FEASIBILITY STUDY ON IMPLEMENTATION OF MEDIUM TEMPERATURE SOLAR THERMAL ENERGY IN INDUSTRIAL PROCESSES - A CASE STUDY IN MALAYSIA

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ABSTRACT

A case study on the feasibility of implementing medium temperature solar thermal energy in industrial processes in Malaysia is conducted. The objective is to determine if it is technically and economically viable to utilize the solar thermal renewable energy at a temperature range of 80-250℃ as a substitute to conventional means of generating thermal energy. Solar energy is the source of most other renewable energies, and Malaysia being situated at the equator makes us geographically favorable to harness this free energy. Almost half of the industrial processes use thermal energy rather than electrical energy, and the output of a solar thermal system can fit in nicely as a contributor to the industries' energy mix. Literature reviews are conducted on the climatology of Malaysia, in particular, the solar irradiance, the technologies involved and the various industries in Malaysia are then studied to identify potential candidates to utilize this renewable energy. Also, different types of solar collector technologies are studied and explored. After that, a particular industry and its industrial process are chosen for a case study. A solar thermal system is designed and sized to fulfill needed energy requirements for the process. Then, a simulation is performed to determine the overall output of the system based on Malaysian meteorological data. Based on the results, the contribution of solar thermal energy in supplementing the plant's energy requirement, i.e. solar fraction is determined. A cost and benefit analysis is done on the system, taking into account of initial investment and consumption cost for a period of 10 years, without consideration of maintenance cost. The results are compared with other means of generating heat, namely boiler, heat pump, electric heater and solar PV powered electric heater. It is determined that solar thermal energy provides the greatest saving. However, due to the large fuel oil subsidy by the Government currently, solar thermal system is attractive for only low temperature ranges.

ABSTRAK

Satu kajian kes mengenai kebolehlaksanaan melaksanakan tenaga terma suria suhu sederhana dalam proses perindustrian di Malaysia telah dijalankan. Objektif kajian ini adalah untuk menentukan jika ia berdaya maju dari segi teknikal dan ekonomi untuk menggunakan tenaga terma suria yang boleh diperbaharu pada julat suhu daripada 80-250C sebagai pengganti kepada cara konvensional seperti dandang dan pemanas elektrik untuk menjanakan tenaga terma. Tenaga suria merupakan sumber kepada kebanyakan tenaga boleh diperbaharui yang lain. Lokasi geografi Malaysia yang terletak di khatulistiwa memanfaatkan kita untuk menggunakan tenaga percuma ini. Hampir separuh daripada proses industri menggunakan tenaga haba daripada tenaga elektrik. Output sistem terma suria boleh digunakan sebagai penyumbang kepada sumber tenaga industri. Kajian literature telah dijalankan ke atas iklim Malaysia, khususnya, sinaran suria, tecknologi tenaga haba suria dan pelbagai industri di Malaysia akan dikaji untuk mengenal pasti calon-calon yang berpotensi untuk menggunakan tenaga boleh diperbaharui ini. Pelbagai jenis teknologi pengumpul suria juga dikaji dan diterokai. Selepas itu, industri tertentu dan proses industrinya telah dipilih untuk menjalankan kajian kes. Satu sistem terma suria direka bentuk untuk memenuhi keperluan tenaga yang diperlukan untuk proses industri tersebut. Kemudian, simulasi dilakukan untuk menentukan output keseluruhan sistem berdasarkan data meteorologi Malaysia. Berdasarkan keputusan simulasi, sumbangan tenaga terma suria dalam memenuhi keperluan tenaga kilang, seperti pecahan suria ditentukan. Satu analisis kos dan faedah dilakukan ke atas system ini untuk tempoh 10 tahun menggunakan kos system and pemasangan. Keputusan ini telah berbanding dengan cara menjana haba yang lain. Kesimpulannya tenaga haba suria paling jimat. Tetapi kenara subsidi kerajaan, ianya jimat hanya untuk suhu rendah.

ACKNOWLEDGEMENT

First of all, I would like to use this opportunity to thank my supervisor, Associate Professor Ir. Dr. Yau Yat Huang for giving me guidance and advices throughout the completion of this thesis.

