EXPERIMENTAL STUDY OF THE EFFECT OF FLOATING SOLAR PANELS ON REDUCING EVAPORATION IN SINGAPORE RESERVOIRS

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Summary

In recent years, an increasing number of countries have shown interest in constructing floating solar power plants as they search for a renewable source of energy. Singapore is one of them.

Blessed with sunlight all year round, Singapore is an ideal location to construct a solar power plant. However, the hot climate also causes Singapore to lose large amount of valuable water resources from reservoirs due to high evaporation rates. As floating solar panel systems are built over water bodies instead of land, they are supposed to have the additional benefit of reducing evaporation rates. Hence the use of floating solar systems is highly relevant to Singapore's context and worth exploring.

Unfortunately, there are currently no concrete evidence available to prove the extent of reduction that floating solar panels have on evaporation rates. Hence, this paper aims to investigate the effect of floating solar panel on reducing evaporation rates in Singapore reservoirs.

A prototype, modelled on the concept of evaporation pans, is built to mimic the situation of floating solar panels over reservoirs. Observations on the evaporation rate are made and compared to a control.

Experiment results showed that floating solar panels above water bodies have a reduction effect of approximately 30% on evaporation rates. However, the height of the solar panel above the water body surface do not have an observable correlation with evaporation rates.

Nevertheless, further observations have to be made before concluding the effect of floating solar panels in reducing evaporation rates. This is due to various limitations in the experiment carried out.

Nomenclature

α	Albedo value
^{o}C	Degree Celsius
^{o}	Degree
Δ	Rate of change of vapor pressure with respect to temperature
γ	Psychrometric constant
λ	Latent heat of vaporization
σ	Stefan-Boltzmann constant
$\%$	Per cent
a, b	Empirical constants
e_a	Actual vapor pressure
$e_s(T)$	Saturation vapor pressure
ET_0	Reference reservoir evaporation
E_{pan}	Pan evaporation
f	Cloudiness factor
$f(u)$	Empirical wind speed function
G	Soil heat flux
K	Kelvin
kg	Kilogram
K_P	Pan coefficient
kPa	Kilo Pascal
m	Meter
mm	Millimetre
MJ	Mega joule
N	North
P	Atmospheric pressure
P	Power
PET	Potential evaporation rate for an open water surface
R_a	Extra-terrestrial radiation
R_L	Net outgoing long wave radiation
R_n	Net radiation above the water surface
R_O	Incoming short wave radiation recorded by weather station
R_S	Net incoming short wave radiation
R_{S0}	Clear sky total global radiation at surface
T_m	Mean air temperature
$T_{max,k}$	Maximum absolute temperature during the 24-hour period
$T_{min,k}$	Minimum absolute temperature during the 24-hour period
u	Wind speed
z	Elevation of weather station

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1. Introduction

Water is essential for the survival of mankind. Since independence, the Singapore government has been aggressively seeking solutions to be self-sufficient in freshwater supplies. This led to the diversified freshwater sources serving Singapore today, or also known as the 'Four National Taps.' They are namely local catchment water, imported water, highly purified reclaimed water (NEWater) and desalinated water.

The local catchment water system is the pioneer method adopted by the Singapore's authority to reduce dependence on importing water from neighbouring country, Malaysia. Located close to the equator, Singapore has a tropical marine climate that provides a significant amount of rainfall annually. Reservoirs are the main component in collecting and storing the rainwater before they are sent for water treatment. Till date, Singapore has developed a comprehensive catchment network that covers two-thirds of Singapore's land surface (Public Utilities Board, 2014).

On the other hand, Singapore's equatorial climate also results in an environment for potentially high evaporative losses. Annually, more than 45 million cubic meters of water is lost from Singapore's reservoir system through evaporation (Babu, Eikaas, Price, & Verlee). This is likely to exacerbate in future with rising temperatures due to global warming. Hence, the government has been exploring safe and cost effective options to protect and maximize the available water resources.

In 2011, the Economic Development Board (EDB) and Public Utilities Board (PUB) announced the construction of Singapore's first floating solar system at Tengeh Reservoir. The 3-hectare, 2–megawatt solar photovoltaic system will be connected to the national grid and is able to generate enough energy from the sun to power 450 four-room flats at any one time (Cheam, 2011). This $11 million pilot project will be studied to explore the potential of using Singapore's remote reservoir water surfaces for solar systems to generate electricity.

One of the motivations for the authority to invest in a floating photovoltaic system is the promoted advantage of the ability to reduce evaporations rates of the water body. The executives of SPG Solar, a photovoltaic system company from California, claims an environmental engineering firm evaluated that water evaporation under the floating arrays decreased by 70% (Woody, 2011). However, there are currently no such concrete data available in Singapore.

This paper aims to investigate the extent of the advocated benefit of floating solar panels reducing evaporation rates in reservoirs, as floating photovoltaic systems could potentially greatly reduce Singapore's losses in its water reserves while generating power at the same time.

2. Preliminary Study

2.1. Floating Solar Panels

The idea of ‘floating solar panels’ is to build the photovoltaic system over water bodies instead of conventional places such as rooftops or open lands. This relatively new concept has been trialled and implemented in regions blessed with abundance of sunlight such as Australia, India and Israel. After the Fukushima disaster, Japan’s search for new, independent, renewable energy sources had also led them to commission the construction of the world’s largest solar power plant, in terms of output, in 2014. This sections aims to investigate the numerous benefits of floating solar panels that were highly publicized.

2.1.1. Maximising Usage of Valuable Land

Environmentalists have always campaigned solar energy as a clean and sustainable source of energy. However, construction of solar power plants requires large plots of open lands. This makes the notion of harvesting solar energy infeasible in countries like Japan and Singapore, where real estate is extremely expensive due to both scarcity of land and high population density. By building solar panels over water bodies, valuable land can be used for other purposes.

2.1.2. Increasing Output and Reducing Maintenance Of Solar Panels

One of the main complications encountered in the usage of solar panels is overheating due to excessive solar radiation and high ambient temperatures. Figure 2.1 illustrates the relationship between the electrical power output, P, and the output voltage, V, of a solar cell as its temperature varies between 0^{o}C and 75^{o}C. As observed in Figure 2.1, the maximum power output of the solar cells decreases as the cell temperature increases. This indicates that overheating of the solar cells will decrease the output of the solar panels significantly.

