialization purpose. The cost evaluations for FFSC have not been conducted in this research because it is still on the experimental stage and the market for the fluorescent fibers is not yet mature.

Thirdly, as experimentations for FFSC were only conducted in the tropic zone especially in the country of Malaysia, future monitoring activities are recommended in the frigid zone and the temperate zone.

Next, based on the monitored 10167 sets of effective data during the 6 months, the system radiation-to-radiation efficiency (ηr) presents a negative trend with the solar radiation PY1. The knowledge for the reason why this kind of negative trend occurs may beyond the author's specializing field. However, being aided by specialists with proper fields of knowledge, say, knowledge in optical physics or hylology, the answer is expected to be revealed in future study.

Finally, studies on new ideas in the FFSC structural design itself are also encouraged since improvements could probably be made in the structural design to enhance the device efficiency, to save materials, or to accommodate with the large-scale installation.

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# APPENDIX A: Wavelength Testing Diagram

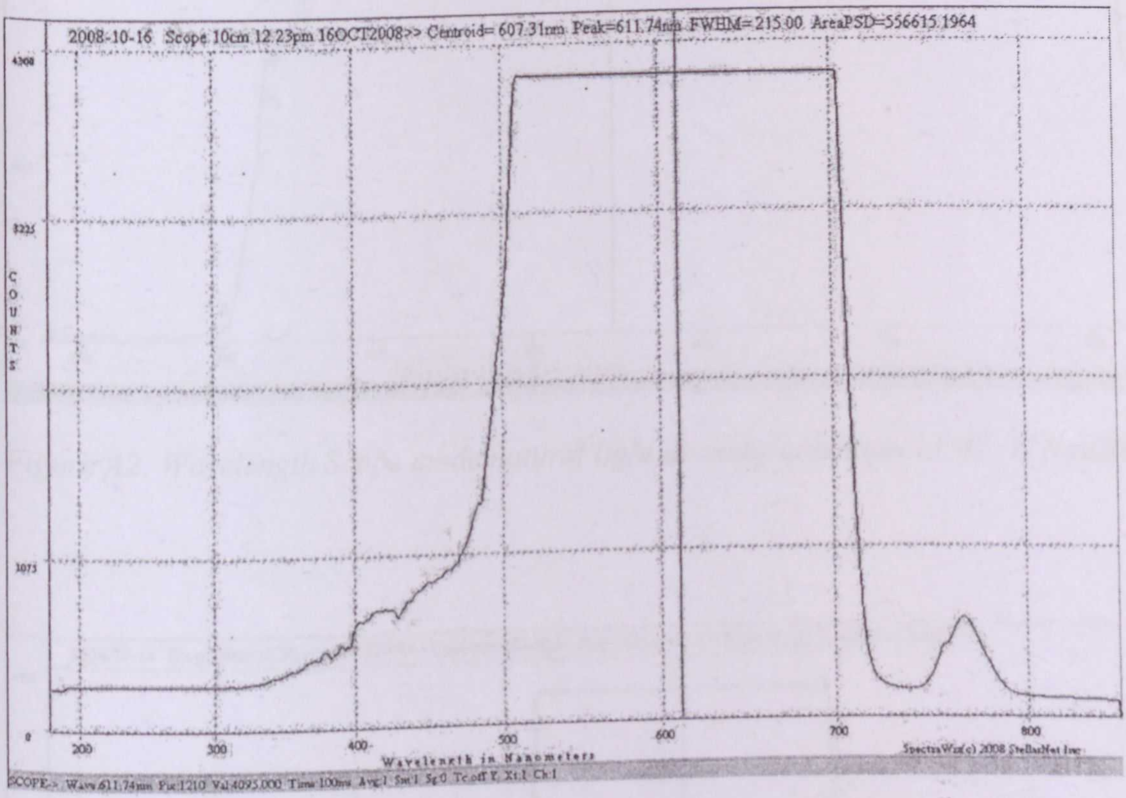


*Figure A1: Wavelength Scope mode 10cm 12:23 16OCT2008*

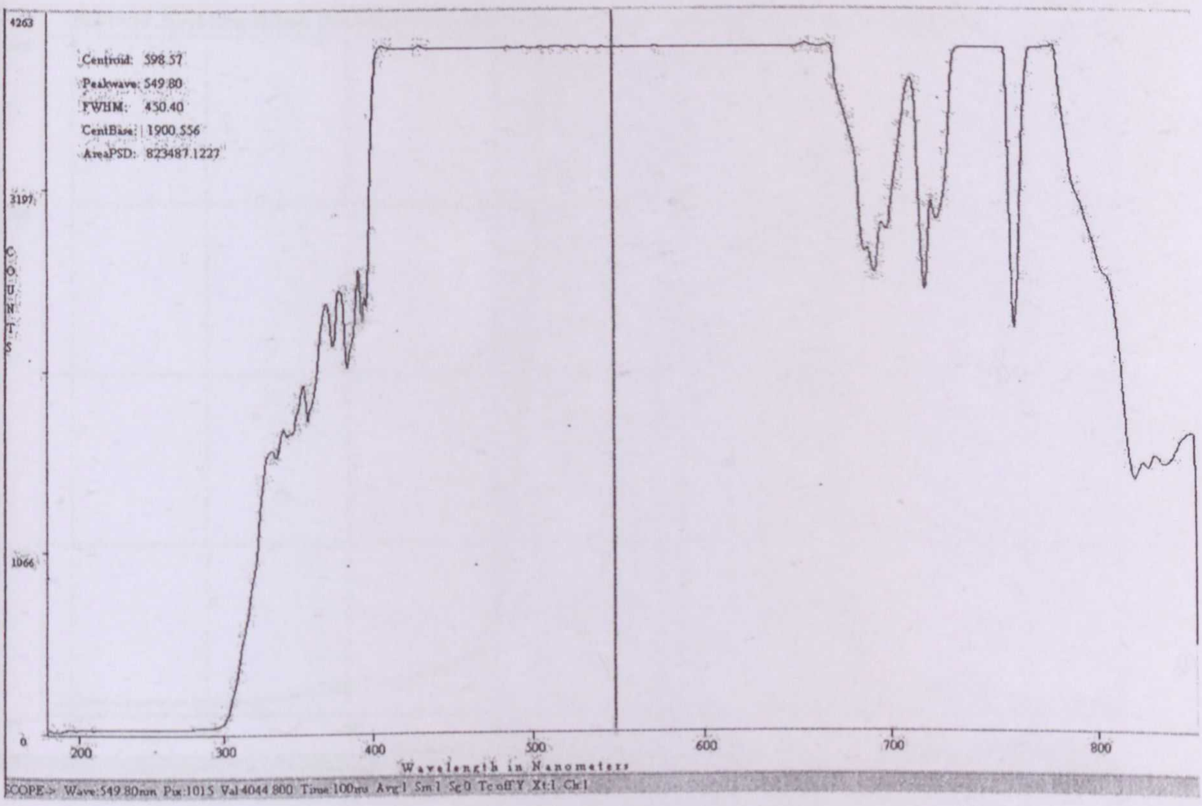


*Figure A2: Wavelength Scope mode natural light at sunny condition 11:47, 12Nov2008*

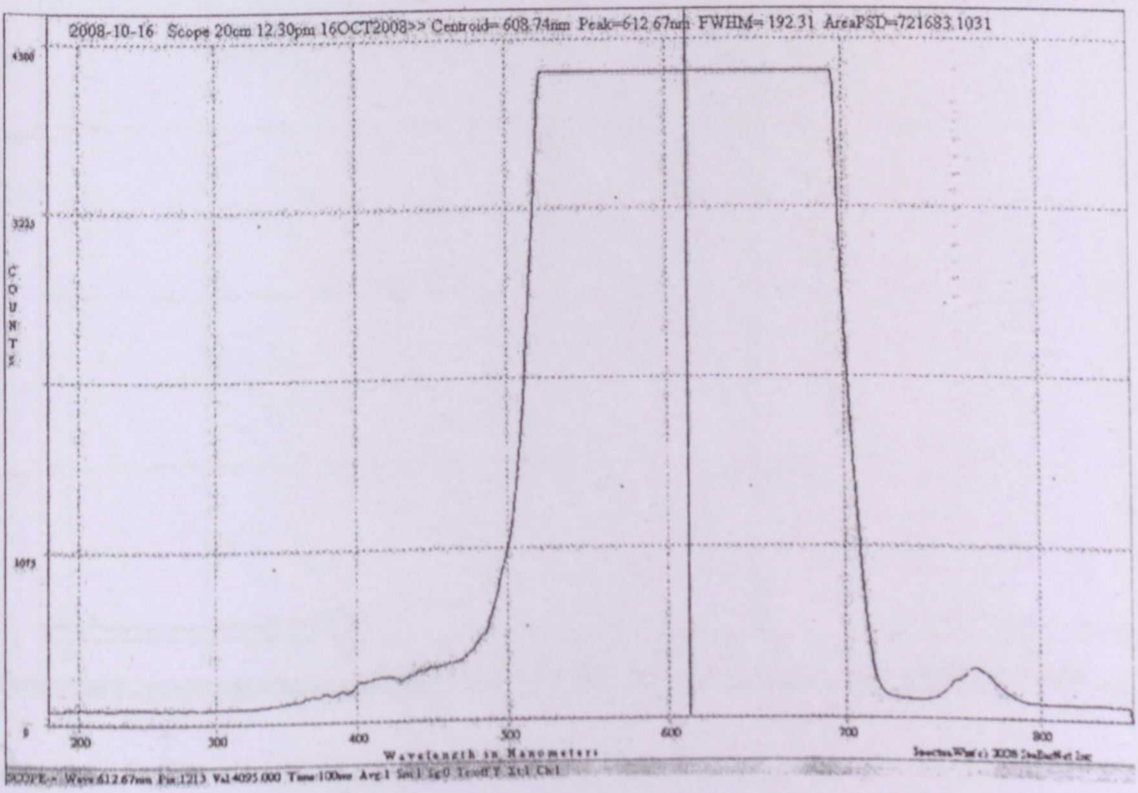


*Figure A3: Wavelength Scope mode 20cm 12:30, 16OCT2008*

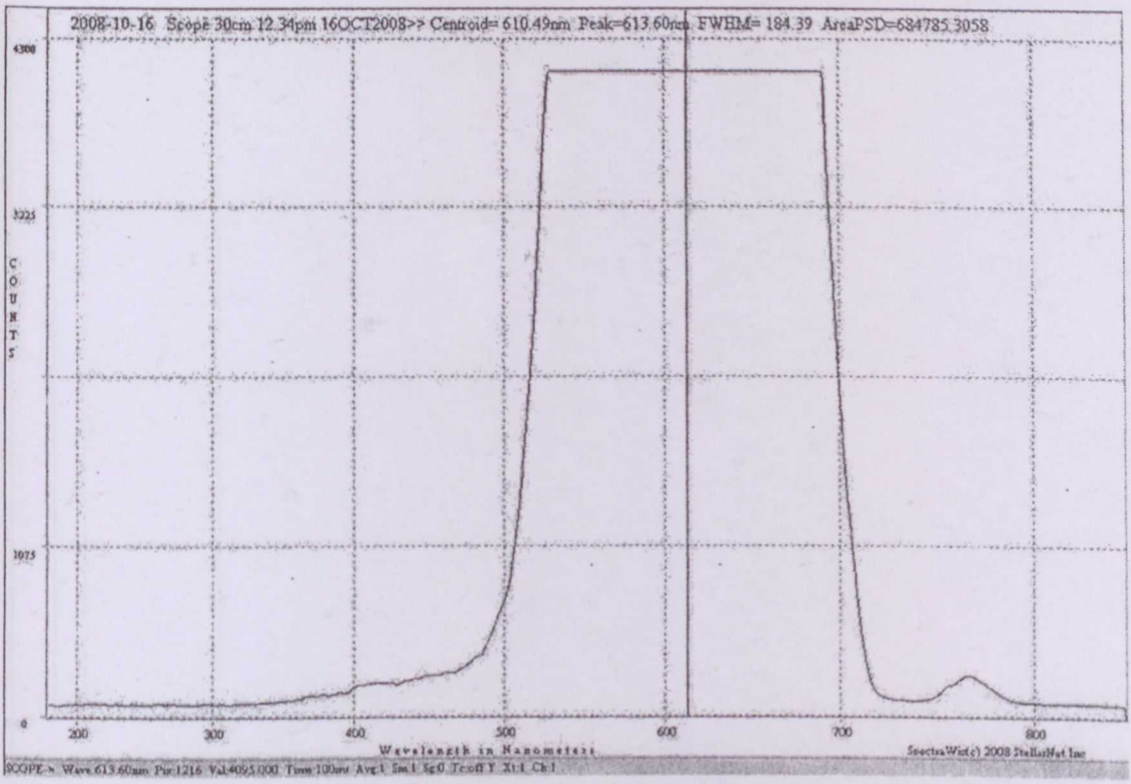


*Figure A4: Wavelength Scope mode 30cm 12:34, 16OCT2008*

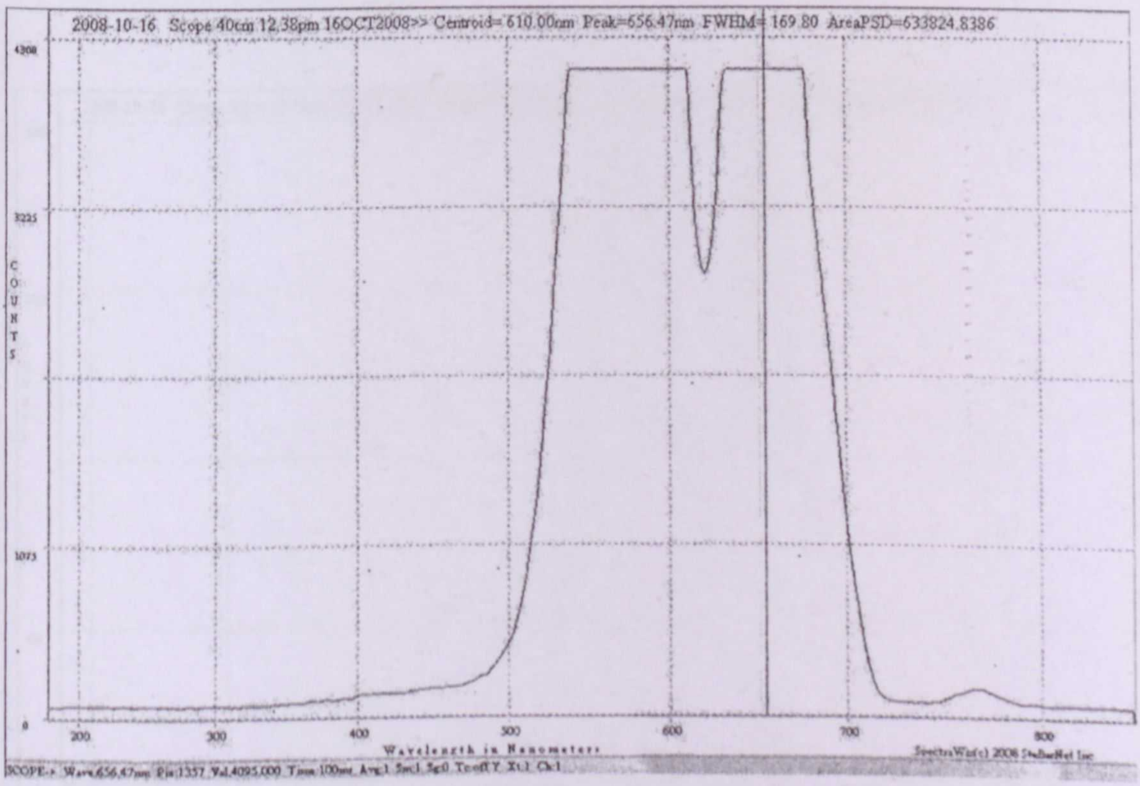


*Figure A5: Wavelength Scope mode 40cm 12:37, 16OCT2008*

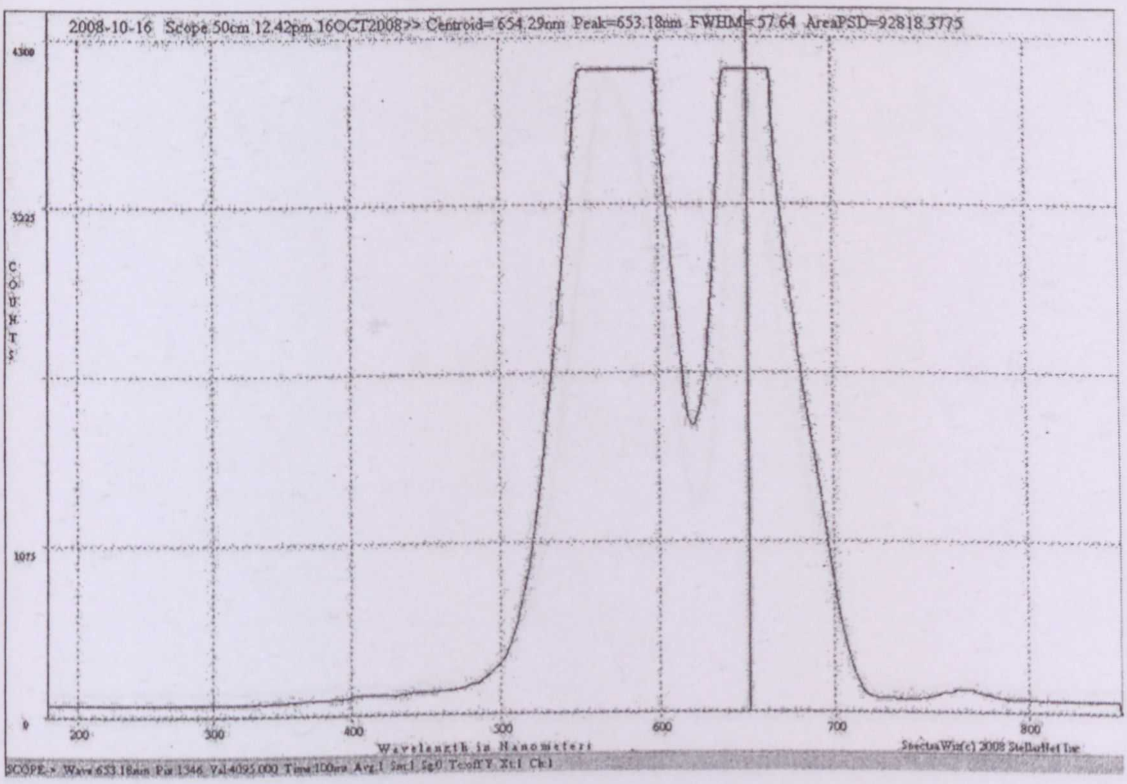


*Figure A6: Wavelength Scope mode 50cm 12:42, 16OCT2008*

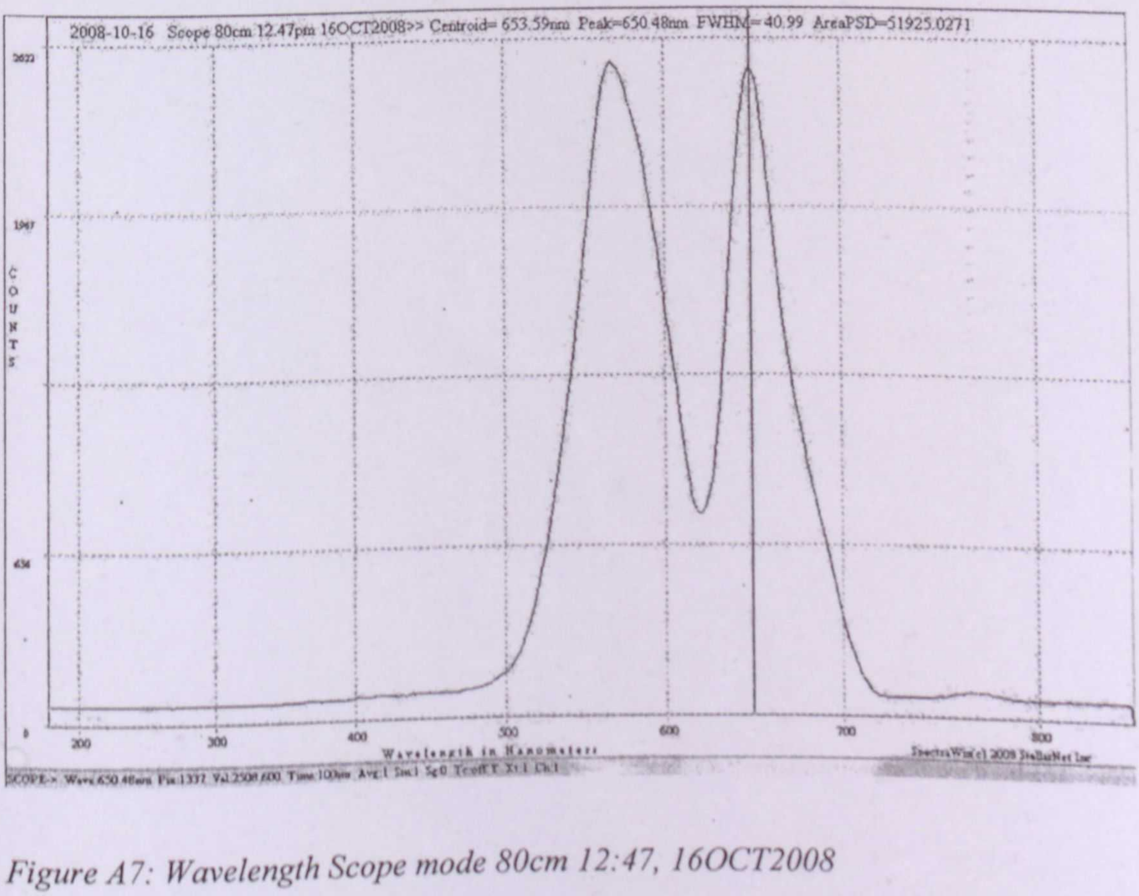


*Figure A7: Wavelength Scope mode 80cm 12:47, 16OCT2008*

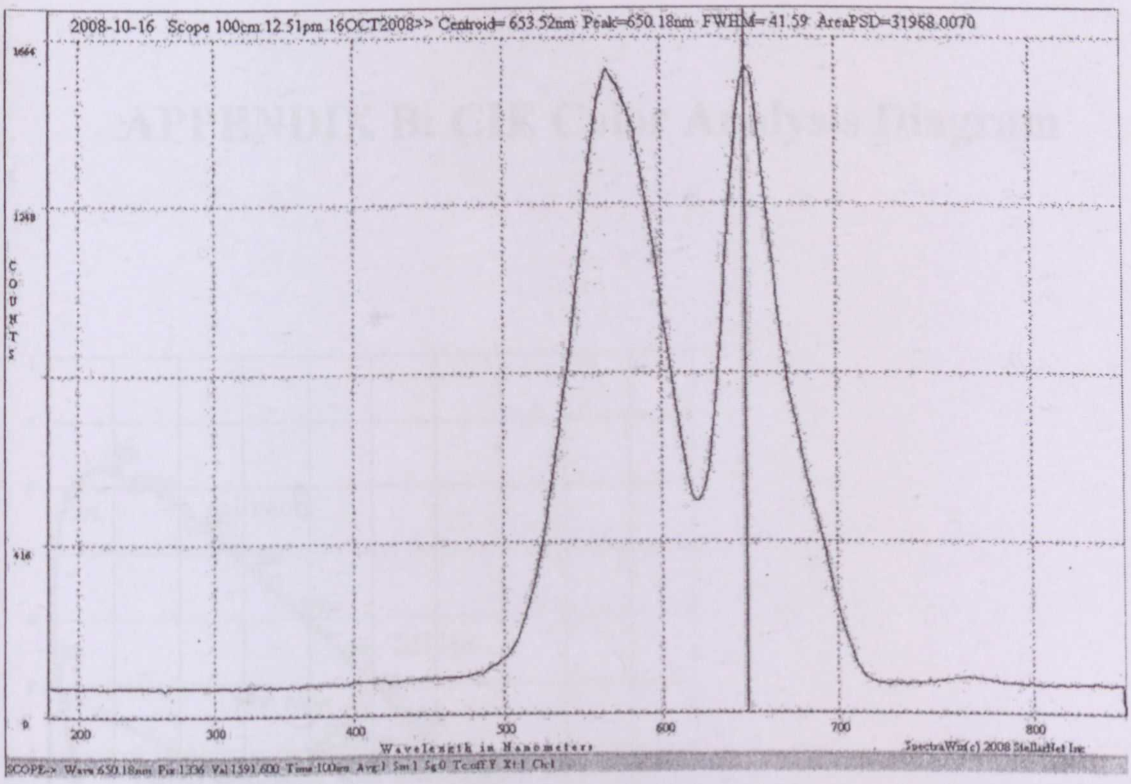
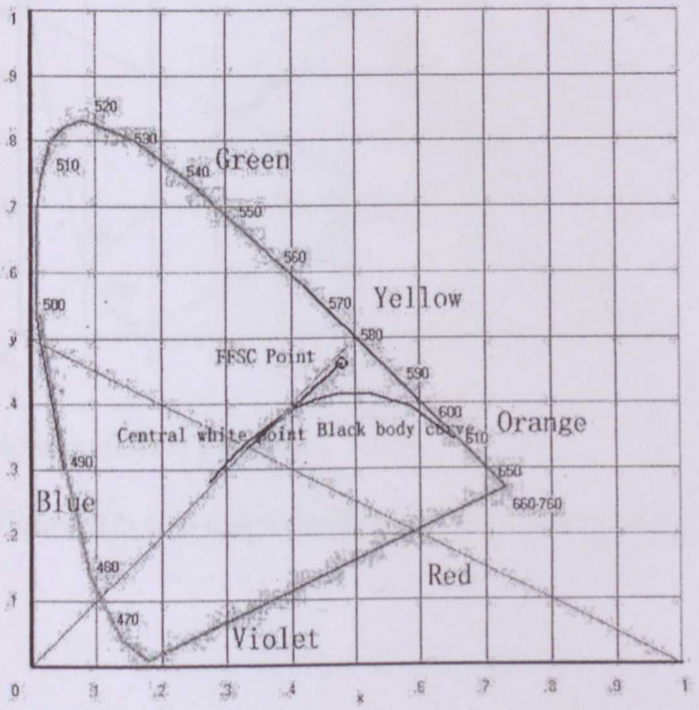