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NOMENCLATURE

Nomenclature	Description	Unit
$SIPH$	Solar Process Industrial Heat	-
kW_{th}	Kilo Watt Thermal	kW
G	Solar Irradiation/ Insolation/ Incident Radiation	kW/m^2
SF	Solar Fraction	%
α	Absorptivity	-
ρ	Reflectivity	-
τ	Transmissivity	-
G_{abs}	Absorbed Radiation	kW/m^2
G_{ref}	Reflected Radiation	kW/m^2
G_{tr}	Transmitted Radiation	kW/m^2
$\%\eta$	Solar Collector Efficiency	%
η_0	Optical Efficiency	%
a_1	Liner Loss Co-efficient	$W/m^2.K$
a_2	Quadratic Loss Co-efficient	W/m^2K^2
Tm	Mean Temperature of Solar Collector	℃
Ta	Surrounding Ambient Temperature	℃
q_s''	Net Solar Irradiation Absorbed	kW
$A_{aperture}$	Solar Collector Aperture Area	m^2
$\dot{m}$	Mass Flow Rate	kg/s
c_p	Specific Heat Capacity	J/kg.K
T_{out}	Temperature of Fluid from Collector	℃
T_{in}	Temperature of Fluid into Collector	℃
C_r	Heat Capacity Ratio	-

Nomenclature	Description	Unit
C_{min}	Lower Heat Capacity Rate	W/K
C_{max}	Higher Heat Capacity Rate	W/K
C_c	Cold Fluid Heat Capacity Rate	W/K
C_h	Hot Fluid Heat Capacity Rate	W/K
NTU	Number of Transfer Unit	-
ε	Heat Transfer Effectiveness	%
U_h	Overall Heat Transfer Co-efficient	$W/m^2.K$
A_h	Heat Transfer Area	m^2
$T_{hot,in}$	Fluid Temperature out from Heat Exchanger on Hot side	℃
$T_{hot,out}$	Fluid Temperature into Heat Exchanger on Hot side	℃
$T_{collector,in}$	Temperature of Fluid into Collector	℃
$T_{collector,out}$	Temperature of Fluid from Collector	℃
$T_{process,in}$	Temperature of Fluid for Process	℃
$T_{process,out}$	Temperature of Fluid Returned from Process	℃

LIST OF APPENDICES

CHAPTER 1:INTRODUCTION

1.1 Background

Solar Thermal is a technology for harnessing solar energy for thermal energy. The temperature of the working fluid or carrier fluid classifies the different thermal systems, namely High, Medium and Low temperature systems. Low temperature systems are where water does not reach the boiling point, being less than 80℃, usually through a flat plate collector. Medium temperature systems is in the region of 80℃ to 250℃, achievable through technologies such as evacuated heat pipes with or without the need of concentrators. Finally, working fluid with temperature more than 250℃ are High Temperature Systems, where concentrators is necessary to be employed to bring the working fluid to such high temperatures.

With the push for renewable energy, Malaysia being geographically stationed in the equator gives overwhelming advantage in receiving high solar irradiation. To leverage our advantage, our government through the Economic Transformation Programme has identified solar photovoltaic technology to be the predominant method of harnessing the energy of the sun.

However, with Malaysia still as an industrious nation, there are a lot of demand for thermal energy, rather than electricity for various manufacturing processes. Citing a report from the EU, electricity consists of 33% while the rest of 67% are thermal energy, and a substantial portion is located in the Medium temperature systems. In the report, there are even breakdowns of the various industries which will benefit much from the "free" thermal energy.

Europe is a country with 4 seasons. Solar irradiation is cyclical and on average lower than Malaysia. However, with so much effort from the EU to research on solar thermal,

and to find it economically feasible and widely implemented, it brings into mind that why not Malaysia also follow suit?

This research report is motivated by this premise.

Widely available findings from the around the world is localized to fit the Malaysian context and decided upon on implementation feasibility. Theoretical information is translated to a customized solution to a particular process for a plant in Malaysia. Subsequently, a cost and benefit analysis is performed.

CHAPTER 2: RESEARCH OBJECTIVES

2.1 Objective

To identify the potential and feasibility of solar thermal energy application for use in industries in Malaysia, through evaluation of:-

1. Malaysia's Solar Energy Potential,
2. Potential of applying in industrial processes,
3. The technology availability,
4. Proposed system design, and
5. Cost and Benefit analysis using 10 year payback period comparing with other conventional means of thermal energy generation.