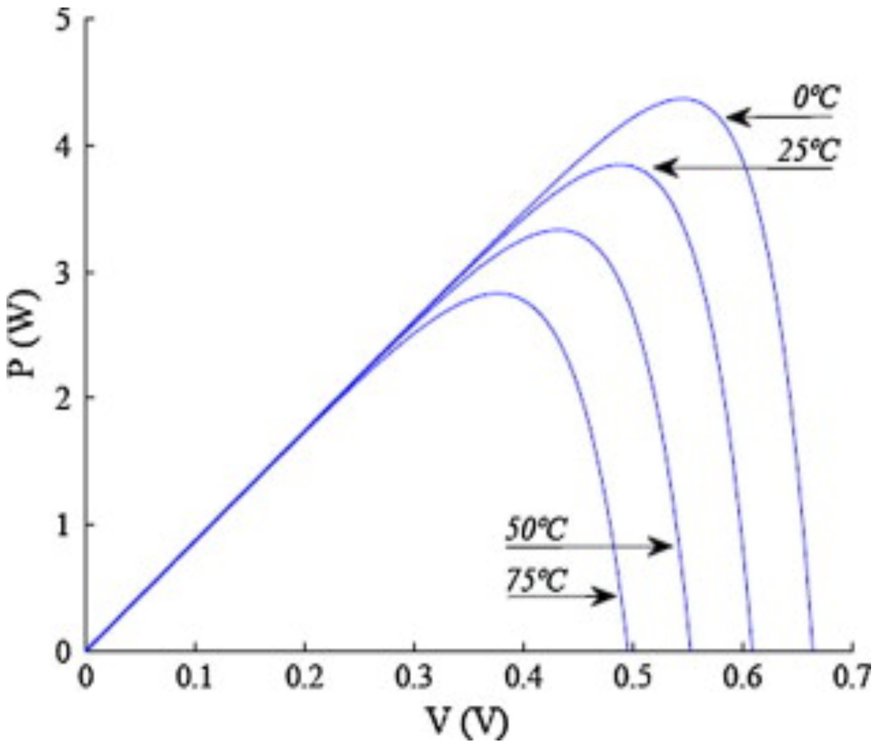

Figure 2.1.1: Power output of a ideal solar cell with varying temperatures (Moharrama, Abd-Elhady, Kandil, & El-Sherif, 2013)

The water bodies that the floating solar panels rest on are projected to have a cooling effect on the rear surface of the solar panels, hence reducing the temperature of the photovoltaic cells and allowing them to generate more power than those set up on land. With the probability of overheating reduced, the frequency of the photovoltaic cells necessitating care will also decrease. Therefore, floating solar panels are expected to have a higher power output and reduced maintenance requirements compared to the regular solar panels installed on the ground or building rooftops.

2.1.3. Increasing Potential of Hydroelectric Dams

Integrating the innovation of floating solar panels with hydroelectric dams improves the dams' capability to generate electricity. By building floating solar panels on the dam's reservoirs, solar power can be used to feed the transmission line. Thus, saving the water in the dam to generate electricity on rainy days or at night. In the event of a drought, instead of hydroelectric dams becoming a dead asset, the presence of floating solar panels will allow the production of electricity to continue (Woody, 2011). Hence, the potential of hydroelectric dams rises with the incorporation of floating solar panels.

2.1.4. Reservoir Biodiversity

Floating solar panels also has the proposed benefit of hindering destructive algae growth by blocking the sunlight needed by the algae to grow (Woody, 2011). In a larger picture, this indicates that floating solar installations over reservoirs can affect the ecology of the floral and faunal communities in reservoirs. As Singapore's reservoirs are natural habitats of many organisms, the effect of floating solar panels on reservoir biodiversity is highly relevant to Singapore's context and should be thoroughly studied. However, this is not a focus of this paper and will not be discussed further.

2.1.5. Reducing Evaporation Rates

The first consideration in choosing the location to construct a solar power plant is the availability of sunlight. While blessed with sunlight, these parts of the world face the inevitable problem of high evaporation rates in their water reservoirs. Deployment of floating solar installations in these sun-drenched regions will provide a 'shade' to the water bodies and is predicted to reduce evaporation rates. This creates a 'win-win' situation where the power of solar energy is fully tapped and utilized while scarce water reserves are protected with the drop in evaporation rates. Although SPG Solar proclaims that reduction in evaporation rates are up to 70%, there have been no released evidence to substantiate the claims till date.

2.2. Evaporation

Evaporation is the process by which water changes from a liquid to a gas or vapour (USGS, 2014). Water molecules are in constant motion and when they collide, they gain energy. When water molecules at the water surface gain sufficient energy from collision to escape from the water surface into the air, evaporation has taken place. Evaporation takes place all the time under every temperature.

2.2.1. Rate of Evaporation

The rate of water evaporation is affected by five main factors – temperature, humidity, wind speed, exposed surface area and air pressure.

The higher the temperature of the water source translates to water molecules moving at a faster speed and having higher kinetic energy. This increases the chances of the water molecules gaining enough energy to overcome the intermolecular bond with neighbouring water molecules and escape from the water surface into the atmosphere. Hence, evaporation rate is directly proportional to the temperature of the evaporating surface.

Humidity refers to the amount of water vapour in the air. At a given temperature, there is a maximum amount of water vapour that the air can hold. The rate of evaporation is dependent on humidity because if the air is already saturated with water vapour, it will not be able to hold additional vapour, resulting in a slow rate of evaporation.

When evaporation takes place, water vapour gathers above the water's surface. This causes a humid region above the water body that deters evaporation, as discussed above. With the presence of wind, the air saturated with water vapour is removed and replaced with 'fresh' air above the water body, making space for more water molecules to escape into the air. The faster the wind speed, the air is readily replaced and the concentration of water vapour in the air above the water body is less likely to increase over time, thus encouraging faster evaporation.

A larger surface area signifies that there are more surface molecules in direct contact with the air. This translates to an increase in the chances of surface water molecules escaping into the atmosphere, thus a faster evaporation rate.

Air pressure affects evaporation by acting like a force exerting on the water body surface. When air pressure is high, there is a larger force pushing down on the water surface, thus making it more difficult for water molecules to escape into the atmosphere as vapour. This will result in a slower evaporation rate.

2.2.2. Latent Heat of Vaporization

Latent heat is the energy released or absorbed by a thermodynamic system during a process where the temperature reading does not change, such as a phase transition.

As evaporation is an endothermic phase transition process, the latent heat of vaporization is specifically the energy absorbed by a liquid body to transit from liquid to vapour. The amount of energy required converting one kilogram of water from its liquid state to gaseous state, or also known as the specific latent heat of vaporization of water, is 2.45 MJ/kg.

2.3. Evaporation in Reservoirs

Evaporation from reservoirs is difficult to measure as there are a number of factors that can affect the evaporation rates, such as the climate and physiography of the water body and its surroundings (FInch & Calver, 2008). Reservoir evaporation is essentially different from land surface evapotranspiration.

2.3.1. Energy Storage

The primary source of energy behind evaporation in both land and reservoirs is incoming solar radiation (Jensen, 2010). However, the difference in the management of net solar radiation by land and water surfaces is distinctive. On land, net solar radiation is converted into sensible and latent heat at soil or plant surfaces. However for water bodies, not all the net solar radiation is absorbed at the water surface. Some of the net radiation will penetrate the water surface to varying depths depending on their respective wavelength (Jensen, 2010).