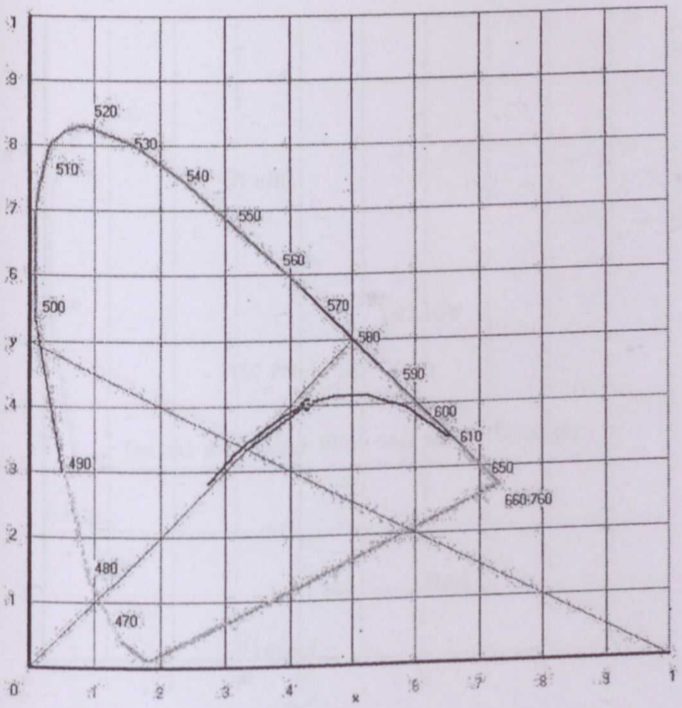
*Figure A8: Wavelength Scope mode 100cm 12:51, 16OCT2008*

# APPENDIX B: CIE Color Analysis Diagram



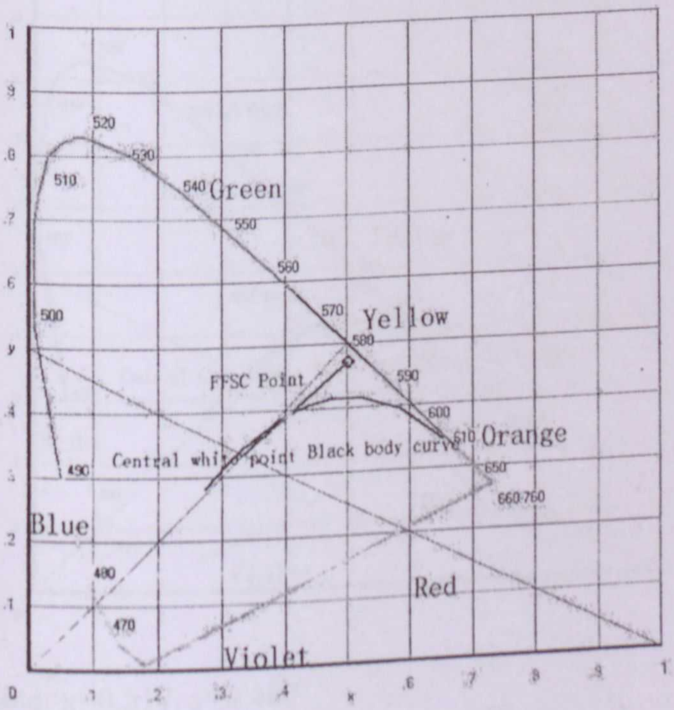
Note: x=0.479, y=0.460

*Figure B1: CIE color analysis 10cm 12:27, 16OCT2008*



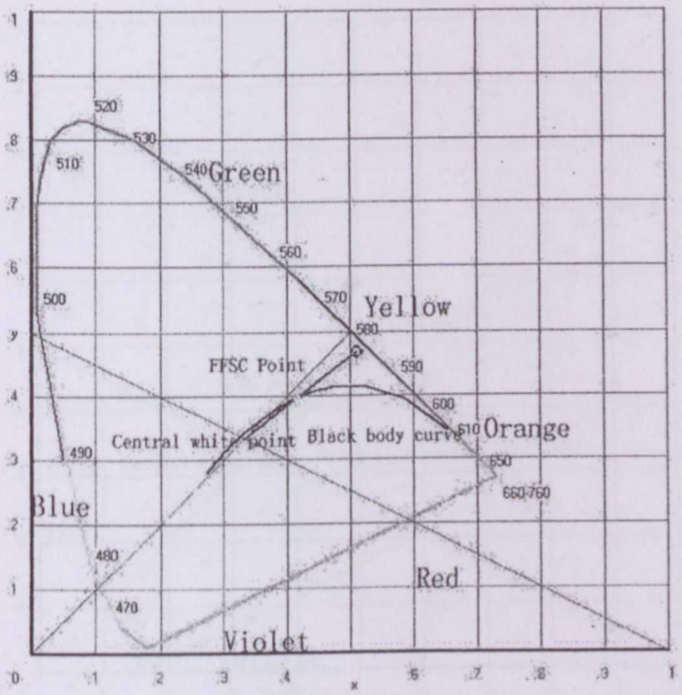
Note: x=0.427, y=0.401

*Figure B2: CIE color analysis for direct sun light 11:33, 12Nov2008*



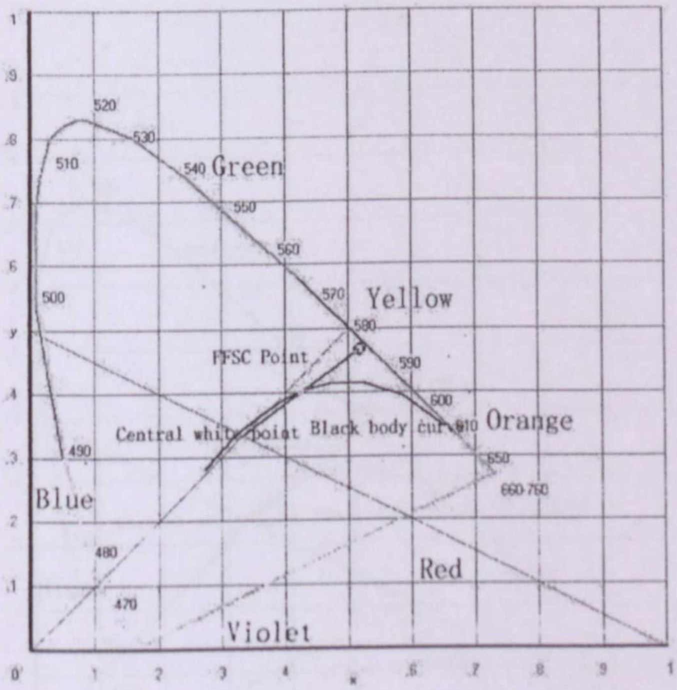
Note: x=0.502, 0.470

*Figure B3: CIE color analysis 20cm 12:33, 16OCT2008*



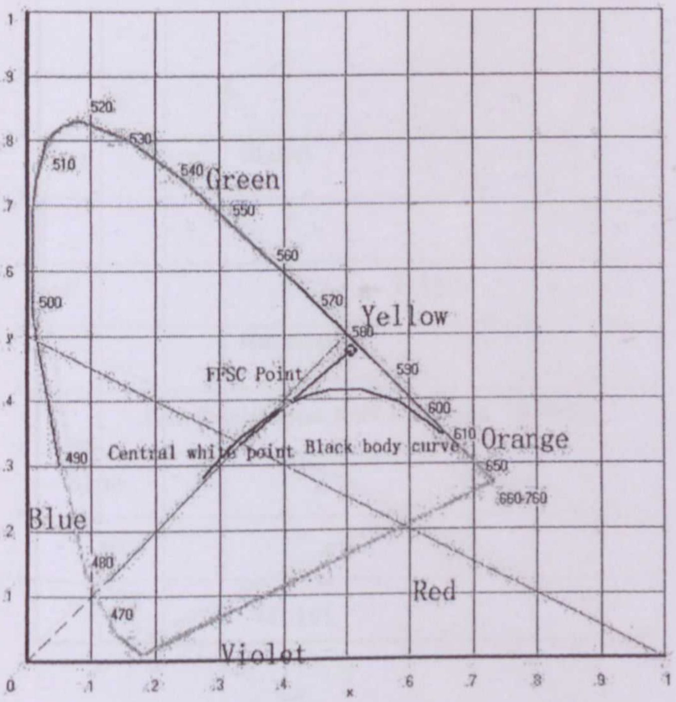
Note: x=0.510, y=0.468

*Figure B4: CIE color analysis 30cm 12:36, 16OCT2008*



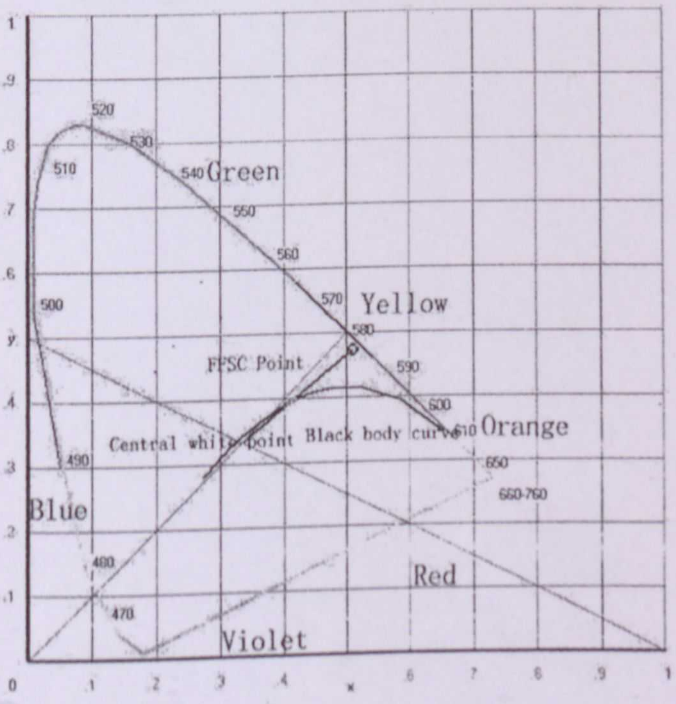
Note: x=0.517, y=0.467

*Figure B5: CIE color analysis 40cm 12:47, 16OCT2008*



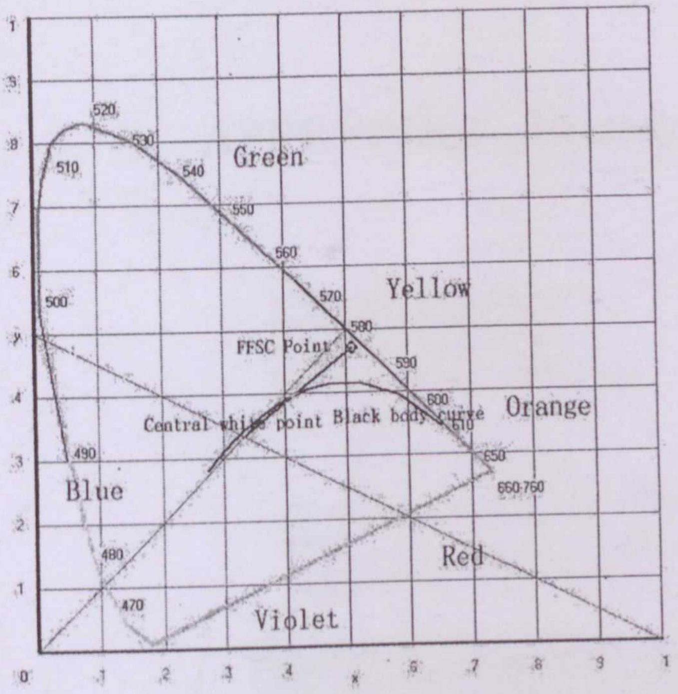
Note: x=0.508, y=0.475

*Figure B6: CIE color analysis 50cm 12:47, 16OCT2008*



Note: x=0.510, y=0.472

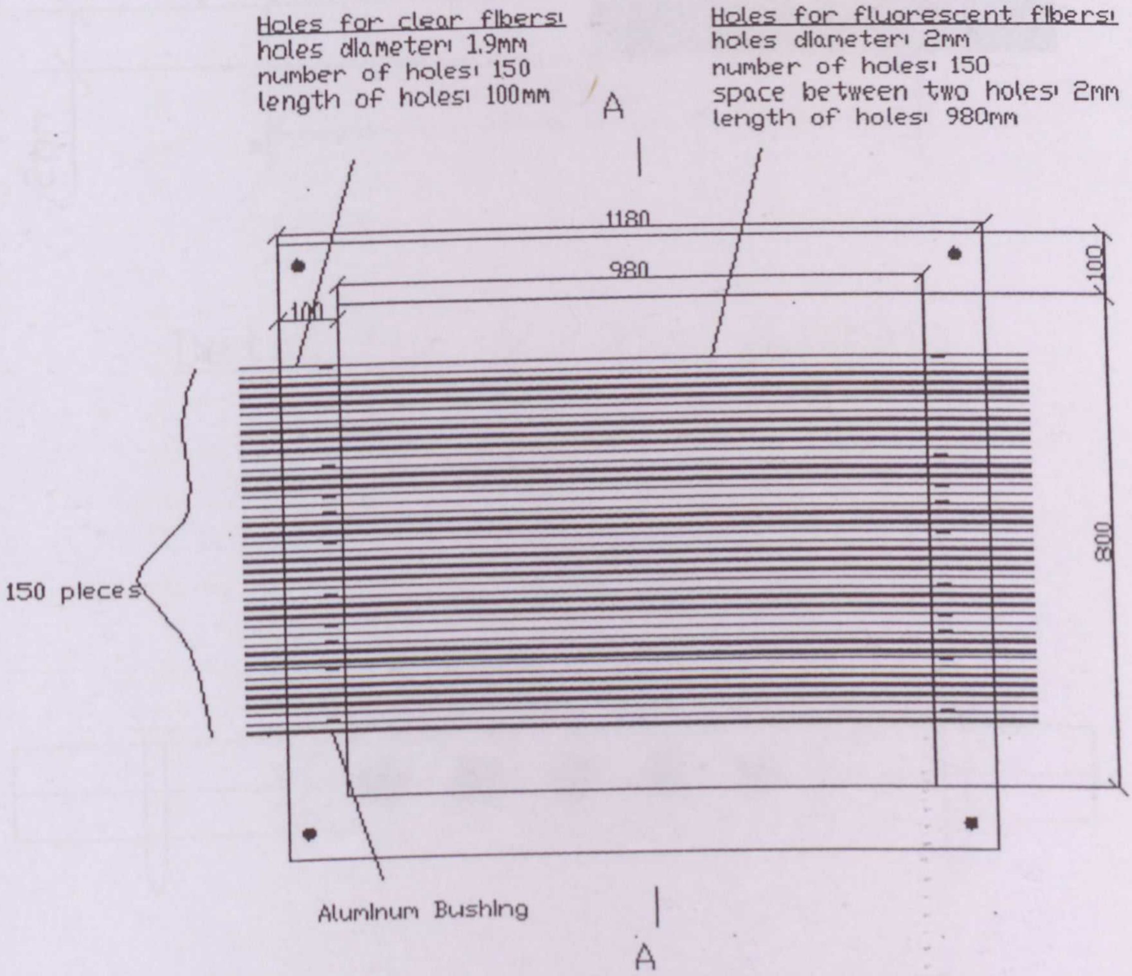
*Figure B7: CIE color analysis 80cm 12:50, 16OCT2008*



Note: x=0.509, y=0.469

*Figure B8: CIE color analysis 100cm 12:52, 16OCT2008*

# APPENDIX C: Drawings of FFSC

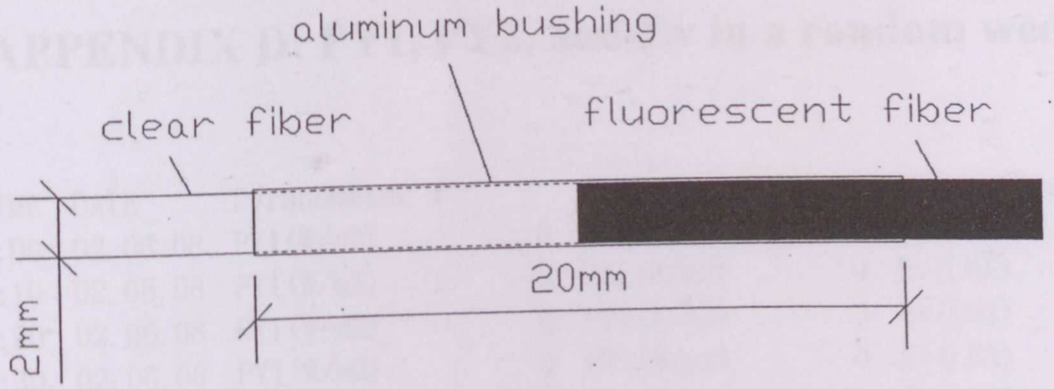


Holes for clear fibers:
holes diameter: 1.9mm
number of holes: 150
length of holes: 100mm

Holes for fluorescent fibers:
holes diameter: 2mm
number of holes: 150
space between two holes: 2mm
length of holes: 980mm