CHAPTER 3: LITERATURE REVIEW

3.1 Solar Thermal Energy

Solar thermal energy is an innovative technology for harnessing solar energy for thermal energy (heat) and is achieved through use of solar thermal collectors. Solar thermal collectors can be classified into three types as low-, medium-, or high-temperature collectors, depending on the working fluid output temperature achievable by the United States Energy Information Administration with Low being below 100 ℃, medium being between 100 ℃ - 400 ℃ and High for beyond 400 ℃.

The potential for solar thermal collectors to supplement the energy needs of industrial sector, known as Solar Industrial Process Heating (SIPH), is huge, which is detailed in the following sections. The formation of Task 33 (Solar Heat for Industrial Processes) by the International Energy Agency Solar Heating and Cooling (IEA SHC) Programme in 2003 is the demonstration of the seriousness of European countries in the push for higher utilization of this technology. Since the completion of the task force in October 2007, a comprehensive report was prepared which provides a good understanding of the technologies involved and the potential for implementation in Europe.

The report provides the result of studies carried out in two industrial sectors from Germany and Greece and overall potential review on Belgium, Australia, Austria, the Iberian Peninsula (Spain and Portugal), and Italy. It found that 90 operating solar thermal plants for process are reported throughout the world, where the total capacity is approximately 25 MWh (35,000 m^2). The plants distribution by sector and country are shown in Figure 3.1 and Figure 3.2.

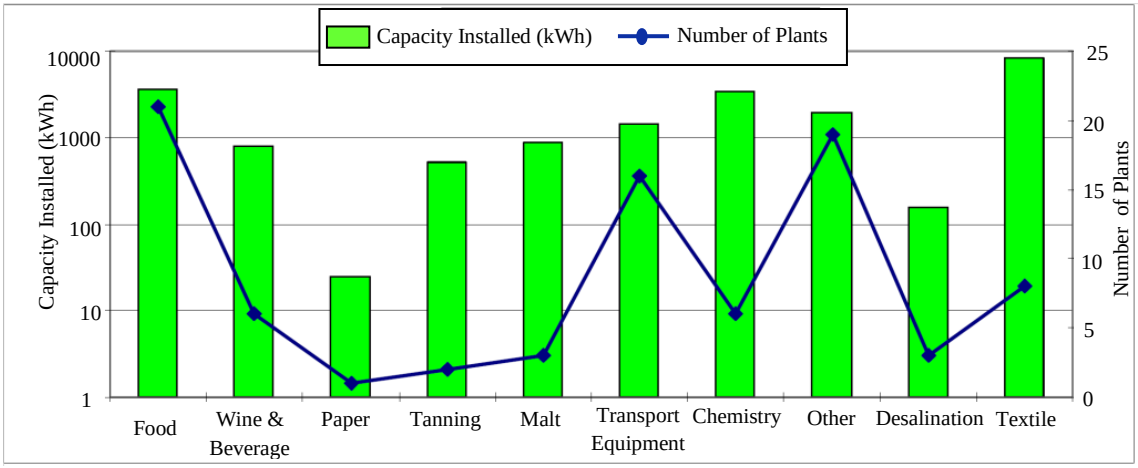


Figure 3.1 Solar industrial process heat plants - distribution by industry sector. Source: IEA SHC Task 33, 2007