Solar radiation that is adsorbed below the water surface is stored as energy and is not immediately accessible for usage in the evaporation process. In other words, there will be a time lag before this stored energy becomes available for conversion into latent and sensible heat.

The duration of the time lag in the change of surface water temperature and evaporation rates is relative to the amount of net radiation adsorbed by the reservoir. Generally, deeper reservoirs and clearer water will allow a higher intensity of solar penetration and to greater depths (Jensen, 2010). This translates to a greater delay due to a larger amount of energy stored by the reservoirs.

2.3.2. Advected Energy

As there are continuous inflow and outflow of water in reservoirs, the effect of advection of energy in the water cannot be neglected. Weisman and Brutsaert's (1973) study showed that advected energy causes the evaporation rate over the lake surface to fluctuate. However, the presence of advected energy is not a significant factor in shallow water bodies where movement of the water is limited.

2.4. Estimating Open Water Evaporation

As evaporation is difficult to measure experimentally over water surfaces, a varied selection of approaches for estimating open water evaporation has been detailed in literature and used in practice over the years. However, none of the methods have been unanimously accepted as the best technique.

The main drawback of using these estimation methods is that the required meteorological variables are usually measured on land instead of over water surfaces due to the difficulty to do so. The thermal lag between the lake and land surfaces reasons the use of land surface data generally insufficient to estimate open water evaporation rates precisely (Granger & Hedstrom, 2011).

The different open water evaporation estimation approaches can be categorised into the following major types – pan evaporation, mass balance energy budget models, bulk transfer models, combination models, equilibrium temperature methods and empirical approaches (FInch & Calver, 2008).

2.4.1. Penman Equation

The Penman equation (Penman, 1948) is one of the most widely used formulas to estimate evaporation. It is a combination of the mass transfer and energy budget approaches that allows the potential evaporation rate of an open water surface to be estimated (FInch & Calver, 2008). Potential evaporation is the evaporation that would occur from a water body when moisture supply is not limiting. Estimation of potential evaporation is the common approach for estimating evaporation as a reference. One key advantage of the Penman equation is that it only requires various weather parameters that can be obtained from weather stations.

The Penman equation is defined as:

$$PET = \frac{\Delta(R_n - G) + \gamma \times f(u)(e_s - e_a)}{(\Delta + \gamma)/\lambda} \quad (2.1)$$

where PET is the potential evaporation rate for an open water surface (mm day^{-1}), Δ is the rate of change of vapor pressure with respect to temperature (kPa ^{o}C^{-1}), R_n is the net radiation above the surface (W m^{-2}), G is the soil heat flux (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa ^{o}C^{-1}), $e_s(T)$ is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), λ is the latent heat of vaporization (2.45 MJ kg^{-1}) and $f(u)$ is a empirical wind speed function.

The psychrometric constant γ can be estimated as:

$$\gamma = 0.00163\frac{P}{\lambda} \quad (2.2)$$

where P = atmospheric pressure (kPa).

Saturated vapor pressure $e_s(T)$ and Δ are related to the mean air temperature T_m (^{o}C) by the equations:

$$e_s(T) = 0.611e^{\left(\frac{17.27T_m}{T_m+237.3}\right)} \quad (2.3)$$

$$\Delta = \frac{4099e_s}{(T_m + 237.3)^2} = \frac{2504e^{\left(\frac{17.27T_m}{T_m+237.3}\right)}}{(T_m + 237.3)^2} \quad (2.4)$$

The net radiation R_n above the water surface can be expressed as:

$$R_n = R_S - R_L \tag{2.5}$$

where R_S is the net incoming short wave radiation (MJ m^{-2}) and R_L is the net outgoing long wave radiation (MJ m^{-2}).

R_L is calculated as:

$$R_L = f\sigma \frac{(T_{max,k}{}^4 - T_{min,k}{}^4)}{2}\left(0.34 - 0.4\sqrt{e_a}\right) \tag{2.6}$$

$$f = 1.35\frac{R_S}{R_{S0}} - 0.35 \tag{2.7}$$

$$R_{S0} = R_a(0.75 + 2\times10^{-5}Z) \tag{2.8}$$

where f is the cloudiness factor, σ is the Stefan-Boltzmann constant (4.903 x 10^{-9} MJ K^{-4} m^{-2} day^{-1}), $T_{max,k}$ is the maximum absolute temperature during the 24-hour period (K), $T_{min,k}$ is the minimum absolute temperature during the 24-hour period (K), R_a is the extra-terrestrial radiation (MJ m^{-2}), R_{S0} is the clear sky total global radiation at surface (MJ m^{-2}) and Z is the station elevation (m).

The wind speed function $f(u)$ is a linear function determined empirically and is defined as:

$$f(u) = a + bu \tag{2.9}$$

where u is the wind speed (km h^{-1}) and a and b are both empirical constants.

As $f(u)$ is site specific, it is best to be determined on site by calibration for higher accuracy of application.

2.4.2. Evaporation Pan

Indirect measurement of evaporation rates using evaporation pans is a generally accepted approach. Different models of evaporation pans have been implemented around the world. One of the most commonly used evaporation pan is the US Class A evaporation pan. It is a circular iron tank with a diameter of 1.21 meters and a depth of 0.25 meters.

However, the amount of evaporation measured from evaporation pans usually exceeds the actual amount of evaporation from large water bodies. As the size of evaporation pans is much smaller when compared to reservoirs, the evaporation pans will have a higher evaporation rate than the reservoirs (Davie, 2008). Furthermore, the metal sides of the evaporation pans will absorb radiation and warm up quicker than the boundaries of a large water body, thus providing an additional source of energy that will intensify the rate of evaporation.

Thus, to estimate the actual evaporation in reservoirs from evaporation pan measurements, the use of a pan coefficient is proposed:

$$ET_0 = K_P E_{pan} \quad (2.10)$$

where ET_0 is the reference reservoir evaporation (mm day^{-1}), K_P is the pan coefficient and E_{pan} is the pan evaporation (mm day^{-1}).

The pan coefficient,K_P, is a dependent on location and empirically derived. It is affected by numerous factors such as the type of pan used, the climate, the surrounding environment and location of the pan (FInch & Calver, 2008). It may also change with time to take into account the lag due to energy storage in large water bodies as evaporations pans are too small in size to mimic such an effect. However, most literatures have suggested a value of $K_P = 0.7$ as a good estimate (Madan, 2009).

3. Experiment Design

The aim of the experiment is to study the effect of floating solar panels on evaporation rates of reservoirs in Singapore using a prototype. The design of the prototype is fundamentally based on the concept of evaporations pans. As the US Class A evaporation pan is often used in research papers concerning evaporation rates, the ideal approach will be to build an exact replicate of the US Class A evaporation pan for the experiment. Unfortunately, this is unrealizable due to limited resources.

Instead, a container was used as the evaporation pan. A solar panel was placed over it to imitate the conditions of floating solar panels over the reservoirs. An identical container with no solar panel positioned over it was also placed beside the prototype to act as a control for comparison basis.