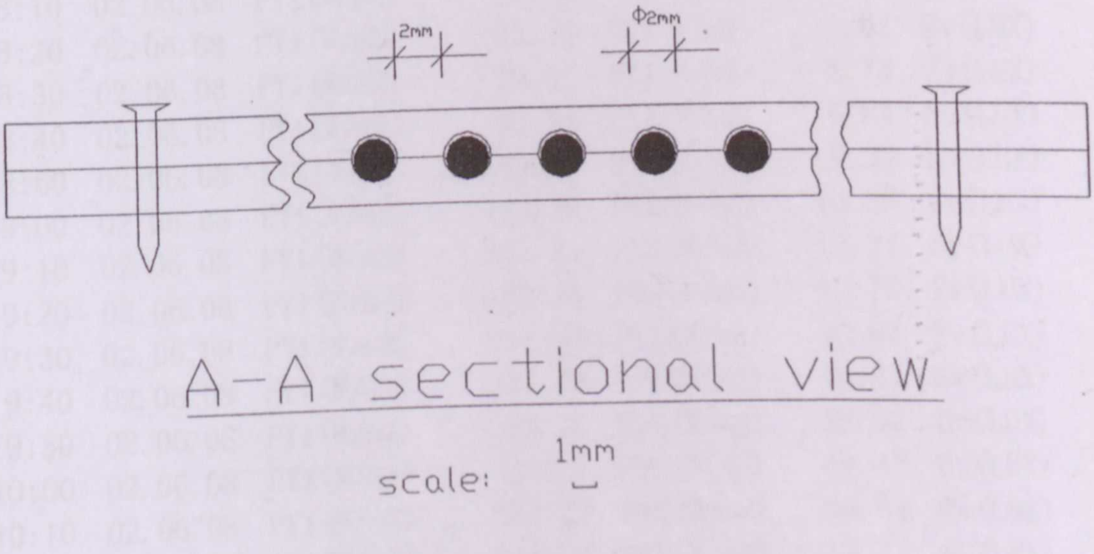
Fluorescent Fiber Solar Concentrator

Scale: 100mm



Detail for Aluminum Bushing

scale: 1mm



A-A sectional view

scale: 1mm

# APPENDIX D: PY1, PY2, and Ev in a random week

| TIME | DATE | Pyranometer 1 | | Pyranometer 2 | | LUX sensor | |
|---|---|---|---|---|---|---|---|
| 6:00 | 02.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:10 | 02.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:20 | 02.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:30 | 02.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:40 | 02.06.08 | PY1(W/m2) | 0.2 | PY2(W/m2) | 0.18 | Ev(LUX) | 12 |
| 6:50 | 02.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:00 | 02.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:10 | 02.06.08 | PY1(W/m2) | 8.93 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:20 | 02.06.08 | PY1(W/m2) | 16.83 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:30 | 02.06.08 | PY1(W/m2) | 28.27 | PY2(W/m2) | 2.03 | Ev(LUX) | 0 |
| 7:40 | 02.06.08 | PY1(W/m2) | 44.69 | PY2(W/m2) | 3.14 | Ev(LUX) | 0 |
| 7:50 | 02.06.08 | PY1(W/m2) | 52.18 | PY2(W/m2) | 3.7 | Ev(LUX) | 0 |
| 8:00 | 02.06.08 | PY1(W/m2) | 60.7 | PY2(W/m2) | 4.25 | Ev(LUX) | 0 |
| 8:10 | 02.06.08 | PY1(W/m2) | 52.39 | PY2(W/m2) | 4.07 | Ev(LUX) | 12 |
| 8:20 | 02.06.08 | PY1(W/m2) | 51.55 | PY2(W/m2) | 4.07 | Ev(LUX) | 0 |
| 8:30 | 02.06.08 | PY1(W/m2) | 79.41 | PY2(W/m2) | 5.73 | Ev(LUX) | 167 |
| 8:40 | 02.06.08 | PY1(W/m2) | 95.84 | PY2(W/m2) | 6.84 | Ev(LUX) | 192 |
| 8:50 | 02.06.08 | PY1(W/m2) | 122.24 | PY2(W/m2) | 8.32 | Ev(LUX) | 231 |
| 9:00 | 02.06.08 | PY1(W/m2) | 152.39 | PY2(W/m2) | 10.36 | Ev(LUX) | 282 |
| 9:10 | 02.06.08 | PY1(W/m2) | 185.23 | PY2(W/m2) | 12.21 | Ev(LUX) | 346 |
| 9:20 | 02.06.08 | PY1(W/m2) | 189.18 | PY2(W/m2) | 12.77 | Ev(LUX) | 359 |
| 9:30 | 02.06.08 | PY1(W/m2) | 261.33 | PY2(W/m2) | 16.84 | Ev(LUX) | 475 |
| 9:40 | 02.06.08 | PY1(W/m2) | 293.13 | PY2(W/m2) | 18.87 | Ev(LUX) | 526 |
| 9:50 | 02.06.08 | PY1(W/m2) | 283.78 | PY2(W/m2) | 18.32 | Ev(LUX) | 513 |
| 10:00 | 02.06.08 | PY1(W/m2) | 281.7 | PY2(W/m2) | 19.43 | Ev(LUX) | 552 |
| 10:10 | 02.06.08 | PY1(W/m2) | 329.72 | PY2(W/m2) | 20.54 | Ev(LUX) | 552 |
| 10:20 | 02.06.08 | PY1(W/m2) | 246.56 | PY2(W/m2) | 15.17 | Ev(LUX) | 411 |
| 10:30 | 02.06.08 | PY1(W/m2) | 212.88 | PY2(W/m2) | 13.51 | Ev(LUX) | 359 |
| 10:40 | 02.06.08 | PY1(W/m2) | 279.62 | PY2(W/m2) | 16.84 | Ev(LUX) | 462 |
| 10:50 | 02.06.08 | PY1(W/m2) | 368.6 | PY2(W/m2) | 21.09 | Ev(LUX) | 578 |
| 11:00 | 02.06.08 | PY1(W/m2) | 716.63 | PY2(W/m2) | 39.97 | Ev(LUX) | 1130 |
| 11:10 | 02.06.08 | PY1(W/m2) | 455.09 | PY2(W/m2) | 26.83 | Ev(LUX) | 770 |
| 11:20 | 02.06.08 | PY1(W/m2) | 428.06 | PY2(W/m2) | 22.76 | Ev(LUX) | 655 |
| 11:30 | 02.06.08 | PY1(W/m2) | 180.87 | PY2(W/m2) | 10.36 | Ev(LUX) | 308 |
| 11:40 | 02.06.08 | PY1(W/m2) | 160.7 | PY2(W/m2) | 9.43 | Ev(LUX) | 269 |
| 11:50 | 02.06.08 | PY1(W/m2) | 221.2 | PY2(W/m2) | 14.43 | Ev(LUX) | 411 |
| 12:00 | 02.06.08 | PY1(W/m2) | 288.35 | PY2(W/m2) | 19.24 | Ev(LUX) | 513 |
| 12:10 | 02.06.08 | PY1(W/m2) | 307.48 | PY2(W/m2) | 20.72 | Ev(LUX) | 552 |
| 12:20 | 02.06.08 | PY1(W/m2) | 239.29 | PY2(W/m2) | 17.02 | Ev(LUX) | 462 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12:30 | 02.06.08 | PY1(W/m2) | 237.62 | PY2(W/m2) | 16.65 | Ev(LUX) | 449 |
| 12:40 | 02.06.08 | PY1(W/m2) | 234.3 | PY2(W/m2) | 16.47 | Ev(LUX) | 436 |
| 12:50 | 02.06.08 | PY1(W/m2) | 166.52 | PY2(W/m2) | 11.84 | Ev(LUX) | 321 |
| 13:00 | 02.06.08 | PY1(W/m2) | 154.46 | PY2(W/m2) | 10.91 | Ev(LUX) | 295 |
| 13:10 | 02.06.08 | PY1(W/m2) | 105.19 | PY2(W/m2) | 7.95 | Ev(LUX) | 218 |
| 13:20 | 02.06.08 | PY1(W/m2) | 104.57 | PY2(W/m2) | 7.77 | Ev(LUX) | 218 |
| 13:30 | 02.06.08 | PY1(W/m2) | 135.34 | PY2(W/m2) | 10.36 | Ev(LUX) | 295 |
| 13:40 | 02.06.08 | PY1(W/m2) | 149.27 | PY2(W/m2) | 11.47 | Ev(LUX) | 308 |
| 13:50 | 02.06.08 | PY1(W/m2) | 211.85 | PY2(W/m2) | 15.73 | Ev(LUX) | 436 |
| 14:00 | 02.06.08 | PY1(W/m2) | 838.46 | PY2(W/m2) | 56.07 | Ev(LUX) | 1451 |
| 14:10 | 02.06.08 | PY1(W/m2) | 893.34 | PY2(W/m2) | 61.07 | Ev(LUX) | 1605 |
| 14:20 | 02.06.08 | PY1(W/m2) | 164.86 | PY2(W/m2) | 11.84 | Ev(LUX) | 346 |
| 14:30 | 02.06.08 | PY1(W/m2) | 144.69 | PY2(W/m2) | 9.62 | Ev(LUX) | 295 |
| 14:40 | 02.06.08 | PY1(W/m2) | 277.75 | PY2(W/m2) | 17.95 | Ev(LUX) | 488 |
| 14:50 | 02.06.08 | PY1(W/m2) | 554.46 | PY2(W/m2) | 34.98 | Ev(LUX) | 937 |
| 15:00 | 02.06.08 | PY1(W/m2) | 835.34 | PY2(W/m2) | 50.89 | Ev(LUX) | 1323 |
| 15:10 | 02.06.08 | PY1(W/m2) | 955.09 | PY2(W/m2) | 54.04 | Ev(LUX) | 1387 |
| 15:20 | 02.06.08 | PY1(W/m2) | 269.85 | PY2(W/m2) | 17.58 | Ev(LUX) | 488 |
| 15:30 | 02.06.08 | PY1(W/m2) | 882.32 | PY2(W/m2) | 51.45 | Ev(LUX) | 1310 |
| 15:40 | 02.06.08 | PY1(W/m2) | 780.24 | PY2(W/m2) | 46.45 | Ev(LUX) | 1181 |
| 15:50 | 02.06.08 | PY1(W/m2) | 756.13 | PY2(W/m2) | 46.45 | Ev(LUX) | 1181 |
| 16:00 | 02.06.08 | PY1(W/m2) | 690.85 | PY2(W/m2) | 43.12 | Ev(LUX) | 1117 |
| 16:10 | 02.06.08 | PY1(W/m2) | 656.34 | PY2(W/m2) | 40.34 | Ev(LUX) | 1027 |
| 16:20 | 02.06.08 | PY1(W/m2) | 580.24 | PY2(W/m2) | 37.2 | Ev(LUX) | 976 |
| 16:30 | 02.06.08 | PY1(W/m2) | 388.98 | PY2(W/m2) | 26.65 | Ev(LUX) | 732 |
| 16:40 | 02.06.08 | PY1(W/m2) | 813.92 | PY2(W/m2) | 46.82 | Ev(LUX) | 1181 |
| 16:50 | 02.06.08 | PY1(W/m2) | 613.3 | PY2(W/m2) | 35.16 | Ev(LUX) | 924 |
| 17:00 | 02.06.08 | PY1(W/m2) | 766.94 | PY2(W/m2) | 39.42 | Ev(LUX) | 1014 |
| 17:10 | 02.06.08 | PY1(W/m2) | 504.78 | PY2(W/m2) | 27.2 | Ev(LUX) | 706 |
| 17:20 | 02.06.08 | PY1(W/m2) | 457.17 | PY2(W/m2) | 23.87 | Ev(LUX) | 603 |
| 17:30 | 02.06.08 | PY1(W/m2) | 330.76 | PY2(W/m2) | 17.76 | Ev(LUX) | 462 |
| 17:40 | 02.06.08 | PY1(W/m2) | 167.56 | PY2(W/m2) | 9.43 | Ev(LUX) | 282 |
| 17:50 | 02.06.08 | PY1(W/m2) | 177.96 | PY2(W/m2) | 11.1 | Ev(LUX) | 295 |
| 18:00 | 02.06.08 | PY1(W/m2) | 76.71 | PY2(W/m2) | 4.62 | Ev(LUX) | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6:00 | 03.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:10 | 03.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:20 | 03.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:30 | 03.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:40 | 03.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 12 |
| 6:50 | 03.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0.18 | Ev(LUX) | 12 |
| 7:00 | 03.06.08 | PY1(W/m2) | 2.28 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:10 | 03.06.08 | PY1(W/m2) | 12.68 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:20 | 03.06.08 | PY1(W/m2) | 18.71 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:30 | 03.06.08 | PY1(W/m2) | 21.82 | PY2(W/m2) | 0 | Ev(LUX) | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7:40 | 03.06.08 | PY1(W/m2) | 34.92 | PY2(W/m2) | 2.96 | Ev(LUX) | 0 |
| 7:50 | 03.06.08 | PY1(W/m2) | 44.07 | PY2(W/m2) | 3.51 | Ev(LUX) | 0 |
| 8:00 | 03.06.08 | PY1(W/m2) | 61.12 | PY2(W/m2) | 4.62 | Ev(LUX) | 154 |
| 8:10 | 03.06.08 | PY1(W/m2) | 94.38 | PY2(W/m2) | 6.47 | Ev(LUX) | 218 |
| 8:20 | 03.06.08 | PY1(W/m2) | 109.77 | PY2(W/m2) | 7.58 | Ev(LUX) | 231 |
| 8:30 | 03.06.08 | PY1(W/m2) | 207.06 | PY2(W/m2) | 11.47 | Ev(LUX) | 334 |
| 8:40 | 03.06.08 | PY1(W/m2) | 154.88 | PY2(W/m2) | 10.17 | Ev(LUX) | 308 |
| 8:50 | 03.06.08 | PY1(W/m2) | 261.53 | PY2(W/m2) | 14.43 | Ev(LUX) | 436 |
| 9:00 | 03.06.08 | PY1(W/m2) | 238.87 | PY2(W/m2) | 14.06 | Ev(LUX) | 411 |
| 9:10 | 03.06.08 | PY1(W/m2) | 297.08 | PY2(W/m2) | 16.65 | Ev(LUX) | 513 |
| 9:20 | 03.06.08 | PY1(W/m2) | 331.8 | PY2(W/m2) | 18.69 | Ev(LUX) | 565 |
| 9:30 | 03.06.08 | PY1(W/m2) | 262.37 | PY2(W/m2) | 16.28 | Ev(LUX) | 462 |
| 9:40 | 03.06.08 | PY1(W/m2) | 421.2 | PY2(W/m2) | 24.24 | Ev(LUX) | 680 |
| 9:50 | 03.06.08 | PY1(W/m2) | 306.86 | PY2(W/m2) | 18.87 | Ev(LUX) | 552 |
| 10:00 | 03.06.08 | PY1(W/m2) | 432.22 | PY2(W/m2) | 23.87 | Ev(LUX) | 693 |
| 10:10 | 03.06.08 | PY1(W/m2) | 334.92 | PY2(W/m2) | 20.91 | Ev(LUX) | 629 |
| 10:20 | 03.06.08 | PY1(W/m2) | 593.55 | PY2(W/m2) | 33.31 | Ev(LUX) | 1014 |
| 10:30 | 03.06.08 | PY1(W/m2) | 620.99 | PY2(W/m2) | 35.16 | Ev(LUX) | 1053 |
| 10:40 | 03.06.08 | PY1(W/m2) | 602.28 | PY2(W/m2) | 34.05 | Ev(LUX) | 1040 |
| 10:50 | 03.06.08 | PY1(W/m2) | 335.96 | PY2(W/m2) | 23.13 | Ev(LUX) | 745 |
| 11:00 | 03.06.08 | PY1(W/m2) | 723.28 | PY2(W/m2) | 38.31 | Ev(LUX) | 1233 |
| 11:10 | 03.06.08 | PY1(W/m2) | 695.42 | PY2(W/m2) | 37.57 | Ev(LUX) | 1207 |
| 11:20 | 03.06.08 | PY1(W/m2) | 861.12 | PY2(W/m2) | 45.9 | Ev(LUX) | 1477 |
| 11:30 | 03.06.08 | PY1(W/m2) | 343.45 | PY2(W/m2) | 21.46 | Ev(LUX) | 668 |
| 11:40 | 03.06.08 | PY1(W/m2) | 541.78 | PY2(W/m2) | 31.09 | Ev(LUX) | 937 |
| 11:50 | 03.06.08 | PY1(W/m2) | 449.06 | PY2(W/m2) | 27.2 | Ev(LUX) | 809 |
| 12:00 | 03.06.08 | PY1(W/m2) | 320.37 | PY2(W/m2) | 19.61 | Ev(LUX) | 603 |
| 12:10 | 03.06.08 | PY1(W/m2) | 833.05 | PY2(W/m2) | 39.79 | Ev(LUX) | 1181 |
| 12:20 | 03.06.08 | PY1(W/m2) | 1018.5 | PY2(W/m2) | 46.64 | Ev(LUX) | 1336 |
| 12:30 | 03.06.08 | PY1(W/m2) | 1025.36 | PY2(W/m2) | 47.93 | Ev(LUX) | 1348 |
| 12:40 | 03.06.08 | PY1(W/m2) | 375.05 | PY2(W/m2) | 22.39 | Ev(LUX) | 655 |
| 12:50 | 03.06.08 | PY1(W/m2) | 1064.65 | PY2(W/m2) | 53.11 | Ev(LUX) | 1503 |
| 13:00 | 03.06.08 | PY1(W/m2) | 598.33 | PY2(W/m2) | 33.68 | Ev(LUX) | 1002 |
| 13:10 | 03.06.08 | PY1(W/m2) | 484.61 | PY2(W/m2) | 28.31 | Ev(LUX) | 835 |
| 13:20 | 03.06.08 | PY1(W/m2) | 341.99 | PY2(W/m2) | 19.43 | Ev(LUX) | 552 |
| 13:30 | 03.06.08 | PY1(W/m2) | 311.22 | PY2(W/m2) | 17.58 | Ev(LUX) | 488 |
| 13:40 | 03.06.08 | PY1(W/m2) | 1086.9 | PY2(W/m2) | 51.08 | Ev(LUX) | 1426 |
| 13:50 | 03.06.08 | PY1(W/m2) | 643.86 | PY2(W/m2) | 36.46 | Ev(LUX) | 1053 |
| 14:00 | 03.06.08 | PY1(W/m2) | 353.63 | PY2(W/m2) | 20.91 | Ev(LUX) | 603 |
| 14:10 | 03.06.08 | PY1(W/m2) | 397.5 | PY2(W/m2) | 23.5 | Ev(LUX) | 668 |
| 14:20 | 03.06.08 | PY1(W/m2) | 272.34 | PY2(W/m2) | 16.1 | Ev(LUX) | 475 |
| 14:30 | 03.06.08 | PY1(W/m2) | 346.36 | PY2(W/m2) | 19.98 | Ev(LUX) | 578 |
| 14:40 | 03.06.08 | PY1(W/m2) | 824.32 | PY2(W/m2) | 39.42 | Ev(LUX) | 1091 |
| 14:50 | 03.06.08 | PY1(W/m2) | 286.27 | PY2(W/m2) | 15.54 | Ev(LUX) | 449 |
| 15:00 | 03.06.08 | PY1(W/m2) | 286.9 | PY2(W/m2) | 15.91 | Ev(LUX) | 449 |
| 15:10 | 03.06.08 | PY1(W/m2) | 260.49 | PY2(W/m2) | 14.8 | Ev(LUX) | 436 |

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|---|---|---|---|---|---|---|---|
| 15:20 | 03.06.08 | PY1(W/m2) | 277.75 | PY2(W/m2) | 16.1 | Ev(LUX) | 449 |
| 15:30 | 03.06.08 | PY1(W/m2) | 66.11 | PY2(W/m2) | 4.44 | Ev(LUX) | 0 |
| 15:40 | 03.06.08 | PY1(W/m2) | 23.9 | PY2(W/m2) | 2.03 | Ev(LUX) | 0 |
| 15:50 | 03.06.08 | PY1(W/m2) | 18.5 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 16:00 | 03.06.08 | PY1(W/m2) | 12.26 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 16:10 | 03.06.08 | PY1(W/m2) | 8.73 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 16:20 | 03.06.08 | PY1(W/m2) | 63.2 | PY2(W/m2) | 4.99 | Ev(LUX) | 154 |
| 16:30 | 03.06.08 | PY1(W/m2) | 95.01 | PY2(W/m2) | 7.03 | Ev(LUX) | 218 |
| 16:40 | 03.06.08 | PY1(W/m2) | 96.88 | PY2(W/m2) | 7.03 | Ev(LUX) | 205 |
| 16:50 | 03.06.08 | PY1(W/m2) | 84.61 | PY2(W/m2) | 6.29 | Ev(LUX) | 179 |
| 17:00 | 03.06.08 | PY1(W/m2) | 118.29 | PY2(W/m2) | 8.14 | Ev(LUX) | 231 |
| 17:10 | 03.06.08 | PY1(W/m2) | 110.39 | PY2(W/m2) | 7.77 | Ev(LUX) | 231 |
| 17:20 | 03.06.08 | PY1(W/m2) | 174.42 | PY2(W/m2) | 11.47 | Ev(LUX) | 308 |
| 17:30 | 03.06.08 | PY1(W/m2) | 122.24 | PY2(W/m2) | 8.88 | Ev(LUX) | 244 |
| 17:40 | 03.06.08 | PY1(W/m2) | 115.17 | PY2(W/m2) | 8.14 | Ev(LUX) | 231 |
| 17:50 | 03.06.08 | PY1(W/m2) | 124.32 | PY2(W/m2) | 8.69 | Ev(LUX) | 244 |
| 18:00 | 03.06.08 | PY1(W/m2) | 149.48 | PY2(W/m2) | 9.99 | Ev(LUX) | 269 |

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|---|---|---|---|---|---|---|---|
| 6:00 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:10 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:20 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:30 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:40 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:50 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:00 | 04.06.08 | PY1(W/m2) | 5.19 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:10 | 04.06.08 | PY1(W/m2) | 9.77 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:20 | 04.06.08 | PY1(W/m2) | 16.83 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:30 | 04.06.08 | PY1(W/m2) | 41.37 | PY2(W/m2) | 2.59 | Ev(LUX) | 0 |
| 7:40 | 04.06.08 | PY1(W/m2) | 40.33 | PY2(W/m2) | 3.51 | Ev(LUX) | 0 |
| 7:50 | 04.06.08 | PY1(W/m2) | 31.8 | PY2(W/m2) | 3.51 | Ev(LUX) | 0 |
| 8:00 | 04.06.08 | PY1(W/m2) | 51.76 | PY2(W/m2) | 4.81 | Ev(LUX) | 154 |
| 8:10 | 04.06.08 | PY1(W/m2) | 148.23 | PY2(W/m2) | 8.32 | Ev(LUX) | 231 |
| 8:20 | 04.06.08 | PY1(W/m2) | 185.03 | PY2(W/m2) | 9.99 | Ev(LUX) | 282 |
| 8:30 | 04.06.08 | PY1(W/m2) | 223.9 | PY2(W/m2) | 11.66 | Ev(LUX) | 334 |
| 8:40 | 04.06.08 | PY1(W/m2) | 238.04 | PY2(W/m2) | 12.77 | Ev(LUX) | 385 |
| 8:50 | 04.06.08 | PY1(W/m2) | 274.84 | PY2(W/m2) | 14.99 | Ev(LUX) | 449 |
| 9:00 | 04.06.08 | PY1(W/m2) | 320.58 | PY2(W/m2) | 17.39 | Ev(LUX) | 526 |
| 9:10 | 04.06.08 | PY1(W/m2) | 361.95 | PY2(W/m2) | 19.8 | Ev(LUX) | 629 |
| 9:20 | 04.06.08 | PY1(W/m2) | 384.61 | PY2(W/m2) | 21.28 | Ev(LUX) | 680 |
| 9:30 | 04.06.08 | PY1(W/m2) | 406.65 | PY2(W/m2) | 22.2 | Ev(LUX) | 706 |
| 9:40 | 04.06.08 | PY1(W/m2) | 479.83 | PY2(W/m2) | 26.09 | Ev(LUX) | 835 |
| 9:50 | 04.06.08 | PY1(W/m2) | 507.9 | PY2(W/m2) | 27.2 | Ev(LUX) | 873 |
| 10:00 | 04.06.08 | PY1(W/m2) | 522.66 | PY2(W/m2) | 28.5 | Ev(LUX) | 899 |
| 10:10 | 04.06.08 | PY1(W/m2) | 578.37 | PY2(W/m2) | 31.27 | Ev(LUX) | 976 |
| 10:20 | 04.06.08 | PY1(W/m2) | 586.07 | PY2(W/m2) | 31.83 | Ev(LUX) | 976 |

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|---|---|---|---|---|---|---|---|
| 10:30 | 04.06.08 | PY1(W/m2) | 596.88 | PY2(W/m2) | 32.57 | Ev(LUX) | 989 |
| 10:40 | 04.06.08 | PY1(W/m2) | 631.8 | PY2(W/m2) | 34.24 | Ev(LUX) | 1027 |
| 10:50 | 04.06.08 | PY1(W/m2) | 646.15 | PY2(W/m2) | 33.68 | Ev(LUX) | 1040 |
| 11:00 | 04.06.08 | PY1(W/m2) | 725.36 | PY2(W/m2) | 36.09 | Ev(LUX) | 1181 |
| 11:10 | 04.06.08 | PY1(W/m2) | 768.6 | PY2(W/m2) | 39.42 | Ev(LUX) | 1310 |
| 11:20 | 04.06.08 | PY1(W/m2) | 765.28 | PY2(W/m2) | 37.75 | Ev(LUX) | 1233 |
| 11:30 | 04.06.08 | PY1(W/m2) | 849.89 | PY2(W/m2) | 42.56 | Ev(LUX) | 1374 |
| 11:40 | 04.06.08 | PY1(W/m2) | 897.5 | PY2(W/m2) | 45.9 | Ev(LUX) | 1438 |
| 11:50 | 04.06.08 | PY1(W/m2) | 876.5 | PY2(W/m2) | 44.23 | Ev(LUX) | 1348 |
| 12:00 | 04.06.08 | PY1(W/m2) | 931.18 | PY2(W/m2) | 45.34 | Ev(LUX) | 1387 |
| 12:10 | 04.06.08 | PY1(W/m2) | 979.83 | PY2(W/m2) | 45.53 | Ev(LUX) | 1374 |
| 12:20 | 04.06.08 | PY1(W/m2) | 956.75 | PY2(W/m2) | 44.41 | Ev(LUX) | 1336 |
| 12:30 | 04.06.08 | PY1(W/m2) | 997.5 | PY2(W/m2) | 48.49 | Ev(LUX) | 1490 |
| 12:40 | 04.06.08 | PY1(W/m2) | 1039.29 | PY2(W/m2) | 53.48 | Ev(LUX) | 1618 |
| 12:50 | 04.06.08 | PY1(W/m2) | 1064.65 | PY2(W/m2) | 55.52 | Ev(LUX) | 1695 |
| 13:00 | 04.06.08 | PY1(W/m2) | 1107.06 | PY2(W/m2) | 56.26 | Ev(LUX) | 1708 |
| 13:10 | 04.06.08 | PY1(W/m2) | 609.97 | PY2(W/m2) | 34.24 | Ev(LUX) | 1027 |
| 13:20 | 04.06.08 | PY1(W/m2) | 1027.85 | PY2(W/m2) | 48.67 | Ev(LUX) | 1490 |
| 13:30 | 04.06.08 | PY1(W/m2) | 1093.97 | PY2(W/m2) | 52.37 | Ev(LUX) | 1528 |
| 13:40 | 04.06.08 | PY1(W/m2) | 636.38 | PY2(W/m2) | 32.2 | Ev(LUX) | 950 |
| 13:50 | 04.06.08 | PY1(W/m2) | 1097.29 | PY2(W/m2) | 54.04 | Ev(LUX) | 1477 |
| 14:00 | 04.06.08 | PY1(W/m2) | 1040.74 | PY2(W/m2) | 52 | Ev(LUX) | 1451 |
| 14:10 | 04.06.08 | PY1(W/m2) | 1059.45 | PY2(W/m2) | 50.89 | Ev(LUX) | 1387 |
| 14:20 | 04.06.08 | PY1(W/m2) | 1135.75 | PY2(W/m2) | 54.41 | Ev(LUX) | 1464 |
| 14:30 | 04.06.08 | PY1(W/m2) | 356.13 | PY2(W/m2) | 23.32 | Ev(LUX) | 680 |
| 14:40 | 04.06.08 | PY1(W/m2) | 218.71 | PY2(W/m2) | 14.62 | Ev(LUX) | 423 |
| 14:50 | 04.06.08 | PY1(W/m2) | 393.34 | PY2(W/m2) | 24.61 | Ev(LUX) | 693 |
| 15:00 | 04.06.08 | PY1(W/m2) | 849.27 | PY2(W/m2) | 43.12 | Ev(LUX) | 1104 |
| 15:10 | 04.06.08 | PY1(W/m2) | 954.67 | PY2(W/m2) | 49.6 | Ev(LUX) | 1271 |
| 15:20 | 04.06.08 | PY1(W/m2) | 289.39 | PY2(W/m2) | 18.5 | Ev(LUX) | 526 |
| 15:30 | 04.06.08 | PY1(W/m2) | 195.84 | PY2(W/m2) | 12.4 | Ev(LUX) | 359 |
| 15:40 | 04.06.08 | PY1(W/m2) | 167.98 | PY2(W/m2) | 10.17 | Ev(LUX) | 308 |
| 15:50 | 04.06.08 | PY1(W/m2) | 182.95 | PY2(W/m2) | 10.73 | Ev(LUX) | 308 |
| 16:00 | 04.06.08 | PY1(W/m2) | 437.62 | PY2(W/m2) | 20.35 | Ev(LUX) | 501 |
| 16:10 | 04.06.08 | PY1(W/m2) | 355.3 | PY2(W/m2) | 17.76 | Ev(LUX) | 436 |
| 16:20 | 04.06.08 | PY1(W/m2) | 209.77 | PY2(W/m2) | 11.84 | Ev(LUX) | 295 |
| 16:30 | 04.06.08 | PY1(W/m2) | 54.67 | PY2(W/m2) | 3.7 | Ev(LUX) | 0 |
| 16:40 | 04.06.08 | PY1(W/m2) | 33.88 | PY2(W/m2) | 2.59 | Ev(LUX) | 0 |
| 16:50 | 04.06.08 | PY1(W/m2) | 6.44 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 17:00 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 17:10 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 17:20 | 04.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 17:30 | 04.06.08 | PY1(W/m2) | 4.15 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 17:40 | 04.06.08 | PY1(W/m2) | 6.02 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 17:50 | 04.06.08 | PY1(W/m2) | 6.23 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 18:00 | 04.06.08 | PY1(W/m2) | 9.14 | PY2(W/m2) | 0 | Ev(LUX) | 0 |

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|---|---|---|---|---|---|---|---|
| 6:00 | 05.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:10 | 05.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:20 | 05.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:30 | 05.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:40 | 05.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:50 | 05.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:00 | 05.06.08 | PY1(W/m2) | 4.98 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:10 | 05.06.08 | PY1(W/m2) | 11.43 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:20 | 05.06.08 | PY1(W/m2) | 24.32 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:30 | 05.06.08 | PY1(W/m2) | 38.25 | PY2(W/m2) | 3.33 | Ev(LUX) | 25 |
| 7:40 | 05.06.08 | PY1(W/m2) | 58.21 | PY2(W/m2) | 4.07 | Ev(LUX) | 0 |
| 7:50 | 05.06.08 | PY1(W/m2) | 84.82 | PY2(W/m2) | 5.36 | Ev(LUX) | 167 |
| 8:00 | 05.06.08 | PY1(W/m2) | 92.93 | PY2(W/m2) | 6.84 | Ev(LUX) | 205 |
| 8:10 | 05.06.08 | PY1(W/m2) | 206.02 | PY2(W/m2) | 11.66 | Ev(LUX) | 334 |
| 8:20 | 05.06.08 | PY1(W/m2) | 262.16 | PY2(W/m2) | 14.62 | Ev(LUX) | 411 |
| 8:30 | 05.06.08 | PY1(W/m2) | 298.12 | PY2(W/m2) | 17.02 | Ev(LUX) | 488 |
| 8:40 | 05.06.08 | PY1(W/m2) | 321.2 | PY2(W/m2) | 17.95 | Ev(LUX) | 513 |
| 8:50 | 05.06.08 | PY1(W/m2) | 347.4 | PY2(W/m2) | 19.24 | Ev(LUX) | 578 |
| 9:00 | 05.06.08 | PY1(W/m2) | 327.02 | PY2(W/m2) | 18.13 | Ev(LUX) | 578 |
| 9:10 | 05.06.08 | PY1(W/m2) | 355.3 | PY2(W/m2) | 19.61 | Ev(LUX) | 629 |
| 9:20 | 05.06.08 | PY1(W/m2) | 397.71 | PY2(W/m2) | 21.83 | Ev(LUX) | 693 |
| 9:30 | 05.06.08 | PY1(W/m2) | 436.59 | PY2(W/m2) | 23.13 | Ev(LUX) | 745 |
| 9:40 | 05.06.08 | PY1(W/m2) | 476.29 | PY2(W/m2) | 24.8 | Ev(LUX) | 783 |
| 9:50 | 05.06.08 | PY1(W/m2) | 417.04 | PY2(W/m2) | 22.39 | Ev(LUX) | 706 |
| 10:00 | 05.06.08 | PY1(W/m2) | 500.41 | PY2(W/m2) | 26.28 | Ev(LUX) | 822 |
| 10:10 | 05.06.08 | PY1(W/m2) | 624.32 | PY2(W/m2) | 33.12 | Ev(LUX) | 1014 |
| 10:20 | 05.06.08 | PY1(W/m2) | 357.38 | PY2(W/m2) | 21.83 | Ev(LUX) | 642 |
| 10:30 | 05.06.08 | PY1(W/m2) | 575.88 | PY2(W/m2) | 32.38 | Ev(LUX) | 976 |
| 10:40 | 05.06.08 | PY1(W/m2) | 757.79 | PY2(W/m2) | 40.16 | Ev(LUX) | 1207 |
| 10:50 | 05.06.08 | PY1(W/m2) | 780.24 | PY2(W/m2) | 39.05 | Ev(LUX) | 1207 |
| 11:00 | 05.06.08 | PY1(W/m2) | 920.37 | PY2(W/m2) | 43.49 | Ev(LUX) | 1336 |
| 11:10 | 05.06.08 | PY1(W/m2) | 933.05 | PY2(W/m2) | 40.9 | Ev(LUX) | 1297 |
| 11:20 | 05.06.08 | PY1(W/m2) | 276.09 | PY2(W/m2) | 14.8 | Ev(LUX) | 449 |
| 11:30 | 05.06.08 | PY1(W/m2) | 965.07 | PY2(W/m2) | 44.41 | Ev(LUX) | 1400 |
| 11:40 | 05.06.08 | PY1(W/m2) | 887.11 | PY2(W/m2) | 42.38 | Ev(LUX) | 1271 |
| 11:50 | 05.06.08 | PY1(W/m2) | 999.37 | PY2(W/m2) | 46.08 | Ev(LUX) | 1387 |
| 12:00 | 05.06.08 | PY1(W/m2) | 686.48 | PY2(W/m2) | 33.68 | Ev(LUX) | 1040 |
| 12:10 | 05.06.08 | PY1(W/m2) | 973.38 | PY2(W/m2) | 38.12 | Ev(LUX) | 1130 |
| 12:20 | 05.06.08 | PY1(W/m2) | 317.04 | PY2(W/m2) | 16.65 | Ev(LUX) | 501 |
| 12:30 | 05.06.08 | PY1(W/m2) | 235.34 | PY2(W/m2) | 13.14 | Ev(LUX) | 398 |
| 12:40 | 05.06.08 | PY1(W/m2) | 327.23 | PY2(W/m2) | 18.69 | Ev(LUX) | 539 |
| 12:50 | 05.06.08 | PY1(W/m2) | 1025.15 | PY2(W/m2) | 48.86 | Ev(LUX) | 1387 |
| 13:00 | 05.06.08 | PY1(W/m2) | 350.72 | PY2(W/m2) | 21.65 | Ev(LUX) | 629 |
| 13:10 | 05.06.08 | PY1(W/m2) | 802.91 | PY2(W/m2) | 39.23 | Ev(LUX) | 1143 |

