Luminescent Solar Concentrator and Photovoltaic Module Integrated System Analysis and Design

ENG 470 Engineering Honours Thesis Final Report

By

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Honours of Electrical Power Engineering and Renewable Energy Engineering

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Murdoch University
Author’s Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

Signed by:
Statement of Contributors

• Conception or design of the work
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Abstract

This thesis report presents the analysis and design work associated with luminescent solar concentrators (LSC) and photovoltaic integrated systems in microalgae cultivation application, which is the dissertation topic of my graduation dissertation in Engineering major, Murdoch University. Around the main topic of LSCs, a few relevant studies have been carried out in sequence. To start with, the contents focus on brief introduction and theoretical analysis and they act as the foundation of the whole analysis. Therefore, the majority works of this part of analysis are finished by looking through literature works; a significant number of relevant articles are cited here. Afterwards, the data from experiment is expressed and presented. From the experiment’s data, the two specimen LSC, flat sheet LSC and hollow cylinder LSC can emit fluorescent light at bottoms up to 6.9 times and 1.85 times stronger than coinstantaneous sunlight illumination respectively. Moreover, when the sample photovoltaic cell is receiving the concentrated fluorescent light from the two LSCs, the cell can produce up to 4mW power from flat sheet LSC emission light irradiance and 13.5mW from tubular LSC emission irradiance. Another major achievement of this project is that an integrated system has been designed, which has the ability to supply the power requirement entirely by itself.
Acknowledgements

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\( \alpha \): Material absorption coefficient
\( c \): The fluorescence molecules concentration of LSCs
\( C_{opt} \): Optical concentration ratio
\( C_{cyl} \): Cylinder LSC concentration ratio
\( C_{sq} \): Square-planar LSC concentration ratio
\( E \): Photon intrinsic energy
\( \eta_{abs} \): Absorption efficiency
\( \eta_{ER} \): External reflection efficiency
\( \eta_{host} \): Host material absorption efficiency
\( \eta_o \): Overall optical transmission efficiency
\( \eta_{trap} \): Trap efficiency
\( \eta_{PLQY} \): Photo luminescent quantum yield
\( \eta_{Stokes} \): Stokes shift efficiency
\( \eta_{self} \): Self-absorption efficiency
\( \eta_{TIR} \): Total internal reflection efficiency
\( G_{geo} \): Geometrical concentration ratio of LSCs
\( h \): Plank constant
\( H \): Height/Thickness of flat sheet LSCs
\( I_0 \): Incident beam intensity
\( I_T \): Absorption beam intensity
\( IR \): infrared light
\( K \): Absorption coefficient
\( l \): Thickness of the absorbing medium
\( L \): Length of LSCs
\( LSC \): Luminescent solar concentrator
\( \lambda \): Photon wavelength
\( n \): Refractive index
\( NIR \): Near infrared
\( N_s \): Proportion of s-polarized light in a composed light
\( N_p \): Proportion of p-polarized light in a composed light
\( R_T \): Total reflectance of the composed light
\( P_{TIR} \): Possibility of total internal reflection
\( P(x, y, \theta, \phi) \): Distance from incident point shadows on LSC cross sectional surface to the emitting point
\( R_s \): Reflectance of s-polarized light
\( R_p \): Reflectance of p-polarized light
\( R \): Tubular LSC outer radius
**r**: Tubular LSC inner radius

**S**: Collecting surface area of LSCs

**T**: Transmitted fraction

**θ_{esp}**: The boundary angle of internal reflection and escape cone refraction

*θ_{i, ϕ}*: Incident angles

**θ_{in}**: The angle of incidence ray with respect to the illuminated surface of LSC when the ray transfers towards LSC edge internally

**θ**: The relative angle between incident light and LSC surface

**W**: Width of flat sheet LSCs

*(*x,y)*: Emission location on an LSC cross-sectional surface
Chapter 1: Introduction

1.1 Solar Energy Outlook

As the original source of all other energy types on the planet, such as wind energy, hydro energy, or carbohydrate energy, solar energy has such advantages worthy of advancement: (1) The energy itself does not cost anything. (2) There is apparently no issue with over exploitation. (3) The photovoltaic reaction does not cause any pollution or emission (Page, 2005). Beyond that, the outlook of solar energy exploitation in the world has an optimistic tendency. Based on the statistic data released by several organizations and individuals, the global photovoltaic capacity has saw an increase in the last two decades, during this period the capacity has kept a double digit percentage increase for each single year, especially in 2014 and 2015, the growth rates are 28% and 33% respectively (Shahan, 2013) (Dincer, 2011). The costs of the procurement and installation have dropped sharply since the photovoltaic technology was put on the market. For example, in the United States countrywide, the average total cost of the photovoltaic modules dropped to 0.7 US$/W from 7 US$/W from 1995 to 2013 (M. A. Green, 2009). As for the generation quality, there is also an increase that reflects on the light to electricity efficiency index. According to a research report, for the multicrystalline silicon photovoltaic cell, the historical statistics of the highest efficiency reported to date gives such data: In December 1975, the efficiency of multicrystalline silicon photovoltaic cell was around 9% and reached 20.4% in May 2004 (M. A. Green, 2009). More than that, the mainstream view of the efficiency prediction is that the multicrystalline silicon photovoltaic efficiency will reach 25% by 2020 (M. A. Green, 2002).

In conclusion, the photovoltaic utilization has become mature enough to be used in practical applications, whether for large scale systems or small generation, and improvements of its quality and finance are still currently being made.

1.2 Solar Energy Concentrating Technologies Introduction and Comparison

As a branch of the solar energy utilizing technology, the concentrator photovoltaic (CPV) technology has also had a long history of development and improved gradually in the last two decades (van Sark et al., 2008). In general, there are two approaches to concentrate the solar radiation from the ambient culture geometric solar energy concentration (GSC) and luminescent solar energy concentration (LSC). For these two kinds of concentration methods, there are both similarities and differences. The basic operating rationale of the two technologies is the same: they are both trying to collect solar light from a large scale and then alter the light direction, and then the light will be received by PV modules at the focal spot. The key difference between LSC and GSC is that LSC can change the concentrated light spectrum wilfully, unlike GSC. GSC
concentrates the light mainly by using mirrors or lenses to reflect the light from a relatively large area to small area, and the received light spectrum will be the same as the solar irradiance spectrum because the process is independent of the photon wavelength. LSC can direct a big portion of diffuse light at an oblique angle in the solar light, but the GSC has a serious constraint for the incident angle, and thus it can only reflect direct light to the collecting point (A. Green, 2014). 

1.3 Luminescent Solar Concentrators

Luminescent Solar Concentrators (LSC) are an invention proposed as an equipment to absorb and concentrate the natural light. It was first invented by Weber and Lambe in 1976 (Weber & Lambe, 1976). The critical components of a LSC can be divided into two parts: host and guest molecular fluorophores. The host is the matrix of LSCs. It is usually a solid transparent organic polymer such as methyl methacrylate or acrylic. As for the fluorophore, it is the core component of the LSC as the concentration function of a LSC is achieved by the fluorophore absorbing, re-emitting, and directing the photons that are intercepted by the host material. The material of the fluorophore can be of various types, from organic to inorganic, or different colours caused by different molecular sizes. Thus, when sunlight illuminates the LSC at the main surface, a part of the light can be absorbed by the fluorophore particulates inlaid in the LSC, and direct the light towards the edges of LSC through total internal reflection. The highest light to electricity efficiency so far has reached 7.1% (van Sark et al., 2008). The light that emitted from LSC edges, which is generally referred to as an emission, can be used in various applications. For instance, it can be directly used as a light source, such as importing the light indoor to behave as daylighting systems, or integrate with building main bodies. It can

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**Figure 1** Left: Direct Photovoltaic system Middle: GSC reflection Right: LSCs concentration
also be integrated with solar panels and then behave like a light source when the emission is received by photovoltaic devices (Levichev et al., 2008) (Levichev et al., 2008) (Levichev et al., 2008) (Levichev et al., 2008) (Levichev et al., 2008) (Levichev et al., 2008) (Levichev et al., 2008) (Levichev et al., 2008). 

![Figure 2 Roof top LSC arrays used as day lighting source (Bornstein, 1984)](image)

In theory, introducing LSCs into a solar energy facility can increase the amount of light received by the photovoltaic modules and consequently increase the electricity output. Based on the experiment results obtained during the project, an optimal 10% enhancement of the PV output can be expected. Also, another advantage of the luminous technology is that the LSCs normally have relatively low market prices compared to photovoltaic cells. Thus, on the financial side, if the required power output amount is fixed; introducing LSCs into photovoltaic modules can reduce the total cost when compared with using photovoltaic modules alone. Moreover, almost all LSC products showed high reliabilities, stabilities, and lifetimes regardless of whether the LSCs are made up of organic material or inorganic chemicals, so they are feasible to be accompanied by photovoltaic modules and put under outdoor conditions over long periods.
Although the LSC technology has a long history of research, development, and usage, it has not played a leading role in the solar energy field because many loss mechanisms exist which limit the light to light conversion to 7.1% or below (van Sark et al., 2008). However, the LSCs can still be used for solar energy generation enhancement, as a secondary purpose. In aquatic cultivations of various kinds of microorganisms, the flurescent light is favoured. To get flurescent light, one valid measure is extracting visible light from sunlight, which is composed of ultraviolet light, visible light and infrared light. In this case, the LSCs are capable of providing visible light, meanwhile the rest of the light will be transferred to the end of the LSCs.
1.4 Microalgae Cultivation System

This project is aiming to design an integrated system that includes a microalgae cultivation system and a photovoltaic system. The microalgae cultivation, whether or not it is operated by phototrophic cultivation, heterotrophic cultivation, or mixotrophic cultivation, requires sufficient light illumination to obtain the highest growth rate. However, providing high intensity artificial light is not a wise option under economic considerations (Chen, Yeh, Aisyah, Lee, & Chang, 2011). In this case, the biological reaction is supposed to be illuminated by natural light during the day. Nonetheless, natural light has disadvantages compared to artificial light. First, sunlight illumination is variable due to climatic factors. Moreover, if the sunlight illuminates the microalgae and culture medium directly, the UV and IR light contained in the full solar spectrum is undesired and will cause a negative impact on the cultivation yield (Vadiveloo, Moheimani, Cosgrove, Bahri, & Parlevliet, 2015). Thus, considering all of the above conditions, to inject sunlight only within the visible light spectrum is a good option, which can remain low in cost and high in productivity at the same time. The goal is in alignment with the LSC performance, which is the conditional transparency performance determined by the photon wavelengths. Therefore, the LSCs in such a case can provide at least two duties: Firstly, the emission from the LSC edge is anticipated to irradiate photovoltaic cells; Secondly, the spectrum depended transmittance characteristic of the LSC can benefit artificial microorganism propagation, which requires elaborate sifted fluorescence for the growth of microorganisms.
1.5 Aims and Objectives

The key interest is to use LSCs to split the sunlight spectrum between two purposes, one is aiding the microalgae propagation and the other is aiding the photovoltaic generation. In addition, the majority of the project will be focusing on the photovoltaic generation part analysis, which suits the operator’s bachelor major. The analysis started with theoretical knowledge, which is mostly based on literature research. Then, the experiments were implemented and are meant both to have critical results and enhance the understanding of LSCs; finally, the last aim of the project is to conceive an LSC-PV integrated system with detailed values and give an approximate evaluation.

1.6 Thesis Structure Overview

This section will generally describe the whole structure in the subsequent chapters. In the next part, background analysis will be presented to attest the experiment results and the design basis. To be specific, Chapter 2 will focus on eight major loss mechanisms of LSCs because the optical losses are the most important factors to influence the LSCs concentrating ability; Then, the loss magnitude associated with the physical geometry of LSC products will be introduced and compared in Chapter 3. After that, Chapter 4 will focus on the experiment in practice throughout the project, all experiment will be categorized into three types. The first one is the optical concentrating abilities of different LSCs, the second one is the electrical tests of the sample photovoltaic module when different LSC products are emitting upon it and the last one will be looking at several influential side factors when the designed system is put in practical use, such as the outdoor temperature level of elements in the system, hourly and seasonal influences and so on. Finally, the result and conclusion section will be drawn to end the experiment chapter.

In Chapter 5, based on all the information from literature reference and experiment results, a theoretical integration system will be designed and the details of the elements of the system will be specified. For each element, at least one market product will be selected to exemplify how to properly construct the integrated system.

In Chapter 6, conclusions will be provided to summarize the results obtained. Moreover, based on these experiences, estimated measures will be given to increase the efficiency of LSCs and the integrated system design. Finally, there will also be brief recommendations for future work.
Chapter 2: Loss mechanisms

2.1 Introduction

During the light processes transmitting in an LSC, there are at least eight loss mechanisms to resist the incident beam intersecting across the path and reaching the LSC edge to emit. This chapter will introduce each mechanism and the factors that differentiate their magnitude, as well as discussing the measures to reduce those losses and consequently improve the overall emission efficiency. For those loss mechanisms which are impacted by the physical geometry and dimension factors, the relevance of the loss mechanism and the geometrical factors are arranged in the subsequent Chapter 3 for consistency of presentation.

Because the theories in some sections of this chapter are considerably related to optical micromechanism knowledge, such as molecular and quantum reactions, some of them cannot be explained to a comprehensive level within the thesis scope. Moreover, the light is complicated to deal with if it is from the sun because sunlight is composed of direct light and diffuse light, of which properties will be changed from time to time; therefore, it does not always suit the calculations based on the property of the light on microcosmic perspective. However, experimental outcomes gained by other scholars will be quoted, and they will integrate some descriptive contents and the formulae to discuss the loss quantification.

The overall optical efficiency of the LSCs \( \eta_o \), is defined as the fraction of the incident light which emits from the edge after sustaining all kinds of losses. Goetzberger developed an equation which can calculate \( \eta_o \) approximately, and it is expressed as:

\[
\begin{align*}
\eta_o &= \eta_{ER} \eta_{trap} \eta_{abs} \eta_{PLQY} \eta_{Stokes} \eta_{host} \eta_{TIR} \eta_{self} \\
(\text{Goetzberger & Wittwer, 1981})
\end{align*}
\]

Where:

- \( \eta_{ER} \) is the proportion of the light photon energy amount reflected from the external surface;
- \( \eta_{trap} \) is the trap efficiency of total internal reflection, which is 100% minus the possibility of the escape cone loss occurrence;
- \( \eta_{abs} \) is the absorption efficiency, which is the proportion of photons of a specific wavelength range that can be absorbed by LSCs;
- \( \eta_{PLQY} \) is the photo luminescent quantum yield efficiency, and it is a rate aims to compare the emitted photons and the total photons absorbed by fluorescence molecules;
- \( \eta_{Stokes} \) is the efficiency used to express the energy decrease when an absorbed photon turns into emitted photon;
- \( \eta_{host} \) is the host absorption efficiency, and its value represents the amount of light absorbed by the host material;
\( \eta_{\text{TIR}} \) is the total internal reflection efficiency, which quantifies a tiny amount of photons that would be scattered by the contamination or moisture droplets;

\( \eta_{\text{self}} \) is the self-absorption efficiency, which is used to consider the light photon losses in the re-absorption phenomenon from the previous fluorophore molecule to another fluorophore molecule.