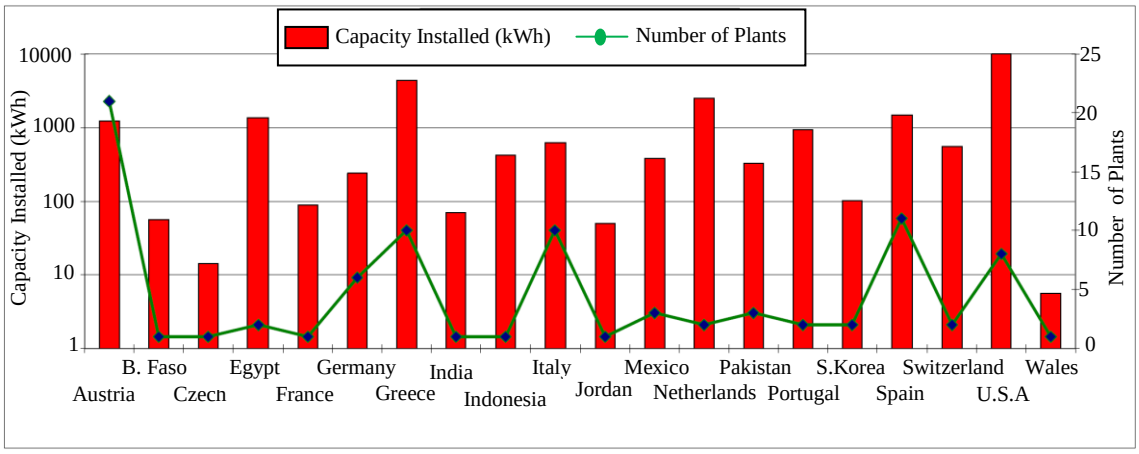


Figure 3.2 Solar industrial process heat plants - distribution by country. Source: IEA SHC Task 33, 2007

The analysis of the countries studied shows that solar thermal could provide the industrial sector with 3-4% of its heat demand. An extrapolation of the national figures to the European level shows that solar thermal could provide 258 PJ/year of thermal energy to the EU25 industrial sector or an installed capacity of 100-125 GW_{th} (143-180 Million m^2) (IEA SHC, 2007). It has been concluded that there is a relevant, promising, suitable and so far almost unexploited market sector for applying solar thermal technology. Support from policy makers are needed to promote this untapped resource.

In another study, 35 solar thermal companies from around the globe were surveyed and the result shows that many large solar thermal energy systems are installed around the globe (Meyer, 2009); unlike the limited number reported by the IEA SHC report. There are around 9000 in China, 200 in India and 320 in Turkey. Majority of systems installed are between 50m^2 to 500m^2. Of the companies surveyed, only three have installed systems larger than 500m^2. Most large scale projects are similar in the fact that most are designed and built since 2005 (Fuller, 2010).

In China, Solar thermal technologies have been rigorously studied in China since the 1980s (Wang, 2009). In terms of solar water heating for domestic uses, the country has an installed capacity of 108 million m^2 collector area in 2007, consisting of 60% of SWHs market globally (Luo, 2008). A breakdown of the market share of SWH collector market share in the world is shown in Figure 3.3.

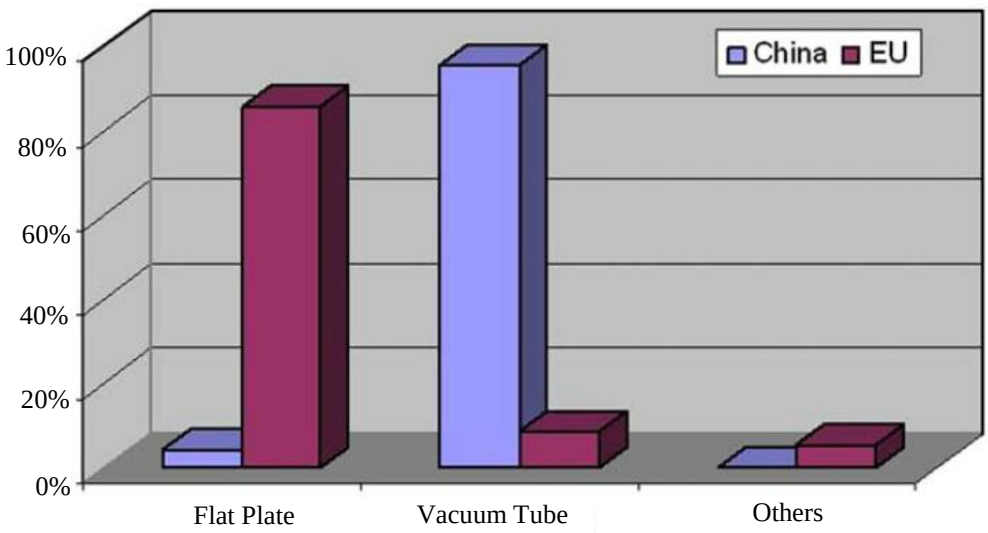


Figure 3.3 Market shares of SWH products in China and EU. Source: Han et. al., 2007.