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| 13:20 | 05.06.08 | PY1(W/m2) | 337.83 | PY2(W/m2) | 19.43 | Ev(LUX) | 552 |
| 13:30 | 05.06.08 | PY1(W/m2) | 388.14 | PY2(W/m2) | 22.39 | Ev(LUX) | 655 |
| 13:40 | 05.06.08 | PY1(W/m2) | 987.73 | PY2(W/m2) | 48.3 | Ev(LUX) | 1348 |
| 13:50 | 05.06.08 | PY1(W/m2) | 1022.03 | PY2(W/m2) | 50.15 | Ev(LUX) | 1374 |
| 14:00 | 05.06.08 | PY1(W/m2) | 332.43 | PY2(W/m2) | 19.06 | Ev(LUX) | 565 |
| 14:10 | 05.06.08 | PY1(W/m2) | 392.93 | PY2(W/m2) | 22.58 | Ev(LUX) | 642 |
| 14:20 | 05.06.08 | PY1(W/m2) | 464.65 | PY2(W/m2) | 22.76 | Ev(LUX) | 616 |
| 14:30 | 05.06.08 | PY1(W/m2) | 146.15 | PY2(W/m2) | 8.69 | Ev(LUX) | 256 |
| 14:40 | 05.06.08 | PY1(W/m2) | 69.43 | PY2(W/m2) | 4.25 | Ev(LUX) | 0 |
| 14:50 | 05.06.08 | PY1(W/m2) | 26.19 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 15:00 | 05.06.08 | PY1(W/m2) | 16.42 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 15:10 | 05.06.08 | PY1(W/m2) | 5.61 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 15:20 | 05.06.08 | PY1(W/m2) | 4.36 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 15:30 | 05.06.08 | PY1(W/m2) | 9.35 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 15:40 | 05.06.08 | PY1(W/m2) | 14.96 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 15:50 | 05.06.08 | PY1(W/m2) | 35.34 | PY2(W/m2) | 2.96 | Ev(LUX) | 0 |
| 16:00 | 05.06.08 | PY1(W/m2) | 64.44 | PY2(W/m2) | 4.99 | Ev(LUX) | 167 |
| 16:10 | 05.06.08 | PY1(W/m2) | 87.11 | PY2(W/m2) | 6.29 | Ev(LUX) | 192 |
| 16:20 | 05.06.08 | PY1(W/m2) | 104.98 | PY2(W/m2) | 7.4 | Ev(LUX) | 205 |
| 16:30 | 05.06.08 | PY1(W/m2) | 114.34 | PY2(W/m2) | 7.95 | Ev(LUX) | 231 |
| 16:40 | 05.06.08 | PY1(W/m2) | 115.38 | PY2(W/m2) | 7.95 | Ev(LUX) | 231 |
| 16:50 | 05.06.08 | PY1(W/m2) | 80.45 | PY2(W/m2) | 5.55 | Ev(LUX) | 167 |
| 17:00 | 05.06.08 | PY1(W/m2) | 40.33 | PY2(W/m2) | 3.14 | Ev(LUX) | 0 |
| 17:10 | 05.06.08 | PY1(W/m2) | 64.86 | PY2(W/m2) | 4.62 | Ev(LUX) | 0 |
| 17:20 | 05.06.08 | PY1(W/m2) | 102.07 | PY2(W/m2) | 6.84 | Ev(LUX) | 192 |
| 17:30 | 05.06.08 | PY1(W/m2) | 100.62 | PY2(W/m2) | 7.03 | Ev(LUX) | 192 |
| 17:40 | 05.06.08 | PY1(W/m2) | 83.16 | PY2(W/m2) | 5.92 | Ev(LUX) | 179 |
| 17:50 | 05.06.08 | PY1(W/m2) | 80.04 | PY2(W/m2) | 5.55 | Ev(LUX) | 154 |
| 18:00 | 05.06.08 | PY1(W/m2) | 42.82 | PY2(W/m2) | 3.14 | Ev(LUX) | 0 |

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|---|---|---|---|---|---|---|---|
| 6:00 | 06.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:10 | 06.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:20 | 06.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:30 | 06.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:40 | 06.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:50 | 06.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:00 | 06.06.08 | PY1(W/m2) | 3.32 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:10 | 06.06.08 | PY1(W/m2) | 8.73 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:20 | 06.06.08 | PY1(W/m2) | 18.5 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:30 | 06.06.08 | PY1(W/m2) | 34.09 | PY2(W/m2) | 2.59 | Ev(LUX) | 0 |
| 7:40 | 06.06.08 | PY1(W/m2) | 48.44 | PY2(W/m2) | 3.51 | Ev(LUX) | 0 |
| 7:50 | 06.06.08 | PY1(W/m2) | 66.32 | PY2(W/m2) | 3.88 | Ev(LUX) | 0 |
| 8:00 | 06.06.08 | PY1(W/m2) | 53.43 | PY2(W/m2) | 3.88 | Ev(LUX) | 0 |
| 8:10 | 06.06.08 | PY1(W/m2) | 67.98 | PY2(W/m2) | 4.81 | Ev(LUX) | 167 |
| 8:20 | 06.06.08 | PY1(W/m2) | 87.31 | PY2(W/m2) | 6.1 | Ev(LUX) | 192 |

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|---|---|---|---|---|---|---|---|
| 8:30 | 06.06.08 | PY1(W/m2) | 96.46 | PY2(W/m2) | 6.66 | Ev(LUX) | 205 |
| 8:40 | 06.06.08 | PY1(W/m2) | 110.39 | PY2(W/m2) | 7.58 | Ev(LUX) | 244 |
| 8:50 | 06.06.08 | PY1(W/m2) | 131.8 | PY2(W/m2) | 8.51 | Ev(LUX) | 269 |
| 9:00 | 06.06.08 | PY1(W/m2) | 152.59 | PY2(W/m2) | 9.99 | Ev(LUX) | 321 |
| 9:10 | 06.06.08 | PY1(W/m2) | 174.42 | PY2(W/m2) | 10.91 | Ev(LUX) | 346 |
| 9:20 | 06.06.08 | PY1(W/m2) | 199.79 | PY2(W/m2) | 12.4 | Ev(LUX) | 385 |
| 9:30 | 06.06.08 | PY1(W/m2) | 239.29 | PY2(W/m2) | 14.62 | Ev(LUX) | 462 |
| 9:40 | 06.06.08 | PY1(W/m2) | 281.49 | PY2(W/m2) | 16.65 | Ev(LUX) | 513 |
| 9:50 | 06.06.08 | PY1(W/m2) | 337.21 | PY2(W/m2) | 19.61 | Ev(LUX) | 616 |
| 10:00 | 06.06.08 | PY1(W/m2) | 401.24 | PY2(W/m2) | 22.95 | Ev(LUX) | 719 |
| 10:10 | 06.06.08 | PY1(W/m2) | 459.66 | PY2(W/m2) | 26.09 | Ev(LUX) | 809 |
| 10:20 | 06.06.08 | PY1(W/m2) | 459.87 | PY2(W/m2) | 27.76 | Ev(LUX) | 847 |
| 10:30 | 06.06.08 | PY1(W/m2) | 523.7 | PY2(W/m2) | 30.9 | Ev(LUX) | 924 |
| 10:40 | 06.06.08 | PY1(W/m2) | 529.1 | PY2(W/m2) | 31.46 | Ev(LUX) | 924 |
| 10:50 | 06.06.08 | PY1(W/m2) | 522.86 | PY2(W/m2) | 30.72 | Ev(LUX) | 873 |
| 11:00 | 06.06.08 | PY1(W/m2) | 393.34 | PY2(W/m2) | 24.06 | Ev(LUX) | 693 |
| 11:10 | 06.06.08 | PY1(W/m2) | 460.08 | PY2(W/m2) | 27.94 | Ev(LUX) | 809 |
| 11:20 | 06.06.08 | PY1(W/m2) | 516 | PY2(W/m2) | 30.35 | Ev(LUX) | 873 |
| 11:30 | 06.06.08 | PY1(W/m2) | 333.47 | PY2(W/m2) | 20.54 | Ev(LUX) | 578 |
| 11:40 | 06.06.08 | PY1(W/m2) | 343.24 | PY2(W/m2) | 20.35 | Ev(LUX) | 578 |
| 11:50 | 06.06.08 | PY1(W/m2) | 381.28 | PY2(W/m2) | 22.76 | Ev(LUX) | 629 |
| 12:00 | 06.06.08 | PY1(W/m2) | 536.79 | PY2(W/m2) | 30.9 | Ev(LUX) | 873 |
| 12:10 | 06.06.08 | PY1(W/m2) | 506.44 | PY2(W/m2) | 29.24 | Ev(LUX) | 822 |
| 12:20 | 06.06.08 | PY1(W/m2) | 522.03 | PY2(W/m2) | 30.16 | Ev(LUX) | 835 |
| 12:30 | 06.06.08 | PY1(W/m2) | 575.88 | PY2(W/m2) | 32.75 | Ev(LUX) | 924 |
| 12:40 | 06.06.08 | PY1(W/m2) | 738.87 | PY2(W/m2) | 37.94 | Ev(LUX) | 1053 |
| 12:50 | 06.06.08 | PY1(W/m2) | 482.95 | PY2(W/m2) | 26.65 | Ev(LUX) | 745 |
| 13:00 | 06.06.08 | PY1(W/m2) | 337 | PY2(W/m2) | 19.61 | Ev(LUX) | 552 |
| 13:10 | 06.06.08 | PY1(W/m2) | 498.96 | PY2(W/m2) | 27.02 | Ev(LUX) | 770 |
| 13:20 | 06.06.08 | PY1(W/m2) | 670.68 | PY2(W/m2) | 34.61 | Ev(LUX) | 1002 |
| 13:30 | 06.06.08 | PY1(W/m2) | 717.67 | PY2(W/m2) | 36.83 | Ev(LUX) | 1040 |
| 13:40 | 06.06.08 | PY1(W/m2) | 650.31 | PY2(W/m2) | 33.87 | Ev(LUX) | 937 |
| 13:50 | 06.06.08 | PY1(W/m2) | 589.6 | PY2(W/m2) | 31.27 | Ev(LUX) | 860 |
| 14:00 | 06.06.08 | PY1(W/m2) | 796.25 | PY2(W/m2) | 41.27 | Ev(LUX) | 1117 |
| 14:10 | 06.06.08 | PY1(W/m2) | 793.97 | PY2(W/m2) | 41.45 | Ev(LUX) | 1143 |
| 14:20 | 06.06.08 | PY1(W/m2) | 593.76 | PY2(W/m2) | 32.01 | Ev(LUX) | 899 |
| 14:30 | 06.06.08 | PY1(W/m2) | 682.95 | PY2(W/m2) | 36.09 | Ev(LUX) | 1027 |
| 14:40 | 06,06.08 | PY1(W/m2) | 370.68 | PY2(W/m2) | 22.2 | Ev(LUX) | 629 |
| 14:50 | 06.06.08 | PY1(W/m2) | 777.75 | PY2(W/m2) | 40.9 | Ev(LUX) | 1117 |
| 15:00 | 06.06.08 | PY1(W/m2) | 829.93 | PY2(W/m2) | 44.41 | Ev(LUX) | 1194 |
| 15:10 | 06.06.08 | PY1(W/m2) | 928.89 | PY2(W/m2) | 49.6 | Ev(LUX) | 1297 |
| 15:20 | 06.06.08 | PY1(W/m2) | 951.55 | PY2(W/m2) | 51.26 | Ev(LUX) | 1336 |
| 15:30 | 06.06.08 | PY1(W/m2) | 885.23 | PY2(W/m2) | 47.93 | Ev(LUX) | 1246 |
| 15:40 | 06.06.08 | PY1(W/m2) | 834.3 | PY2(W/m2) | 46.64 | Ev(LUX) | 1194 |
| 15:50 | 06.06.08 | PY1(W/m2) | 782.74 | PY2(W/m2) | 43.67 | Ev(LUX) | 1117 |
| 16:00 | 06.06.08 | PY1(W/m2) | 696.88 | PY2(W/m2) | 39.05 | Ev(LUX) | 976 |

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|---|---|---|---|---|---|---|---|
| 16:10 | 06.06.08 | PY1(W/m2) | 673.38 | PY2(W/m2) | 37.38 | Ev(LUX) | 924 |
| 16:20 | 06.06.08 | PY1(W/m2) | 625.36 | PY2(W/m2) | 35.35 | Ev(LUX) | 899 |
| 16:30 | 06.06.08 | PY1(W/m2) | 644.49 | PY2(W/m2) | 35.53 | Ev(LUX) | 886 |
| 16:40 | 06.06.08 | PY1(W/m2) | 216.63 | PY2(W/m2) | 14.99 | Ev(LUX) | 423 |
| 16:50 | 06.06.08 | PY1(W/m2) | 610.6 | PY2(W/m2) | 33.31 | Ev(LUX) | 822 |
| 17:00 | 06.06.08 | PY1(W/m2) | 517.67 | PY2(W/m2) | 28.87 | Ev(LUX) | 719 |
| 17:10 | 06.06.08 | PY1(W/m2) | 472.76 | PY2(W/m2) | 26.46 | Ev(LUX) | 655 |
| 17:20 | 06.06.08 | PY1(W/m2) | 432.64 | PY2(W/m2) | 23.69 | Ev(LUX) | 603 |
| 17:30 | 06.06.08 | PY1(W/m2) | 407.27 | PY2(W/m2) | 22.58 | Ev(LUX) | 578 |
| 17:40 | 06.06.08 | PY1(W/m2) | 356.75 | PY2(W/m2) | 18.69 | Ev(LUX) | 488 |
| 17:50 | 06.06.08 | PY1(W/m2) | 71.72 | PY2(W/m2) | 13.32 | Ev(LUX) | 359 |
| 18:00 | 06.06.08 | PY1(W/m2) | 67.35 | PY2(W/m2) | 7.95 | Ev(LUX) | 231 |

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|---|---|---|---|---|---|---|---|
| 6:00 | 07.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:10 | 07.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:20 | 07.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:30 | 07.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:40 | 07.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:50 | 07.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0.18 | Ev(LUX) | 0 |
| 7:00 | 07.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:10 | 07.06.08 | PY1(W/m2) | 6.44 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:20 | 07.06.08 | PY1(W/m2) | 12.05 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:30 | 07.06.08 | PY1(W/m2) | 9.97 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:40 | 07.06.08 | PY1(W/m2) | 23.49 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:50 | 07.06.08 | PY1(W/m2) | 59.45 | PY2(W/m2) | 3.88 | Ev(LUX) | 0 |
| 8:00 | 07.06.08 | PY1(W/m2) | 64.65 | PY2(W/m2) | 4.07 | Ev(LUX) | 0 |
| 8:10 | 07.06.08 | PY1(W/m2) | 84.19 | PY2(W/m2) | 5.18 | Ev(LUX) | 154 |
| 8:20 | 07.06.08 | PY1(W/m2) | 141.58 | PY2(W/m2) | 7.95 | Ev(LUX) | 231 |
| 8:30 | 07.06.08 | PY1(W/m2) | 196.46 | PY2(W/m2) | 9.99 | Ev(LUX) | 256 |
| 8:40 | 07.06.08 | PY1(W/m2) | 186.27 | PY2(W/m2) | 11.66 | Ev(LUX) | 321 |
| 8:50 | 07.06.08 | PY1(W/m2) | 312.47 | PY2(W/m2) | 15.73 | Ev(LUX) | 449 |
| 9:00 | 07.06.08 | PY1(W/m2) | 439.29 | PY2(W/m2) | 21.46 | Ev(LUX) | 616 |
| 9:10 | 07.06.08 | PY1(W/m2) | 470.47 | PY2(W/m2) | 23.32 | Ev(LUX) | 680 |
| 9:20 | 07.06.08 | PY1(W/m2) | 476.29 | PY2(W/m2) | 24.06 | Ev(LUX) | 719 |
| 9:30 | 07.06.08 | PY1(W/m2) | 512.47 | PY2(W/m2) | 26.09 | Ev(LUX) | 796 |
| 9:40 | 07.06.08 | PY1(W/m2) | 528.69 | PY2(W/m2) | 27.2 | Ev(LUX) | 822 |
| 9:50 | 07.06.08 | PY1(W/m2) | 602.28 | PY2(W/m2) | 30.16 | Ev(LUX) | 912 |
| 10:00 | 07.06.08 | PY1(W/m2) | 651.35 | PY2(W/m2) | 33.12 | Ev(LUX) | 1014 |
| 10:10 | 07.06.08 | PY1(W/m2) | 673.59 | PY2(W/m2) | 34.24 | Ev(LUX) | 1040 |
| 10:20 | 07.06.08 | PY1(W/m2) | 779 | PY2(W/m2) | 38.49 | Ev(LUX) | 1143 |
| 10:30 | 07.06.08 | PY1(W/m2) | 322.03 | PY2(W/m2) | 18.87 | Ev(LUX) | 552 |
| 10:40 | 07.06.08 | PY1(W/m2) | 465.48 | PY2(W/m2) | 25.91 | Ev(LUX) | 770 |
| 10:50 | 07.06.08 | PY1(W/m2) | 401.45 | PY2(W/m2) | 22.58 | Ev(LUX) | 655 |
| 11:00 | 07.06.08 | PY1(W/m2) | 401.03 | PY2(W/m2) | 22.95 | Ev(LUX) | 642 |
| 11:10 | 07.06.08 | PY1(W/m2) | 583.99 | PY2(W/m2) | 31.64 | Ev(LUX) | 899 |

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11:20  07.06.08  PY1(W/m2)   696.04  PY2(W/m2)  38.49  Ev(LUX)  1117
11:30  07.06.08  PY1(W/m2)  1099.37  PY2(W/m2)  56.26  Ev(LUX)  1644
11:40  07.06.08  PY1(W/m2)   495.01  PY2(W/m2)  27.02  Ev(LUX)   770
11:50  07.06.08  PY1(W/m2)   481.91  PY2(W/m2)  27.57  Ev(LUX)   770
12:00  07.06.08  PY1(W/m2)   412.47  PY2(W/m2)  23.32  Ev(LUX)   655
12:10  07.06.08  PY1(W/m2)   574.84  PY2(W/m2)  32.38  Ev(LUX)   899
12:20  07.06.08  PY1(W/m2)   287.94  PY2(W/m2)  16.47  Ev(LUX)   449
12:30  07.06.08  PY1(W/m2)   259.25  PY2(W/m2)  14.43  Ev(LUX)   411
12:40  07.06.08  PY1(W/m2)   334.51  PY2(W/m2)  19.61  Ev(LUX)   526
12:50  07.06.08  PY1(W/m2)   563.82  PY2(W/m2)  32.75  Ev(LUX)   899
13:00  07.06.08  PY1(W/m2)   329.52  PY2(W/m2)   19.8  Ev(LUX)   526
13:10  07.06.08  PY1(W/m2)   353.01  PY2(W/m2)  20.91  Ev(LUX)   565
13:20  07.06.08  PY1(W/m2)   367.98  PY2(W/m2)  21.83  Ev(LUX)   578
13:30  07.06.08  PY1(W/m2)   290.85  PY2(W/m2)  17.76  Ev(LUX)   462
13:40  07.06.08  PY1(W/m2)   297.92  PY2(W/m2)  17.76  Ev(LUX)   488
13:50  07.06.08  PY1(W/m2)   353.84  PY2(W/m2)  20.91  Ev(LUX)   552
14:00  07.06.08  PY1(W/m2)   472.76  PY2(W/m2)  27.57  Ev(LUX)   719
14:10  07.06.08  PY1(W/m2)    463.4  PY2(W/m2)  26.83  Ev(LUX)   719
14:20  07.06.08  PY1(W/m2)   393.97  PY2(W/m2)  22.58  Ev(LUX)   616
14:30  07.06.08  PY1(W/m2)   491.26  PY2(W/m2)  27.57  Ev(LUX)   745
14:40  07.06.08  PY1(W/m2)   376.09  PY2(W/m2)  21.46  Ev(LUX)   590
14:50  07.06.08  PY1(W/m2)   383.78  PY2(W/m2)  22.02  Ev(LUX)   578
15:00  07.06.08  PY1(W/m2)   324.74  PY2(W/m2)  18.87  Ev(LUX)   501
15:10  07.06.08  PY1(W/m2)   260.49  PY2(W/m2)  15.17  Ev(LUX)   411
15:20  07.06.08  PY1(W/m2)   305.61  PY2(W/m2)  17.76  Ev(LUX)   462
15:30  07.06.08  PY1(W/m2)   242.82  PY2(W/m2)  14.25  Ev(LUX)   372
15:40  07.06.08  PY1(W/m2)   231.18  PY2(W/m2)  13.69  Ev(LUX)   359
15:50  07.06.08  PY1(W/m2)   164.65  PY2(W/m2)    9.8  Ev(LUX)   269
16:00  07.06.08  PY1(W/m2)   134.51  PY2(W/m2)   8.32  Ev(LUX)   231
16:10  07.06.08  PY1(W/m2)   132.84  PY2(W/m2)   8.14  Ev(LUX)   218
16:20  07.06.08  PY1(W/m2)   103.32  PY2(W/m2)   6.84  Ev(LUX)   192
16:30  07.06.08  PY1(W/m2)    99.37  PY2(W/m2)   6.66  Ev(LUX)   179
16:40  07.06.08  PY1(W/m2)   108.52  PY2(W/m2)   7.21  Ev(LUX)   192
16:50  07.06.08  PY1(W/m2)    83.99  PY2(W/m2)   5.73  Ev(LUX)   154
17:00  07.06.08  PY1(W/m2)    58.83  PY2(W/m2)   4.25  Ev(LUX)     0
17:10  07.06.08  PY1(W/m2)    45.32  PY2(W/m2)   3.33  Ev(LUX)     0
17:20  07.06.08  PY1(W/m2)    49.48  PY2(W/m2)   3.51  Ev(LUX)     0
17:30  07.06.08  PY1(W/m2)    61.95  PY2(W/m2)   4.44  Ev(LUX)     0
17:40  07.06.08  PY1(W/m2)    51.55  PY2(W/m2)   3.51  Ev(LUX)     0
17:50  07.06.08  PY1(W/m2)    45.11  PY2(W/m2)   3.14  Ev(LUX)     0
18:00  07.06.08  PY1(W/m2)     7.48  PY2(W/m2)      0  Ev(LUX)     0