Before detailed explanations, table 1 quoted measurement results and estimations of the overall efficiency and all sub-efficiencies from GoetzBerger's publication in 1981. The testing objective is a 40cm×40cm×0.3cm slab LSC object, and with natural light perpendicularly irradiating upon it.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_{\text{ER}} )</td>
<td>96%</td>
</tr>
<tr>
<td>( \eta_{\text{trap}} )</td>
<td>75%</td>
</tr>
<tr>
<td>( \eta_{\text{abs}} )</td>
<td>20-30%</td>
</tr>
<tr>
<td>( \eta_{\text{PLQY}} )</td>
<td>95-100%</td>
</tr>
<tr>
<td>( \eta_{\text{Stokes}} )</td>
<td>75%</td>
</tr>
<tr>
<td>( \eta_{\text{host} + \eta_{\text{TIR}}} )</td>
<td>90-95%</td>
</tr>
<tr>
<td>( \eta_{\text{self}} )</td>
<td>75%</td>
</tr>
<tr>
<td>( \eta_{\text{o}} )</td>
<td>7-12%</td>
</tr>
</tbody>
</table>

2.2 External reflection and External Reflection Efficiency \( \eta_{\text{ER}} \)

External reflection is one of the loss mechanisms due to the reflection that occurs at the interface of two mediums when the light enters the second medium from the original medium. Based on the Fresnel equation (See Appendix A), the light reflectance quantity is determined by such factors: the percentage share of two polarization types in a light, the irradiance angle \( \alpha_i \), and refractive index \( n \) and so on. To be specific, the light polarization that composes a ray has two kinds: s-polarized and p-polarized. They are perpendicular and parallel to the \( \alpha_i \) respectively, and therefore they require different trigonometric functions to calculate the reflection rates. For natural light, it is made up of half polarized and half unpolarised light. The equation to calculate reflection amount for two polarizations and the total reflection of the compound light is appended in Appendix A due to the thesis length limit.
The incident angle $\theta_i$, is the angle between the incident ray of light and a line normal to the surface, which is annotated in Appendix A. With the incident angle increase from 0°, which is equivalent to vertical illumination, to 90°, which is equivalent to horizontal illumination, the reflectance percent will increase. However, more than the relative angle between the light source and the irradiated objective will make a difference on incident angle, the interface of two mediums also plays an important role to determine the incident angle. This factor will be explained in Section 3.3.1 since it is a geometry factor that influences the LSC.

As the graph in Figure 6 shows, the reflectance rate of unpolarised light increases when the incident angle increases from 0 to 90°.
As for the refractive index $n$, it is related to the medium's own characteristics. The refractive index of air is 1 while the refractive index of an LSC is usually approximated to $n_2 = 1.5$ due to the materials used.

### 2.3 Trapping Efficiency $\eta_{\text{trap}}$ and Escape Cone Losses

The trapping efficiency $\eta_{\text{trap}}$ is the parameter to express the ability of products to hold the light that satisfies the absorption wavelength range of the fluorophore inside the LSC. In some literature, it is also named as the possibility of total internal reflection $P_{\text{TIR}}$. To quantify this parameter, it shall be started with the escape cone loss calculation. It opposes the trap efficiency, which is the parameter to express the percent of the light that would depart from LSC internally.

Escape cone loss is a significant loss mechanism caused by the re-refraction effect after the photons refract into LSCs and during the intersection in LSCs. In other words, when rays move toward the edge of LSCs by total internal reflection on the LSCs internal surface, a portion of the photons would leave the LSC. It is because when the LSC fluorophores trap parts of light waves from a beam of light, the trapped light would be re-emitted in random directions by fluorophores and the angle it hits the internal surface will determine if the light wave escapes. In theory, the light wave escapes when the incident light angle with respect to the material surface, $\theta_{\text{ph}}$, is smaller than the escape verge angle $\theta_{\text{esc}}$. The last angle $\theta_{\text{esc}}$ is quantified by the division of the refractive indexes of the optically dense medium and the optically thin medium. Figure 7 indicates the situation that two beams of light are both trapped by the fluorophore but one of them returns...
to the air, and the other one moves to the cuboid end because they meet the LSC boundary at different angles.

![Diagram of LSC](image)

**Figure 7** Schematic of the incoming light absorbed by a luminophore, and two possible emitting directions that lead to escape cone loss and total internal reflection, respectively (McDowall, Butler, Bain, Scharnhorst, & Patrick, 2013)

In the simplified calculation of the escape cone loss, the magnitude of escape cone losses is only related to the refractive index of the LSC host material. To be specific, LSCs composed of a high refractive index material are better than those with a low index one. The escape cone loss will decrease when projection angle $\beta$ increases. (The schematic is shown in Appendix B) In conclusion, the escape cone loss can be minimized to: $f_{\text{esc}} = 1 - \sqrt{1 - n^{-2}}$, and can be up to: $f_{\text{esc}} = 1/n$. So, if $n=1.5$ is used, $\eta_{\text{trap}}$ of a cylindrical LSC can be from 33-74%, which depends on the emission location, and the further it occurs to the cylindrical axis, the larger $\eta_{\text{trap}}$ is.

For a flat sheet LSC, the escape cone loss is no longer influenced by the emission location and incident angle factors, but only related to the refractive index of the material, and the equation becomes: $f_{\text{esc}} = 1 - \sqrt{1 - n^{-2}}$

If a more accurate calculation is required, the shape and dimensions of LSCs should also be considered to influence the escape cone loss percentage and trapping efficiency. The further discussion of the geometrical factor influencing escape cone losses is available in **Section 3.3.2**.

### 2.4 Absorption Efficiency $\eta_{\text{abs}}$

The absorption efficiency $\eta_{\text{abs}}$ is an essential factor because the absorption is the precondition of the end edge emission. Statistically, it cuts down the irradiance light towards emitting to PV modules more than any other loss decrements. Once the light photons transmit into a LSC, generally there are only two paths despite the continuation waste: they would either be absorbed by the dye fluorophore among the host material or transmit through the host material. Therefore, improving the absorption ability of LSCs is the foundation and the core options to reinforce the LSCs emission performance. The absorption efficiency is defined as the integral of the absorbed spectrum $S_{O(\lambda)}$, to that of the initial source light spectrum $S_{\text{sum}(\lambda)}$ (Pedrotti & Pedrotti, 1993). To calculate $\eta_{\text{abs}}$, Beer-Lambert law shall be used:
\[
\eta_{abs} = \frac{I_0}{I_t} = -\log_{10} \frac{I_0}{I_t} = \log_{10} \frac{1}{T} = K \cdot l \cdot c
\]

Where \( I_0 \) is the incident beam intensity, in the unit of W/m\(^2\)·nm\(^2\);
\( I_t \) is the absorption beam intensity, in the unit of W/m\(^2\)·nm\(^2\);
\( T \) is the transmitted fraction;
\( K \) is the absorption coefficient, in our case the unit takes \( dm^3 \cdot g^{-1} \cdot cm^{-1} \);
\( l \) is the thickness of the absorbing medium, in the unit of cm;
\( c \) is the fluorescence molecules concentration of LSCs, in the unit of g/dm\(^3\).

There are three approaches to enhance the absorption spectral efficiency.

One approach is to extend the fluorescence molecule absorption spectral range. To be specific, the absorption spectral range of the LSCs can be extended by diversifying the product pigment types. Including a range of dyes in the same LSC product can dramatically extend the absorption gross. The theory that supports this idea is: adopting multiple fluorophore types can enlarge the absorption range to the summation of each unique absorption range. Graph 1 quoted from double layered plasmonic thin-film luminescent solar concentrators based on polycarbonate supports, 2014 give the absorbance spectrum for four special organic dyes, and the mixture dyes composed by the same four dyes (El-Bashir, Barakat, & AlSalhi, 2014). As the idea is given by Zewail, the multidye LSC can cover 70% at most of the solar spectrum. It is vastly superior to single organic dye selection, which only absorbs 20-40% photons on the total solar spectrum (Batchelder, Zewail, & Cole, 1981).
Secondly, for the matrix with the same type of pigment, increasing the pigment concentration is also able to increase the absorbing ability. Moreover, unlike the dye diversification method, it does not vary the absorbing range. Graph 2 shows the absorption intensity of the light spectra for six LSCs objectives, of whose dye pigments have the same quality but different quantity (Batchelder et al., 1981).

![Graph 2 Metal-enhanced fluorescence of PTLSC films at different AuNPs concentrations (AM 1.5 Spectrum) (El-Bashir et al., 2014)](image)

Thirdly, $\eta_{\text{abs}}$ can be reinforced by increasing the thickness of LSCs. Based on the Eq 2.2, the $\eta_{\text{abs}}$ increases in proportion to the thickness. However, enlarging the product thickness is not recommended as a sufficient measure to increase the absorbance of the LSC because it also affects other loss quantities negatively. More than that, there are manufacturing issues to limit the LSC’s thickness, and therefore most market products are about 0.5 cm thick.
Table 2 The PV cell performance for the same LSCs in different thickness (Al-Hamdani, Ibrahim, & Alrda, 2015)

<table>
<thead>
<tr>
<th>Sample Thickness (mm)</th>
<th>P_max (mW)</th>
<th>V_max (V)</th>
<th>I_max (mA)</th>
<th>Eff%</th>
<th>FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>175.3</td>
<td>6.376</td>
<td>27.50</td>
<td>7.013</td>
<td>0.873</td>
</tr>
<tr>
<td>0.5</td>
<td>178.9</td>
<td>6.579</td>
<td>27.20</td>
<td>7.157</td>
<td>0.866</td>
</tr>
<tr>
<td>1</td>
<td>183.0</td>
<td>6.560</td>
<td>27.90</td>
<td>7.320</td>
<td>0.805</td>
</tr>
<tr>
<td>1.5</td>
<td>192.3</td>
<td>6.678</td>
<td>28.80</td>
<td>7.693</td>
<td>0.922</td>
</tr>
<tr>
<td>2</td>
<td>169.8</td>
<td>6.519</td>
<td>30.2</td>
<td>7.874</td>
<td>0.852</td>
</tr>
<tr>
<td>2.5</td>
<td>201.4</td>
<td>6.356</td>
<td>31.70</td>
<td>8.059</td>
<td>0.832</td>
</tr>
<tr>
<td>3</td>
<td>195.6</td>
<td>6.611</td>
<td>29.6</td>
<td>7.827</td>
<td>0.900</td>
</tr>
</tbody>
</table>

2.5 Photoluminescent Quantum Yield Efficiency $\eta_{PLQY}$

Photoluminescent quantum yield efficiency $\eta_{PLQY}$ is a ratio of the emission photons amount to the total absorbed photons amount. It can also be named as Quantum yield efficiency or fluorescence quantum efficiency. It determines what percentages of the light photons which have already been captured by dye molecules will be decay. The number difference between the absorbed photons and emitted photons is caused by vibrational relaxation. The formula 3.3 expresses the calculation for $\eta_{PLQY}$:

$$Eq3.3: \eta_{PLQY} = \frac{\# \text{ Photons emitted}}{\# \text{ Photons absorbed}}$$

$\eta_{PLQY}$ is one such parameter that can produce a formula that involves the main influential factors but is very complex. Instead, it can still be analysed by observing the measurement outcomes or measures to optimize it in practice. Firstly, the $\eta_{PLQY}$ is unique for every single dye material type, regardless of the emission spectral range; Secondly, if the dye material is fixed to be the same type, such as organic fluorephores, the quantum yield loss become larger and larger with the increase of the dye molecules’ peak emission wavelength. For organic dye dotted LSCs, the visible emitting dyes normally have near unity quantum yields, but the $\eta_{PLQY}$ drops largely when the emission spectrum reaches and exceeds near infra red range (NIR) spectral range, which is around 700nm (Zastrow, 1994).
2.6 Stokes Shift and Stokes Efficiency $\eta_{\text{Stokes}}$

Stokes shift is defined as the difference between the peak value of the intrinsic absorption spectra and emission spectra of one type of material. When the material absorbs photons that match the absorption spectra range itself, to release the photons and the energy, it will divert the photons wavelength to move forward from absorption spectra to the emission spectra. During this process, the vibrational relaxation will happen on the molecules and the Stokes efficiency $\eta_{\text{Stokes}}$ is used to indicate the absorption-emission converting efficiency of fluorophores.

Since the absorbing wavelength range is always ahead of the emission wavelength, the process of the conversion from absorption to emission always releases energy. The idea can be proven by the equation related to photon energy $E$ and wavelength $\lambda$:

$$E = \frac{hc}{\lambda}$$

Where $h$ is the Plank constant, and it takes $4.135667662 \times 10^{-15}$ EV*s in this case;
$c$ is the speed of light, and it takes $3 \times 10^8$ m/s;
$\lambda$ is the wavelength of the photon.

Based on the Eq2.4, it is clear that the energy of a light photon is inversely proportional to wavelength. In this case, organic dyes are superior to inorganic dyes because of the Stokes shifts of organic molecules are much narrower than that of inorganic dyes. A measurement of one rare-earth complex molecule which is designated as “MO49” is a persuasive example. As shown in Graph 4, for MO49, the absorption spectra peak

Graph 3 Quantum yields of organic dyes versus peak emission wavelength (Zastrow, 1994).
is around 300nm, but the emission spectra peak is about 620nm; thus the Stokes shift is about 300nm, which is too large to be adopted as an LSC. In this case, it will cut about 50% photon energy down to complete the conversion from absorption to emission (Werts, Jukes, & Verhoeven, 2002).

To contrast, the Stokes shift of majority organic dyes is from 10nm to 50nm, which is tiny if compared with the peak magnitude their absorption and emission spectra (Wilson, 2010). For instance, a dye named BASF Lumogen F Orange 240, its Stokes shift is about 10nm, and consequently, it comes with high $\eta_{Stokes}$ value. In approximate calculation, the $\eta_{Stokes}$ value is default to be 75%, which is referenced by Goetzberger’s publication in 1981 (Goetzberger & Wittwer, 1981).

Graph 4 Absorption and emission spectra of Lumogen F Orange 240 dye (Wilson, 2010).

2.7 Host Absorption and Host Absorption Efficiency $\eta_{host}$

Host absorption is another major loss mechanism, and as the name implies, the loss is related to the host material of LSCs. Although the material that has been used to construct LSC by far covers a few kinds (such as polymathic methacrylate, Plexiglas, Lucite, and so forth), all these available material options have a similar organic microstructure and optical transparency performance. They would more or less absorb light photons due to harmonic reactions that occur on the molecular perspective, or mutual vibrations occur in atomy bonds. The host absorption is negligible if it occurs in the visible light under 700 nm waveforms but become
significant for the NIR spectrum and IR spectrum cases and NIR is the absorption spectrum of the organic material that has been vastly adopted as LSCs host material (Wilson, 2010).