It can be seen that China is the market leader for vacuum tube. This fact is kept in mind during sourcing for evacuated heat tube manufacturers. Kulkarni (2008) has various models for solar thermal design. However, a more simplistic approach is utilized here, to be explained in Chapter 4.

Globally there are many literatures available on the topic of SIPH. However, there are few on this topic in Malaysia. Most of the current studies highlight the potential but there are no comparison of dollars and cents to it. This knowledge gap is to be cleared in this dissertation.

3.2 Thermal Energy Usage in Industrial Processes

A typical industrial energy system can be split into 4 functional parts, as below:-

1. A power supply as the source of the motive force is needed. It can be derived from electricity, gas, oil or biomass. These primary sources of power are then converted to desired usable energy form, such as electricity, steam, compressed air or hot water to feed into the process.
2. A production plant, where various industrial process is applied to inputs for a desired output products.
3. An energy recovery system, where its presence is to optimize and further utilize the remaining energy present after the power plant or production plant.
4. A cooling system. Most production process would need to bring down the temperature for the final product. Thermodynamically, cooling is required for the power plant for a continuous cycle to exist.

The block diagram shown in Figure 3.4 represents a typical conventional industrial energy system, as explained

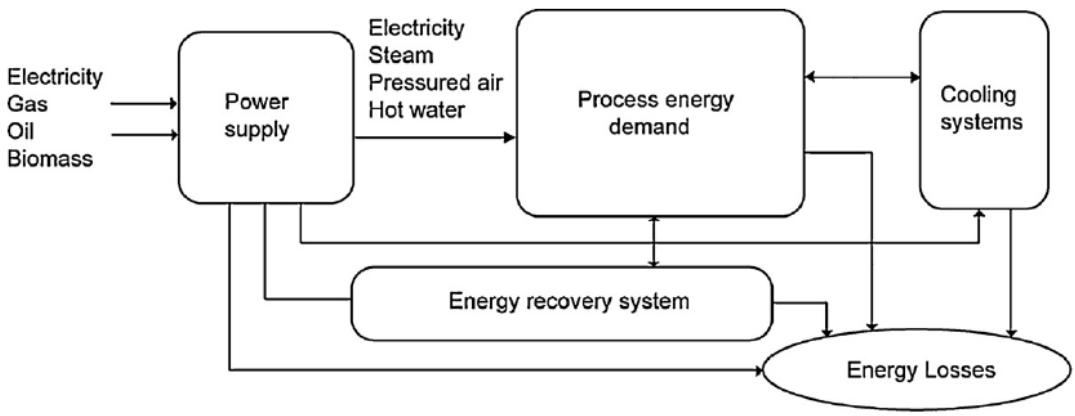


Figure 3.4 Block diagram of a typical industrial energy system. Source: Schnitzer, 2007.

Solar thermal can be applied for the production of power supply in electricity form or the heat energy to be applied directly to bring up the temperature of the process. In industrial processes, thermal energy is a major source of energy used as for example evident from studying a typical Sankey diagram for a dyehouse, shown in Figure 3.5. Hot water constitutes almost half of the energy used.