The height of the solar panel placed above the water body was also varied to observe for potential effects on the evaporation rate.

3.1. Equipment Selection

The size of the prototype is one of the main considerations when selecting the equipment. A prototype that is too small will be meaningless while too big a prototype will be insensitive, as it will take a long time to show a significant drop in the water level. Furthermore, selections of the equipment were made with the budget taken into thought. The specifications and photographs of the equipment can be found in Appendix A.

3.1.1. Solar Panel

The retailing of solar panels is not readily available around Singapore and there are not many vendors to choose from. The solar division of Kamtex Industries Pte Ltd was one of them.

The effect of the floating solar panels on the evaporation rate is expected to have a strong correlation with the extent of the water body surface area covered by the solar panel. Hence, to meet the aim of the experiment of investigating the effect of floating solar panels on the water evaporation rate, the size of the solar panel takes precedence over the power output of the solar panel during selection. Conversely, the sizes of the containers available on the commercial market are also taken into consideration when choosing the size of the solar panel to ensure their dimensions are similar. This is to mitigate the effect of external factors influencing the evaporation rate of the water in the container.

The dimensions of the selected solar panel are 470 x 345 x 25 mm (Length x Breadth x Height).

3.1.2. Solar Panel Stand

Typical solar panel stands available on the market are unsuitable for the experiment, as they do not allow the alteration of height and angle of the solar panels once fixed on. Hence to meet the experiment requirement of varying the height of the solar panel above the water body, a customized solar panel stand has to be fabricated.

The customized solar panel stand allows the solar panel to be adjusted from a height of 30 mm to 230 mm above the water body. The solar panel is also able to rotate on the customized solar panel stand. Thus, the angle of inclination of the solar panel can be changed to as desired.

3.1.3. Container

The standard US Class A evaporation pan is a metal cylindrical. However, it is challenging to find containers made of metal in Singapore. Most of the containers available in the commercial market are made of plastic. Furthermore, as the solar panel is rectangular and the solar panel stand is fabricated accordingly, it is practical to use a rectangular container so it will be able to fit within the frame of customized solar panel stand.

Existing floating solar panel systems built over water bodies do not cover the entire water surface area as it is illogical to do so. Hence to imitate the system of floating solar panels over reservoirs in the prototype, the solar panel should preferably be smaller than the water body surface. However, if the solar panel is substantially smaller than the container, the effect of placing the solar panel cannot be fully measured and will defeat the purpose of the experiment.

With the various considerations mentioned above and limited by the assortment available in the commercial market, a plastic container with internal dimensions of 530 x 430 x 115 mm (Length x Breadth x Height) is chosen.

3.2. Location

The requirement when selecting the location to place the prototype is an open area with no obstruction of sunlight and airflow. This is to replicate the conditions at a reservoir where the climate will play an influential role in the evaporation rate. Hence, the initial location selected was the National University of Singapore (NUS) school field.

However, after a few test runs, it was observed that the prototype has to be left in the open overnight for significant results. Therefore, security of the setup became an issue.

Ultimately, after approval by the school, the final experiment location was chosen to be at the rooftop of NUS Engineering Block E2. This is an ideal experiment site as there are no obstructions of sunlight and wind from nearby buildings and it is a place with restricted access. This secures the safekeeping of the setup and minimizes the probabilities of disturbance to the experiment by the public.

Furthermore, there is a weather station situated at the rooftop of NUS Engineering Block E2. With the close proximity of the weather station and the exact position of the setup, it is fair to confidently accept that the weather parameters measured by the weather station are accurate to the weather conditions experienced by the experiment setup.

The selected location is shown below in Figure 3.1:

Figure 3.2.1: Location of experiment

3.3. Weather Station

The weather station located at the rooftop of NUS Engineering Block E2 is at a height of approximately 90m above sea level. It provides the following weather parameters: air pressure, air temperature, solar radiation, relative humidity (RH), wind speed, wind direction and rainfall. The data for the various weather parameters are accessible on the NUS Geography Weather Station portal. Specifications of the various weather instruments can be found in Appendix B.

3.4. Experiment Procedure

The final setup of the experiment with the prototype and the control placed beside each other on the roof top NUS Engineering Block E2 is illustrated below in Figure 3.2.

Figure 3.4.1: Final experiment setup

Each cycle of the experiment takes a duration of 24 hours to complete, from 10 am to the following day 10 am. The same period of 24 hours is used for each cycle to minimize the difference in the climate experienced by the setup. The duration of 24 hours is chosen for practicality reasons as too short a period will not be able to produce significant results for comparison, while chances of rainfall increases with the duration of time period. This is important as rainfall will cause the results for the experiment cycle to be voided. This will be further explained below.

Before a cycle of the experiment begins, the containers were topped up with water till overspill. This is to ensure the two containers are filled to their brim. Depth of the initial water level in the two containers were measured and recorded after the overflowing stops. After 24 hours, the final water depth in both containers were then measured and recorded again to calculate the respective drop in water level.

The solar panel was placed horizontally over the container, with an initial height of 30 mm above the water surface. Three cycles of experiment were conducted for each height; in other words three sets of results were attained for every height. The experiment is then repeated for increasing elevations of the solar panel above the water body, with increments of 50 mm each time until the final height of 230 mm above the water body is achieved. This is to investigate the relationship between the solar panel's height above the water body and the effect on evaporation rate.

The initial and final water level were measured with a measuring tape of precision 1 mm. Particular attention was paid to avoid parallax error when taking the water depth readings due to diffraction in the water. The measurements were also consistently taken from the middle of the container to prevent reading errors due to uneven ground.

The middle point of the containers is marked by an imprint during the manufacturing process.

In an event of rain during the 24-hour cycle of the experiment, the results for the particular day will be voided. It is difficult to accurately interpret the exact alteration in water level caused by the rainfall as splashing may occur when the rain hits the water surface. Furthermore, should there be a heavy downpour, overflowing of the containers may transpire resulting in unaccountable errors. The prototype with a solar panel positioned horizontally over the container will obstruct the collection of rainfall into the container, hence making comparison with the control inaccurate. Hence, for simplicity and focus on the effect of evaporation rate, only results from experiment cycles with no rainfall will be accepted.

3.5. Calculation Methodology

With reference to section 2.4, the Penman equation was used to calculate the potential evaporation rate for the open water surface based on the day's weather parameters obtained from the weather station. This computed value is then compared to the pan coefficient corrected water level drop in the control container as a theoretical reference.

The daily mean air temperature, incoming solar radiation, wind speed and relative humidity used in the Penman equation is obtained by averaging the hourly measurements within the day. As the incoming solar radiation recorded by the weather station is in units of [W m^{-2}], the daily averaged value is to be converted into [MJ m^{-2}] for consistency in application of Penman equation. The conversion is attained by the following equation:

$$[MJm^{-2}] = [Wm^{-2}] \times 60 \times 60 \times 24 \times 10^{-9} \quad (3.1)$$

The date and the latitude of the location govern the intensity of extra-terrestrial solar radiation received at the top of the atmosphere on a horizontal surface. Equipped with the date and Singapore's latitude of 1.3000° N, the amount of extra-terrestrial solar radiation received each day during the experiment can be obtained using Maurer's (n.d.) program. Similarly, as the output from the program is in units of [W m^{-2}], a conversion of units has to be made using equation (3.1) for consistency purposes in Penman equation.