The magnitude of host absorption is determined by such factors as the emission locations \((x, y)\), the incident angles \((\theta, \varphi)\), the material absorption coefficient \(\alpha\) and the particular distance from incident point to the emitting point \(P(x, y, \theta, \varphi)\) (McIntosh, Yamada, & Richards, 2007). Eq 2.5 reveals the calculations of host absorption in different situations:

\[
\eta_{host} = \frac{2\int_0^{2\pi} \int_0^\pi (1 - \exp(-\alpha P(x, y, \theta, \varphi))) \sin \theta \, d\theta \, d\varphi}{4\pi \cos(\theta_c)}
\]  

(McIntosh et al., 2007)

For a cuboid shape material, the distance between the emission points to the nearest edge \(P(x, y, \theta, \varphi)\) normally has four solutions, depending on which one cross-sectional rectangular side out of four is the closest to the emission point, the detailed explanation is in Appendix B.

In practice, there are three controllable mechanisms to reduce the host absorption:

1. Set the light source illuminates to the LSCs at a particular angle to maximum integral of the \(\theta_c\), the numerator in Eq2.5. However, it is quite complex to analyse because it involves uncontrollable indexes and some of them are interactional. Moreover, the light locating can only be operated when the light is an artificial light source, which is contradictory to the project initial direction.

2. Keep the emission wavelength of the fluorophore molecules within visible spectra. For the most organic material, harmonics and overtones of the C-H and C-O bond vibrations in the molecule will cause poor transparency for the input light photons with wavelength over 700nm. A measurement of the transparency of the acrylic product can prove the hypothesis. When the purely PMMA material without fluorophores doped is put under the various fluorescence light illumination, different fluorescent light shows the different attenuation based on light spectra. For the visible fluorescent light, the PMMA absorbs 0.1% light per centimetre on average; For the 800 nm fluorescent light, the value jumps to 0.4% per centimeter, and 3.2% for the 1000 nm infrared light (Correia, Lima, André, Ferreira, & Carlos, 2015). In conclusion, regardless of the host material types, the most efficient method to avoid high host absorption is to prevent taking VIR and IR emission (Ballato, Foulger, & Smith Jr, 2004) (Kaino, Fujiki, Oikawa, & Nara, 1981).

3. Adjust the shape and dimensions of LSCs to meet the minimum host absorption magnitude. Unlike most other loss mechanisms, host absorption is highly related to the geometrical factors of the LSCs, which includes the length, cross-sectional surface dimensions, etc. All above factors can more or less change the magnitude of \(P(x, y, \theta, \varphi)\), thereby they will change the host absorption efficiency \(\eta_{host}\) based on Eq 2.5. In general, a LSC sized at a thinner thickness and shorter length absorbs less light with its host material than a
thicker and longer one if one assumes that the two LSCs are only different in physical dimensions. The
detailed explanation about the geometrical factor influence is in section 4.3.3.

2.8 Total Internal Reflection Efficiency $\eta_{TIR}$

The total internal reflection efficiency $\eta_{TIR}$ is a factor aimed to put the imperfection characters of the LSC
material into consideration. In a realistic situation, in LSC products manufacturing, grains would be more or
less mixed into the product, and those grains will block the emission path and then reflect photons if the
absorbed photons hit them. More than the grain impurity, the roughness factor, regardless of the roughness
on inner LSC or exterior LSC can also reflect the photons out of a LSC. There are some other potentials such
as bead or frost brought by various ambient climates and so on. Hence, the total internal reflection efficiency
$\eta_{TIR}$ is introduced to consider the influence of practical factors and manufacture tolerance, and because of
that there has no method to calculate the summary of the internal reflection losses so far. However, it can
be obtained by measurement at a very high accuracy level. Based on a few reference documents, for PMMA
material with tiny surface, the total internal reflection waste for one single generation except considering
the reiterative TIR caused by re-absorption, is assumed to stay at 0.02%, so $\eta_{TIR}$ is 99.98%. In addition, if a
 photon has the wavelength that lies within the mutual spectrum of the material absorption and emission
spectra, the $\eta_{TIR}$ might be a lot larger than 0.02% of the total light, for example, if the photons get five
hundred times re-absorbed, then $\eta_{TIR}$ will be $(1-0.02\%)^{500} = 90.48\%$ (Thomas, Drake, & Lesiecki, 1983).

2.9 Self-Absorption and Self-Absorption Efficiency $\eta_{\text{self}}$

Self-absorption is a loss mechanism caused by the spectrum shift between absorption and emission. Self-
absorption happens on light photons in the absorption and emission mutual spectra of LSCs, the photons
absorbed by the dye molecule within this mutual range have a high possibility to be re-absorbed by another
dye molecule (Dienel, Bauer, Dolamic, & Brühwiler, 2010; Earp, Smith, Swift, & Franklin, 2004; Wang et al.,
2013). After that, the light photons got re-absorbed might be re-emitted by the subsequent molecule,
otherwise, leave the LSCs or be dissipated due to the escape cone loss, quantum yield losses, and total
internal reflection loss(Olson, Loring, & Fayer, 1981; Sansregret, Drake, Thomas, & Lesiecki, 1983). For those
photons that have successfully being reemitted, the process will then be repeated a lot of times, depending
on the dye fluorophore concentration and transmission distance. For most of the cases, the fraction of the
residual photons is nearly zero after ten reabsorption generations around; the table 3 shows a fraction of
photons that remains after each reabsorption generation from measurement results taken by a cylindrical
LSC dyed Red 305 with nonunity quantum yield ($\eta_{PLQY} = 80\%$) (Otmar, Hooning, & van der Kolk, 2014)
Table 3 Emitted fem, lost via escape cones fesc, absorbed fabs, and transmitted to the LSC-PV interface ftrans with respect to the initial number of absorbed photons (Otmar et al., 2014)

<table>
<thead>
<tr>
<th>$i$</th>
<th>$f_{em} (%)$</th>
<th>$f_{esc} (%)$</th>
<th>$f_{abs} (%)$</th>
<th>$f_{trans} (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80.0</td>
<td>20.4</td>
<td>52.7</td>
<td>6.9</td>
</tr>
<tr>
<td>2</td>
<td>42.2</td>
<td>10.7</td>
<td>27.7</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>22.2</td>
<td>5.7</td>
<td>14.6</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>11.7</td>
<td>3.0</td>
<td>7.7</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>6.2</td>
<td>1.6</td>
<td>4.1</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>3.3</td>
<td>0.8</td>
<td>2.2</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>1.8</td>
<td>0.5</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
<td>0.3</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>43.0</td>
<td></td>
<td>14.6</td>
<td></td>
</tr>
</tbody>
</table>

There are three factors which can influence $\eta_{self}$ efficiently of a LSC, which are the dye concentration, fluorophore absorption-emission overlapping, and the quantum yield.

As Graph 2 and Graph 5 presented, the absorption spectrum of the LSCs with the fluorophore dye in the same qualities but different quantities will have a similar tendency but different magnitudes of the absorption spectrum, therefore, the various dye concentrations will cause a different overlapping area between absorption and emission spectrum. Consequently, less dye concentration will lead to less emitted photons to reabsorption.
Graph 5  Absorption spectra (percent absorption vs. wavelength) at PbSe QD solution concentrations of 0.35 
µM, 1.1 µM, 5.3 µM and 39.6 µM and emission spectrum (normalized PL intensity VS wavelength) of PbSe QDs in a
5mm thick container (Wilton et al., 2014).

The second factor that can make a difference to $\eta_{self}$ is the quantum yield of the material. As the content in 
section 3.6 stated, in a nonunity LSC material, there is a gap between the number of absorbed photons and 
emitted photons, and it will also affect the number of photons emitted in generation i+1 from absorbed 
photons in generation i (Otmar et al., 2014).
Graph 6 Self-absorption efficiency VS PbSe QD concentration© for simulated 300*300*2.5mm3 LSCs with c ranging from 0.1 to 50uM and ηPLQY=0.40 and 0.80 (Wilton et al., 2014).

In conclusion, the most favourable LSCs to increase $\eta_{self}$ should be high quantum efficiency and low dye concentrations. The detailed qualifying is too complex and has been omitted in the thesis, yet the value is: for an organic dyed LSCs, the $\eta_{self}$ values fluctuate from 40-80% depend on the dye concentration and quantum yield (Otmar et al., 2014).
Chapter 3 Geometrical factor

3.1 Introduction

When considering the choice of the outline shape of LSCs, there are at least three options that are compatible with small size PV modules, which are the flat sheet, solid cylinder, and hollow cylinder. However, to consider the integration of microorganism cultivation, for those designs in appropriate sizes, the hollow cylindrical shape is the only possible choice to provide a sealed void for microorganism to grow in a liquid culture medium. The analysis of the geometrical factor of LSCs in this chapter goes a further step to prove that a hollow cylinder is superior to the flat sheet and solid cylinder for collecting and concentrating beam. There are two reasons; One is the empty configuration obviously would have a larger outer size than a solid configuration if their host material volumes are the same, which means the former would intercept more light from ambient culture. Secondly, a hollow cylinder LSC can make the beam stay away from its central axis because all geometry related loss mechanisms show the same trend: the light that intersects in the fringe of the LSCs would lose less of a portion of the light than it of the light that intersects in the centre.

3.2 Geometrical Concentration Ratio $G_{geo}$

Except a few means discussed in the former chapter to lower each loss mechanisms magnitude, making the LSCs material in a better use by optimising its geometrical concentration ratio is another approach to improving the optical concentrating efficiency. To analyse the shape factors to impact the area for light collecting, here we introduce a coefficient, geometrical concentration ratio $G$, which represents the ratio between the light collection area and light emission area. Therefore, the ratio can be written as:

$Eq \ 3.1: \ G_{cyls} = \frac{2RL}{\pi R^2} = \frac{2L}{\pi R}$,

Which shall be used for solid cylindrical LSC/LSCs, where $R$ represents the radius of the cylinder, and $L$ represents the length of LSCs.

$Eq \ 3.2: \ G_{sq} = \frac{LW}{HW} = \frac{L}{H}$

Which shall be used for flat sheet LSC, where $L$, $W$, $H$ represent the length, width, and height of the LSC respectively.

$Eq \ 3.3: \ G_{h cyls} = \frac{2RL}{\pi (R^2-r^2)} = \frac{2L/R}{\pi (1-\frac{r^2}{R^2})}$

Which shall be used for hollow cylindrical LSC/LSCs, where $L$, $R$, $r$ represent the length, outside radius, and inside radius respectively.
To put the above three geometrical concentrating ratios in comparison, it is worthwhile to unify the emission area and the host material volume of the above three analysed LSC shapes to be the same value and then rank their light collection surface area to compare their concentration abilities.

Assume there are three LSCs manufactured in flat sheet, solid cylinder, and hollow cylinder respectively, and their dimensions are:

<table>
<thead>
<tr>
<th>Table 4 Three shapes LSC dimension label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Bottom surface length/radius</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Bottom surface Area</td>
</tr>
</tbody>
</table>

Then the light collecting areas of LSCs become:

<table>
<thead>
<tr>
<th>Table 5 Light receiving surface area comparison of three shapes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
</tr>
<tr>
<td>Lateral cross-sectional surface length $L_L$</td>
</tr>
<tr>
<td>Lateral cross-sectional surface area $S_L$</td>
</tr>
</tbody>
</table>
In conclusion, for LSCs to have the equal length and light emission area, a hollow cylinder always has a larger $G_{geo}$ value than a solid one; if the thickness of the flat sheet is smaller than the given value, which is $H_f < \frac{R}{2}$, which occurs in almost all partial cases, the geometrical concentration ratio of the cylinder LSC is going to be larger than flat sheet as well.

### 3.3 Loss Mechanisms Impacted by the Geometrical Differences

In this section, three loss mechanisms are brought up again to analyse each of their values with the effect of geometrical difference. To be specific, they are external reflection, escape cone loss, and host absorption because all above three loss mechanisms are highly related to the LSCs’ shape, size, and empty factors and so forth. There are three general factors that can influence the LSC contracting ability, which are the relative incident angle, length, and distance from emission location to the central axis of the LSCs cylinder.

#### 3.3.1 External Reflection

As the content in Section 3.3, the external reflection is influenced by the incident angle $\alpha$, but the light receiving surfaces of LSCs can make the relative incident angle to be different. For a curved surface, the shape of the illuminated object is also an important factor. For example, the incident angle between the curved face of the cylinder LSCs and a light ray is going to be larger than the incident angle between a flat surface in the same physical position and the same directed light ray. Moreover, if the circular radius of the cylinder increased, $\theta_i$ would also increase. In summary, generally speaking, a flat surface is superior to an uneven surface on minimizing the external reflection.

Based on a study published in 2007, when the sunlight perpendicularly illuminates on flat glass or plexiglass, and the refraction index of the illuminated objective follows a default value of 1.5, the external reflection rate follows the common value of 4.0% (McIntosh et al., 2007). For one single cylinder product, the rate can
be increased to a maximum of 8% because the cylinder wall enlarges the gradient between light and receiving surface, which is equivalent to the incident angle increase. However, if a few cylinders can be put in the same orientation and they cling to each other with little gaps, such as the configuration shown in Fig 9 the external reflection would decrease. Around 2% of the irradiation reflects back to the air for a two cylinder array, and one thousandth for the three cylinder case, and nearly zero for four cylinder array or above.
3.3.2 Escape cone magnitude with Geometrical Influence

As mentioned in Section 2.4, to calculate the escape cone loss more accurately, the calculation should involve the geometrical factors of LSCs. For a cylindrical LSC, the magnitude of escape cone losses is affected by geometrical factors greatly. Firstly, the more the emission location approaches the cylinder circle centre axis, the more losses emerge. Secondly, the escape cone losses get larger when the angle $\beta$ increases, and $\beta$ is the angle between the ray path projection on the cylinder bottom circle and the bottom circle axis that overlaps the incident dot. To calculate the proportion of light that escapes $f_{esc}$ from an infinite cylinder LSC,
if the emission is assumed to be isotropic, the below equation can derive the loss percent (McIntosh et al., 2007):

$$\text{Eq4.1: } f_{esc} = \frac{1}{\pi} \sqrt{\frac{n^{-2} - (\frac{r}{R})^2 \sin^2 \beta}{1 - (\frac{r}{R})^2 \sin^2 \beta}} d\beta$$

As Figure 10 shows, on one cross section surface of a hollow cylinder LSC, beams were captured by fluorophores at different points on the tube wall and caused different distances from the emission point to the central axis. The equation 4.1 draws the conclusion that if all other factors are unchanged, the escape cone losses will increase with the emission location approaching further to the cylinder central axis.

Figure 10 Schematic of the bottom cross sectional area and emission location A, B, and respective radius to the centre.
Graph 8 Escape fraction trend with changes of the relative emission location, r/R (McIntosh et al., 2007)

3.3.3 Host Absorption

As stated in the former Section 2.8, the host absorption is related to the dimension of the LSCs. Thus, in this section, the geometrical influence on host absorption will continue to be presented, and there will be some measurement data quoted and concluded in statistical chart format.