 6:00  08.06.08  PY1(W/m2)        0  PY2(W/m2)      0  Ev(LUX)     0
 6:10  08.06.08  PY1(W/m2)        0  PY2(W/m2)      0  Ev(LUX)     0
 6:20  08.06.08  PY1(W/m2)        0  PY2(W/m2)   0.18  Ev(LUX)     0
```

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6:30 | 08.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0.18 | Ev(LUX) | 0 |
| 6:40 | 08.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 6:50 | 08.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0.18 | Ev(LUX) | 0 |
| 7:00 | 08.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:10 | 08.06.08 | PY1(W/m2) | 0 | PY2(W/m2) | 0.18 | Ev(LUX) | 12 |
| 7:20 | 08.06.08 | PY1(W/m2) | 2.49 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:30 | 08.06.08 | PY1(W/m2) | 5.4 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:40 | 08.06.08 | PY1(W/m2) | 9.14 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 7:50 | 08.06.08 | PY1(W/m2) | 13.51 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 8:00 | 08.06.08 | PY1(W/m2) | 18.91 | PY2(W/m2) | 0 | Ev(LUX) | 0 |
| 8:10 | 08.06.08 | PY1(W/m2) | 25.36 | PY2(W/m2) | 2.22 | Ev(LUX) | 0 |
| 8:20 | 08.06.08 | PY1(W/m2) | 38.66 | PY2(W/m2) | 3.14 | Ev(LUX) | 0 |
| 8:30 | 08.06.08 | PY1(W/m2) | 61.33 | PY2(W/m2) | 4.44 | Ev(LUX) | 0 |
| 8:40 | 08.06.08 | PY1(W/m2) | 105.61 | PY2(W/m2) | 7.58 | Ev(LUX) | 218 |
| 8:50 | 08.06.08 | PY1(W/m2) | 155.3 | PY2(W/m2) | 11.1 | Ev(LUX) | 295 |
| 9:00 | 08.06.08 | PY1(W/m2) | 131.8 | PY2(W/m2) | 9.43 | Ev(LUX) | 256 |
| 9:10 | 08.06.08 | PY1(W/m2) | 144.9 | PY2(W/m2) | 10.73 | Ev(LUX) | 282 |
| 9:20 | 08.06.08 | PY1(W/m2) | 166.52 | PY2(W/m2) | 11.84 | Ev(LUX) | 308 |
| 9:30 | 08.06.08 | PY1(W/m2) | 212.26 | PY2(W/m2) | 14.8 | Ev(LUX) | 385 |
| 9:40 | 08.06.08 | PY1(W/m2) | 271.72 | PY2(W/m2) | 18.69 | Ev(LUX) | 488 |
| 9:50 | 08.06.08 | PY1(W/m2) | 297.08 | PY2(W/m2) | 20.17 | Ev(LUX) | 539 |
| 10:00 | 08.06.08 | PY1(W/m2) | 314.76 | PY2(W/m2) | 21.65 | Ev(LUX) | 578 |
| 10:10 | 08.06.08 | PY1(W/m2) | 336.59 | PY2(W/m2) | 22.76 | Ev(LUX) | 590 |
| 10:20 | 08.06.08 | PY1(W/m2) | 376.92 | PY2(W/m2) | 25.17 | Ev(LUX) | 668 |
| 10:30 | 08.06.08 | PY1(W/m2) | 373.8 | PY2(W/m2) | 24.61 | Ev(LUX) | 655 |
| 10:40 | 08.06.08 | PY1(W/m2) | 357.17 | PY2(W/m2) | 23.69 | Ev(LUX) | 616 |
| 10:50 | 08.06.08 | PY1(W/m2) | 381.7 | PY2(W/m2) | 24.8 | Ev(LUX) | 642 |
| 11:00 | 08.06.08 | PY1(W/m2) | 393.34 | PY2(W/m2) | 25.17 | Ev(LUX) | 655 |
| 11:10 | 08.06.08 | PY1(W/m2) | 397.71 | PY2(W/m2) | 26.09 | Ev(LUX) | 668 |
| 11:20 | 08.06.08 | PY1(W/m2) | 477.54 | PY2(W/m2) | 30.9 | Ev(LUX) | 822 |
| 11:30 | 08.06.08 | PY1(W/m2) | 492.93 | PY2(W/m2) | 32.01 | Ev(LUX) | 860 |
| 11:40 | 08.06.08 | PY1(W/m2) | 499.16 | PY2(W/m2) | 32.2 | Ev(LUX) | 860 |
| 11:50 | 08.06.08 | PY1(W/m2) | 591.26 | PY2(W/m2) | 37.57 | Ev(LUX) | 1014 |
| 12:00 | 08.06.08 | PY1(W/m2) | 582.32 | PY2(W/m2) | 36.09 | Ev(LUX) | 976 |
| 12:10 | 08.06.08 | PY1(W/m2) | 596.88 | PY2(W/m2) | 36.27 | Ev(LUX) | 976 |
| 12:20 | 08.06.08 | PY1(W/m2) | 693.13 | PY2(W/m2) | 41.08 | Ev(LUX) | 1117 |
| 12:30 | 08.06.08 | PY1(W/m2) | 652.59 | PY2(W/m2) | 38.31 | Ev(LUX) | 1040 |
| 12:40 | 08.06.08 | PY1(W/m2) | 508.52 | PY2(W/m2) | 28.87 | Ev(LUX) | 770 |
| 12:50 | 08.06.08 | PY1(W/m2) | 456.96 | PY2(W/m2) | 26.09 | Ev(LUX) | 693 |
| 13:00 | 08.06.08 | PY1(W/m2) | 368.6 | PY2(W/m2) | 21.28 | Ev(LUX) | 565 |
| 13:10 | 08.06.08 | PY1(W/m2) | 335.55 | PY2(W/m2) | 19.24 | Ev(LUX) | 526 |
| 13:20 | 08.06.08 | PY1(W/m2) | 354.46 | PY2(W/m2) | 20.54 | Ev(LUX) | 552 |
| 13:30 | 08.06.08 | PY1(W/m2) | 426.61 | PY2(W/m2) | 24.24 | Ev(LUX) | 642 |
| 13:40 | 08.06.08 | PY1(W/m2) | 350.51 | PY2(W/m2) | 20.35 | Ev(LUX) | 539 |
| 13:50 | 08.06.08 | PY1(W/m2) | 252.59 | PY2(W/m2) | 14.8 | Ev(LUX) | 411 |
| 14:00 | 08.06.08 | PY1(W/m2) | 252.39 | PY2(W/m2) | 14.62 | Ev(LUX) | 411 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 14:10 | 08.06.08 | PY1(W/m2) | 271.1 | PY2(W/m2) | 15.73 | Ev(LUX) | 423 |
| 14:20 | 08.06.08 | PY1(W/m2) | 308.73 | PY2(W/m2) | 17.76 | Ev(LUX) | 488 |
| 14:30 | 08.06.08 | PY1(W/m2) | 332.01 | PY2(W/m2) | 19.24 | Ev(LUX) | 513 |
| 14:40 | 08.06.08 | PY1(W/m2) | 400.2 | PY2(W/m2) | 23.13 | Ev(LUX) | 603 |
| 14:50 | 08.06.08 | PY1(W/m2) | 389.6 | PY2(W/m2) | 22.39 | Ev(LUX) | 603 |
| 15:00 | 08.06.08 | PY1(W/m2) | 340.12 | PY2(W/m2) | 19.61 | Ev(LUX) | 526 |
| 15:10 | 08.06.08 | PY1(W/m2) | 322.24 | PY2(W/m2) | 18.69 | Ev(LUX) | 513 |
| 15:20 | 08.06.08 | PY1(W/m2) | 299.58 | PY2(W/m2) | 17.76 | Ev(LUX) | 475 |
| 15:30 | 08.06.08 | PY1(W/m2) | 258.62 | PY2(W/m2) | 15.17 | Ev(LUX) | 398 |
| 15:40 | 08.06.08 | PY1(W/m2) | 214.55 | PY2(W/m2) | 12.58 | Ev(LUX) | 346 |
| 15:50 | 08.06.08 | PY1(W/m2) | 195.84 | PY2(W/m2) | 11.47 | Ev(LUX) | 308 |
| 16:00 | 08.06.08 | PY1(W/m2) | 199.37 | PY2(W/m2) | 11.84 | Ev(LUX) | 321 |
| 16:10 | 08.06.08 | PY1(W/m2) | 172.34 | PY2(W/m2) | 10.17 | Ev(LUX) | 282 |
| 16:20 | 08.06.08 | PY1(W/m2) | 190.85 | PY2(W/m2) | 11.47 | Ev(LUX) | 308 |
| 16:30 | 08.06.08 | PY1(W/m2) | 228.48 | PY2(W/m2) | 13.32 | Ev(LUX) | 359 |
| 16:40 | 08.06.08 | PY1(W/m2) | 194.8 | PY2(W/m2) | 11.47 | Ev(LUX) | 321 |
| 16:50 | 08.06.08 | PY1(W/m2) | 151.35 | PY2(W/m2) | 9.06 | Ev(LUX) | 244 |
| 17:00 | 08.06.08 | PY1(W/m2) | 145.32 | PY2(W/m2) | 8.51 | Ev(LUX) | 244 |
| 17:10 | 08.06.08 | PY1(W/m2) | 153.43 | PY2(W/m2) | 9.06 | Ev(LUX) | 244 |
| 17:20 | 08.06.08 | PY1(W/m2) | 144.49 | PY2(W/m2) | 8.51 | Ev(LUX) | 231 |
| 17:30 | 08.06.08 | PY1(W/m2) | 128.06 | PY2(W/m2) | 7.77 | Ev(LUX) | 218 |
| 17:40 | 08.06.08 | PY1(W/m2) | 124.53 | PY2(W/m2) | 7.4 | Ev(LUX) | 205 |
| 17:50 | 08.06.08 | PY1(W/m2) | 96.88 | PY2(W/m2) | 5.92 | Ev(LUX) | 179 |
| 18:00 | 08.06.08 | PY1(W/m2) | 75.46 | PY2(W/m2) | 4.62 | Ev(LUX) | 0 |

# APPENDIX E: Calibration of Equipments

Skye

# Calibration & Test Certificates

Skye Instruments Ltd
21, Ddole Enterprise Park
Llandrindod Wells
Powys LD1 6DF

Tel: 01597 824811 Fax: 01597 824812
Email: skyemail@skyeinstruments.com
Web: www.skyeinstruments.com

SKYE INSTRUMENTS LTD.
21, DDOLE ENTERPRISE PARK,
LLANDRINDOD WELLS,
POWYS LD1 6DF U.K.
TEL: +44 (0) 1597 824811 FAX: +44 (0) 1597 824812
E-Mail: skyemail@skyeinstruments.com

## CALIBRATION CERTIFICATES ENCLOSED:

**DataHog / MiniMet datalogger**

**Relative Humidity / Air Temperature**

**Relative Humidity**

**Air Temperature**

**Light Sensor 1..................................................**

**Light Sensor 2..................................................**

**Light Meter.....................................................**

**Wind Speed**

**Raingauge**

**Air Pressure – Manufacturers calibration**

**Air Pressure – Datalogger factors**

**Water Level**

**Soil Moisture Tensiometers**

**Other...........................................................**

**Other...........................................................**

**Other...........................................................**

**MiniMet Service Contract Order Form**

SKYE INSTRUMENTS LTD.
21, DDOLE ENTERPRISE PARK,
LLANDRINDOD WELLS,
POWYS LD1 6DF U.K.
TEL: +44 (0) 1597 824811 FAX: +44 (0) 1597 824812
E-Mail: skyemail@skyeinstruments.com

# DATAHOG2 / MINIMET2

## Datalogger Factory Default settings

ou have just received a new datalogger, it will have been set up with the following default factory ngs.

our datalogger has just been serviced or recalibrated by Skye your own settings will have not been red.

logger settings will become operational as soon as power applied. Please follow the instructions ched to the logger base to press PSU reset button inside the battery compartment.

| | |
|---|---|
| GGER TIME | Greenwich Mean Time |
| GGER DATE | Current DD.MM.YY |
| GGER MODE | Continuous logging<br>(Stop / Start mode is disabled) |
| MPLE INTERVAL | 30 seconds (except for raingauge channels which are set to 30 minutes to store total not averaged rainfall per interval) |
| RAGE INTERVAL | 30 minutes |
| MORY FULL MODE | Overwrite oldest record when full |
| TAFILE IDENTIFIER | 12 characters made up from the loggers 5 figure serial number plus xxxxtxt e.g. for logger with serial number 12345 the DataFile Identifier will be 12345 xxxxtxt |
| IBRATION FACTORS | If the logger is supplied with sensors as a system, all necessary sensor calibration factors have been entered. Please see the Datalogger Hardware Configuration Certificate. |

**F THESE LOGGER SETTINGS MAY BE CHANGED OR CUSTOMIZED TO YOUR OW PREFERENCES**

Please see the Datalogger Manual for details.

*HARDWARE CONFIGURATION AND CALIBRATION CERTIFICATE*

Powys, LD1 6DF, UK
Tel: 01597 824811 Fax: 01597 824812

**DATAHOG2 TYPE :** SDL 5450 **SERIAL NO.:** 1107 33460 **Certifcate Issue Date:** 07.12.2007

| Software Channel No. | Hardware Channel No. | Socket No. | Configured for Input Type | Gain Code | Termination Code | Scale Code | Full Scale Value | Zero Offset | Units | Sensor Serial No and/or Calibration Factor (when supplied by Skye) |
|---|---|---|---|---|---|---|---|---|---|---|
| 00 | 33 | 1 | Light | 01 | n/a | 01 | 3950.1 | +0000 | W.m$^{-2}$ | SKS 1110/I 1107 33461, 0.05024 µA per W.m$^{-2}$ |
| 01 | 34 | 2 | Light | 01 | n/a | 01 | 3516.2 | +0000 | W.m$^{-2}$ | SKS 1110/I 1107 33462, 0.05644 µA per W.m$^{-2}$ |
| 02 | 35 | 3 | Light | 02 | n/a | 01 | 244.07 | +0000 | kLux | SKL 310/I 1107 33463, 0.1597 µA per kLux |
| 03 | 02 | 4 | Differential Voltage | 01 | 00 | 01 | 200.00 | +0000 | mV | |
| 04 | 05 | 5 | Differential Voltage | 01 | 00 | 01 | 200.00 | +0000 | mV | |
| 05 | 36 | 6 | Current | 01 | n/a | 01 | 198.45 | +0000 | µA | |
| 06 | 37 | 7 | Current | 01 | n/a | 01 | 198.45 | +0000 | µA | |
| 07 | 06 | 8 | RH & Air Temperature | 00 | 00 | 02 | 2000.0 | +0000 | °C | SKH 2070/I |
| 08 | 09 | 8 | RH & Air Temperature | 00 | 00 | 01 | 200.00 | +0000 | % RH | SKH 2070/I |

Feedback Resistors Fitted for Current Type Channels

| Gain | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| Resistor Value | kΩ<br>5.226 | kΩ<br>10.078 | kΩ<br>51.31 | kΩ<br>101.60 | kΩ<br>513.5 | kΩ<br>998.5 | MΩ<br>5.110 | MΩ<br>10.129 |

**Eprom Version** H192 **Datafile Identifier** 33460xxxxtxt

Where fitted the following standards apply:

RH/Temperature - This probe has been calibrated for relative humidity and air temperature to standard factory specifications at nominal points -1% and 75.4% RH and 27 degrees celsius.

Pyranometer - Calibrated directly against a calibrated reference World Meteorological Office, First Class Pyranometer under natural daylight conditions. Uncertainty + 5% (typically + 3%) based on an estimated confidence of not less than 95%

Other Light sensors - Calibrated against a National Physical Laboratory UK reference standard lamp. Uncertainty + 5% (typically + 3%) based on an estimated confidence of not less than 95%

Air Pressure - Transducers checked against a NAMAS traceable transducer

Wind Sensors & Raingauges - As per manufacturers supplied calibration information

**Signed**........B. Gims........................ **For and on behalf of Skye Instruments Ltd**

SKYE INSTRUMENTS LTD.
21, DDOLE ENTERPRISE PARK,
LLANDRINDOD WELLS,
POWYS. LD1 6DF. U.K.
TEL: +44 (0) 1597 824811 FAX: +44 (0) 1597 824812
email: skyemail@skyeinstruments.com
website: www.skyeinstruments.com

# CALIBRATION CERTIFICATE

NO: PYR/ 5657 1207

**UNIT TYPE** PYRANOMETER SENSOR

**SERIAL NO:-** SKS 1110/I 1107 33461

**OUTPUTS:-** 0.05024 µA / watt m-²

10.000 µV / watt m-²

**DATE OF CALIBRATION** 04/09/2007

**A/D UNIT** E2168

Calibrated outdoors under natural daylight conditions by the ratiometric method, against a WMO Secondary Standard Pyranometer, which is traceable to the World Ratiometric Reference via the Met Office standard cavity radiometer.
Uncertainty + 5% (typically + 3%) based on an estimated confidence of not less than 95%.

Calibrated By:- D. TROTTER

Checked By:- A.Mylurg

Issue Date:- 05.12.07

THIS UNIT IS DUE FOR RECALIBRATION WITHIN 2 YEARS OF THE ABOVE CALIBRATION DATE.

SKYE INSTRUMENTS LTD.
21, DDOLE ENTERPRISE PARK,
LLANDRINDOD WELLS,
POWYS. LD1 6DF. U.K.
TEL: +44 (0) 1597 824811 FAX: +44 (0) 1597 824812
email: skyemail@skyeinstruments.com
website: www.skyeinstruments.com

# CALIBRATION CERTIFICATE

NO: PYR/ 5658 1207

**UNIT TYPE** PYRANOMETER SENSOR

**SERIAL NO:-** SKS 1110/I 1107 33462

**OUTPUTS:** 0.05644 µA / watt m-²

10.22 µV / watt m-² with 30m cable

**DATE OF CALIBRATION** 04/09/2007

**A/D UNIT** E2168

Calibrated outdoors under natural daylight conditions by the ratiometric method, against a WMO Secondary Standard Pyranometer, which is traceable to the World Ratiometric Reference via the Met Office standard cavity radiometer. Uncertainty + 5% (typically + 3%) based on an estimated confidence of not less than 95%.

Calibrated By:- D. TROTTER

Checked By:-

Issue Date:- 06·12·07

THIS UNIT IS DUE FOR RECALIBRATION WITHIN 2 YEARS OF THE ABOVE CALIBRATION DATE.

**SKYE INSTRUMENTS LTD.**
**21, DDOLE ENTERPRISE PARK,**
**LLANDRINDOD WELLS,**
**POWYS. LD1 6DF. U.K.**
TEL: +44 (0) 1597 824811 FAX: +44 (0) 1597 824812
E-Mail: skyemail@skyeinstruments.com

# CALIBRATION CERTIFICATE No: LUX/565/1207

UNIT TYPE :- PHOTOMETRIC SENSOR (LUX CALIBRATION)

SERIAL NO. :- SKL 310/I 1107 33463

OUTPUTS :- 0.1597 µA per kLux

100.0 µV per kLux

DATE OF CALIBRATION :- NOVEMBER 2007

LAMP REFERENCE :- SK3

A/D UNIT:- 039 353

Calibrated against a National Physical Laboratory UK reference standard lamp. Uncertainty ± 5% (typically ± 3%) based on an estimated confidence of not less than 95%.

CALIBRATED BY:- D. TROTTER DATE:- 13.11.07

CHECKED :- A.McLurg DATE:- 05.12.07

THIS UNIT IS DUE FOR RECALIBRATION WITHIN 2 YEARS OF THE ABOVE CALIBRATION DATE.

DATE OF LAST CALIBRATION :- N/A

% CHANGE SINCE LAST CALIBRATION :- N/A

# Single Channel
# Light Sensors

**WEEE Mark**

If you want to dispose of this product, do not mix with general household waste. There are separate collection systems for used electronic products in accordance with legislation under the WEEE Directive and is effective only within the European Union.

**Updated August 2004**

# SINGLE CHANNEL LIGHT SENSORS

## *CONTENTS*

# SINGLE CHANNEL LIGHT SENSORS

## *1 INTRODUCTION*

Skye Instruments Limited family of specialist light sensors include sensors to measure different parts of the ultra violet, visible and infra-red spectrum for a wide range of applications.

All sensors use high quality photodiodes and spectral filters, and are individually calibrated to National Standards. Each is supplied with a traceable Calibration Certificate.

The single channel Light Sensors are fully waterproof and guaranteed submersible to 4m depth. They are ideal for monitoring light levels in all environments around the world.

There are five types of sensor in this range, three PAR or Photosynthetically Active Radiation sensors (PAR Quantum, PAR Special and PAR Energy), a total solar radiation Pyranometers plus Lux sensors for human or animal studies.