Evaporation estimates using the Penman equation are sensitive to the albedo value. In order to produce unbiased evaporation estimates, an optimal albedo value needs to be calibrated. Tan, Shuy & Chua (2006) conducted an investigation in Singapore by computing estimates of daily evaporation rate using different albedo values and compared them with the measured daily evaporation rates. The plot in Figure 3.3 indicated that an albedo value of 0.1259 generated unbiased evaporation estimates.

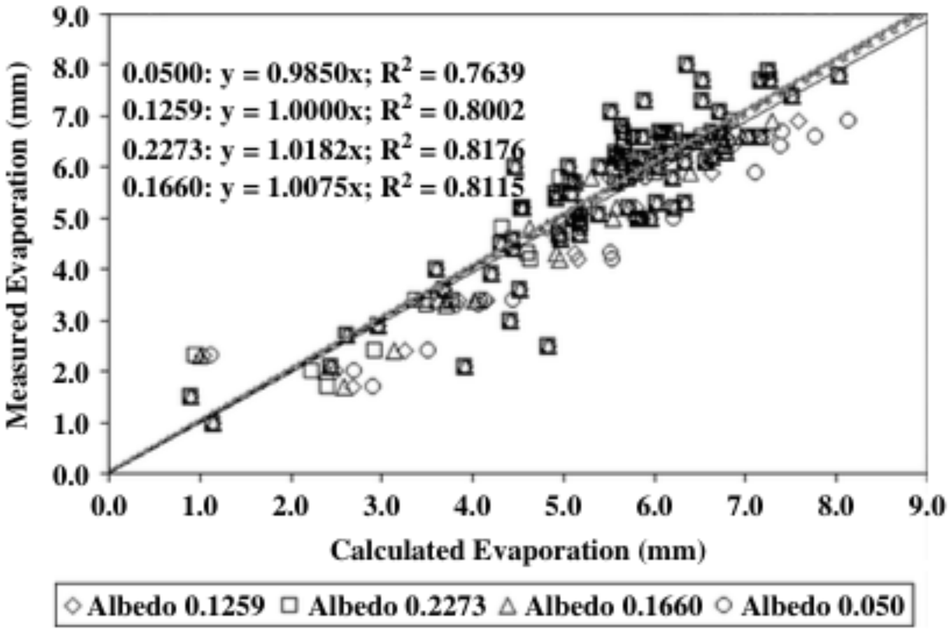

Figure 3.5.1: Estimation of unbiased albedo value (Tan, Shuy, & Chua, 2006)

The net incoming short wave radiation is defined as:

$$R_S = (1 - \alpha)R_O \times 60 \times 60 \times 24 \times 10^{-9} \quad (3.2)$$

where R_S is the daily net incoming short wave radiation (MJ m^{-2}), α is the albedo value (0.1259) and R_O is the incoming short wave radiation recorded by the weather station (W m^{-2})

Since the wind function, $f(u)$ is empirical and varies with location, it is recommended to be calibrated on site for higher accuracy. However, this is challenging to obtain due to limited knowledge on methodology, resources and time. Upon consulting other modified versions of the Penman equation, such as the FAO[1] Penman-Monteith equation, the wind speed function has been simply replaced by the measured wind speed. Hence the same approach has been implemented by employing the recorded wind speed, u (m s^{-1}) in place of $f(u)$.

As mentioned in section 2.5, a pan coefficient has to be applied to the evaporation pan measurements for translation of the results to the actual evaporation in reservoirs. The pan coefficient value applied in the experiment is 0.7 following the recommendations in various literatures.

[1] Food and Agriculture Organization of the United Nations

4. Results and Discussions

4.1. Comparing Penman with Control

Table 4.1 presents the average weather parameters of the day, the potential evaporation rate calculated using Penman equations and the measured drop in water level of the control container.

Table 4.1.1: Estimated evaporation rates from Penman equation and experiment control

Date	P	T_m	R_o	RH	u	PET	E_{pan}	ET_0
	(kPa)	(^oC)	W m^{-2}	%	m s^{-1}	mm day^{-1}	mm day^{-1}	mm day^{-1}
24/3/15	100.3	27.9	157.9	69.6	3.6	5.5	7.0	4.9
25/3/15	100.3	28.1	149.3	69.4	4.3	5.8	8.0	5.6
26/3/15	100.4	28.2	143.0	70.2	4.2	5.5	7.0	4.9
27/3/15	100.3	28.2	169.7	72.7	3.9	5.9	9.0	6.3
30/3/15	100.2	28.3	123.5	74.5	2.5	3.7	6.0	4.2
31/3/15	100.2	27.6	130.2	78.1	2.1	3.4	6.0	4.2
4/4/15	99.9	28.7	185.6	75.1	1.7	5.1	8.0	5.6
6/4/15	100.0	28.0	156.9	76.6	2.9	4.7	7.0	4.9
8/4/15	100.1	28.7	126.9	71.8	2.9	4.3	6.0	4.2
10/4/15	100.2	28.8	168.7	69.0	2.5	5.3	8.0	5.6
11/4/15	100.3	27.3	119.0	75.4	2.8	3.6	6.0	4.2
13/4/15	100.2	28.4	157.1	71.1	2.7	5.0	7.0	4.9
14/4/15	100.1	28.7	155.1	67.5	2.9	5.3	7.0	4.9
15/4/15	100.3	28.8	159.1	68.4	2.7	5.3	7.0	4.9
16/4/15	100.3	29.0	152.7	66.5	3.5	5.8	8.0	5.6

The calculated evaporation rate using Penman equation is plotted against the drop in water level of the control container after correction with the pan coefficient, in a scatter graph, as illustrated in Figure 4.1. Under ideal conditions, the two sets of results are expected to be identical. The closer the scatter plots are to the identity line, indicates the similarity of the two sets of results. If the two data sets are equal to each other, the scatter plot will fall exactly on the identity line.