As Graph 9 shows, the length of LSC is the most essential for the host absorption efficiency regardless of whether the LSC is forged to a flat sheet or cylinder. Secondly, the host absorption will slightly vary if the emission paths have different distances to the closest host verge. If the route of emission is in the centre of the cross-sectional surface, the host material will absorb more photons than if the emission path is closer to the fringe.
Graph 9 Host absorption in a cylindrical LSC when luminescence occurs at the surface (Solid symbols) and the cylindrical axis (empty symbols) as a function of position $x$ and absorption coefficient $\alpha$ normalised to the LSC length $L$ (McIntosh et al., 2007)

3.4 Optical concentration ratio $C_{opt}$

To add the loss mechanisms influence in the analysis and obtain the overall concentration ability, another parameter is worth introducing. Optical concentration $C_{opt}$, which can be calculated by the equation:

$$Eq\ 3.3: C_{opt} = G_{geo} \ast \eta_o$$

The geometrical factor index $G_{geo}$ is traceable in the former section 3.2, and the overall efficiency $\eta_o$ is in Eq 3.1.
Based on the research and reference literature, the conclusion can be drawn in such a way: If the host material amount that used to construct an LSC is fixed, a hollow cylinder shape can accumulate and concentrate more light for emission than a solid cylinder, and hollow cylinder shape accumulates and concentrates more light for emission than a flat sheet if their lengths are below $1/(100 \times \alpha)$ meters which is about ten meters; or their concentrating abilities are equal if the two products length exceed $1/(100 \times \alpha)$ meters.
Graph 11 Host absorption in a cylindrical LSC for luminescence at the surface (r=R) and the cylindrical axis (r=0), in a square-planar LSCs as a function of the absorption coefficient normalised to the LSC length. (McIntosh et al., 2007)
Chapter 4 Experiment Measurement and Analysis

4.1 Introduction

This purpose of this chapter is to describe and conclude a few essential measurements that have been performed throughout the experiment’s period. During the whole project, two batches of LSCs were gained and tested, they are both made from acrylic mixed with fluorescent dye material in different colours. One batch was shaped as a flat sheet while the other is a hollow tube with open ends. At the planning stage when the project commenced, a few parameters associated with the LSCs performance were measured and the experiment implementation methods were conceived. Generally, the experiments can be divided into three kinds, which depend on the anticipated results: The optical quality measurement, the electricity factor measurements, and the outdoor environmental measurements. The optical measurements are significant since the transmission and emission distribution of sunlight is one of the most important factors to influence the system performance, which reflects both on the photovoltaic generation and microalgae production. The electricity measurements will provide useful information to the photovoltaic system design by showing the electricity power output directly from the experiment. Although the measurement objectives had always been operated at very tiny sizes that are only up to 30 mW, it still can be useful because the operators have taken cautious care to guarantee the measurement accuracy and thus the error of the results has been minimized. As for the environmental measurements, they are mainly for analysing the feasibility and the climatic adaptability of the integration system in the practical situation, and some other potential factors that may impact the system performance. In the subsequent sections, the equipment and instruments will be introduced and the rest of the content in this chapter will briefly describe each experiment, give the measurement results, and draw conclusions in order.

4.2 Flat sheet and Tubular LSCs

Flat sheet LSCs

In this project, a few flat sheet LSCs dyed in different colours and fabricated in different lengths were adopted. They were used to observe the light concentrating ability variations influenced by LSC dye and length. In total, there are four colours available for the flat sheet LSCs, which are orange, blue, red, and green. As for the size options, all sheets are 0.5-centimeter-thick and 5 centimetres wide, and for each colour, there are 5 centimetres, 10 centimetre, 20 centimetre, 21.5 centimetre, 32 centimetre, 37 centimetre and 42 centimetre products available.
Figure 11 Sample flat sheet LSCs

Tubular LSCs

In this project, three tubular LSCs were adopted to analyse the concentrating ability influenced by the LSC length and colour. There are two colours available for the tubular LSCs, which are in red and green respectively; there is also a clear tube, which is used to make comparisons between coloured tubes and uncoloured tubes in some experiments. As for the size options, the three tubes have the same dimensions. The inner diameter of the tubes is 1.75 inches/4.445 centimeters, the outer diameter is 2 inches/5.08 centimetres, and the tubes are all 72 inches/183 centimetres long.

Figure 12 Red and green LSCs, the clear tube is filled with green pigment water.

4.3 Important Equipment or Instruments

In this section, the important equipment and instruments that have been used in the measurements will be enumerated and introduced. By presenting all facilities, the functions of them can be outlined and thus the following content regarding the experiments can be better understood.
Spectral meter SolarRad

**SolarRad** is a type of spectral diometer to make all kinds of optics measurements. There are two major parts of the equipment, one is the optic sensor to allow the light input and the processor, which is assigned to analyse the spectrum of the input light. One of the major functions of SolarRad is measuring the input light irradiance in unit of watt per square meter over each wavelength range in half nanometres. In addition, based on the user manual, the equipment can give valid data for the light between 300-1100 nanometre wavelength range. As for the light source types, although they were mainly designed to measure the sunlight properties, it is also suitable for the other light sources. By taking a test run, the emission light from sample LSCs was proven to be appropriate for this equipment to test.

![SolarRad components](image)

**Figure 13 SolarRad components**

Shedding box

To analyse the emission light from the LSCs, it is important to isolate the emission light from any lights of other origins. Therefore, a box and two lids with different grooves were drawn with the drawing software AutoCAD and produced with a 3D printer. The box base can allow the photovoltaic cell or CIGS film to lay inside. As for the lids, there are grooves across through them, thus the flat sheet LSC or the tubular LSC can be inserted into the box and overlays the PV modules. Because the whole box was made with PVC plastic, it can block the ambient light perfectly and only passes the LSC edge emission.
Solar simulator

Solar analyser is an indoor fixture to analyse the photovoltaic device performance under artificial simulative sunlight illumination. The operation procedures of the solar analyser in experiments in this project follow this sequence: Firstly, to provide adjustable light to illuminate the sample photovoltaic modules; Secondly, according to the user’s will, the electrical output will be measured and recorded, the voltage-current, power-current relative changes as well.
PROVA

PROVA is a portable device that is used to analyse the photovoltaic module’s working performance when the photovoltaic device is irradiated by sunlight. Users are allowed to choose a time point to record the photovoltaic effect details while the photovoltaic device is operating under a satisfactory condition. Then, the IV and PV curve of the photovoltaic product will be plotted and users can discretionarily decide if the data shall be saved.

Figure 16 Solar analyzer PROVA 210

Multimeter

A few multimeters were used at different times in the project to test the sample photovoltaic device working performance. Unlike other more superior and professional instruments, such as the solar analyser or the solar simulator, these ordinary multimeters showed high compatibility and accuracy with very small generating units.

Light meter

In order to obtain the instantaneous solar irradiance magnitude during the recording of other parameters such as the electricity output from the solar cell when illuminated by LSCs or the cell is irradiated by sunlight
directly, an appropriate and convenient instrument was provided. The sensor of the device receives the sunlight and the irradiance magnitude will be displayed on the main screen, in units of watts/m².

![Light meter MAVOLUX](image)

**Figure 17 Light meter MAVOLUX**

**Datataker**

An instrument called a datataker and with a part number DT80 series 3 was used to record the temperature values during a specific period of time for several objectives. The DT80 completed the task by using with the type T thermocouples.

![Datatker DT50 series3](image)

**Figure 18 Datatker DT50 series3**

**4.4 PV cell**

In this project, multiple mono crystalline silicon photovoltaic cells were selected as samples, and they are aimed to test the electrical output enhanced by the emission of the LSC products. However, there are a few steps to handle before adopting the sample cells to use.

Pre-preparation: Sample LSC wiring and performance test
Because all the electrical measurements are based on small size photovoltaic cells, which is around 0.25Watts, it is worthwhile to test generating ability of the sample cell. However, like most market products, the original photovoltaic cell was unwired and it could not make a very reliable conductive connection to any type of equipment because it lacks conductors connected on the anode and cathode contacts, which are glazed on the front and back surface of photovoltaic cell respectively. In this situation, it is necessary to weld conductors onto the photovoltaic cell contacts to allow the electron flow to the measuring equipment and consequently quantify the voltage, current and power output.

Figure 19 Unwired photovoltaic cell

Figure 20 Wired photovoltaic cell
Once the photovoltaic cell was set up, its key parameters of open circuit voltage, short circuit current, maximum power point under sunlight illumination were required. To achieve the goal, the supervisor and the project owner decided to use the solar simulator with a part number *SPI-SUN SIMULATORTM 5600SLP* to handle the work and the reason behind this decision was that in the initial thought, based on the equipment manual, the solar simulator can provide adjustable simulated sunlight and the machine has better accuracy. However, the tests have all failed, and the reason was contributed to the working size of the solar analyser being too large for a small solar cell with output power rated at around 0.2 Watts. In this case, the task was proceeded by the solar analyser PROVA 210. Unlike the high technical equipment *SPI-SUN SIMULATORTM 5600SLP*, PROVA can only allow the PV cell illuminated under sunlight and then, measure the output. In this case, the IV and PV curve created by PROVA is shown as below:

![IV and PV Curve of the Sample Solar Cell](image)

**Graph 12 IV and QV curves for the sample PV cell at standard test condition**

The critical parameters and the ambient temperature information are shown in Table 6.
Table 6 Tested sample PV cell data

<table>
<thead>
<tr>
<th>Date &amp; Time</th>
<th>24/05/2017 13:48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Irradiance</td>
<td>1000W/m²</td>
</tr>
<tr>
<td>Vopen (V)</td>
<td>0.474</td>
</tr>
<tr>
<td>Ishort (A)</td>
<td>1.473</td>
</tr>
<tr>
<td>Vmaxp (V)</td>
<td>0.252</td>
</tr>
<tr>
<td>Imaxp (A)</td>
<td>0.923</td>
</tr>
<tr>
<td>Pmax (W)</td>
<td>0.232</td>
</tr>
<tr>
<td>Temperature(°C)</td>
<td>20</td>
</tr>
</tbody>
</table>

Based on the results produced by the PROVA, the sample mono crystalline silicon solar cell is assessed as an eligible product and under standard test condition (STC), the cell is estimated to be producing an open circuit voltage at 0.48 volts, a short circuit current at 1.47 amperes, the maximum power 0.25 Watt, all above values are approximated measuring. Therefore, it was expected to be capable of handling the LSCs electrical test.

4.5 Optical Measurement

To analyze the concentrating and transmitting performance of LSCs, measuring the emission and transmission light of the sample LSCs is absolutely necessary. Therefore, following the schedule made in the project plan, the optical measurements were started right after the first three months of the project for the background search and literature review. In general, the optical measurements in this project have two fractions, and they are the concentrating tests and transparency tests. The concentrating ability of LSCs is reflected on the edge emission properties of LSCs which have been explained earlier; as for the transparency test, there are two key values, one is integrating with the illuminated sunlight power to derivative the LSC absorbance, the other is analysing the microalgae cultivation light source that can be supplied by different LSCs.

Measurement No.1 Flat sheet LSC emission

Main objective of the measurement: The emission light properties of the flat sheet LSC under sunlight conditions
Operation date: 28/10/2016
Operation venue: Engineering building top floor terrace, Murdoch University
Brief procedures of the experiment:
The first experiment of the project was aimed to measure the trend of the flat sheet LSC emission energy and the energy distribution on the light spectrum. There were LSCs in four different colours, seven different lengths for each colour being tested. All LSCs were put on the horizontal surface and fixed by iron stands. The measurement was taken in a short period under the sun, and the sunlight irradiance fluctuates from 900W/m² to 1100W/m², thus the input light is regarded to be the same for all objective LSCs. The measuring spectrometer, SolarRad, is able to measure the photons grouped by their wavelengths in steps of 0.5nm and send the data to the program on computers. The original data obtained from the measurement should be filtered because the data of the energy values for light photons above 1000nm wavelength is worthless.

Results:
Once the data was obtained, arranged and selected, we presented the results with Excel:

![Graph 13 The emission light irradiated energy VS wavelength (Blue)](image-url)
Graph 14 The emission light irradiated energy VS wavelength (Green)
Graph 15 The emission light irradiated energy VS wavelength (Orange)

Graph 16 The emission light irradiated energy VS wavelength (Red)
The list below gives the total energy among the edge emission for each LSC, the approximate emission wavelength range evaluated by observations, the spectral scattering of the emission light energy which is the proportion of the total energy of light photons that lie in the designated wavelength range over the emission light energy amount, and the calculated light to light efficiency.

**Table 7 Measurement No1 detailed information**

<table>
<thead>
<tr>
<th>Length</th>
<th>Total Power(W/m²)</th>
<th>Main Emission Spectra Area Energy(W/m²)</th>
<th>Spectral Scattering</th>
<th>Light to Emission Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>278.3436</td>
<td>89.9115</td>
<td>32.30%</td>
<td>11.64%</td>
</tr>
<tr>
<td>10</td>
<td>278.3365465</td>
<td>89.91337</td>
<td>32.30%</td>
<td>5.36%</td>
</tr>
<tr>
<td>20</td>
<td>274.2060685</td>
<td>110.077825</td>
<td>40.14%</td>
<td>2.75%</td>
</tr>
<tr>
<td>21.5</td>
<td>286.681423</td>
<td>128.585365</td>
<td>44.85%</td>
<td>2.79%</td>
</tr>
<tr>
<td>32</td>
<td>257.120571</td>
<td>107.51152</td>
<td>41.81%</td>
<td>1.83%</td>
</tr>
<tr>
<td>37</td>
<td>271.3039635</td>
<td>100.468675</td>
<td>37.03%</td>
<td>1.65%</td>
</tr>
<tr>
<td>42</td>
<td>265.7979825</td>
<td>127.07924</td>
<td>47.81%</td>
<td>1.35%</td>
</tr>
</tbody>
</table>

**Green(500nm-630nm)**
<table>
<thead>
<tr>
<th>Length(cm)</th>
<th>Total Energy(W/m²)</th>
<th>Main Emission Spectra Area Energy(W/m²)</th>
<th>Spectral Scattering</th>
<th>Light to Light Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>499.869</td>
<td>282.2315</td>
<td>56.46%</td>
<td>20.90%</td>
</tr>
<tr>
<td>10</td>
<td>363.743005</td>
<td>159.382645</td>
<td>43.82%</td>
<td>7.00%</td>
</tr>
<tr>
<td>20</td>
<td>750.34102</td>
<td>533.267275</td>
<td>71.07%</td>
<td>7.52%</td>
</tr>
<tr>
<td>21.5</td>
<td>655.44087</td>
<td>446.88368</td>
<td>68.18%</td>
<td>6.38%</td>
</tr>
<tr>
<td>32</td>
<td>962.1505625</td>
<td>744.97175</td>
<td>77.43%</td>
<td>6.84%</td>
</tr>
<tr>
<td>37</td>
<td>803.4737105</td>
<td>584.86095</td>
<td>72.79%</td>
<td>4.87%</td>
</tr>
<tr>
<td>42</td>
<td>1041.17627</td>
<td>838.52865</td>
<td>80.54%</td>
<td>5.28%</td>
</tr>
</tbody>
</table>