This manual covers the non-amplified output sensor versions, where the output signal comes direct from the sensor photodiode. Amplified versions and add on amplifiers are also available form Skye, please enquire for details.

These sensors are cosine corrected, which means that they accept incoming light according to Lambert's Cosine Law. Essentially this means that light is measured from the hemisphere directly above the sensor.

## *2 LIGHT SENSORS FOR MEASURING FROM ANY LIGHT SOURCE*

**SKP 210 - PAR Special**
**SKP 215 - PAR Quantum**
**SKL 310 - LUX Sensor**
**SKE 510 – PAR Energy Sensor**

Par PAR (Photosynthetically Active Radiation)

These four sensors have cosine - corrected heads, each containing a semi conductor diode and filter system responding to light according to the response curves in Appendix 1.

They are all fully waterproof and may be left exposed to rain and used in humid climates. They are guaranteed for underwater use up to 4m depth.

Each sensor has been calibrated against a reference lamp, whose own calibration has been carried out at the National Physical Laboratory (N.P.L.). They are calibrated for use with any natural or artificial light source.

## *3 LIGHT SENSORS FOR TOTAL SOLAR RADIATION*

**SKS 1110 – Silicon Cell Pyranometer**

The pyranometer cosine corrected head contains a special high grade silicon photocell, sensitive to ight between 350 and 1100nm. The head is completely sealed and can be left indefinitely in exposed onditions.

This sensor has been calibrated under open-sky conditions, against reference pyranometers and hence eferred to the World Radiometric Reference. The calibration thus refers to Solar energy in the waveband 00nm to 3000nm, i.e. the acceptance band of thermopile pyranometers.

Because of the different spectral responses of the silicon photocell and the thermopiles, to obtain accurate readings the unit must be used in the same conditions as its calibration, i.e. under open sky only. The calibration of the SKS 1110 silicon cell pyranometer is not valid for measuring solar radiation inside glasshouses or polytunnels etc.

Different conditions of sun, cloud, etc., will slightly affect calibration, but absolute errors will always be within 5% and typically much better than 3%.

Linearity is excellent, with a maximum of 1% deviation up to levels of 3000 watts/sq.m (greater than normal solar irradiance).

## 4 *POSITIONING OF ALL TYPES OF SENSOR.*

For accurate positioning of the sensor Skye recommend the use of a levelling unit (SKM 221). Great care should be given to the placing of the sensor, in order to achieve accurate and repeatable results. Avoid objects, trees, etc., that will shade the sensor selectively, compared with the areas under study.

## 5 *COSINE CORRECTION.*

Since the sensor is intended to measure light falling on a horizontal plane (i.e. the ground), it is designed to collect light from the whole hemisphere of sky above it. This is why light sensors are cosine corrected.

Light rays perpendicular to the sensor are fully measured, while those at 90° are not accepted (they pass parallel to the surface of the plane or the ground and never intercept it). Rays at intermediate angles are treated according to the cosine of their angle to the perpendicular. Imagine the sun overhead, you feel its rays strongest when directly overhead, and much weaker when the sun is near the horizon. The sensor measures light from the different angles in a similar way, stronger when overhead than at low angles.

The cosine response of the sensor is shown in Appendix 2. The cosine errors to angle of 70° are minimal and are less than 5% to an angle of 80°. The graph shows the actual response of the sensor as a percentage of the ideal response. At 90°, event the most insignificant acceptance of light represents an infinite error, and because of this, accurate plotting beyond 85% is not practical. Errors from such low angle light in nature are generally not material in most studies.

## 6 *SENSOR MAINTENANCE*

Light Sensors require very little maintenance apart from keeping the top light collecting surface (small white diffusing disc) clean and dust free. This can be done using a soft cloth dampened with de-ionised water. Take care not to scratch this surface as this may affect the sensor calibration.

Skye Instruments light sensors and meters are recommended to be calibrated every 2 years. Please return to Skye where the sensor will be calibrated against the reference lamp and a new calibration certificate issued.

## 7 *CONNECTIONS.*

Connection to obtain either mV or microamp output is shown in Appendix 3. Please note that external voltages must not be applied to the sensor, the silicon photocell and precision resistive elements may be damaged by reverse voltage or excess current.

## 8 *NON-STANDARD SENSORS.*

The sensor part number may include a suffix as follows:

/LT

These sensors have been fitted with cable suitable for low temperatures. Whilst the special cable is rated for use at low temperatures, it is still advisable to avoid undue stress, movement, etc., of the cable when at low temperatures. A special modified levelling unit (SKM 221S) is available to give extra support to the cable and minimise unnecessary movement.

A voltage only output is available. The red wire is the positive output and the blue wire is the ground/screen. All other sensor specifications remain the same.

/S

These sensors have a 3 core cable, and a grey wire connected to the screen on the tail end only - there is no connection inside the sensor.

All other specifications remain the same.

/V

These sensors have a voltage output only.

The red wire is the positive output and the blue wire is the ground / screen. All other specifications remain the same.

/I

These sensors have been fitted with a 5 pin plug for a Skye DataHog logger connection and wired for a current input socket of the logger, as shown below:

| | |
|---|---|
| Pin 1 | not connected |
| Pin 2 | not connected |
| Pin 3 | Red |
| Pin 4 | Blue |
| Pin 5 | Green |

# SINGLE CHANNEL LIGHT SENSORS

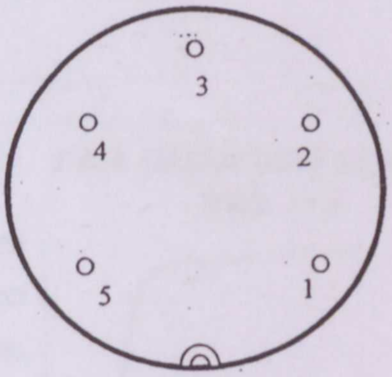
/D/I

These sensors have been fitted with a 5 pin plug for a Skye DataHog logger connection and wired for a differential voltage input socket of the logger, as shown below:

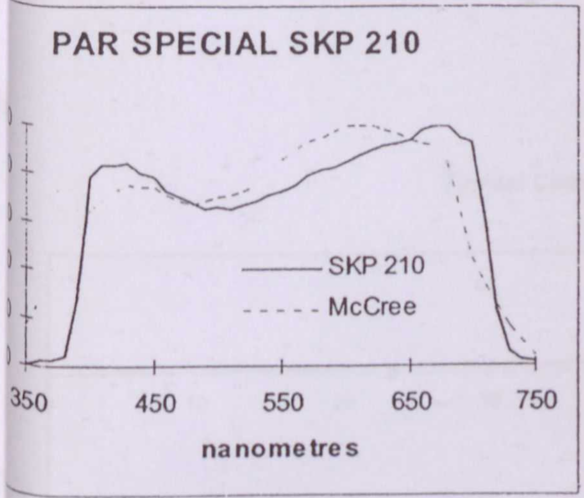
| | | |
|---|---|---|
| Pin 1 | | not connected |
| Pin 2 | Blue | Linked to Pin 3 |
| Pin 3 | Red | Linked to Pin 2 |
| Pin 4 | Grey | Linked to Pin 5 |
| Pin 5 | | Linked to Pin 4 |

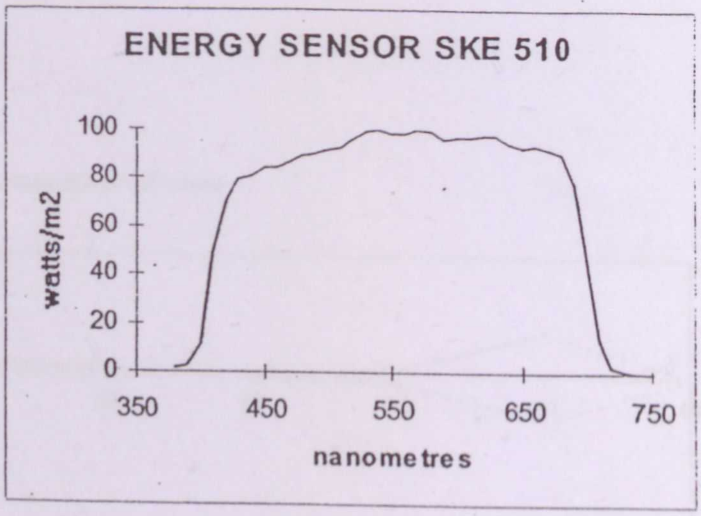
**DATAHOG WATERPROOF BINDER 5 PIN PLUG**

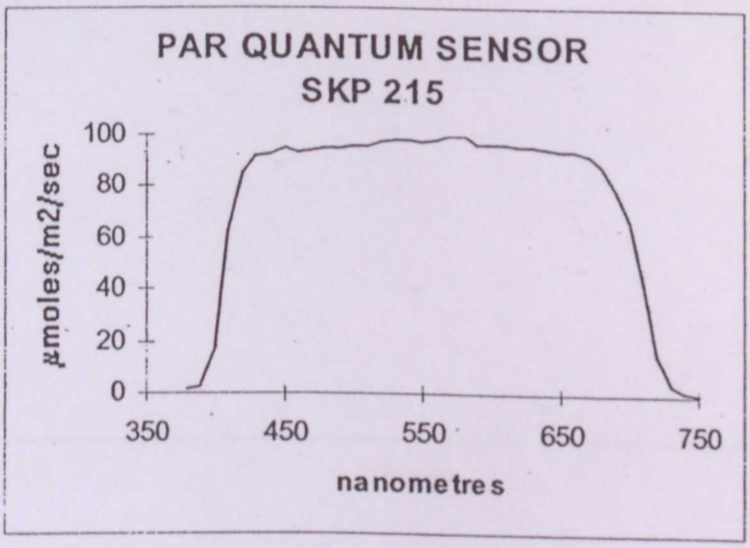
OUTSIDE PIN VIEW

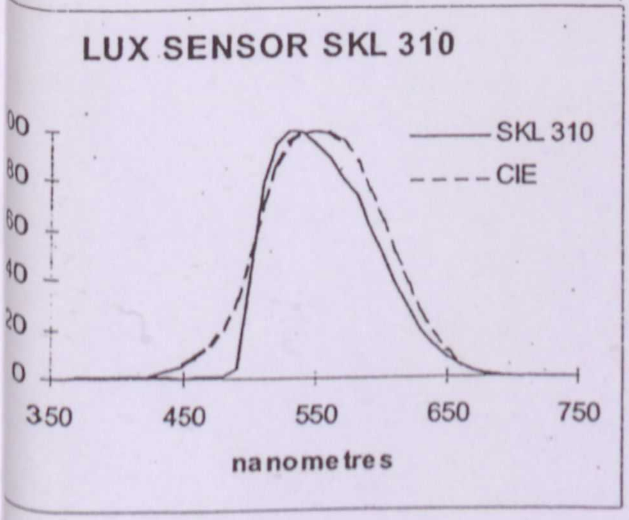


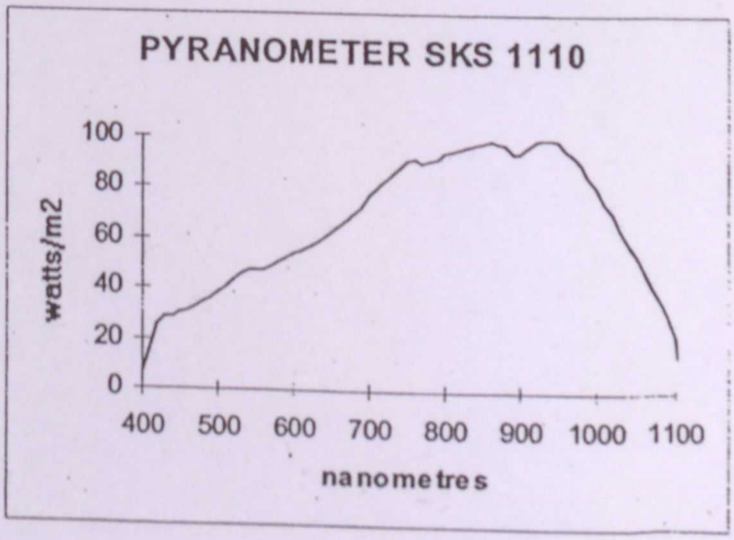
## *APPENDIX 1 – RESPONSE CURVES*



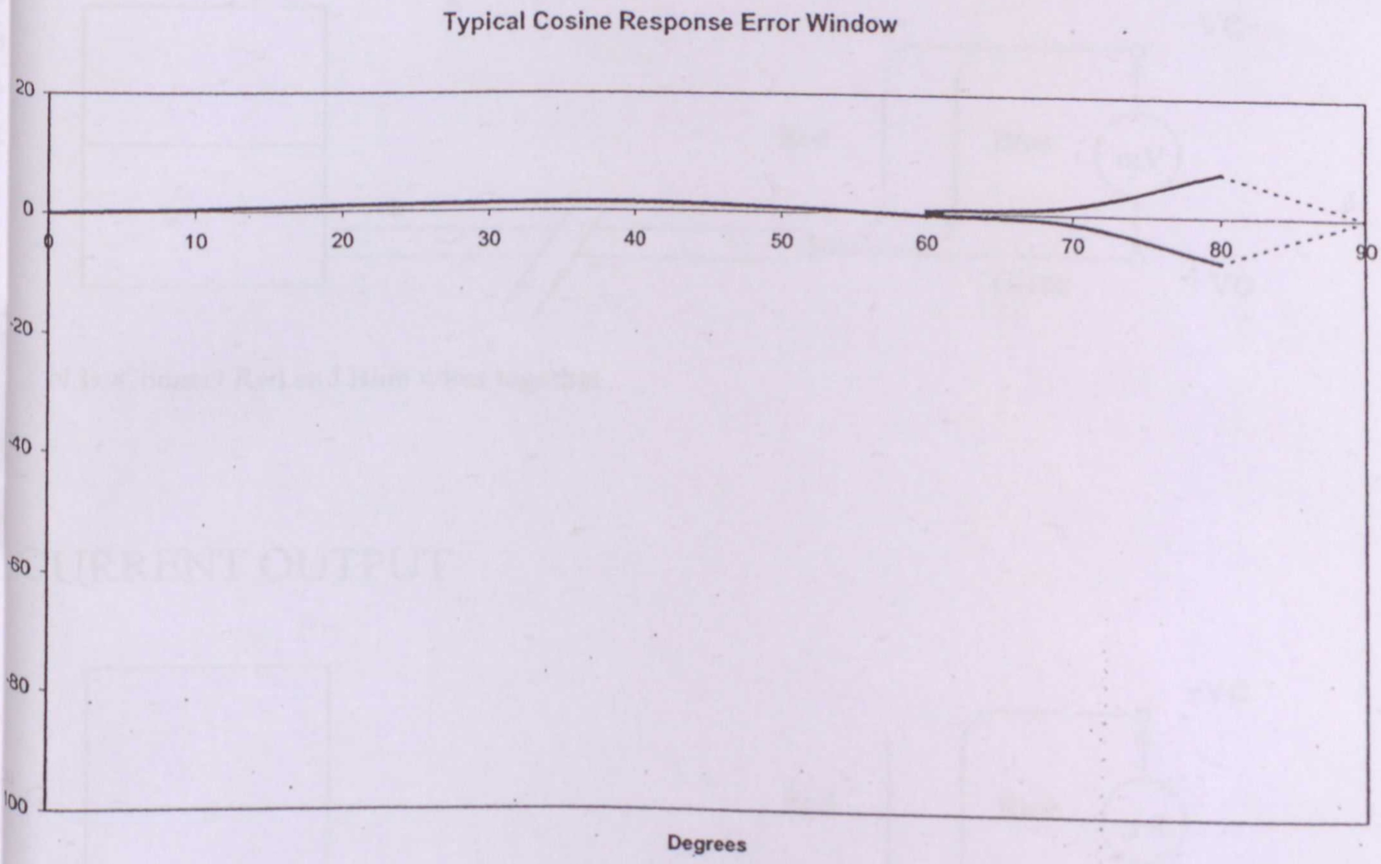






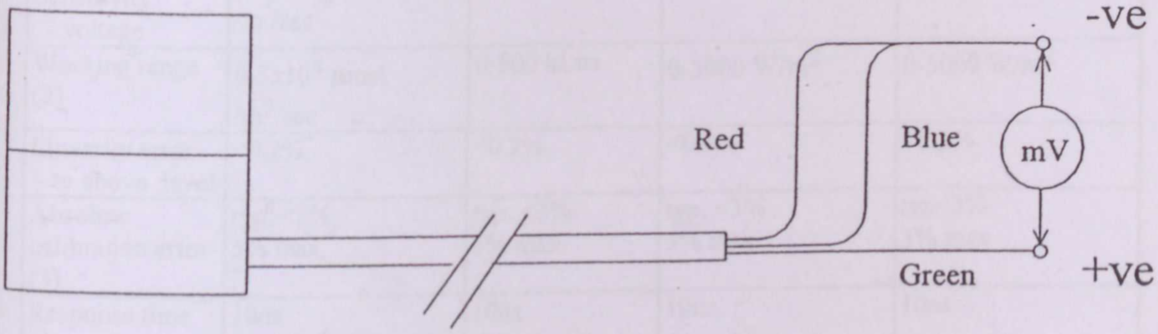


## APPENDIX 2 – COSINE CORRECTION



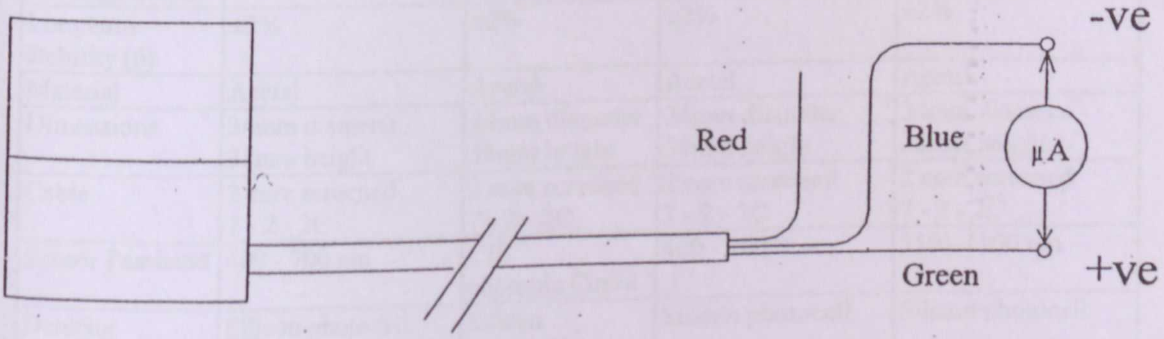
## *APPENDIX 3 - WIRE CONNECTIONS*

## VOLTAGE OUTPUT



N.B. Connect Red and Blue wires together.

## CURRENT OUTPUT



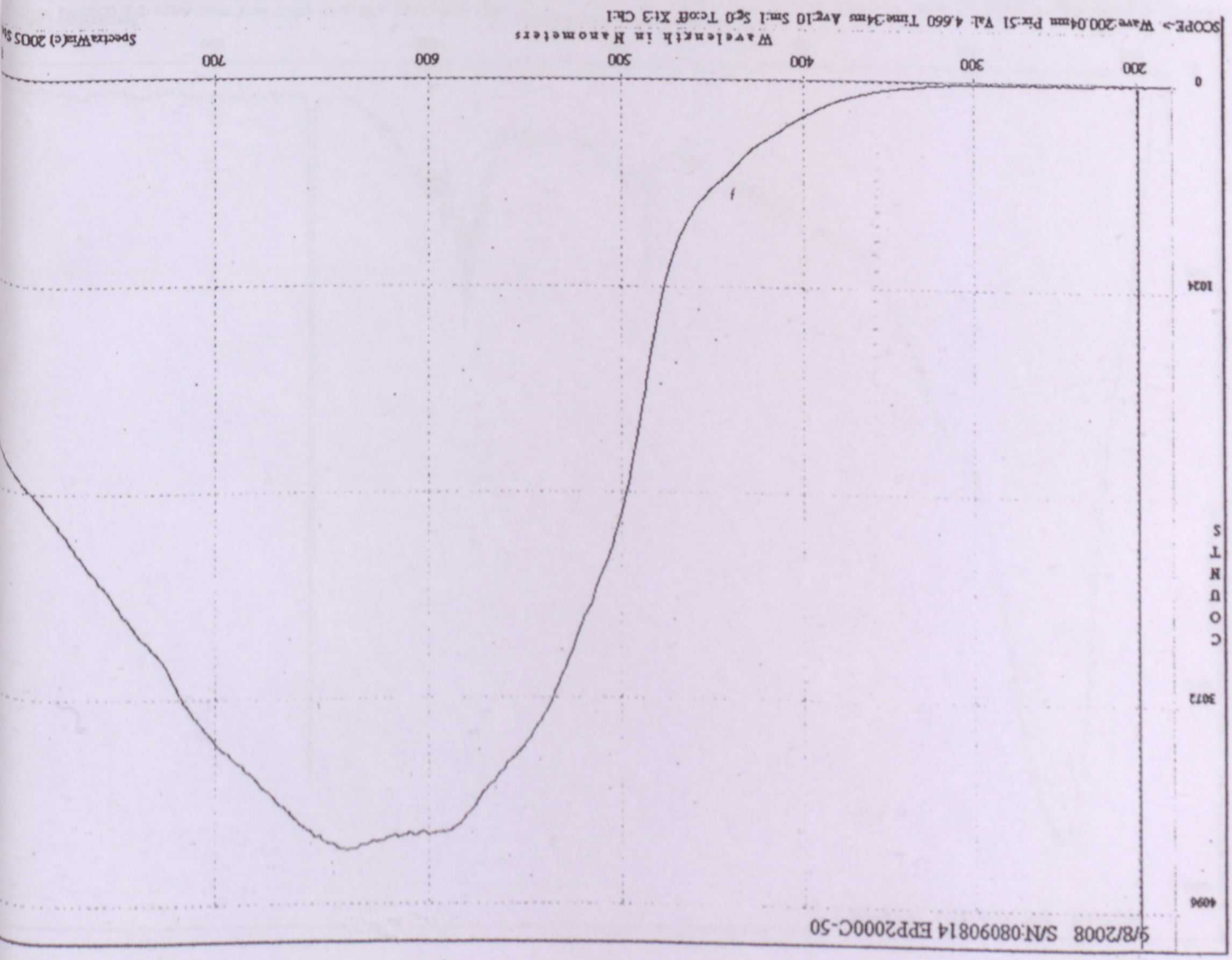
N.B. Red wire left disconnected.

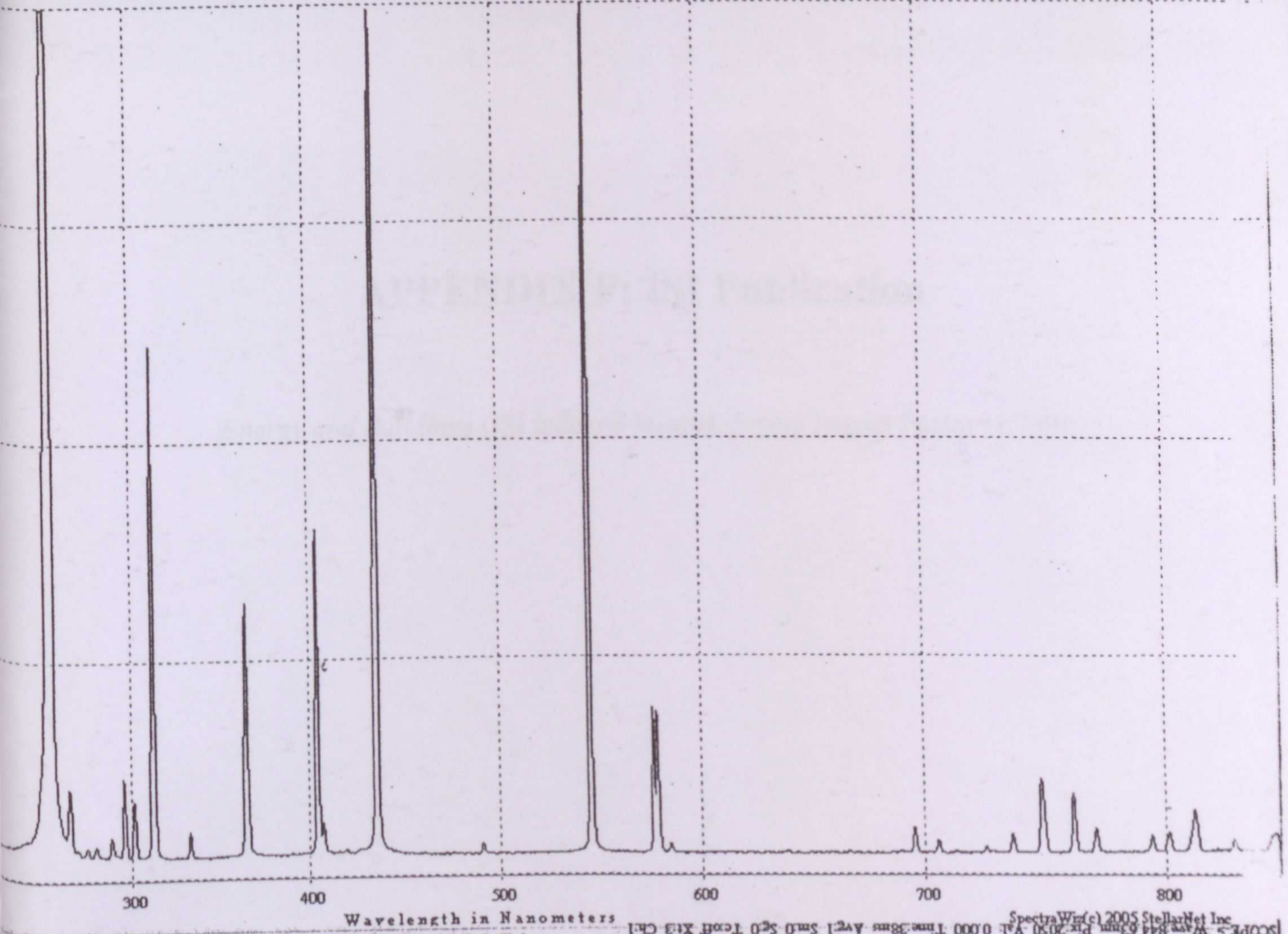
## *APPENDIX 4 - SPECIFICATIONS*

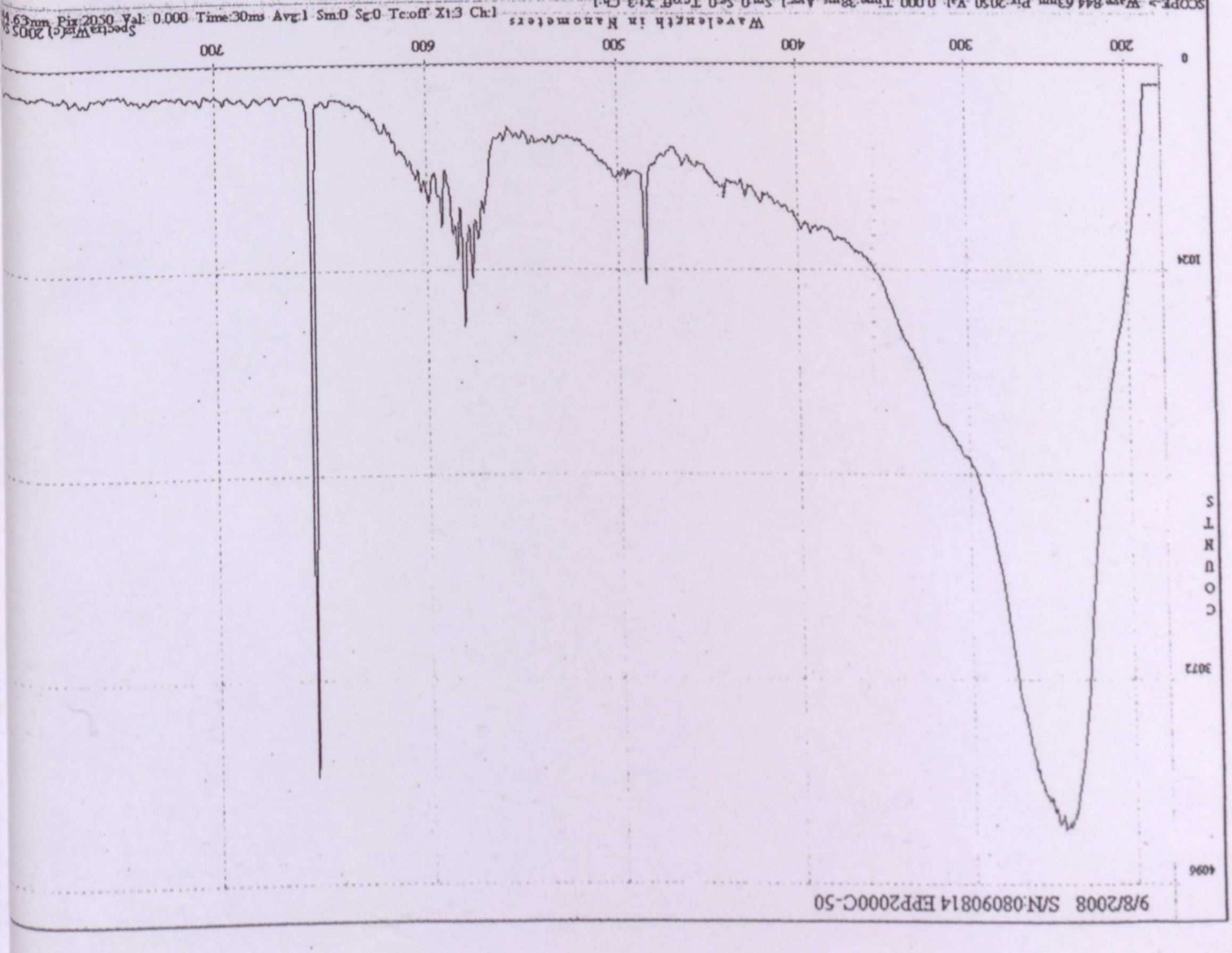
| | **SKP 210/212/215** | **SKL 310/315** | **SKE 510/515** | **SKS 1110** |
|---|---|---|---|---|
| Sensitivity - current (1) | 1.6μA/ 100 μmol /m$^2$/sec | 1.5μA/ 10 kLux | 3.5μA/ 100 W/m$^2$ | 5μA/ 100Wm$^2$ |
| Sensitivity - voltage | 1 mV/ 100 μmol /m$^2$/sec | 1mV/ 10 kLux | 1mV/ 100W/m$^2$ | 1mV/100W/m$^2$ |
| Working range (2) | 0-5x10$^4$ μmol /m$^2$/sec | 0-500 kLux | 0-5000 W/m$^2$ | 0-5000 W/m$^2$ |
| Linearity error - to above level | <0.2% | <0.2% | <0.2% | <0.2% |
| Absolute calibration error (3) | typ. <3%<br>5% max. | typ. <3%<br>5% max. | typ. <3%<br>5% max. | typ<3%<br>5% max |
| Response time (7) - voltage output | 10ns | 10ns | 10ns | 10ns |
| Cosine error 4 | 3% | 3% | 3% | 3% |
| Azimuth error (5) | <1% | <1% | <1% | <1% |
| Temperature Co-efficient | ±0.1%/°C | ±0.1%/°C | ±0.1%/°C | ±0.2%/°C |
| Internal resistance - voltage output | c.650ohms | c.650ohms | c.300ohms | c.180ohms |
| Longterm stability (6) | ±2% | ±2% | ±2% | ±2% |
| Material | Acetal | Acetal | Acetal | Acetal |
| Dimensions | 34mm diameter<br>38mm height | 34mm diameter<br>38mm height | 34mm diameter<br>38mm height | 34mm diameter<br>38mm height |
| Cable | 2 core screened<br>7 - 2 - 2C | 2 core screened<br>7 - 2 - 2C | 2 core screened<br>7 - 2 - 2C | 2 core screened<br>7 - 2 - 2C |
| Sensor Passband | 400 - 700 nm | CIE photopic Curve | 400 - 700 nm | 350 - 1100 nm |
| Detector | Silicon photocell | Silicon photocell | Silicon photocell | Silicon photocell |
| Filters | Glass type and/or metal interference | Glass type and/or metal interference | Glass type and/or metal interference | Glass type and/or metal interference |

| Wavelength | Pixel/2 | Pixel^2 | WaveEst | WaveError | Pixel # | |
|---|---|---|---|---|---|---|
| 202.55 | 28.5 | 812.25 | 202.45 | 0.10 | 57 | Zn |
| 206.2 | 33 | 1089 | 206.04 | 0.16 | 66 | Zn |
| 213.86 | 43 | 1849 | 214.01 | -0.15 | 86 | Zn |
| 253.65 | 93.5 | 8742.25 | 253.78 | -0.13 | 187 | |
| 302.15 | 156.5 | 24492.25 | 302.28 | -0.13 | 313 | |
| 312.56 | 170 | 28900 | 312.51 | 0.05 | 340 | |
| 365.01 | 240.5 | 57840.25 | 365.01 | 0.00 | 481 | |
| 404.66 | 295 | 87025 | 404.54 | 0.12 | 590 | |
| 435.83 | 339 | 114921 | 435.77 | 0.06 | 678 | |
| 546.07 | 502 | 252004 | 546.21 | -0.14 | 1004 | |
| 579.07 | 553 | 305809 | 579.06 | 0.01 | 1106 | |
| 696.54 | 747 | 558009 | 696.62 | -0.08 | 1494 | |
| 706.72 | 764.5 | 584460.25 | 706.64 | 0.08 | 1529 | |
| 727.29 | 801 | 641601 | 727.25 | 0.04 | 1602 | |
| 738.40 | 821 | 674041 | 738.36 | 0.04 | 1642 | |
| 750.39 | 843 | 710649 | 750.44 | -0.05 | 1686 | |
| 763.51 | 867 | 751689 | 763.45 | 0.06 | 1734 | |
| 772.38 | 883.5 | 780572.25 | 772.29 | 0.09 | 1767 | |
| 794.82 | 926.5 | 858402.25 | 794.92 | -0.10 | 1853 | |
| 801.48 | 939 | 881721 | 801.39 | 0.09 | 1878 | |
| 811.53 | 959 | 919681 | 811.64 | -0.11 | 1918 | |
| 826.45 | 988.5 | 977132.25 | 826.54 | -0.09 | 1977 | |
| 842.46 | 1020.5 | 1041420.25 | 842.39 | 0.07 | 2041 | |

| Wavelength | Calibration Coeficients | | |
|---|---|---|---|
| C1 = | 0.808788 dispersion | S/N:08090814 | |
| C2 = | -0.000156 2nd order | 50ums | S2 |
| C3 = | 179.52 starting wavelength | RoHS | |
| | | e844 | |




300
400
500
600
700
800
Wavelength in Nanometers
SpectraWiz(c) 2005 StellarNet Inc
4.63nm Pix:2050 Val: 0.000 Time:30ms Avg:1 Sm:0 Sg:0 Tc:off X1:3 Ch:1


SCOPE -> Wave:844.63nm Pix:2050 Val: 0.000 Time:38ms Avg:1 Sm:0 Sg:0 Tc:off X1:3 Ch:1
Wavelength in Nanometers
SpectraWiz(c) 2005 S
700
600
500
400
300
200
0
1024
3072
4096
COUNTS
9/8/2008 S/N:0809814 EPP2000C-50

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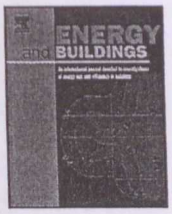

# aylighting can be fluorescent: Development of a fiber solar concentrator nd test for its indoor illumination

hen Wang *, H. Abdul-Rahman, S.P. Rao

*nter of Project and Facilities Management (PFM), Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia*

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ABSTRACT

Many limitations such as the strict dependence on beam irradiation and difficulties for wiring remain in conventional remote daylighting devices. This paper provides a brief discussion on the working theory and limitations for those conventional devices and presents a new concept developed by the first author for remote indoor daylighting. Based on the developed concept, a new device was designed and fabricated accordingly, which is an optical fiber solar concentrator consisting of a PMMA plate and 150 pieces of three-color 1 m long Φ2 mm fluorescent fibers. This new device is mounted on a university building roof and the concentrated light is transported to a remote dark room through 10 m long Φ2 mm clear optical fibers. Outdoor testing and evaluations for remote indoor daylighting and power production have been conducted. A 6-month monitored data from 24th May 2008 to 23rd Nov 2008 has been presented and the results reveal this new device a pleasant potential in remote indoor daylighting for large amount application in building integration.

## Introduction

Besides the rapidly rising price of petroleum, anthropogenic ctivities, especially the burning of fossil fuels, have released ollutants into the atmosphere increasing global warming and epleting the ozone layer. To improve the situation there needs to e a decrease in energy of which fossil fuel is used. As a result there as been an increased interest in renewable energy systems. Solar nergy is made widely available for daylighting, and direct roduction of electricity [1]. The need for workable energy options perhaps the greatest single challenge facing the world in the 21st entury. The acuteness of the challenge at this point in time results om the "perfect storm" of supply and demand, security, and nvironmental concerns, namely: (1) a projected doubling of nergy use and tripling of electricity demand within a half century, alling for a substantial increase in fossil fuel supplies or dramatic ansformation of the fossil fuel-based energy infrastructure; (2) eological and geopolitical realities concerning the availability of il and, to some extent, natural gas, specifically the concentration f resources and political instability in the Middle East, underlie ajor security concerns; and (3) greenhouse gas emissions from ssil fuel combustion are increasingly at the center of decisions bout how the global energy system evolves, one that carries on in he "business as usual" overwhelming dependence on fossil fuels or one that introduces technologies and policies that greatly improve efficiency, dramatically expand use of less carbon-intensive or "carbon free" energy, and implement large-scale carbon dioxide capture and sequestration [1].

Artificial lighting is one of the major sources of electrical energy costs in office buildings, and both directly through lighting energy consumption and indirectly by production of significant heat gain, which increases cooling loads [2]. Electric lighting represents up to 30% of building electricity consumption in commercial and office buildings [3]. Lighting energy used in most buildings can routinely be cut 30–50 percent through a combination of improved technology, automatic controls, and better lighting design [4]. Nevertheless, more than half of existing commercial building floor area still uses old-style, less-efficient systems. Efficient lighting designs are used in only a small minority of spaces, and control systems that maximize the use of daylight are even less common [2,4].