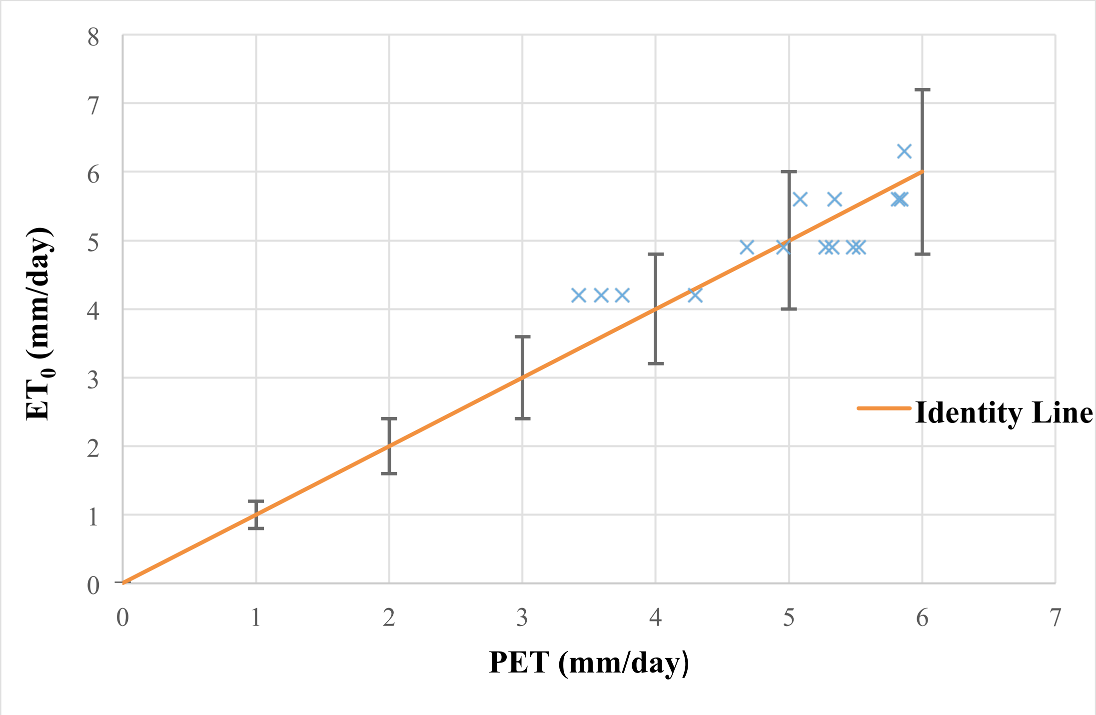

Figure 4.1.1: Plot of ET_0 against PET compared against identity line

As mentioned in section 2.4.1, Penman equation is a combination of mass transfer and energy budget methodologies, Harwell (2012) stated in his report that numerous researches have revealed that estimation of evaporation rates from evaporation pans commonly fall within 20% of energy-budget and water-budget estimates. Observed in Figure 5, the scatter plots all fall within the 20% error range of the identity line. The errors bars with caps marked in black indict the error range. Hence, it is fair to conclude that the experiment setup is a realistic imitation of conditions at a reservoir.

4.2. Comparing Prototype with Control

In order to investigate the effect of solar panels on evaporation rate, the prototype was compared to the control. Table 4.2 and Figure 4.2 illustrate the respective drop in water level of the prototype and the control for each experiment day. There is a clear indication that the presence of the solar panel do have the expected effect of reducing evaporation rates. While the control has an average daily evaporation rate of 7.1 mm, the prototype has an average daily evaporation rate of 5.3 mm; a difference of 2.2 mm.

Table 4.2.1: Comparison of evaporation rate between prototype and control

Date	P (kPa)	T_m (°C)	R_o W m^{-2}	RH %	u m s^{-1}	E_{pan} mm day^{-1}	Prototype Evaporation Rate mm day^{-1}	Difference mm day^{-1}
24/3/15	100.3	27.9	157.9	69.6	3.6	7.0	5.0	2.0
25/3/15	100.3	28.1	149.3	69.4	4.3	8.0	6.0	2.0
26/3/15	100.4	28.2	143.0	70.2	4.2	7.0	5.0	2.0
27/3/15	100.3	28.2	169.7	72.7	3.9	9.0	5.0	4.0
30/3/15	100.2	28.3	123.5	74.5	2.5	6.0	6.0	0.0
31/3/15	100.2	27.6	130.2	78.1	2.1	6.0	4.0	2.0
4/4/15	99.9	28.7	185.6	75.1	1.7	8.0	5.0	3.0
6/4/15	100.0	28.0	156.9	76.6	2.9	7.0	6.0	1.0
8/4/15	100.1	28.7	126.9	71.8	2.9	6.0	5.0	1.0
10/4/15	100.2	28.8	168.7	69.0	2.5	8.0	6.0	2.0
11/4/15	100.3	27.3	119.0	75.4	2.8	6.0	5.0	1.0
13/4/15	100.2	28.4	157.1	71.1	2.7	7.0	6.0	1.0
14/4/15	100.1	28.7	155.1	67.5	2.9	7.0	5.0	2.0
15/4/15	100.3	28.8	159.1	68.4	2.7	7.0	4.0	3.0
16/4/15	100.3	29.0	152.7	66.5	3.5	8.0	7.0	1.0

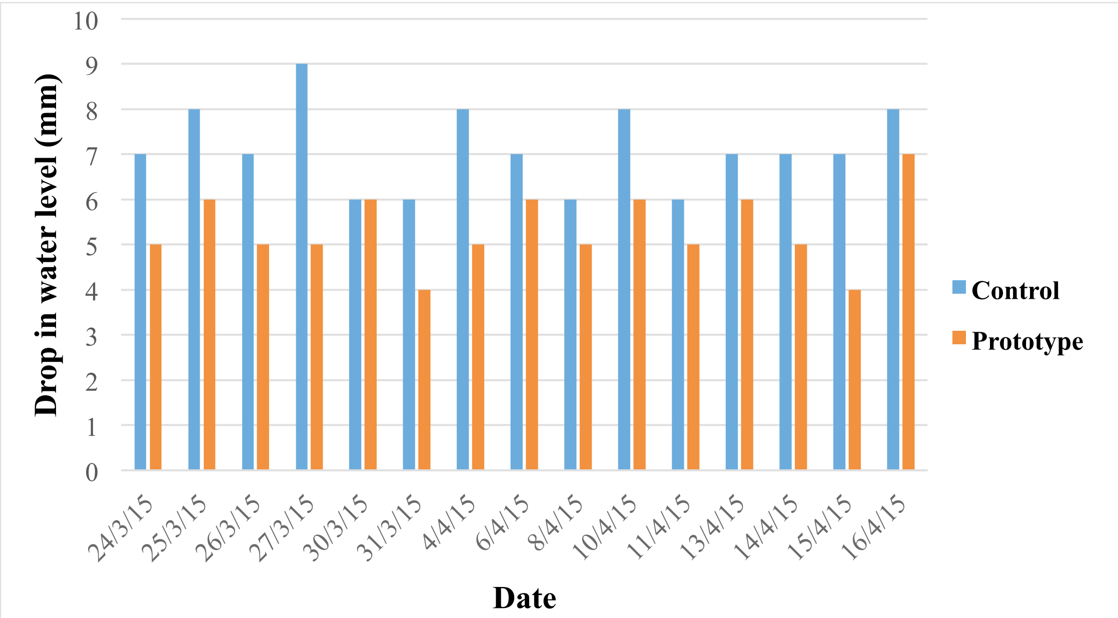

Figure 4.2.1: Comparison of evaporation rate between prototype and control

The difference in drop of water level between the prototype and the control is presented in a column chart and sorted according to the quantity of occurrences. As shown in Figure 4.3, the difference ranges from 0 to 4 mm. A difference of 2 mm between the drop in the water level of the prototype and the control is observed to have the highest frequency. A differential of 2.2 mm in water level translates to a reduction of 31% in daily evaporation rate on average. Still, this is considerably lower than the reduction of 70% claimed by SPG Solar.