**Orange (600nm-750nm)**

<table>
<thead>
<tr>
<th>Length(cm)</th>
<th>Total energy(W/m²)</th>
<th>Main Emission Spectra Area Energy(W/m²)</th>
<th>Spectral Scattering</th>
<th>Light to Light Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>703.837525</td>
<td>478.187395</td>
<td>67.94%</td>
<td>29.43%</td>
</tr>
<tr>
<td>10</td>
<td>639.49404</td>
<td>428.5979</td>
<td>67.02%</td>
<td>12.31%</td>
</tr>
<tr>
<td>20</td>
<td>909.1172885</td>
<td>701.3767</td>
<td>77.15%</td>
<td>9.12%</td>
</tr>
<tr>
<td>21.5</td>
<td>892.419061</td>
<td>695.03065</td>
<td>77.88%</td>
<td>8.68%</td>
</tr>
<tr>
<td>32</td>
<td>1247.775583</td>
<td>1038.56875</td>
<td>83.23%</td>
<td>8.87%</td>
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<td>37</td>
<td>698.414644</td>
<td>499.84491</td>
<td>71.57%</td>
<td>4.24%</td>
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<td>42</td>
<td>1615.841044</td>
<td>1391.485</td>
<td>86.12%</td>
<td>8.20%</td>
</tr>
</tbody>
</table>

**Red (600nm-750nm)**

<table>
<thead>
<tr>
<th>Length(cm)</th>
<th>Total Energy(W/m²)</th>
<th>Main Emission Spectra Area Energy(W/m²)</th>
<th>Spectral Scattering</th>
<th>Light to Light Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>715.783335</td>
<td>514.610115</td>
<td>71.89%</td>
<td>29.93%</td>
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<tr>
<td>10</td>
<td>513.47874</td>
<td>324.642</td>
<td>63.22%</td>
<td>9.89%</td>
</tr>
<tr>
<td>20</td>
<td>875.3291555</td>
<td>683.85036</td>
<td>78.12%</td>
<td>8.78%</td>
</tr>
<tr>
<td>21.5</td>
<td>1071.368094</td>
<td>884.55588</td>
<td>82.56%</td>
<td>10.43%</td>
</tr>
<tr>
<td>32</td>
<td>1123.519676</td>
<td>927.97874</td>
<td>82.60%</td>
<td>7.99%</td>
</tr>
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<td>37</td>
<td>823.1198075</td>
<td>637.880145</td>
<td>77.50%</td>
<td>4.99%</td>
</tr>
<tr>
<td>42</td>
<td>806.5711975</td>
<td>655.792795</td>
<td>81.31%</td>
<td>4.09%</td>
</tr>
</tbody>
</table>

**Conclusion and discussion:**

It can be seen that the emission magnitude and efficiency results from the measurements are in accordance with the rules obtained from the literature review: (a) For the same colour LSC, the total emission amounts
are positive in relation to the LSC length; (b) The emission spectrum curve for the LSCs in different colours will show the peak value in different spectral wavelength ranges. (c) The concentrating ability and light to emission efficiency will decrease with the increase of the LSC length.

**Measurement No.2 Flat sheet LSC Transmission and Absorption**

Main objective of the measurement: The transmitted light properties of the flat sheet LSC test under sunlight conditions

Operation date: 09/11/2016

Operation venue: Engineering building top floor terrace, Murdoch University

Brief procedures of the experiment:
The spectrum associated measurement was produced to analyse the transparency performance of LSCs. The measurement followed the same operating procedures with Measurement No.1, used the same test equipment and flat sheet LSC products with the previous measurement except altered the tested light from the edge emission to the transferred light at the back sun side. Therefore, once the LSCs were put on the horizontal surface and fixed by iron stands, the spectral sensor of SolarRad was located beneath the LSCs surfaces and ensured the sensors were prevented from receiving any direct sunlight illumination. Moreover, because the transmission of the sunlight from the illuminated surface to the backlight surface has very low relation with the length of LSCs, the measurement used only one LSC in the same length for each colour, and there were LSCs in four different colours being tested. In addition, the absorption spectrum of each LSC can be obtained by using the direct sunlight energy contained in each spectrum range, which is also measured by SolarRad instrument, and minus the transmission light energy in the same spectrum range.

Results:
Once the data was obtained, arranged and selected, the results could be presented by Excel Program, the scatter plots of the LSC’s transmission and the direct sunlight spectrum during the operation are shown in the graphs below:
The total energy amount of the transmission light and absorption light in each LSC case is shown in the table below:

**Table 8 Transmission and absorption energy statics**

<table>
<thead>
<tr>
<th></th>
<th>Transmission (W/m²)</th>
<th>Absorption (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight=1310W/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>6.57E+02</td>
<td>6.57E+02</td>
</tr>
<tr>
<td>Green</td>
<td>6.45E+02</td>
<td>6.69E+02</td>
</tr>
<tr>
<td>Orange</td>
<td>4.86E+02</td>
<td>8.28E+02</td>
</tr>
<tr>
<td>Red</td>
<td>9.08E+02</td>
<td>4.06E+02</td>
</tr>
</tbody>
</table>

In the next, the LSC absorption was calculated by making a subtraction of the transmission spectrum energy from the direct sunlight spectrum energy, and the plots will be combined with emission light energy spectrum to compare the relationship between absorption and emission, which are shown as:
Graph 19 Absorption spectrum and emission spectrum (Blue)

Graph 20 Absorption spectrum and emission spectrum (Green)
Graph 21 Absorption spectrum and emission spectrum (Orange)

Graph 22 Absorption spectrum and emission spectrum (Red)
Conclusion:
As the scatter plots showed in all above graphs and data in the table, two trends that can be found: (a) The absorption spectra cover the most part of the full light spectrum while the emission spectra are much more concentrated, which means the LSCs absorbed sunlight in a relatively wide range but most light photons that are outside the main absorption range have been excluded from LSCs before emitting from the LSC ends; (b) The emission peak always shifts to higher wavelength range from the absorption peak on the spectrum, which coincides with the Stokes shift that was analysed in the previous Section 2.6, based on the measurement data, the theory has been proven that the Stokes shift permanently exists.

Measurement No 3. Tubular LSC Emission

Main objective of the measurement: The emission light properties of the tubular LSC test under sunlight conditions
Operation Date: 20/01/2017
Operation Venue: Engineering building top floor terrace, Murdoch University
Brief procedures of the experiment:
The implementation of the experiment followed similar procedures and used the same testing equipment as the previous experiments, which is for setting the objective on the horizontal surface and testing the bottom edge emission light. Nonetheless, this experiment changed the testing objectives to three hollow tubular LSCs instead of flat sheet LSCs. The three tubular LSCs are in red, green and the other one is clear without any coloured dye. Moreover, the LSCs were covered by a light tight cardboard on the opposite side of where the emission lights were detected. It was operated for changing the LSCs illuminated length and analysing the emission output each time, which is nearly equal with using LSCs in different lengths. The SolarRad would record the emission light for each case:
Graph 23 The emission light irradiated energy VS wavelength (Green)
Graph 24 The emission light irradiated energy VS wavelength (Red)
## Table 9 Measurement No 3 detailed information

### Green (500nm-710nm)

<table>
<thead>
<tr>
<th>Length</th>
<th>Total Energy (W/m^2)</th>
<th>Main Absorption Area Energy (W/m^2)</th>
<th>Spectral Scattering</th>
<th>Light to Emission Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>111.2993522</td>
<td>111.2993522</td>
<td>100%</td>
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<td>269.1838099</td>
<td>269.1838099</td>
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<td>384.3033742</td>
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<td>0.84</td>
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<td>0.81</td>
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<td>100%</td>
<td>0.60</td>
</tr>
</tbody>
</table>

### Red (600nm-750nm)

<table>
<thead>
<tr>
<th>Length</th>
<th>Total Energy (W/m^2)</th>
<th>Main Absorption Area Energy (W/m^2)</th>
<th>Spectral Scattering</th>
<th>Light to Emission Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>135.2183413</td>
<td>135.2183413</td>
<td>100%</td>
<td>1.15</td>
</tr>
<tr>
<td>40</td>
<td>207.9576201</td>
<td>175.385625</td>
<td>84.32%</td>
<td>0.88</td>
</tr>
<tr>
<td>60</td>
<td>409.6217311</td>
<td>409.6217311</td>
<td>100%</td>
<td>1.16</td>
</tr>
<tr>
<td>80</td>
<td>543.4286006</td>
<td>543.4286006</td>
<td>100%</td>
<td>1.15</td>
</tr>
<tr>
<td>100</td>
<td>821.2938173</td>
<td>821.2938173</td>
<td>100%</td>
<td>1.39</td>
</tr>
<tr>
<td>120</td>
<td>876.1307027</td>
<td>876.1307027</td>
<td>100%</td>
<td>1.24</td>
</tr>
<tr>
<td>140</td>
<td>902.0264273</td>
<td>902.0264273</td>
<td>100%</td>
<td>1.09</td>
</tr>
<tr>
<td>160</td>
<td>961.0638662</td>
<td>961.0638662</td>
<td>100%</td>
<td>1.02</td>
</tr>
<tr>
<td>183</td>
<td>1060.918755</td>
<td>1060.918755</td>
<td>100%</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Conclusion:
Based on the measurement results, the tubular LSC emission complied with three familiar trends: (a) For the same colour LSC, the total emission amounts are positive related with the LSC length; (b) The emission spectrum curve for the LSCs in different colours will show the peak value in different spectral wavelength ranges; (c) In general, the concentrating ability and light to emission efficiency will decrease with the increase of the LSC length.

Measurement No 4 Tubular LSC transmission and absorption

Main objective of the measurement: The transmission and absorption optical properties of the tubular LSC test under sunlight conditions
Operation Date: 19/05/2017
Operation Venue: Engineering building top floor terrace, Murdoch University

Brief procedures of the experiment:
The experiment was operated for analysing how the LSC tubes would pass the irradiative light through or absorb the light and accumulate it to further light transmission. The strategy of the experiment is similar to measurement No 2. All LSC data was taken when the LSCs were fixed in iron stands and put on a horizontal surface. The scale of this experiment only covered two pieces of LSCs in green and red respectively. Once the
LSCs and SolarRad was set up, the direct sunlight spectral based energy data was recorded first as background information. The light that had transferred through the cross section of the tubes was recorded by putting the SolarRad sensor under the tube wall. The LSC absorption can be calculated by subtracting the transmission light from the background irradiance.

Result:

Graph 26 Spectra of sunlight and LSC Transmission
The Emission Spectrum and Absorption Spectrum of Tubular LSC in Red

Graph 27 Emission and Absorption spectra of tubular LSC(Red)
Conclusion: Based on the emission curves and the derivate absorption curves for both LSC tubes, the transmission and absorption characterises of the tubular LSCs have been found to be similar with the Experiment 2 with a similar goal: (a) The absorption spectra cover the most part of the full light spectrum while the emission spectrums are much more concentrated, which means the LSCs absorb sunlight in a relatively wide range but most of the light photons that are outside the main absorption range have been excluded from LSCs before emitting at the LSC ends; (b) The emission peak always occurs later than the absorption peak on the spectrum, which coincides with the Stokes shift that was analysed in the previous Chapter 2.6, and based on the measurement data, the theory has been proven that the Stokes shift permanently exists.

4.6 Electrical Factors Measurement

The electricity measurements were operated to research how the quality of the irradiated light from the LSC edge emission would influence the electricity output of the PV-LSC integrated module and then derive the conclusion. It was convenient to the system design by comparing the generating performance of the same Photovoltaic module illuminated by different LSCs. To be specific, all measurements were operated in three methods: (a) Connect the photovoltaic cell to the portable measuring solar analyser device “PROVA”, measure the interactional variation of power, voltage and current outputs and use the data to create IV, PV curves. (b) Connect the photovoltaic cell to multimeter and read the specific value of photovoltaic voltage
and current. (c) Use a large size indoor fixture and under incandescent lamp light conditions, measure the interactional variation of power, voltage and current outputs of the photovoltaic sample, and use the data group to create IV and PV curves.

The data measurement of the LSC-silicon PV cell system was started in week 11, Semester 2, 2016, but in the initial stage, the measurements experienced a few difficulties, such as incorrect wirings of the PV cell, the incompatibility between the test sample and a big solar simulator facility and lack of experiences. Such trivial issues were solved one by one with the help from my supervisor David Parlevliet. Thereafter, measurements were operated more and more successfully and smoothly and they all showed satisfactory results. The following content will briefly describe the initial preparation which is necessary for every experiment and then, the procedures and results of each experiment will be presented as well as the conclusion. Moreover, the LSC concentrating ability shown on the PV cell’s electrical magnitude was expected to meet a similar trend with the conclusions drawn in literary theory analysis and the data trend in optical measurements.

Measurement No. 5 PV cell IV parameters from flat sheet LSC emission(Sunlight)

Main Objective of the Measurement: The electrical output of a mono crystalline silicon solar cell when it is illuminated by flat sheet LSCs only
Experiment Date: 2nd October, 2016
Experiment Venue: Student village, Murdoch University
Brief Procedures of the Experiment:
In this experiment, the solar cell was put in the shedding box and it would receive emission lights from different LSCs one by one. In the meantime, the solar cell was connected to the multimeter and thus the voltage and current output for each time will be recorded in order.
Results:

After all flat sheet LSCs were tested, the data was arranged below:

<table>
<thead>
<tr>
<th>Length/Colour</th>
<th>Blue</th>
<th>Green</th>
<th>Orange</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V(V)</td>
<td>I(mA)</td>
<td>P(mW)</td>
<td>V(V)</td>
</tr>
<tr>
<td>42cm</td>
<td>0.116</td>
<td>4.3</td>
<td>0.4988</td>
<td>0.205</td>
</tr>
<tr>
<td>37cm</td>
<td>0.118</td>
<td>4.5</td>
<td>0.531</td>
<td>0.208</td>
</tr>
<tr>
<td>32cm</td>
<td>0.112</td>
<td>4.2</td>
<td>0.4704</td>
<td>0.205</td>
</tr>
<tr>
<td>21.5cm</td>
<td>0.12</td>
<td>4.6</td>
<td>0.552</td>
<td>0.202</td>
</tr>
<tr>
<td>20cm</td>
<td>0.118</td>
<td>4.9</td>
<td>0.5782</td>
<td>0.202</td>
</tr>
<tr>
<td>10cm</td>
<td>0.138</td>
<td>5.9</td>
<td>0.8142</td>
<td>0.192</td>
</tr>
<tr>
<td>5cm</td>
<td>0.148</td>
<td>6.8</td>
<td>1.0064</td>
<td>0.188</td>
</tr>
</tbody>
</table>

Conclusion: By observing the results, it is easy to find that all LSCs in green, orange and red comply with the same trend; that the output power of the test solar cell will be larger if it is illuminated by the emission light from a longer LSC rather than shorter. However, the blue group showed opposite trend with the other groups, that the electricity output is inversely related to the LSC length. It is mainly caused by the inferior concentrating ability of the LSCs in blue colour and measuring error.
Measurement No. 6 PV cell IV parameters from flat sheet LSC emission (Artificial light)

Main Objective of the Measurement: The Electrical Parameters Test on LSCs Sheet under Artificial Illumination

Experiment Date: 3rd February, 2017
Experiment Venue: 3-001A Research Lab, Physical Science Building, Murdoch University

Brief Procedures of the Experiment:
The test aimed to acquire the output data of the sample PV cell when it is only illuminated by the emission light from LSCs in different lengths and colours under an artificial constant light. The experiment used the solar analyser in room PS 3-001A and the light used to illuminate the LSCs is from a fixed high luminance lamp, which is an element of the whole system. Under the shedding of the cardboard and the metal cage built for insulating the room light from sunlight, the LSCs were irradiated by the experimental purpose lamp only and therefore the input light for each LSC is regarded to be the same. At the same time, the sample PV cell was connected to the measuring probe to detect the photovoltaic effect performance and it was shaded by the lid of the shading box to insulate any direct illuminations. The output results were transmitted to the computer and presented with the LabVIEW program.