As a solution to the energy issues, solar energy is made widely available for daylighting 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 (LSCs), and so on [5–11].

In the above mentioned conventional remote daylighting devices, many limitations such as strict dependence on beam irradiation and difficulties for wiring still remain to date. In mitigating these limitations, a new concept for remote indoor daylighting is developed and a new device called fluorescent fiber solar concentrator (FFSC) is designed and fabricated accordingly in

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* Corresponding author. Tel.: +60 162189875; fax: +60 379675713.
*E-mail addresses:* derekisleon@gmail.com (C. Wang), arhamzah@um.edu.my H. Abdul-Rahman), raosp1@gmail.com (S.P. Rao).

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oi:10.1016/j.enbuild.2009.11.011

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00. Such a device has been achieved and the experimental sults are in good agreement with the preliminary study.

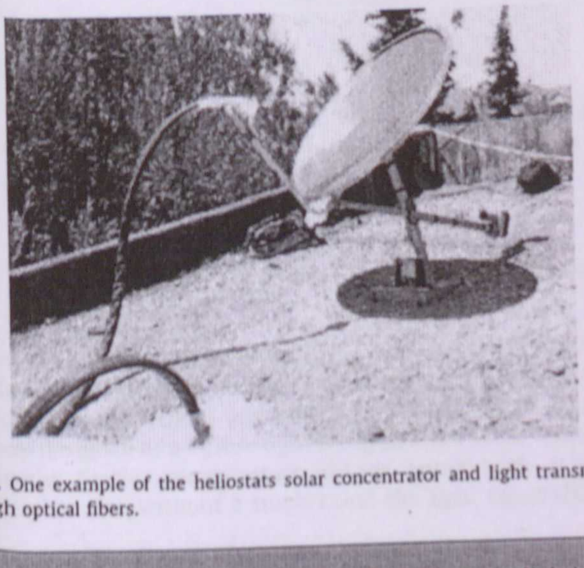
### 2. *Conventional solar concentrators*

Sunlight holds considerable unrealized potential for application energy efficient room lighting designs. There are currently few isting systems that efficiently utilize sunlight to provide fficient room lighting to remote non-daylit rooms [10,17,18]. nidolic optics can be used for lighting of a room with an mmediate daylighting aperture [17,18]. Recently, systems involng concentrating collectors [10], heliostats [19], or mirror light pes [20] have been developed for illumination of remote rooms. disadvantage of conventional solar concentrators is while stems using mirrors or lens may be advantageous for largeale room lighting, they chiefly rely on beam solar irradiation and quire tracking mechanisms to avoid astigmatism and other light sses experienced during collection of solar energy so that they se their functions in cloudy and diffuse conditions [9]. Fig. 2 esents an example of the heliostats solar concentrator and light ansmission through optical fibers developed by Kandilli et al. 1].

In order to remove the tracker, a static solar concentrator is oposed by Masato and Toshiro [22] to match the aesthetic atures of towns. The concentrator consists of vertical plate solar lls and white/transparent switch-able bottom plate, which is perated with external power. The bottom is switched to be a iffuse reflection white surface when the cell generates electric ower, and switched to be a light transmissible transparent surface hen the cell does not deliver power. The light collection of this ncentrator was analyzed by using multiple total internal flection model and ray tracing simulation. However, the results e not significantly satisfying for a static solution for solar ncentration.

### 3. *Luminescent solar concentrator (LSC)*

Luminescent solar concentrators (LSCs) have attracted the ttention of a large number of scientists and engineers since the rst proposal by Weber and Lambe [23]. The operation of the LSC, hich can be considered as a peculiar kind of light guide, is based n the following principles. One or more high quantum yield pecies are dissolved in a rigid highly transparent medium of high efractive index. Solar photons entering the plate are absorbed by e luminescent species and reemitted in random directions. ollowing Snell's law, a large fraction of the emitted photons will e trapped within the plate and transported by total internal reflections to the edge of the plate, as illustrated in Fig. 3, where they will be converted by appropriate photovoltaic cells [24–26]. 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 [27,28].



g. 2. One example of the heliostats solar concentrator and light transmission rough optical fibers.

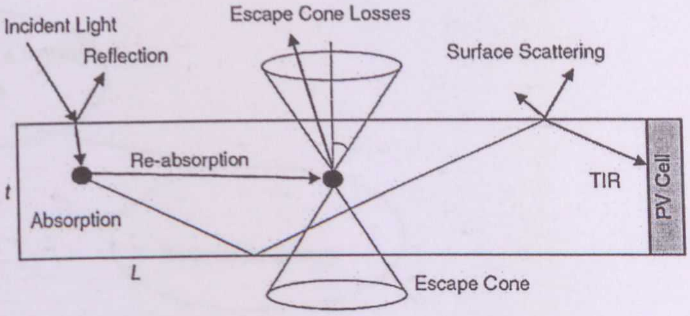


**Fig. 3.** Example of schematic representation of luminescent solar concentrator (LSC).

An LSC daylighting system has been produced by Earp et al. [11], which transports sunlight to remote 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 lux, prototypes with collector area 1.2 m × 0.135 m 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 [11].

## 3. 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 [7,8]. As discussed in Section 2.1.2, only optical fibers are competent for this requirement. However, the light concentrated by Earp et al.'s [11] 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 Section 2, Fig. 4 illustrates the necessities to design FFSC. In Fig. 4, there are two groups of solutions able to be practiced in the building sector for energy issues, namely: building energy saving and renewable energy applications, which are presented in the left branch and the right branch, respectively.

According to the left branch shown in Fig. 4, as an approach for energy saving, daylighting 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 [13,6]. Light pipes were designed to transfer daylight to unreached areas. However, the light pipes have their limitation for difficulties in wiring so that daylight 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 Fig. 4 shows various solar concentrators that were designed using optical approaches such as mirrors or lens as a solution to solar energy applications. Since they are only sensitive

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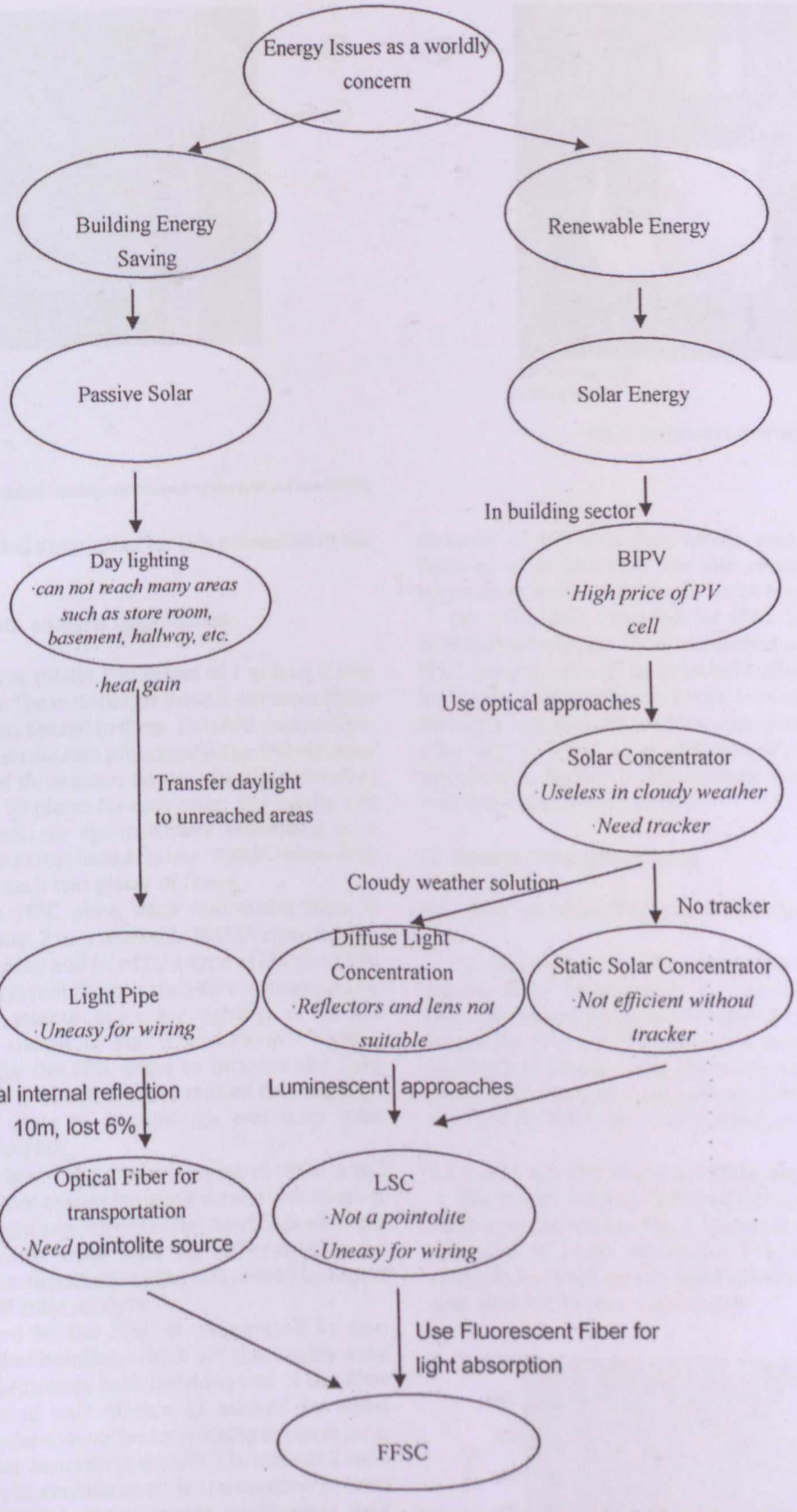
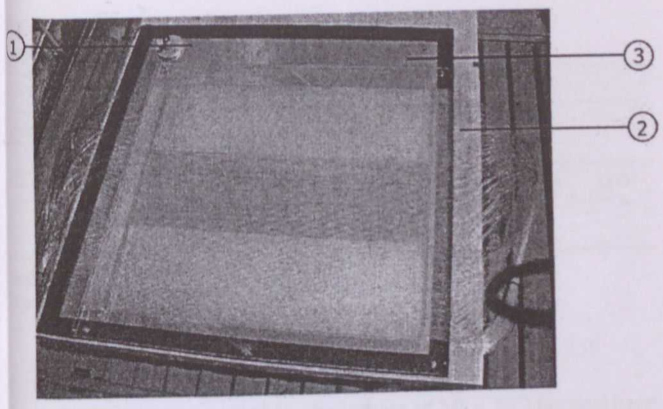


**Fig. 4.** From energy issue to solar using: the necessity of FFSC (concept developed by the first author, 2008).

beam irradiation, they do not function well in cloudy weather diffuse conditions and a tracker is always needed. Luminescent ar concentrators (LSCs) and some static solar concentrators re then designed as a diffuse light solution and a static solution, pectively. Static concentrators always come with a poor centration 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 developed FFSC system is expected to solve this problem as well.

Both branches in Fig. 4 illustrates that a new solar concentration system is necessary to be designed targeting on the above mentioned problems. Therefore, a device named FFSC is developed

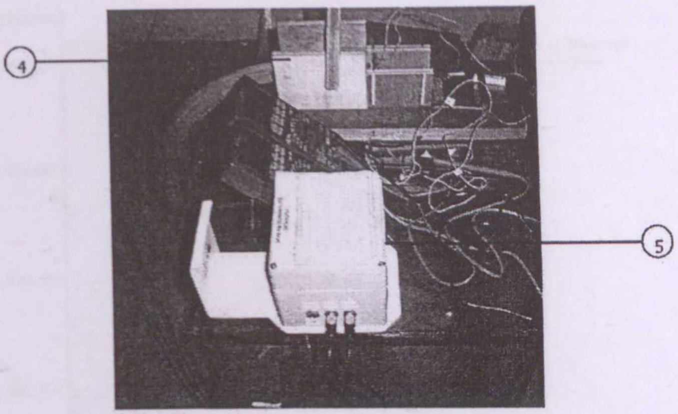


① Pyranometer 1

② FFSC plate

③ Mirror

5. FFSC installed on the building roof (concept developed by the first author, 2008).



④Finishing end
⑤Data logger

**Fig. 6.** Equipments used for testing.

this study and the detailed description for it is presented in the xt section.

## Design of FFSC and data analysis approaches

The FFSC plate consists of totally 150 pieces of 1 m long 2 mm iameter fluorescent fibers. The material for these fluorescent fibers acrylic with quantum dots seeded in them. Detailed composition d structure of the quantum dots are proprietary. The 150 pieces of uorescent fibers consist of three colors (green, red, and yellow) as own in Fig. 5. There are 50 pieces for each color. The totally 150 ieces of fluorescent fibers are symmetrically embedded in a 200 mm × 1200 mm polymethyl methacrylate (PMMA) plate with space of 2 mm between each two pieces of fibers.

At both edges of the FFSC plate, each fluorescent fiber is nnected with a 10 m long, 2 mm diameter PMMA clear optical ber by an aluminum bushing and fixed by a type of UV glue. The ght absorbed by the fluorescent fibers is therefore transported by ese clear fibers to a remote place for lighting or power roduction purpose. As shown in Fig. 5, a 1300 m × 1300 m flector is installed under the FFSC plate to increase the light bsorption. A pyranometer connected with a remote data logger is xed together with the plate to monitor the real time solar radiation received by the FFSC.

One reason for using three-color fibers is trying to cover a full pectrum band [11]. Another reason for using three-color fibers is ecause the transported light coming out of the finishing end could onsiderably mix into white color light by self-scattering for lumination purposes. The mixed white light was proved by naked ye observation and a CIE color analysis.

The light concentrated by the FFSC is transported by two 0 mm diameter clear fiber bundles, which are reasonably easy r wiring in building integration. Each finishing end of the fiber undles has a diameter of only 30 mm as marked by serial umber (4) in Fig. 6. In order to monitor its working performance, he fluorescent fiber solar concentrator (FFSC) is mounted on a uilding roof and the light concentrated is transported by two 0 m long clear fiber bundles into a remote windowless dark oom. One pyranometer, which is coded as Pyranometer 1, is stalled with the FFSC plate to measure the solar radiation. The ght radiation of one FFSC finishing end is measured by another yranometer coded as Pyranometer 2. The values measured by he Pyranometer 1 and Pyranometer 2 are denoted as *PY*1 and Y2, respectively, which are recorded by a remote data logger at n interval of 10 min for 24 h a day. The unit for *PY*1 and *PY*2 is W/ $^2$. Another finishing end is installed upon a Lux sensor with a distance of 100 mm. The values read by the Lux sensor are denoted as *Ev* and they are also recorded by the remote data logger at an interval of 10 min for 24 h a day. The unit for *Ev* is lux.

The 24-h data recorded for FFSC from 6:00 to 20:00 were selected for each day. Various parameters has been studied for the FFSC system, namely: light-to-light efficiency ($\eta l$), lighting effect, energy-to-energy efficiency ($\eta e$), luminous efficacy ($\eta e - l$) of the finishing end, and the negative association between light-to-light efficiency ($\eta l$) and solar radiation (*PY*1), and so on, which are discussed in Section 5. The statistic methods such as correlation and linear test are employed.

## 5. Results from monitoring

### 5.1. Solar radiation (PY1) and FFSC output (PY2)

As mentioned in the above section, the solar radiation measured by Pyranometer 1 is denoted as *PY*1, and the light radiation measured by Pyranometer 2 is denoted as *PY*2. The mean values for *PY*1 and *PY*2 in these 6 months are 307.73 W/m$^2$ and 17.02 W/m$^2$, respectively. The maximum values for *PY*1 and *PY*2 in these 6 months measured both at 13:00 on 14th June 2008, which are 1308.31 W/m$^2$ and 64.77 W/m$^2$, respectively.

#### 5.1.1. PY1 and PY2 in one particular day

The hourly values of *PY*1 and *PY*2 on a particular day 24th May 2008 are presented in Fig. 7. The peak values of *PY*1 and *PY*2 both appeared at 13:00, which are 1151.76 W/m$^2$ and 60.89 W/m$^2$, respectively. Both the *PY*1 and *PY*2 values are negligible before 7:00 and after 19:00 on a normal day.

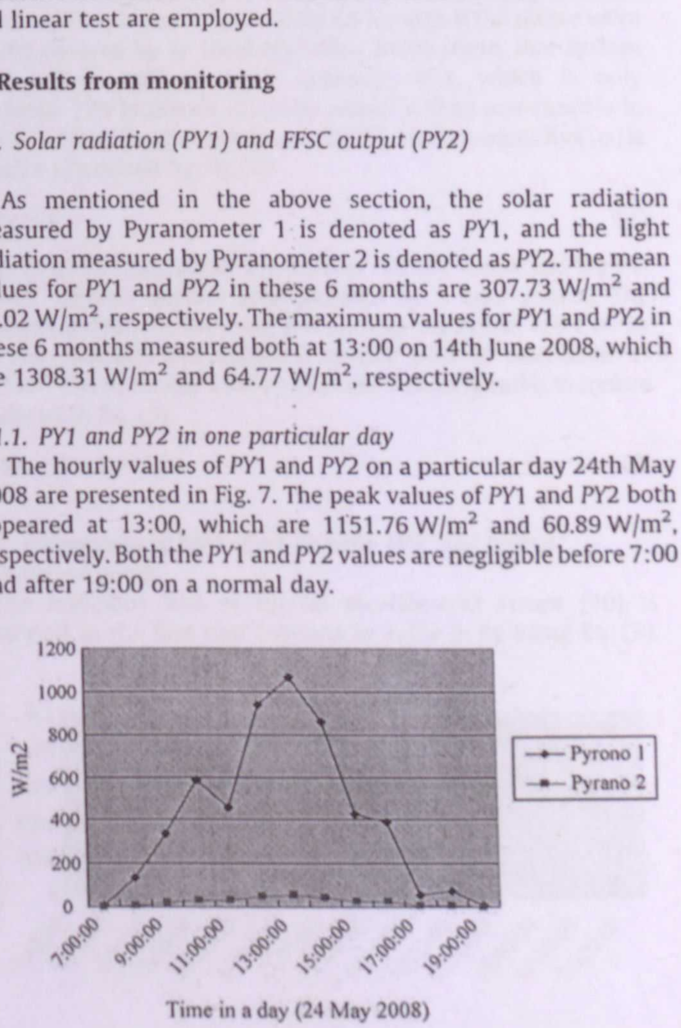


**Fig. 7.** *PY*1 and *PY*2 in a particular day.

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e 1
ession of *PY*1 and *PY*2.

| NOVA[b] | | | | | | |
|---|---|---|---|---|---|---|
| del | Sum of squares | df | Mean square | *F* | Sig. | |
| | Regression | 291.779 | 1 | 291.779 | 458.973 | .000[a] |
| | Residual | 18.436 | 29 | .636 | | |
| | Total | 310.215 | 30 | | | |

redictors:(constant), Pyranometer1.
ependent variable: Pyranometer2.

### . The linearity between PY1 and PY2

o make it more presentable, the values of 10 × *PY*2 is used here ead of simply using *PY*2 to compare with the *PY*1 values since magnifying coefficient 10 is a constant. Fig. 8 shows that the and 10 × *PY*2 have very similar curves, from which it assumes *PY*1 and *PY*2 are linear. The assumption is proved by the linear as illustrated in Table 1 and Fig. 9.

### FFSC light-to-light efficiency ($\eta l$)

ystem light-to-light efficiency is defined by Eq. (1)

$$\frac{PY2}{PY1} \qquad (1)$$

ere *PY*1 is the solar radiation measured by Pyranometer 1, the installed on the building roof, and *PY*2 is the light radiation asured by Pyranometer 2, the one installed with the fiber dle finishing end. This section presents the FFSC light-to-light ciency ($\eta l$) and its stability. In one typical day on 24th May 8, the maximum value of $\eta l$ is 0.079 (17:20) and the minimum ue is 0.046 (at 13:40). The mean value of $\eta l$ on that day is 0.052 h the standard deviation of 0.0095, which is under a 0.01 level. refore, the mean value of 0.052 is significantly representative that day. Fig. 10 presents the curve of the light-to-light ciency $\eta l$ from 7:30 to 18:30 on 24th May 2008.

Notice that the maximum value of $\eta l$ 0.079 appears at 17:20 en the solar irradiation is much weaker than that at 13:40 when solar irradiation supposes to be around peak value on a day, but minimum $\eta l$ 0.046 appears at 13:40. An assumption has refore risen that the light-to-light efficiency has a negative ociation with the solar radiation. The discussion on the negative ociation between light-to-light efficiency ($\eta l$) and solar radian (*PY*1) are presented in Section 5.6.

The 6-month mean value of $\eta l$ is 0.057. Table 2 presents the nthly mean values of light-to-light efficiency in these 6 months n 24th May 2008 to 23rd November 2008. The standard iation for $\eta l$ in the 6-month is 0.0015, which is under a 0.01 level, so that the mean value of 0.057 is concluded to be significantly stable and representative for these 6 months.

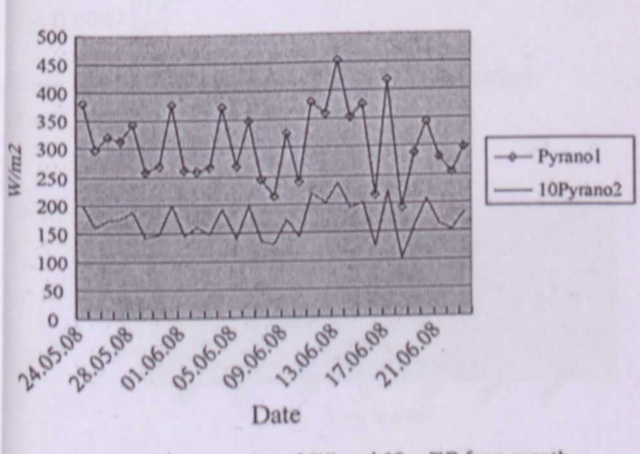

**Fig. 8.** Daily mean value of *PY*1 and 10 × *PY*2 for a month.

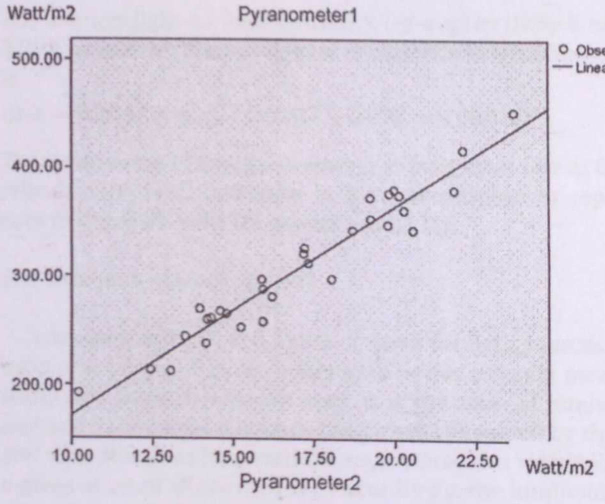

**Fig. 9.** Linear test of *PY*1 and *PY*2.

### 5.3. System lighting effect

#### 5.3.1. Calculate luminous flux ($\varphi$) from illuminance ($Ev$)

As described by Schiler [29], the illuminance 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 1 lm. Alternatively, an isotropic one-candela light source emits a total luminous flux of exactly $4\pi$ lumens. If the source were partially covered by an ideal absorbing hemisphere, that system would radiate half as much luminous flux, which is only $2\pi$ lumens. The luminous intensity would still be one-candela in those directions that are not obscured [29]. The luminous flux ($\varphi$) is therefore calculated by Eq. (2):

$$\varphi = Ev \times S \qquad (2)$$

where $Ev$ is the illuminance detected by the Lux sensor and the $S$ is the half sphere's surface area radiated by a light source. The distance between the finishing end and the Lux sensor is 0.1 m. So that the radiated half sphere's surface area is calculated as 0.063 m$^2$. The luminous flux ($\varphi$) from one finishing end is therefore calculated in Eq. (3):

$$\varphi = Ev \times S = 0.063\,Ev \qquad (3)$$

#### 5.3.2. Comparison of light effect between FFSC and typical incandescent lamps

The luminous flux of typical incandescent lamps [30] is illustrated in the first two columns in Table 3. By using Eq. (3),