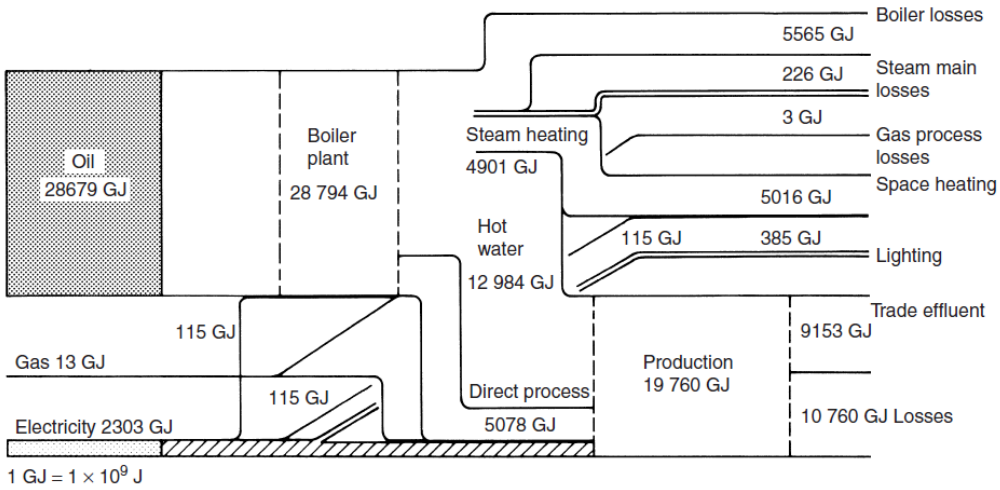


Figure 3.5 A typical energy usage pattern for a dyehouse. Source: Plant Engineers Handbook, 2001.

A large number of industrial applications utilized heat with temperature ranging from 80 ℃ to 240 ℃ (Proctor, 1977 & Kalogirou, 2003). Studies into the industrial energy usage pattern demonstrate that solar thermal energy has many usages in the medium temperature levels (i.e. 80–240 ℃) (Kalogirou, 2003). Process heat of less than 100 ℃ is required by 13% of industrial thermal applications while approximately 27% consists of processes up to 200 ℃ (Goyal, 1999).

Solar thermal applications in industrial sectors can be classified as below (Mekhilef et al, 2010):

1. Hot water or steam demand processes
2. Drying and dehydration processes
3. Preheating
4. Concentration
5. Pasteurization, sterilization
8. Industrial space heating
9. Textile
10. Food
11. Buildings
12. Chemistry
13. Plastic

6. Washing, cleaning
7. Chemical reactions
14. Business establishments

The temperature range of common industrial processes is given by Figure 3.6 (Kalogirou, 2003).

Industry	Process	Temperature (°C)
Food industry	Sterilization	60-120
	Pasteurization	60-80
	Cooking	90-100
	Bleaching	60-90
	Washing	60-90
Chemical	Soaps	200-260
	Synthetic rubber	150-200
	Processing heat	120-180
	Pre-heating water	60-90
Plastics	Preparation	120-140
	Distillation	140-150
	Separation	200-220
	Extension	140-160
Textile	Bleaching, dyeing	60-90
	Drying, degreasing	100-130
	Fixing	160-180
	Pressing	80-100

Processes and temperature ranges
(kalogirou, 2003)

Figure 3.6 Processes and temperature ranges. Source: Kalogirou, 2003.

As an example of SIPH application in real life, we turn to China, the world's leader in evacuated tube solar collectors. For current industrial usage in China, most are used for drying of agricultural products. Solar drying is gaining traction because of the flexibility of the drying process allows it to be done at a lower temperature for a longer time, which coincidently is beneficial to the quality of the product. For these purposes, more than 100 sets of solar dryers are distributed across China (Xiao et. al., 2004). As an example of successful applications, in Guangdong Province a 620 m^2 aperture area large-scale solar assisted dryer for sausage drying was built in 2000 (Liu, 2000). The system was found to reduce coal consumption by 30%. Another example of industrial application can be found in Shangshu Dongfang Yinran Factory. It is a large scale solar-roof heating system with a total aperture area of 10,000 m^2 (Zhiqiang Liu et. al., 2011).

In Australia, the awareness of SIPH was already present 30 years ago. Through the active promotion of the government bodies, at least 16 systems were installed around the continent. The systems installed range from $75m^2$ to $3855m^2$, using mostly flat plate collectors. However, there are few, if any of those remnants in operation (Fuller, 2010). It was believed at that moment that low energy price were the cause of the low acceptability of SIPH. At the turn of the century, things changed. Industries for example food processing have adopted evacuated tube solar collector offered by Solahart, Australian's biggest solar thermal collector manufacturer (AGO, 2006). Now, the largest reported installation is in a hospital in South Australia consisting of 296 solar panels. Despite the huge potential (Beath, 2012), the adoption in industrial process heating is still few, if any (Fuller, 2010).

SIPH acceptance by the global market is still lukewarm, although there are vast improvements at the turn of the century. Malaysia has recognized the potential of solar energy, in the form of a great push by the government for solar energy technology implementation through the Economic Transformation Programme, Entry Point Project 10 (ETP, 2010). However, the focus was on solar generated electricity and solar thermal for process heat have not received the attention that it should.