Figure 22 The layout of the flat sheet LSC-photovoltaic measurement handled by Solar simulator

Results:
Once all flat sheet LSCs were tested, the sample cell electricity production in each LSC illuminated scenario is shown as:
Graph 29 PV cell IV curve produced by flat sheet LSC emission (Blue)

Graph 30 PV cell PV curve produced by flat sheet LSC emission (Blue)
Graph 31 PV cell IV curve produced by flat sheet LSC emission (Orange)

Graph 32 PV cell PV curve produced by flat sheet LSC emission (Orange)
Graph 33 PV cell IV curve produced by flat sheet LSC emission (Red)
Graph 34 PV cell PV curve produced by flat sheet LSC emission (Red)

Graph 35 PV cell IV curve produced by flat sheet LSC emission (Green)
By observing the results, it is easy to find that the PV cell generation when illuminated by flat sheet LSC's emission follows two trends: (a) The output power of the test solar cell will be greater if it is illuminated by the emission light from a longer LSC rather than shorter; (b) The maximum output power of the test solar cell was up to 1mW when the cell was illuminated by 42cm red LSCs, which is the largest output power record in this experiment.

**Measurement No.7 PV cell IV parameters from tubular LSC emission (Sunlight)**

Main objective of the measurement: The electrical output of the tubular LSC under sunlight conditions

Operation date: 24/5/2017

Operation venue: Engineering building top floor terrace, Murdoch University

Brief procedures of the experiment:

On 24th, May, 2017, a measurement was taken in order to obtain the sample PV cell output while it was only irradiated by green and red tubular LSC emission. The LSC tubes were set horizontally and fixed by iron stands, and during a period of time, they were both irradiated by sunlight that fluctuated from 400W/m² to 1000W/m². At one set of the end terminal of the LSC, the sample PV cell was put inside the shedding box and covered by lid. The leads connected with the photovoltaic contacts were stretched out of the shedding box through two small holes drilled on the box wall, and with this layout, the cell was connected to PROVA. Thereafter, The LSC tube was inserted into the groove of the lid to make sure the emission light could reach...
the photovoltaic cell. Once all the preparation was done, the portion of LSCs that was illuminated by sunlight would be gradually shortened, in steps of 20cm, which is achieved by covering light tight material on the top of the LSC tube on the other side. For each time of changing the illuminated length, the sample photovoltaic performance would be recorded, as well as the real time irradiance.

Results:
Once the recording was completed, the results were saved in PROVA and they were imported into Excel. Thus, the current-voltage plot and power-current plot for each case can be drawn:
Graph 37 PV cell PV curve produced by tubular LSC emission (Green)

Graph 38 PV cell IV curve produced by tubular LSC emission (Green)
Graph 39 PV cell IV curve produced by tubular LSC emission (Red)

Graph 40 PV cell PV curve produced by tubular LSC emission (Red)
Troubleshooting and conclusion

By inspecting the above data and plots, it can be seen that the IV and PV curves all followed a weird trend, which are quite unreasonable. According to the communication between my supervisor and I, there were only three possible reasons to make the curves look strange. Firstly, the problem might come from the incident light spectrum, specifically speaking, the red and green polymathic methacrylate material can only transfer light on their each specific spectrum ranges, thus the photovoltaic effects were influenced by spectral factors due to the PV cell external quantum efficiency. Secondly, the instrument PROVA measuring accuracy contradicted the low electricity output from low light illumination. The last possible reason might be from the instrument, such as an unsuitable setting, or some other errors inside the PROVA. Thereafter, a few quick tests were taken in order to seek the real specific cause. To define the reason, each variable was performed singularly in each test. In brief, at the beginning, the photovoltaic cell was set under the sun directly and tested by PROVA. Then, the photovoltaic cell was shaded entirely by flat sheet LSCs to get a stronger filtered light reflection in order to compare with the original tubular LSC emission at the end terminal ring, which is relatively narrow. Finally, the cell was located within the shedding box and covered by the lid, where sunlight will reflect into the box through the groove of the lid, and finally illuminate the solar cell. In all above three attempts, PROVA reported normal curves, though the magnitudes were different. Therefore, by operating these tests, such assumptions can be made:
The whole PV cell was illuminated by sunlight directly, the IV and PV curves have normal shapes, which mean the PV cell was in good quality;
The whole PV cell was illuminated by filtered luminescent light, the IV and PV curves have normal shapes, which means the PV cell generation is not influenced by the incident light spectrum;
The PV cell was most shaded and could only be illuminated by sunlight through a thin circular groove, the IV and PV curves have normal shapes, which means the PV cell can operate under very little input light and PROVA has no issue to measuring and recording such low electricity output.

Based on all the tests, the reason why the measured IV and PV curves deviated the traditional trends was concluded: it was probably due to the wrong settings of the instrument PROVA during the original measurement. However, these are still meanings hold in the data. The general trend matched the expectation that the photovoltaic cell generation will be influenced by the LSC length, colour. If the incident sunlight has been considered as AM1.5 and it is fixed at 1000W/m² with ambient temperature at 25°, the photovoltaic effect output amount is positive but nonlinear in relation to the length of LSC. In this case, the similar measurement was handled by multimeter two weeks after this experiment, and by operating the experiment, an assumption can be proved that the odd results were caused by instrument PROVA rather than the testing objectives.
Measurement No. 8 PV cell IV parameters from tubular LSC emission (Natural light)

Main objective of the measurement: The electrical output of the tubular LSC under sunlight conditions

Operation date: 1st: 03/02/2017 2nd: 22/6/2017

Operation venue: Bush Court, Physical Science Building, Murdoch University

Brief procedures of the experiment:

The general layout of the LSCs and photovoltaic cell in this experiment generally followed the similar configuration of Measurement No. 7, whereas the measuring task was handled by two multimeters. Moreover, to obtain groups of V-I data while the photovoltaic cell is operating at different conditions, a slide resistor was introduced and such a circuit was wired up:

Once the preparation was done and the circuit was built, gradually move the contactor of the slide resistor to change the resistance connected in the circuit from zero to maximum. During the movement, the reading of the voltage meter will increase while the current meter reading will decrease. From time to time, stop moving the contactor and record the two multimeter readings.

Results:

Graph 41 PV cell IV curve produced by tubular LSC emission (Green)
Graph 42: PV cell PV curve produced by tubular LSC emission (Green)

Graph 43: PV cell IV curve produced by tubular LSC emission (Red)
Based on the experiment held earlier, the maximum operating power of the sample photovoltaic...
Conclusion

By observing the results, it is obvious that the generation of the sample PV cell when it is illuminated by tubular LSCs follows such trends: (a) The PV cell will be producing more power when it is illuminated by the longer LSC than if it is illuminated by the shorter LSC in the same colour; (b) The red LSC can make PV cell generate more power than green if the length factor is set to be the same.

4.7 Environmental factors measurements

In this section, two measurements were handled in order to extend the analytical scale to the whole system, considering the practical situation consideration. The temperature of each element in the integrated system when they are operating outdoor in a long period was simulated and measured. The following content will focus on introducing the two experiments, for the sake of analysing the critical factors that determine several design options and prove the feasibility of the design.

Measurement No. 9 Temperature test of the simulated system

The temperature test was processed for receiving the simultaneous temperatures of the system during a period of time. As mentioned in the Chapter 1 for many times, the integration system is designed to be used in outdoor conditions. Therefore, the climatic factor shall be analysed, because it brings impact to at least two key interests in this system. Firstly, the microalgae cultivation growth rate is very sensitive to the culture liquid temperature. According to a report released in 2013, for most microalgae species, the propagation can be operated between 15°C to 30°C and with optimal conditions between 20°C to 25°C [1]. Secondly, the photovoltaic cell voltage will be influenced by the its own temperature. Normally, if the temperature is increased, the photovoltaic module voltage will reduce and the current does not vary very much, so consequently the output power will be reduced if the module surface receives and absorbs more heat. The decrease rate may fluctuate depending on the photovoltaic product type, product detail and so on. In general, for monocrystalline and polycrystalline solar cell, the power-temperature coefficient is about -0.5%/°C. In conclusion, if a photovoltaic cell is illuminated by fluorescence, the real temperature of the solar cell is possibly being lower than the solar cell that receives natural light at the same density, and it will be advantageous for photovoltaic effect generation.

The temperature measurement was taken by a device called “Datataker” that was connected by leads to the computer during the measuring period. The device has five channels so it allows five different objectives to be tested by thermocouples at the same time. To be specific, the measurement took the temperature of five objectives:
Table 11 Measuring objective description

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green LSC</td>
<td>Filled with the mixture of water and green food colouring and sealed by rubber end cups</td>
</tr>
<tr>
<td>Red LSC</td>
<td>Filled with the mixture of water and green food colouring and sealed by rubber end cups</td>
</tr>
<tr>
<td>Clear LSC</td>
<td>Filled with the mixture of water and green food colouring and sealed by rubber end cups</td>
</tr>
<tr>
<td>PV cell</td>
<td>In 32 degrees gradient, facing towards north, aimed to red LSC edge.</td>
</tr>
<tr>
<td>Air</td>
<td>Thermocouple hung in the air, stay close to the whole system</td>
</tr>
</tbody>
</table>

During the whole experiment, a lot of issues came up, such as the incompatibility between the computer program and Datataker, data transmission issue, and so on, and they made the experiment process very slow. Because of the report length limit, the experience is not going to be introduced in depth. However, one of the failed experiences is worthwhile to be discussed. On the 30th of February, 2017, the experiment started recording and the whole system was finished setting up at night time. I had left the experiment locus after confirming the tubes, liquids, Datataker were running well at the moment and the delogger program on the PC showed reasonable temperature values for the objectives. However, I was regretful that the liquid in the tubes had warmed up in the following morning and some of the liquid expended out of the tubes by compressing rubber end cups. What’s worse, under the influence of the pressure, the liquid flowed through...
the gap between two pole wires of thermocouples and dripped inside of the Datataker. When the accident was found in the morning of 1st March, the device could not work in nature and the program was sent infinite temperature values. The oversight did not only damage the device, but also postponed the experiment’s completion because the following time was spent on finding the problem, fixing the device, and arranging for the experiment to start over. The accident was attributed to ignorance of the pressure effect and to eliminate this, a simply and efficient method is raising the Datataker position, dropping the thermocouples and make sure there is at least 30 centimetre height gap between the Datataker and the lowest point of the thermocouples. In summary, the lesson learned from this failure is that spending a reasonable time to predict all the potential hazards and thinking of precaution measures before undertaking any real actions is wise option and it can save much more than its expenditures. The experiment was accomplished on 26th April 2017, nearly two months after commencement. Thereby, the data for the tubes, PV cell, and the ambient air is shown in the curve:

Graph 46 Temperature values of three different colour tubes, PV cell and Air
Chapter 5 System Design and Performance Estimation

In this section, a DC off grid 12V system will be designed and explained. To begin, all the general elements that are needed to construct the integrated system will be stated and briefly introduced. Since that, the quantitation of the all necessary parameters of the system will be presented in order to show that the designed system can operate properly and satisfy all necessary requirements. It will be proven that the three major loads, which are pumps, sprays and red light-emitting diode (LED) can be supplied by LSC-PV system entirely. A set of online products which are eligible to compose the design system have been selected and the detailed information has been placed in each corresponded appendix.

5.1 Essential Elements

Based on the integrated system function requirements, the design shall include a few important components or elements:

**Dyed Tubular LSC**

The plexiglass acrylic tube with red dyeing will be used and generally it has two functions. Firstly, it carries microalga cultivation and secondly it concentrates sunlight and emits it to the photovoltaic cell. The detail of the tubes can be checked in Appendix C.

**Mono crystalline silicon photovoltaic cells**

A type of mono crystalline silicon photovoltaic cell product selected from online source is supposed to be used in the integrated system. The part number is **Vikocell TDB125** and the detailed data can be checked in Appendix D.

**DC cable:**

DC cable is supposed to be carefully selected based on the power transmission requirement and safety requirement both. The basic selection principle is that the rated voltage and current of the DC cables shall be larger than the PV array open circuit voltage and short circuit current respectively, and plus 25% safety margin.

**DC isolator:**

DC isolator plays an important role in PV system protection, and in the most cases, it is mandatory to be installed in commercial and industries PV system, with regardless of AC or DC system. There are a few functions of DC isolator. Firstly, it prevents direct current arc flash and unexpected high current flows into the battery or loads; Secondly, it provides a safe measure for users to cut off the power. Although the
designed system is unlikely to be endangered by arc flash because of the low nominal voltage rating (12V), the DC isolator has still been taken into consideration for safety reasons. Therefore, a DC isolator with has been chose based on DC isolator rating rules in relevant regulation/standards. The DC isolator manufacture details can be checked in Appendix E

MPPT Charge controller

As it has been mentioned in the former section, the solar energy generation has a sizeable variety on the output power due to climatic and seasonal factors. Thus, the electrical parameters have to be regulated prior to flowing into load and battery. To achieve the function, an MPPT charge controller is supposed to be introduced. In addition, the charger controller can also increase the system safety and stability performance, such as prevent overcharging, overloading and reverse current from the battery. It can also display the system electrical parameters to make users be aware of the real time power generation.

Pumps:

As mentioned in the former Chapters, one of the most important elements for the system to cultivate microalgae is the effectiveness of the pumping system because the microalgae cultivation activity is required to keep the culture liquid flowing at some specific velocity in the photobioreactor tubes. However, after reading a few related documentations, there is a very complete relationship between the flow speed of the culture liquid and biomass productivity, which cannot be deeply analyzed. Moreover, neither the research topic of this project nor the major of mine has high relevance to microorganism knowledge. Therefore, the pumping standard of the designed system is set in this way: the cycle of rotating the total amount liquid within the photobioreactor array should be less than an hour. Thus, in a 48-tubular photobioreactor array unit, the performance of the selected pump can make sure it fits the requirement based the manufacture data. (See Appendix F). To be specific, it will take 51.42mins to finish one cycle liquid rotating.