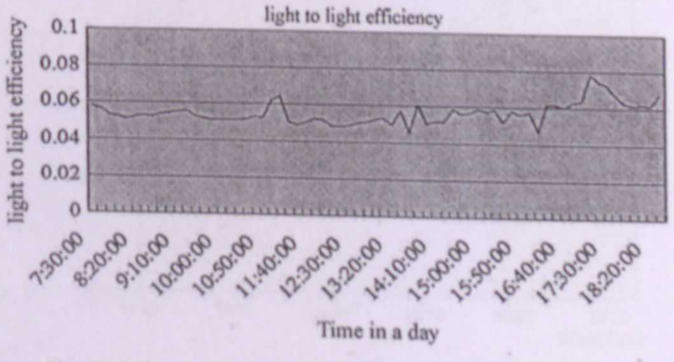

**Fig. 10.** Daily curve of light-to-light efficiency ($\eta l$) on 24 May 2008.

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ble 2
Month monthly mean value of $\eta l$.

| June 2008 | July 2008 | August 2008 | September 2008 | October 2008 | November 2008 |
|---|---|---|---|---|---|
| 0.056 | 0.058 | 0.057 | 0.059 | 0.055 | 0.056 |

ble 3
nverting typical incandescent lamps' lumen to lux.

| Watt of lamps | Lumen | Lux |
|---|---|---|
| 5W | 25 | 397 |
| 15 W | 110 | 1746 |
| 25 W | 200 | 3175 |

he luminous flux of incandescent lamps is converted into luminance, which is shown in the last column of Table 3. As lustrated in Fig. 11, the lighting effect provided by one of the FFSC nishing end is above 400 lux (equal to a 5 W incandescent lamp ith 25 lm) from 8:30 to 16:30, which almost covers the whole ffice hours on a day. The monitored maximum *Ev* provided by one FSC finishing end in these 20 days is 1811 lux, which is at 13:00 on 1st May 2008, when it is even higher than a 15 W incandescent mp according to Table 3.

### 4. *Energy-to-energy efficiency* ($\eta e$)

The energy-to-energy efficiency ($\eta e$) is defined as the ratio of otal energy output yielding from both finishing ends divided by he solar energy irradiated on the fluorescent fibers, which is lustrated by Eq. (4):

$$\eta e = \frac{P_{out}}{P_{sun}} \tag{4}$$

he effective area of the FFSC plate is

$$0 = \Phi \times L \times n = 0.002 \times 1 \times 150 = 0.3\,\mathrm{m}^2$$

here $\Phi$ and $L$ are the diameter and the length of the fluorescent bers, respectively. The variable $n$ is the number of piece for uorescent fibers, which is 150. The effective area of one finishing nd is

$$S_f = \pi \times R_f \times R_f = 3.14 \times 0.015 \times 0.015 = 0.0007\,\mathrm{m}^2$$

here $R_f$ is the radius of the finishing end. Therefore, the energy-to-nergy efficiency $\eta e$ is calculated as

$$\eta e = \frac{P_{out}}{P_{sun}} = 2 \times PY2 \times \frac{S_f}{PY1 \times S0} = \left(2 \times \frac{0.0007}{0.3}\right)\frac{PY2}{PY1}$$
$$= 0.0047\frac{PY2}{PY1}$$

here $PY2/PY1 = \eta l$ as defined in Eq. (1), therefore,

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

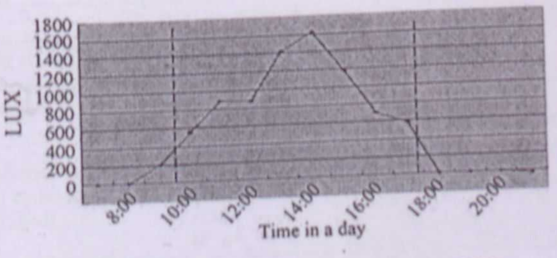

**Fig. 11.** Lux values in a particular day 24 May 2008.

The average light-to-light efficiency ($\eta l$-avg) in these 6 months is 0.057, so that the average light to energy efficiency in these 31 days is

$$\eta e\text{-}a = 0.0047 \times \eta l\text{-}a = 0.0047 \times 0.056 = 0.000268$$

The mean value of energy-to-energy efficiency as low as 0.000268 reveals that FFSC currently is not yet suitable to replace the conventional PV cells for power producing.

### 5.5. *Luminous efficacy* ($\eta e - l$)

Luminous efficacy is a figure of merit for light sources. It is the ratio of luminous flux (in lumens) to power (usually measured in watts). As most commonly used, it is the ratio of luminous flux emitted from a light source to the power consumed by the source, and thus describes how well the source provides visible light from a given amount of energy [31]. Accordingly, the luminous efficacy ($\eta e - l$) for FFSC is defined by Eq. (5):

$$\eta e - l = \frac{2\varphi}{P_{sun}} \tag{5}$$

where $\varphi$ is the luminous flux produced by one finishing end, and $P_{sun}$ is the solar energy irradiated on the fluorescent fibers. Since there are two finishing ends equally sharing the irradiation from the fluorescent fibers, the coefficient "2" is used here in Eq. (5). Therefore, the luminous efficacy ($\eta e - l$) is calculated as shown in Eq. (6):

$$\eta e - l = \frac{2\varphi}{P_{sun}} = 2 \times \left(\frac{0.063Ev}{PY1 \times S0}\right) = 2 \times \left(\frac{0.063Ev}{PY1 \times 0.3}\right) = \frac{0.42Ev}{PY1} \tag{6}$$

A significant value of 0.01 in the linear test conducted for *Ev* and *PY1* indicates that the values of *Ev* and *PY1* are linear so that *Ev*/*PY1* is considered here as a comparatively stable value (Fig. 12). Hence, an average ratio of *Ev*/*PY1* could be used in the above equation as a constant in general. From the monitored data, the monthly mean value of *Ev*/*PY1* is calculated as 1.53. Therefore, the luminous efficacy ($\eta e - l$) of the FFSC finishing end is as below:

$$\eta e - l = 0.42 \times \frac{Ev}{PY1} = 0.42 \times 1.53 = 0.643\,\mathrm{lm/W}$$

### 5.6. *Negative association between light-to-light efficiency ($\eta l$) and solar radiation (PY1)*

Base on the monitored 10167 sets of effective data in the 6 months with an interval of 10 min, the system light-to-light efficiency ($\eta l$) presents a negative association with the solar radiation *PY1*. As shown in Fig. 13, all these 10167 sets of data are

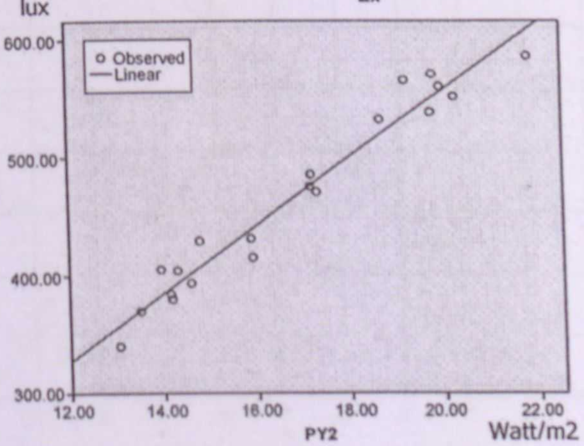

**Fig. 12.** Linear test of *Ev* and *PY2*.

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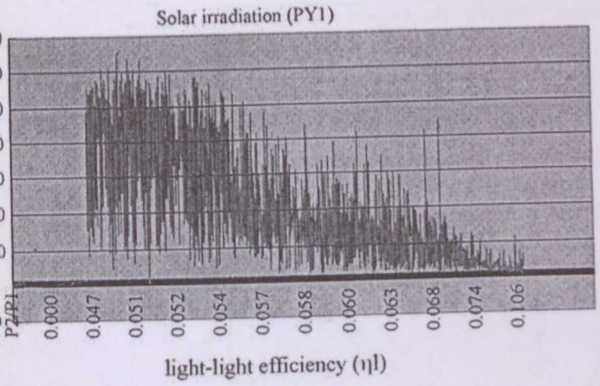

**Fig. 13.** Negative association between $\eta l$ and $PY1$.

nmetrically sorted by the light-to-light efficiency ($\eta l$) in an ending order while the corresponding values of the solar iation ($PY1$) present a descending trend. It is proved in Table 4 t there is a negative correlation coefficient (−0.643) for the ociation between light–light efficiency and solar irradiation, icating that the relationship between these two variables is that values of one variable decrease as the other increases.

### *CIE color analysis and spectral distribution*

The CIE (Commission Internationale de l'Eclairage, the International Commission on Color) color analysis and wavelength test the artificial light produced by FFSC were conducted on a dom day 16th Oct 2008 from 9:00 to 15:00. The weather on that was sunny with a clear sky from 9:00 to 11:00, while from 30 to 13:30 it was sunny with little clouds. Since 14:00, it was rcast and raining until the evening. The device used for the CIE or analysis and the wavelength test is the EPP2000 and ISA2000 ctrometer, the responding range for which is from 190 nm to 0 nm. Since the visible light waveband drops between 400 nm 700 nm [32], and according to Geoffrey and Earp et al. [32,11], average wavelength for the white light is around 555 nm, this ice is suitable for the test. In order to find out the relationship ween the output color and the various sky conditions, a same up of tests was repeated three times on the same day. The first up of tests was conducted at around 10:00 (clear sky condition), it was repeated at around 12:30 (sunny with little clouds). The group of tests was conducted at around 14:30 (overcast ndition).

Fig. 14 presents the screen of the CIE color analysis conducted der the irradiant mode at around 12:30 (sunny with little uds). As indicated in Fig. 14, the solid curve in the right of the gram is the black body curve. There are two diagonals forming a ss in the central area and the cross point is indicated as "central ite point" in the diagram, where $x = 0.333$, $y = 0.333$. Any ected point drops on or near this central white point is nsidered as white color [31]. The FFSC point in the diagram drops between the central white point and the yellow area, where $x = 0.479$ and $y = 0.460$, indicating that the FFSC light output leans a bit towards the yellow area comparing to the absolutely white light. Referring to the CIE diagram for the direct sunlight ($x = 0.427$, $y = 0.401$) shown in Fig. 15, the FFSC point ($x = 0.479$ and $y = 0.460$) appears a great match to the direct sunlight. Therefore, it concludes that the FFSC light output under a clear sky is a kind of yellow-white color light and its color has a good match to that of the direct sunlight. According to Yoshi [31] and Schiler [29], a yellow-white color light is comforting to human eyes.

le 4
relation of $\eta l$ and $PY1$.

| | Light–light efficiency | Solar irradiation |
|---|---|---|
| ght–light efficiency | | |
| Pearson correlation | 1.000 | −.643** |
| Sig. (2-tailed) | | .000 |
| *N* | 10167 | 10167 |
| lar irradiation | | |
| Pearson correlation | −.643** | 1.000 |
| Sig. (2-tailed) | .000 | |
| *N* | 10167 | 10167 |

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

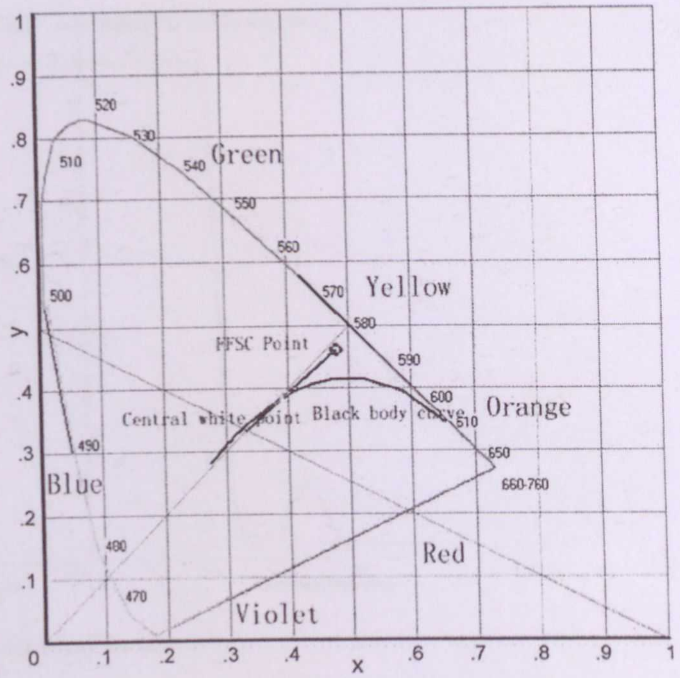

**Fig. 14.** CIE color analysis for FFSC.

The wavelength test was conducted at around 12:30 on the same day on 16th Oct 2008. The sky condition at that time was sunny with little clouds, which was one of the general weather conditions in the tropic zone. Fig. 16 presents a wavelength screen in the scope mode at 12:23, from which it indicates on the top of

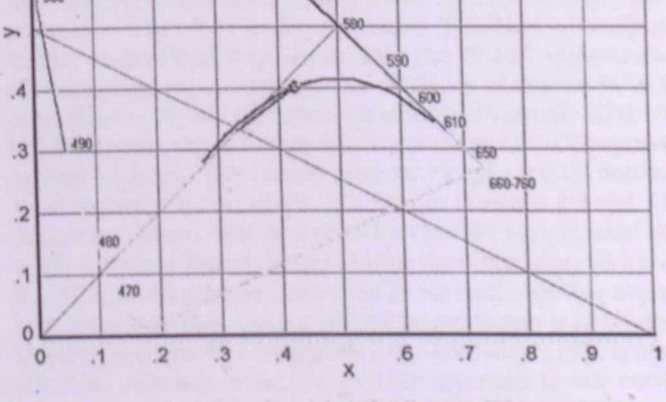

**Fig. 15.** CIE color analysis for direct sunlight.

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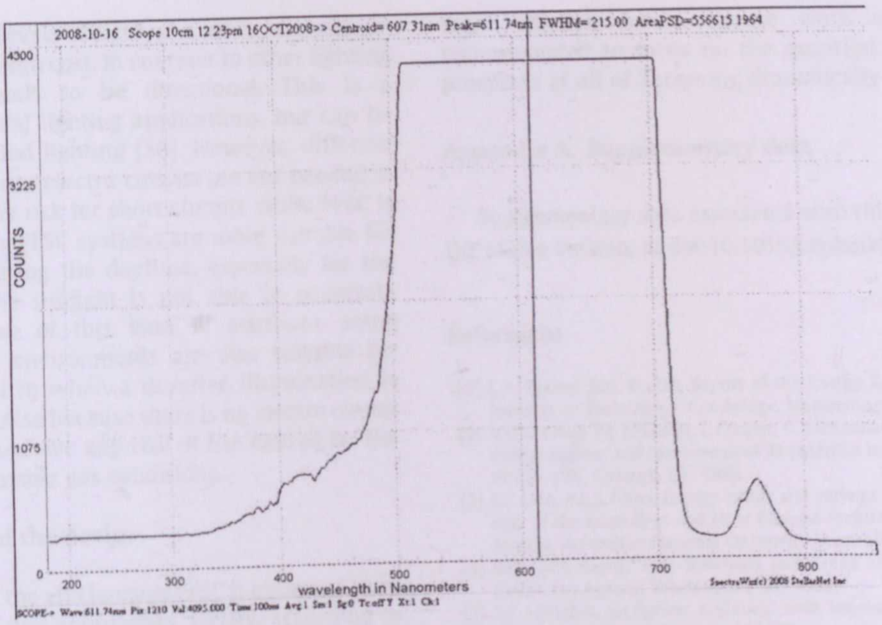

Fig. 16. Wavelength scope mode for FFSC.

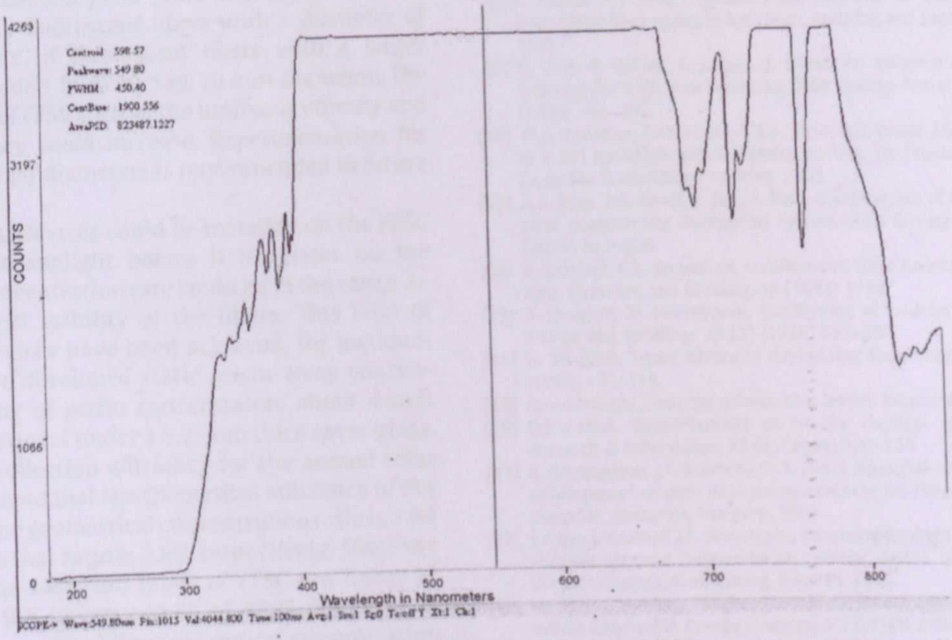

Fig. 17. Wavelength scope mode for natural light.

he screen that the centroid is 607.31 nm. The wave band at 07.31 nm is close to the average band for the white light, which is 55 nm. Comparing to the wavelength centroid of 598.57 nm neasured for the natural daylight under the clear sky condition as hown in Fig. 17, the wavelength results reveal a great match etween the FFSC light output and the natural daylight.

## . Discussions on economics

The value of FFSC luminous efficacy at 0.643 lm/W is much ower than that of the natural daylight at around 110 lm/W [33]. When compared to standard artificial light sources such as ncandescent light bulbs at 16–40 lm/W, fluorescent lamps at 0–80 lm/W and light-emitting diode (LED) at 10 lm/W [33], the FSC luminous efficacy as 0.643 lm/W is considered low, but it is higher than the luminous efficacy of a combusting candle at 0.3 lm/W according to Wapedia [34]. However, since the sunlight is free, different from all the electrical light sources, FFSC does not use any electricity when it is under operation. This kind of attribute is similar as the PV-LED approach since the PV-LED systems do not also consume any electricity. The efficiency of normal PV cells is around 0.11 [35] and the luminous efficacy of normal LED is 10 lm/W [33], so that the luminous efficacy of normal PV-LED systems is around 1.1 lm/W. The normal price for PV cells is 6 US dollars per Watt so that the cost of PV cells for per lumen is around 5.5 US dollars per lumen. The total price for the FFSC system used in this study is around 500 US dollars. During the office hours on a normal day FFSC could provide more than 25 lm luminous flux according to this study so that the cost of FFSC for per lumen is 20 US dollars. Comparing to the PV-LED approach (5.5 US dollars), FFSC is not cost effective. Actually, even the PV-LED approach is not currently economical to produce high levels of lighting. Current LED screw-in

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it bulbs offer either low levels of light at a moderate cost, or derate levels of light at a high cost. In contrast to other lighting hnologies, LED light tends to be directional. This is a advantage for most general lighting applications, but can be advantage for spot or flood lighting [36]. However, different n the PV-LED systems, since electro circuits are not needed in C systems, there is no any risk for short circuits while FFSC is rating. Hence, potentially FFSC systems are more suitable for aqueous illumination during the daytime, especially for the lerwater areas where the sunlight is not able to penetrate ough effectively. Because of this kind of attribute, some remely moist operation environments are also suitable for C systems to be applied in when a durative illumination is ded during the daytime. Also because there is no electro circuit ded, FFSC systems do not have any risk of fire caused by the ctrical current in inflammable gas conditions.

## Future improvements of the device

For future improvement, the efficiency of FFSC is expected to be reased by the following two approaches. Firstly, according to hards [24], Reisfeld [25], and Batchelder et al. [26], the size and form of the cross-section could impact on the proportion of otons trapped by the LSC plate and the reduction of the cross tional area of the luminescent plate could increase the photon s. In this research, only fluorescent fibers with a diameter of m are used. Therefore, if fluorescent fibers with a larger meter could be embedded in FFSC, say 10 mm diameter, the formance parameters of FFSC such as the luminous efficacy and light-to-light efficiency could increase. Experimentation for orescent fibers with larger diameters is recommended in future dy.

Secondly, some optical devices could be installed on the FFSC te to concentrate the sunlight before it irradiates on the orescent fibers. The concentration rate could be in the range 2– onsidering the thermal stability of the fibers. This kind of ical concentration devices have been achieved, for instance, matsu et al. [37] have developed static prism-array concentor modules consisting of prism concentrators about 4-mm ck assembled unidirectional under a 3.2-mm thick cover glass. culating the optical collection efficiency for the annual solar adiation in Tokyo, it found that the theoretical efficiency of the dules is 94.4% when the geometrical concentration ratio is 1.88 d that it is 89.1% when that ratio is 2.66, respectively. Since the liation output and the radiation input of FFSC are linear as oved by this study, the improvement of FFSC efficiency is pected to be in the range of 2–3 if proper optical concentration vices are installed.

## Conclusions

Outdoor testing and evaluations for remote indoor daylighting d power production have been conducted for the developed new vice named FFSC from 24th May2008 to 23rd November 2008. e negative association between light-to-light efficiency ($\eta l$) and ar irradiation is detected and analyzed for the first time. The low ergy-to-energy efficiency value of 0.000268 proves that FFSC is t practical yet to replace the conventional BIPV approach for wer producing. However, the reasonable light-to-light efficiency th a mean value of 0.057 and the lighting effect up to 110 lm veal FFSC a pleasant potential in remote indoor daylighting for ge amount application in building integration. Moreover, mparing to the conventional artificial lighting powered by PV lls which is converting light to electricity and then back to light ain which lost a lot of efficiency in multi converting, the idea of SC as a shortcut light–light conversion is considered to have a more efficient future. Future work on this technology is recommended to focus on the question of whether it has any prospects at all of becoming dramatically more efficient.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2009.11.011.

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