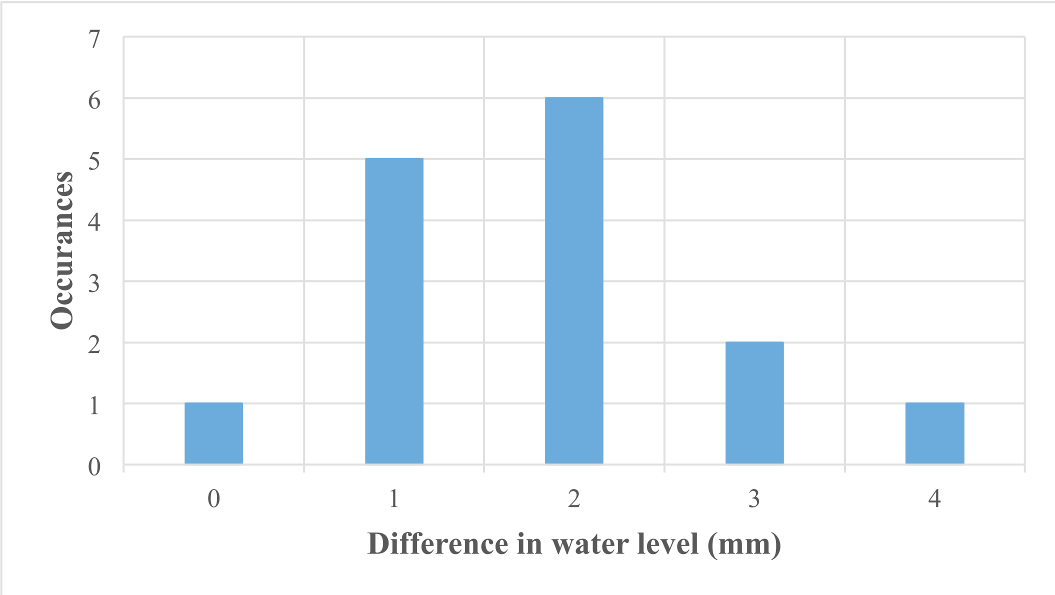

Figure 4.2.2: Occurrences of water level difference between prototype and control

With the inner dimensions of the container, a water level height of 2.2 mm indicates that 0.000466 m^3 of water was saved from evaporation by positioning the solar panel above the water body. Taking the density of water as 1000 kg m^{-3} and latent heat of vaporization as 2.45 MJ/kg, this translates to 1.14 MJ of energy.

However, this does not account for the energy saved in raising the temperature of the water. During the course of the day, the temperature of the water in the container of the control rises, before falling as night fall approaches. On the other hand, with the solar panel acting as a shade, the temperature of the water in the prototype's container maintained fairly constant throughout the day. Increase in the water temperature, if any, are also at a slower rate compared to the control. It is challenging to track the differences in the water temperatures as they are dependent on the day's weather and time measured. By observations, differences in water temperature between the two set ups ranges between 0 to 2 ^{o}C.

4.3. Height of Solar Panel and Evaporation Rate

The height of the solar panel placed above the water body surface is anticipated to have an effect on evaporation rates. The higher the solar panel is positioned above the water body surface, the larger the volume of air flow existing between the solar panel and the water surface. A faster evaporation rate is expected as there is more capacity to hold water vapour, thus the daily evaporation rates for the respective heights of solar panel placed above the water body surface is recorded in Table 4.3.

Table 4.3.1: Evaporation rate sorted by height of solar panel above water body

Date	Height of Solar Panel	E_{pan}	Prototype Evaporation Rate	Difference
	mm	mm day^{-1}	mm day^{-1}	mm day^{-1}
24/3/15	30.0	7.0	5.0	2.0
25/3/15	30.0	8.0	6.0	2.0
13/4/15	30.0	7.0	6.0	1.0
8/4/15	80.0	6.0	5.0	1.0
10/4/15	80.0	8.0	6.0	2.0
11/4/15	80.0	6.0	5.0	1.0
26/3/15	130.0	7.0	5.0	2.0
27/3/15	130.0	9.0	5.0	4.0
14/4/15	130.0	7.0	5.0	2.0
4/4/15	180.0	8.0	5.0	3.0
6/4/15	180.0	7.0	6.0	1.0
15/4/15	180.0	7.0	4.0	3.0
30/3/15	230.0	6.0	6.0	0.0
31/3/15	230.0	6.0	4.0	2.0
16/4/15	230.0	8.0	7.0	1.0

The average daily evaporation rates of the prototype and control for each height of solar panel above the water body surface are plotted in a stacked column chart in Figure 4.4. The difference in the average daily evaporation rate between the prototype and the control for each respective height is also reflected in the diagram.

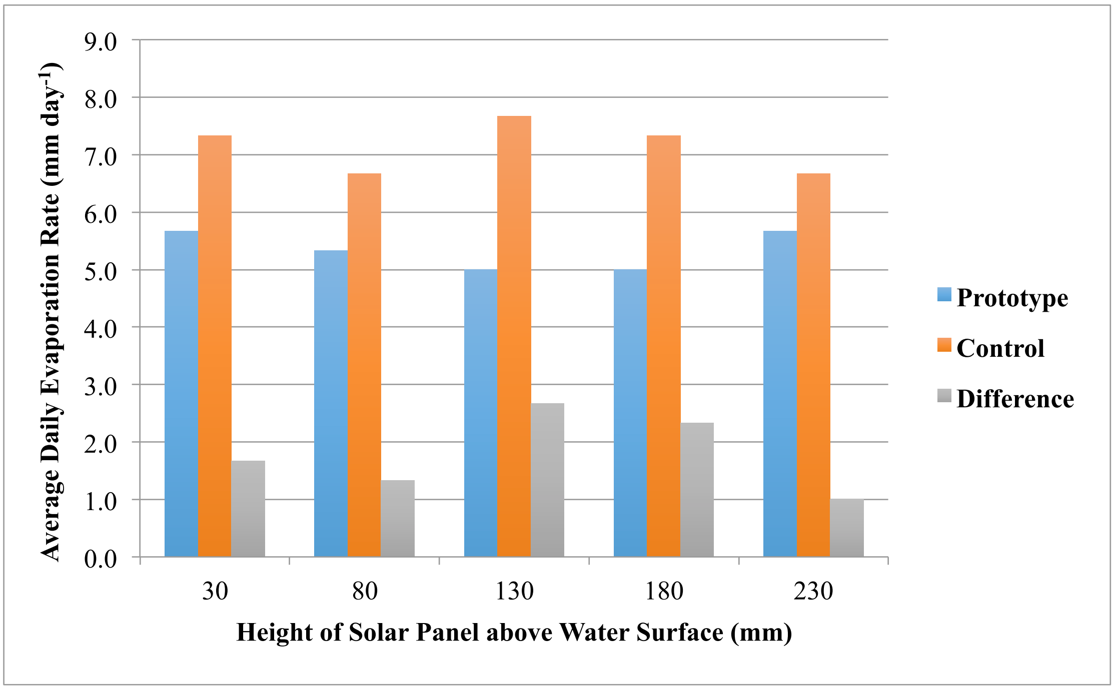

Figure 4.3.1: Average evaporation rates sorted by height of solar panel above water surface