Sprays:

In an outdoor condition, there is a high possibility for the whole system to absorb a huge amount of heat. However, in a microalgae cultivation system, one of the best interests is to keep the temperature low to make sure of an ideal culture. To achieve the purpose, an efficient and low cost method is spraying the water onto tubular photobioreactors frequently (Richmond, Boussiba, Vonshak, & Kopel, 1993). By checking online source, there is a suitable at small rated power spray can achieve the goal. It shall be set to operate twice per hour, and for each time it will continuously operate for 12.5 minutes each time and during this time it consumes power at 12V*2.5A=30W. Thus hourly energy consumption is $E_{h,\text{spray}} = 30W \times \frac{12.5 + 2}{60} h = 12.5 W \cdot h$. As for the spraying task, the spray is capable of watering 50 liters water to a large area during each operating period.

Red LEDs:
Once the power requirement of pump and spray has been satisfied, the remnant power generated from photovoltaic array might still run some light emitting diodes (LED) that produce red light. The red light is supposed to be transferred to photobioreactors and consequently increase the microalgae growth rate. Therefore, a type of red LED product rated at 9W has been selected based on the situation. Considering the system photovoltaic generating ability is relied on climatic and seasonal factors, the electricity yield will have a large fluctuation from time to time. Based on this reason, the LEDs are only introduced for getting an optimal use of generated electricity and the illumination enhancement to the microalgae cultivation is favoured but not absolutely necessary. Therefore, in the whole system, the red LEDs will have minor priority of power supply than the pump and the spray, the operating duration of the LED in a day is quite flexible.

5.2 Electrical design

A few general sequences of designing the integrated system will be followed. According to the system load requirement and general knowledge of PV system design, a schematic diagram shown in Figure24 will give the overall concept of the design.
Once the general system composing and configuration was determined, the design work is divided into a few steps and they will be carried out in order:

**Estimate the per-unit LSC-PV system generating ability**

Because of the size and required power amount issues, the photovoltaic cell is expected to be illuminated by luminescent solar concentrator edge emission and the direct sunlight both to guarantee a significant power.
generation. As Figure 27 shows, the photovoltaic is set at 32 degrees inclined to receive the sunlight as balance as possible in different hours in a day, and the reason of the slope angle value is that the system is designed basing on the geography of Perth, WA, of which is at south latitude 32 degrees. Moreover, the photovoltaic cell is required to be processed, to be specifically, a circular hole should be incised at the center of the cell to allow the tubes can be connected with each other and the microalgae cultural liquid can be flow through. Therefore, under the standard test condition, the selected photovoltaic cell illuminated by sunlight and tubular LSC emission will be able to produce 2.78W a piece by reasonable estimations. (See Appendix G)
Figure 27 LSC-Photovoltaic unit design schematic (a)

Figure 28 LSC-Photovoltaic unit design schematic (b)
Figure 29LSC-Photovoltaic unit design schematic (c)

PV module sizing & Configuration

Based on the PV-LSC integrated unit generating ability, load size, familiar sizing rules and other consideration, the PV module sizing is determined to be connected 24 cells in a string, and two strings in parallel. Therefore, the LSC-PV cell array generating size rated at STC condition is:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{mpp}$ (W)</td>
<td>134.50W</td>
</tr>
<tr>
<td>$V_{mpp}$ (V)</td>
<td>12.408</td>
</tr>
<tr>
<td>$I_{mpp}$ (A)</td>
<td>10.84</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>15.192</td>
</tr>
<tr>
<td>$I_{sc}$ (A)</td>
<td>11.72</td>
</tr>
<tr>
<td>FF</td>
<td>75.5%</td>
</tr>
</tbody>
</table>

Load Profile Calculation

When the integrated system is operating to handle microalgae cultivation task, the total hourly load profile will be about:
Table 13 Load profile summary

<table>
<thead>
<tr>
<th>Load Item</th>
<th>Hourly consumption (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>30</td>
</tr>
<tr>
<td>Spray</td>
<td>12.5</td>
</tr>
<tr>
<td>LED</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>51.5</td>
</tr>
</tbody>
</table>

MPPT Charge Controller sizing

When sizing the charge controller, the controller is required to be able to transfer the maximum current that can be produced by the solar arrays, and plus 25% safety margin. Therefore, the charge controller current rating can be calculated as:

\[ I_{cc} = 1.25 \times I_{sc, PV\ array} = 1.25 \times 11.72A = 14.65A \]

Where \( I_{cc} \) is the current rating of the charge controller, in unit of A;

\( I_{sc, PV\ array} \) is the photovoltaic cell array short circuit current, in unit of A.

Based on the rating requirement, a suitable product has been selected to add in system and the detail is available in Appendix I

DC cable sizing

When a DC cable is sized, the maximum allowed flowing current of DC cable should be 125% of the short circuit current of the PV array. Therefore, the minimum DC cable rated current should be:

\[ I_{min, cable} = 1.25 \times I_{sc, PV\ array} = 1.25 \times 11.72A = 14.65A \]

Based on the current calculation, the DC transmission cable will be choosing to market products with part number WH3073 as positive pole side cable and WH3075 as negative pole side cable. The manufacture information of the two products is in Appendix E

Battery sizing

Assume if the photovoltaic system is under outage condition, the battery capacity can back up the maximum load profile for the total day hours for three days, which is considered as 3*12=36hrs. Moreover, in order to optimize the battery lifetime, the battery should always have 30% of its total capacity to be empty.

Therefore, the battery size can be calculated as:

\[ Ah_{battery} = \frac{\text{hourly load} \times \text{back up hours} \times V_{mpp, array}}{0.7 \times \eta_{batt}} = \frac{51.5\text{Wh} \times 36\text{hrs}}{12.408V \times 0.7 \times 0.9} = 237Ah \]

where

Hourly load is the maximum hourly load requirement of the system;
Back up hours is the required hour numbers that the battery can supply the maximum hourly load without photovoltaic cell generation;

$V_{mpp, array}$ is the operating voltage at the maximum power operating power at STC.

$\eta_{batt}$ is the efficiency of the battery, and it is assumed to be 90%.

Based on the sizing requirement, a suitable battery Caravan 4WD which is rated at 12V and 250Ah has been selected, and the detailed information can be checked in Appendix J.
Chapter 6 Conclusion

The project has been completed and was generally successful. The theoretical research made solid contribution on LSC concentrating ability analysis, in the meantime showed suggestions for improving concentrating abilities as well. Based on Goetzberger’s analysing results, when an LSC was illuminated by sunlight, 7%-12% of all the light that reflect on the LSC can be transferred to the end of the LSC and emit out (Goetzberger & Wittwer, 1981). The light to light efficiency decreases significantly when the size of LSC increases.

The experiments have been accomplished throughout about eight months and all anticipated results have been successfully obtained. It connects the logical relevance between the preceding literature review and the following numerical system calculation, which is an outstanding analytical approach in engineering major. By inspecting the experiment results, the theatrical research can be proven in reasonable depth. Moreover, it improved the understanding of the relative knowledge, which is more perceptually intuitive than academic essay research. In the subsequent analysis, the experiment results made a significant contribution toward the calculation, evaluation and design of the LSC concentrating ability, PV-LSC generating capacity and the integrated system. However, although the outcome is successful, difficulties have been very frequently met due to various causes, such as insufficient experiences, defective preparations and some other objective factors. Thus, the experiment implementation has to be diversified and made flexible. For example, in the electrical measurement of a photovoltaic cell when irradiated by LSC emission, its tiny power output has made measurement difficult. In this case, four measuring tools of three different types have been used and all measured results have been observed and analysed. Despite if it is correct results, and finally valid results have been successfully recorded.

For two test samples, flat sheet LSCs and tubular LSCs, both showed significant abilities to concentrate light energy. To be specific, the flat sheet LSC samples, the 42cm red LSC was emitting 1610W/m$^2$ when the sunlight was at 234.69W/m$^2$ intensity, which means the emission from flat sheet LSCs can be up to 6.9 times of the background light. As for the tubular LSCs, the 183cm red tubular LSC was emitting 1060W/m$^2$ when the sunlight was at 552W/m$^2$ intensity, which means the emission from tubular LSCs can be up to 1.92 times of the background light.

In electrical factor measurements, the experiments integrated sample LSCs and sample PV cell together, to compare the LSC concentrating ability fluctuations by testing the PV cell output. To be specific, the flat sheet LSC, the maximum output power of the test solar cell was 3.9mW when the cell was illuminated by 37cm red LSCs. As for the tubular LSC, the maximum output power of the test solar cell was 13.5mW when the cell was illuminated by 183cm red LSCs.
The design work in Chapter 5 showed a general idea of how the PV part of the integrated system should be designed to meet the requirement. Moreover, it is also worthwhile to understand associated microbiology knowledge a bit further and use it in the system design to improve the feasibility of the designed system. In the design, $15.192V(V_{oc}) \times 11.72A(I_{sc}) \times 75.5\% (FF)$ PV array is expected to handle all power requirement of the microalgae cultivation task.

For future work, a few suggestions based on the experience of the project operator are given in below:

The light to light efficiency of LSC is of worthy increase and to achieve the goal, there are two efficient and simple measures: (a) Increasing the dye density of LSC so that the LSC can absorb more photons that on the same wavelength range from incident light; (b) Diversifying the dye colours for the same LSC so that the LSC can absorb light photons from a much wider wavelength range.

The size clashes between LSC and PV cell that illuminated by the LSC shall be carried out further. The layout that LSC concentrated light and transfer to PV cell is much limited by the relatively small area of the LSC bottom surface. Thus, to obtain a desired PV cell generation amount, the PV cell has to receive direct sunlight and LSC emission both at the same time, which makes the PV cell output incapable of increase as many times as the difference between LSC emission to the incident light that reflects LSC.

The system efficiency can also be increased by choosing the PV modules with proper external quantum efficiency that fits the LSC emission. Because of the project scope, this factor has not been deeply researched but it is a significant factor that can influence the PV cell output when illuminated by LSC emission.
Bibliography


Outbax Camping. (2017). 50L ATV WEED SPRAYER SPORT SPRAY TANKS CHEMICAL GARDEN


Appendix A

To calculate the external reflectance of the incident light, it is necessary to analyze the reflectance of two polarized light types independently. The equations are:

For s-polarized light:

\[ R_s = \left( \frac{n_1 \cos \theta - n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta \right)^2}}{n_1 \cos \theta + n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta \right)^2}} \right)^2, \]

And for p-polarized light:

\[ R_p = \left( \frac{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta \right)^2}}{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta \right)^2} - n_2 \cos \theta} \right)^2, \]

where \( n_1, n_2 \) is the refractive index of the first medium and second medium respectively, and \( \theta \) is the incident angle.

Then the composed light reflectance is:

\[ R_T = N_s \times R_s + N_p \times R_p \]

where \( R_T \) is the total reflectance of the composed light, \( N_s \) and \( N_p \) is each polarization proportion that constitute the objective light.

For unpolarized light, such as sunlight, the previous equation can be simplified to:

\[ R_T = \frac{R_s + R_p}{2} \]
Appendix B

This appendix proposes to introduce the geometrical parameters which are useful in LSC research and calculations, such as angles between the incident beam and each direction of LSCs, length factors, and so on.

Figure 30 Propagation of a ray within a cylinder where emission occurs at O and intersects the cylindrical surface at D making an angle $\delta$ to the normal of the surface (McIntosh et al., 2007)

Figure 31 The instruction of determining $P(x,y,\theta,\phi)$ formula (McIntosh et al., 2007)
\[ P(x, y, \theta, \varphi) = x / [\cos(\pi - \varphi) \sin(\theta)], \text{ when } \arctan(\frac{x}{(L - y)}) + \pi/2 < \varphi < \arctan(x/y) + \pi \text{ (Subarea A in Fig30)} \]

\[ P(x, y, \theta, \varphi) = (L - y) / \cos\varphi \sin(\theta) \text{, if } \arctan(L - y) / (L - x) < \varphi < \arctan(x/L - y) + \pi/2 \text{ (Subarea B in Figure30)} \]

\[ P(x, y, \theta, \varphi) = (L - x) / \cos\varphi \sin(\theta), \text{ if } \arctan(y/(L - x)) < \varphi < \arctan[(L - y) / (L - x)] \text{ (Subarea C in Fig30)} \]

\[ P(x, y, \theta, \varphi) = y / [\cos(\frac{3}{2\pi} - \varphi) \sin(\theta)], \text{ if } \arctan(x/y) + \pi < \varphi < \arctan(y/(L - x)) \text{ (Subarea D in Fig30)} \]

(McIntosh et al., 2007)

For a cylindrical LSC, there are two solutions for \( P \), and they are:

\[ P = (L - x) / \sin(\theta) \sin(\varphi), \text{ when } \pi/2 < \varphi < 3\pi/2, \]

And \( P = x / \sin(\theta) \sin(\varphi) \), when \(-\pi/2 < \varphi < \pi/2\) (McIntosh et al., 2007)

(McIntosh et al., 2007)
Appendix C

Tubular LSCs

Material and quality: Fluorescent red extruded plexiglass acrylic tube

Part No: EATFLRED21492.000*1.750*72

Size information:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>2 Inches/5.08cm</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>1.75 Inches/4.45cm</td>
</tr>
<tr>
<td>Length</td>
<td>72 Inches/182.88cm</td>
</tr>
<tr>
<td>Volume</td>
<td>0.00284m³</td>
</tr>
</tbody>
</table>

(ePlastics, 2016)
Appendix D

Solar cell
Selected Photovoltaic cell product **Vikocell TDB125** manufacturing data

### Table 15 Vikocell TDB125 physical configuration parameters

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>125</td>
<td>±0.5</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>125</td>
<td>±0.5</td>
</tr>
<tr>
<td>Thickness(μm)</td>
<td>160</td>
<td>±20</td>
</tr>
</tbody>
</table>

### Table 16 Vikocell TDB125 electricity parameters

<table>
<thead>
<tr>
<th>Parameters (Units)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>17.64</td>
</tr>
<tr>
<td>P_{mpp} (W)</td>
<td>2.7</td>
</tr>
<tr>
<td>V_{mpp} (V)</td>
<td>0.517</td>
</tr>
<tr>
<td>I_{mpp} (A)</td>
<td>5.242</td>
</tr>
<tr>
<td>V_{oc} (V)</td>
<td>0.633</td>
</tr>
<tr>
<td>I_{sc} (A)</td>
<td>5.670</td>
</tr>
<tr>
<td>FF</td>
<td>75%</td>
</tr>
</tbody>
</table>
Figure 32 The engineering drawing of the front and back surface of photovoltaic module TDB 125

(Huizhou Weike Solar Technology, 2017)
## Appendix E

### Table 17 DC cable manufacture details

<table>
<thead>
<tr>
<th>Part No</th>
<th>WH-3073</th>
<th>WH-3073</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poles</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>Rated Current</td>
<td>15A</td>
<td>15A</td>
</tr>
<tr>
<td>Stranding</td>
<td>26*0.3mm</td>
<td>26*0.3mm</td>
</tr>
<tr>
<td>Total diameter</td>
<td>3.3mm</td>
<td>3.3mm</td>
</tr>
<tr>
<td>AWG</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Material</td>
<td>Tinned copper cable</td>
<td>Tinned copper cable</td>
</tr>
<tr>
<td>PVC insulation</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Max Temperature</td>
<td>80 degrees</td>
<td>80 degrees</td>
</tr>
<tr>
<td>Roll length</td>
<td>100m</td>
<td>100m</td>
</tr>
</tbody>
</table>

(Jaycar Electronics, 2017a, 2017b)
Appendix F

Table 18 Selected pump details

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>12V</td>
</tr>
<tr>
<td>Flow rate</td>
<td>0.7GPM/0.1589m³/h</td>
</tr>
<tr>
<td>Pressure (PSI)</td>
<td>70</td>
</tr>
<tr>
<td>Current (A)</td>
<td>2.5</td>
</tr>
<tr>
<td>Self-Priming</td>
<td>YES</td>
</tr>
<tr>
<td>Mounting Base L*W (inch)</td>
<td>3 1/4*2 1/4</td>
</tr>
<tr>
<td>Temperature Capacity (°F)</td>
<td>140</td>
</tr>
<tr>
<td>Inlet Port (inch)</td>
<td>3/8</td>
</tr>
<tr>
<td>Outlet Port (inch)</td>
<td>3/8</td>
</tr>
</tbody>
</table>

(Ozietrade, 2017)

If the product is pumping microalgae filled in 48 tubular photobioreactor, the time it takes the pump to make one cycle rotation will be:

\[
T = \frac{48 \cdot V_{\text{tube}}}{0.1589 \text{m}^3/\text{h}} = \frac{48 \cdot 0.002837 \text{m}^3}{0.1589 \text{m}^3/\text{h}} = 0.8567 \text{hrs}/51.42 \text{mins}
\]
Appendix G

To estimate the LSC-PV integrated system, the most convenient way is dividing the electricity generation from the photovoltaic cell into two parts, one is the photovoltaic effect aroused by LSC emission and the other one is the direct sunlight emissions. For the portion of electricity generated from the tube emission source, it will be calculated by data from one of the former experiment No 8, and it will also combine with reasonable assumptions and verifications.

(a) Emission generation calculation

Based on the sample photovoltaic cell measurement in Section 4.4, when the cell was set at a 32 degree gradient angle, facing north, the electrical parameters will be listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sc}$ (A)</td>
<td>1.473</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>0.474</td>
</tr>
<tr>
<td>$P_{max}$ (W)</td>
<td>0.232</td>
</tr>
<tr>
<td>$I_{mpp}$ (A)</td>
<td>0.923</td>
</tr>
<tr>
<td>$V_{mpp}$ (V)</td>
<td>0.252</td>
</tr>
<tr>
<td>FF</td>
<td>33.22%</td>
</tr>
</tbody>
</table>

At 1000W/m$^2$ solar irradiance, 20degree ambient air temperature

Therefore, at standard test conditions, the sample cell working performance will be:

$$I_{sc, stc} = \frac{1000}{1000} \times 1.473 = 1.473 A$$

$$V_{oc, stc} \times (1 - \gamma_v (T_{cell} - 25)) = 0.474,$$

Where $\gamma_v$ is the voltage temperature coefficient of the solar module, the value is assumed to be 0.5%/degree;

$T_{cell}$ is the cell temperature during the measurement, the value is assumed to be 25 degrees higher than the ambient air temperature, so $T_{cell} = 45 degrees$

Therefore $V_{oc} = 0.5267 V$

And $P_{max} = V_{oc} \times I_{sc} \times FF = 0.2577 W$

In the next, a group of data from Measurement No 7 shall be re-observed. When the photovoltaic cells is solely illuminated by 183cm tubular red LSC, and the LSC is illuminated by sunlight t at 500W/m$^2$ intensity, the maximum power that can be generated by the sample photovoltaic cell is 0.01817 Watts;
Therefore, when the LSC is illuminated by sunlight at 1000W/m², and emission of LSC reflects on the photovoltaic module will produce $P_{\text{max},1000W}=0.0327\times P_{\text{max},1000W} = 0.01817 \times \frac{1000}{500} = 0.03634W$.

Therefore, if the external quantum efficiencies of two mono-crystalline silicon products are relatively similar, which is very possible because the external quantum efficiency is highly material depended, then such an equation can be inferred:

$$\frac{P_{\text{max},\text{sample}}}{P_{\text{max},\text{selected}}} = \frac{P_{\text{max, sample cell emission}}}{P_{\text{max, selected cell emission}}}$$

where

$P_{\text{max, sample}}$ is the sample cell maximum power output under STC conditions, which is equal to 0.2577 Watts;

$P_{\text{max, selected}}$ is the selected sample cell maximum power output under STC conditions, which is equal to 2.7 Watts;

$P_{\text{max, sample cell emission}}$ is the sample cell maximum power output when it was only irradiated by sample red tubular LSC, and the LSC is illuminated by 1000W/m² sunlight, which is equal to 0.03634Watts.

$P_{\text{max, selected cell emission}}$ is the selected cell maximum power output when it was only irradiated by sample red tubular LSC, and the LSC is illuminated by 1000W/m² sunlight;

Based on the equation and known values, the $P_{\text{max, selected cell emission}}$ can be calculated by:

$$P_{\text{max, selected cell emission}} = \frac{P_{\text{max, sample cell emission}} \times P_{\text{max, selected}}}{P_{\text{max, sample}}} = \frac{0.03634 \times 2.7}{0.2577} = 0.3807W$$

Because the shortage of the desired photovoltaic cell, weather factors and the working load limits of the project and other reasons, the experiments and research can only partly support the system performance quantification. Thus, the above estimation is inevitability incorporated with some assumptions which are based on photovoltaic and luminescent solar concentrator basis and they are listed below:

- The photovoltaic module short circuit current is proportionate to the irradiance intensity
- The external quantum efficiency of two photovoltaic cells is same.
- The two photovoltaic cells have the same temperature voltage coefficient, and the value adopts - 0.5%/degrees
- The irradiance effect of photovoltaic cell open circuit voltage is neglected
- The fill factor values of each photovoltaic cell is fixed with regardless of illumination conditions

(b) Direct sunlight irradiance generating calculation

As mentioned before and it is also as the Figure 26, Figure 27, and Figure 28 showed, the selected photovoltaic cell needs to be incised a circle based on the requirements. In this case, the photovoltaic cell operating curve will follow such a trend: under the same illumination condition, the open circuit voltage of incised cell is the same with original cell, and the short circuit current will be proportional to the portion of
the area that has been cut from the main body. Moreover, the fill factor will be considered as unchanged. The assumption has been approved to be valid by checking literature work (Sathyanarayana, Ballal, PS, & Kumar, 2015). Therefore, the equation of the power output from deceived cell will be:

\[
\frac{P_{\text{cut}}}{P_{\text{original}}} = \frac{V_{\text{oc}} * I_{\text{sc}} * FF}{V_{\text{oc}} * I_{\text{sc}} * FF} = \frac{V_{\text{oc}} * (I_{\text{sc}} * \frac{A_{\text{cut}}}{A_{\text{whole}}}) * FF}{V_{\text{oc}} * I_{\text{sc}} * FF} = \frac{A_{\text{cut}}}{A_{\text{whole}}}
\]

Based on the requirement, \( A_{\text{cut}} = A_{\text{whole}} - A_{\text{tube bottom inner circle}} \)

By checking Appendix D the selected photovoltaic cell area is:

\[ A_{\text{whole}} = 12.5\text{cm} * 12.5\text{cm} = 156.25\text{cm}^2 \]

By checking Appendix C the tube bottom inner circle area:

\[ A_{\text{tube bottom inner circle}} = \left(\frac{4.445\text{cm}}{2}\right)^2 * \pi = 15.52\text{cm}^2 \]

Therefore, based on above equation and data, the maximum power that can be generated from cut cell will be:

\[
P_{\text{cut}} = \frac{A_{\text{cut}}}{A_{\text{whole}}} * P_{\text{original}} = \frac{156.25\text{cm}^2 - 15.52\text{cm}^2}{156.25\text{cm}^2} * 2.7\text{Watts} = 2.4\text{Watts}
\]

Based on the former two sections calculation and estimation, at STC conditions, the maximum operating power \( P_{\text{max}} \) of PV-LSC system shown in Figure 27 is equal with:

\[
P_{\text{max, total}} = P_{\text{max, direct}} + P_{\text{max, emission}} = 2.4\text{Watts} + 0.3807\text{Watts} = 2.7807\text{Watts}
\]

In addition, followed the approximation that has been made, that the open circuit voltage and fill factor will be same with the original photovoltaic cell, under STC condition, the short circuit current of the photovoltaic cell when the cell is irradiated by LSC emission and direct sunlight both will be:

\[
I_{\text{sc}} = \frac{P_{\text{max, total}}}{V_{\text{oc}} * FF} = \frac{2.7807}{0.633\text{V} \times 0.75} = 5.86\text{A}
\]

And the maximum operating point voltage and current will be estimated by:

\[
I_{\text{mpp}} = \frac{I_{\text{mpp, original}}}{I_{\text{sc, original}}} * I_{\text{sc}} = \frac{5.242}{5.670} * 5.86\text{A} = 5.42\text{A}
\]

\[
V_{\text{mpp}} = \frac{V_{\text{mpp, original}}}{V_{\text{oc, original}}} * V_{\text{oc}} = \frac{0.517}{0.633} * 0.633\text{V} = 0.517\text{V}
\]

Where \( I_{\text{mpp}} \) is the PV-LSC unit maximum power point current;

\( V_{\text{mpp}} \) is the PV-LSC unit maximum power point.

The above calculation is based on the assumption that the PV-LSC operating IV curve will be at the same shape with it of the original cell.

In conclusion:

Based on all above calculations, estimations and assumptions, the cut photovoltaic cell illuminated by LSC emission and direct sunlight under STC conditions will be:
Table 20 Proceed LSC-PV cell generation ability at STC

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{mpp}$ (W)</td>
<td>2.78W</td>
</tr>
<tr>
<td>$V_{mpp}$ (V)</td>
<td>0.517</td>
</tr>
<tr>
<td>$I_{mpp}$ (A)</td>
<td>5.42</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>0.633</td>
</tr>
<tr>
<td>$I_{sc}$ (A)</td>
<td>5.86</td>
</tr>
<tr>
<td>FF</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Appendix H

The maximum PV array operating voltage $= V_{OC\, ARRAY} + \gamma_m(T_{min} - T_{STC})$

where

$V_{OC\, ARRAY}$ is the open circuit voltage of the array at STC, in volts

$\gamma_m$ is the voltage temperature co-efficient, which is taken -0.03V/degree

$T_{min}$ is the expected minimum daily cell temperature, in degrees

$T_{STC}$ is the cell temperature at standard test conditions, in degrees and it is 25 degrees.

By checking the photovoltaic array configuration and the open circuit voltage of LSC-PV integrated unit data in Appendix G, $V_{OC\, ARRAY} = 0.633 \times 24 = 15.192\, V$

By checking the measurement No9, during day time, especially the time around sunrise and sunset, the cell temperature will be nearly equal to the air temperature; and by checking online climatic statistics, the minimum daytime temperature in Perth occurs in June, at about 11 degrees. (Bureau of Meteorology, Australian Government, 2011)

Therefore, the expected minimum daily cell temperature would be 11 degrees

Thus, the maximum PV array operating voltage = $15.192 + (-0.03) \times (11 - 25) = 15.612\, V$

The current rating of DC isolator will be determined by:

$I_{rating} = n \times I_{sc,\, string} \times 1.25$

where

$n$ is the string numbers that are connected in parallel;

$I_{sc,\, string}$ is the short circuit current in photovoltaic cell string;

1.25 is the margin that left for the PV array current increase before DC isolator operates.

By checking the short circuit current of LSC-PV integrated unit data in Appendix G, $I_{sc,\, string} = 5.86\, A$

Because the photovoltaic array has two strings in parallel, $n=2$.

Thus, the current rating of the DC isolator = $2 \times 5.86 \times 1.25 = 14.65\, A$
Appendix I

Table 21 15A PWM PV charge controller details

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum charge current</td>
<td>15A</td>
</tr>
<tr>
<td>Maximum load current</td>
<td>15A</td>
</tr>
<tr>
<td>Nominal output</td>
<td>12V</td>
</tr>
<tr>
<td>Maximum solar array power</td>
<td>270W</td>
</tr>
<tr>
<td>Over discharge protection</td>
<td>10.8V</td>
</tr>
<tr>
<td>Over charge protection</td>
<td>14.5V</td>
</tr>
<tr>
<td>Reset</td>
<td>12V</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20 to +60degrees</td>
</tr>
</tbody>
</table>

(ECO-WORTHY, 2017)
## Appendix J

### Table 22 Pro Power 12V Volt 250AH Battery information

<table>
<thead>
<tr>
<th>Nominal Voltage</th>
<th>12V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Capacity</td>
<td>250.0 AH</td>
</tr>
</tbody>
</table>
| Dimension | Length: 520 ±3mm (20.47 inches)  
| | Width: 269 ±2mm (10.59 inches)  
| | Container Height: 220 ±2mm (8.66 inches)  
| | Total Height (with Terminal): 225 ±2mm (8.85 inches)  |
| Approx Weight | Approx 63 Kg |
| Rated Capacity | 250.0 AH/12.5A (20hr,1.80V/cell,25°C) |
| Max. Discharge Current | 2500A (5s) |
| Operating Temp.Range | Discharge : -15 ~ 60oC  
| | Charge : 0 ~ 60oC  
| | Storage : -15 ~ 60oC  |
| Cycle Use | Initial Charging Current less than 60A.  
| | Voltage 14.4V~15.0V at 25oC (77o F)  
| | Temp. Coefficient -30mV/oC  |

(Pro Power, 2017)
# Appendix K

## Table 23 Spray information

<table>
<thead>
<tr>
<th>Item description</th>
<th>Spray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>50L</td>
</tr>
<tr>
<td>Flow</td>
<td>1.07 GPM</td>
</tr>
<tr>
<td>Volts</td>
<td>12V</td>
</tr>
<tr>
<td>Amp Draw</td>
<td>2.6amp max</td>
</tr>
<tr>
<td>Pressure</td>
<td>80PSI</td>
</tr>
<tr>
<td>Spraying tube adjustable length</td>
<td>80-127cm</td>
</tr>
<tr>
<td>Hose Diameter</td>
<td>6mm</td>
</tr>
<tr>
<td>DC cable length</td>
<td>3m</td>
</tr>
</tbody>
</table>

(Outbax Camping, 2017)