Using the average daily evaporation rates for comparison, the height of the solar panel above the water body surface does not have the predicted effect on evaporation rates. Despite increasing the height of the solar panel above the water surface and expecting a faster evaporation rate, the difference in evaporation rates between the prototype and the control does not decrease correspondingly. In fact, no visible pattern can be observed. This indicates that varying the height of the solar panel placed above the water body does not cause a significant effect on evaporation rate that results in a clear correlation.

4.4. Limitations of Experiment and Recommendations

Although the results of the prototype showed a reduction in daily evaporation rates of approximately 31%, it will be careless to accept it as the verdict. The experiment has its limitations that potentially affected the experiment results and further observations have to be carried out before drawing conclusions.

4.4.1. Small Sample Size

Due to time constraint and controlled by bad weather, only 12 sets of readings were obtained for the study. This is a relatively small sample size when compared to other experimental studies regarding evaporation rates. Researches on evaporation rates usually take place over years to observe and verify a pattern before a conclusion can be drawn. This is because evaporation rates are strongly influenced by the season changes during the year. Although Singapore does not have four seasons, it is subjected to the Monsoon season that causes wet and dry phases in particular months.

As seen in Figure 6, the occurrence of the respective water level differences between the prototype and control are relatively comparable. Over a longer period of data collection, the mean and mode of the data may deviate significantly. Hence, more observations should be made for a holistic study.

4.4.2. Short Experiment Cycle Duration

The rationale for setting 24 hours as the duration of each experiment cycle has been discussed in section 3.4. However, as water in reservoirs is undoubtedly kept for a lengthier period of time, the effect of solar panels on evaporation rate over an extended period of time is important. Evaporation rates do not follow a fixed pattern and the results cannot be interpolated. Hence, it is necessary to conduct experiment cycles of a longer interval to observe the effects. However, as the probability of rain during the experiment increases with longer cycle duration, it is likely a method has to be implemented to take the intensity of rainfall into consideration.

4.4.3. Sensitivity of Experiment

A measuring tape with a precision of 1 mm is used to measure the initial and final water depths. This method is simple to practice but subjected to reading errors. Furthermore, minuscule loss in water volume may not be reflected in a drop in the water level. A better approach will be to measure the weight of the water in the containers before and after the experiment. This allows a more precise measurement of the amount of water evaporated during the experiment.

5. Conclusions and Suggested Future Work

This chapter summarizes the work performed in this study and discuss the future work which can be pursued in this topic.

5.1. Conclusions

A prototype was built to study the effect of floating solar panels on evaporation rates in Singapore reservoirs. The experiment is modelled based on the concept of evaporation pans. A control was also set up for comparison purposes.

The Penman equation was used to calculate the potential evaporation rate in the reservoirs based on the average weather parameters of the day. The drop in water level of the control's container was then measured and corrected with a pan coefficient of 0.7, before comparison with the calculated Penman equation value. Results showed it is reasonable to conclude that the experiment set up is a fair representation of an actual reservoir.

Floating solar panels above the water body does have a reduction effect on evaporation rates as predicted. Comparing the difference in drop of water levels between the prototype and the control, it was observed that that the floating solar panel reduces evaporation rates by approximately 30% on average.

The height of the solar panel placed above the water surface was also varied to study for a correlation with evaporation rates. However, a pattern was unable to be observed, suggesting that varying the height of solar panels above water body surfaces do not a significant effect on the evaporation rate.

Further observations have to be made before concluding on the effect of floating solar panels on evaporation rates in reservoirs. Time constraint has resulted in a small collection of data attained. This is inadequate and conclusions drawn from the results may change if more data points are obtained. The short time period of each experiment cycle is also insufficient to conclude the long-term effects of floating solar panels on evaporation rates in reservoirs.

5.2. Suggested Future Work

The solar panel in the experiment setup was purposely placed horizontally above the water surface to observe the relationship between the height of the solar panel above the water surface and evaporation rates. However, solar panels are normally installed at an angle. The study on the angle of inclination of the solar panel and effect on evaporation rates was proposed but unable to carry out due to a lack of time. As floating solar panels are also installed at an angle above water bodies, it will be beneficial to investigate the effect a sloping solar panel and its angle of inclination has on evaporation rates.

From the experiment, floating solar panels above water bodies helps to prevent wastage of solar energy in raising water temperature and reducing evaporation. However the amount of solar energy 'saved' that is actually converted into electricity by the solar panel is a question that has yet to be answered.

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7. Appendices

Appendix A

Table A.1: Specifications of solar panel

Model	**KMX-20**
Maximum Power	20 W
Open Circuit Voltage	22.3 V
Short Circuit Current	1.21 A
Working Voltage	17.8 V
Working Current	1.12 V
Working Temperate	-45 ^{o}C to 80 ^{o}C
Tolerance	± 3%

Figure A.1: Selected solar panel

Figure A.2: Solar panel stand with container

Figure A.3: Adjustable height and angle of solar panel on stand

Appendix B

Table B.1: Weather instruments specifications

Variable	Instrument	Manufacturer (Model)	Units	Accuracy
Pressure	Barometric pressure sensor	Vaisala (PTB101B - CS105)	kPa	+/- 0.2 kPa at 20 ^{o}C
Air temperature	T sensor	Vaisala (CS500)	^{o}C	+/- 0.5 ^{o}C
Relative humidity	RH sensor	Vaisala (CS500)	% RH	+/- 2.5 % RH
Wind speed	Cup anemometer	RM Young (wind sentry set 03001)	m/s	+/- 0.5 m/s Threshold: 0.5 m/s
Wind direction	Wind vane	RM Young (wind sentry set 03001)	0-360^{o} (c.w.)	+/- 5%
Incoming solar radiation	Pyranometer	LI-COR (LI-200X)	W/m 2	+/- 3% (typical)
Total rainfall	Rain gauge	Hydrological Services (CS700)	mm/time (5 min or 1 hr)	+/- 2% Resolution: 0.2 mm
Power	Solar panel	SOLAREX (MSX15R)	W	
	Data logger	CSI (CR10X)		