To get a full appreciation of the solar aspect of SIPH, an overview of harnessing solar energy and its potentials is provided in the following sections.

3.3 Malaysia Energy Usage Pattern

The energy demand of Malaysia in 2009 is 16,132 MW, compared to 10 years before the demand of electricity is just 9690 MW (The Malaysia Economic in Figures, 2010). This constitutes a rising in electricity demand from 1999 of about 66.5%. In the year 2000, the major user of energy in Malaysia is by the transport sector. However, in the year 2009, there is a shift in the trend of energy usage. The prime consumption of total energy is the industrial sector at 43%, surpassing the transport sector which stands at 36%. A further look in the usage pattern in the industrial sector reveals that the main form of energy consumed were generated from gas and electricity. Industrial energy consumption has dominated more than 50% of total global energy consumption (Mekhilef et al, 2010). From the statistics provided by Malaysia Energy Information Hub, the final energy demand by sector and final electricity consumption by sector for the country in the year 2010 is plotted in Figure 3.7 and Figure 3.8.

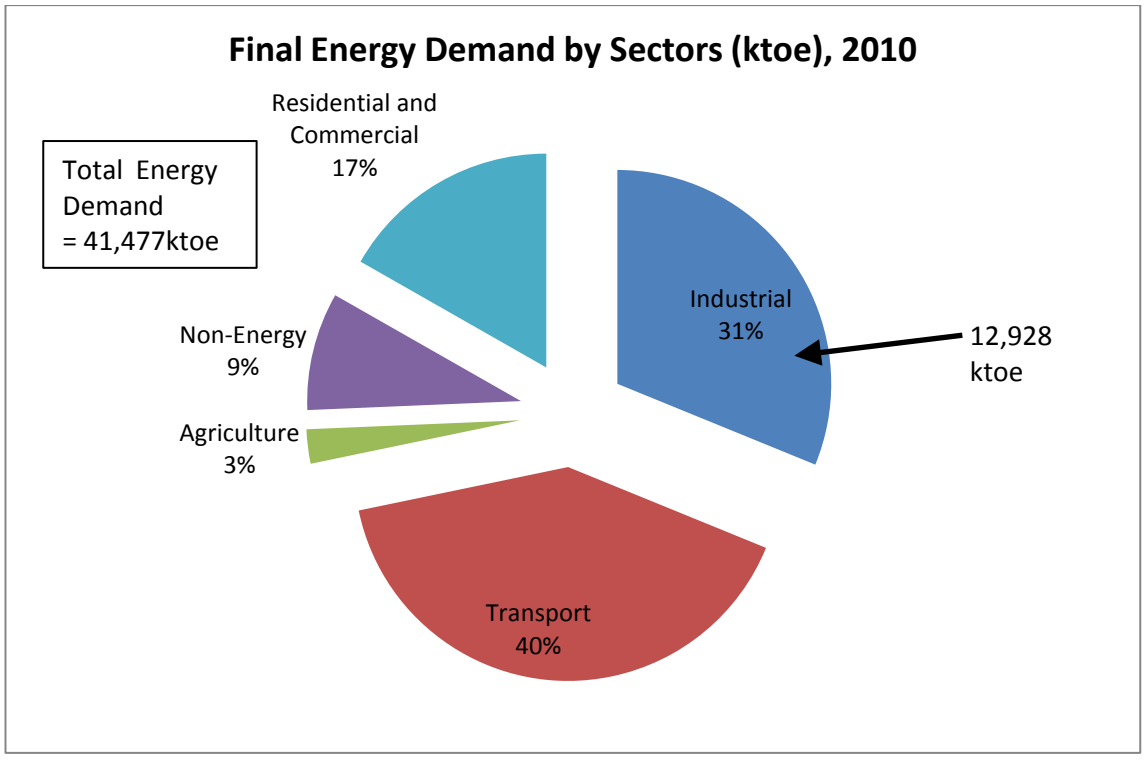


Figure 3.7 Final Energy Demand by Sector (ktoe), 2010. Source: MEIH, 2012.

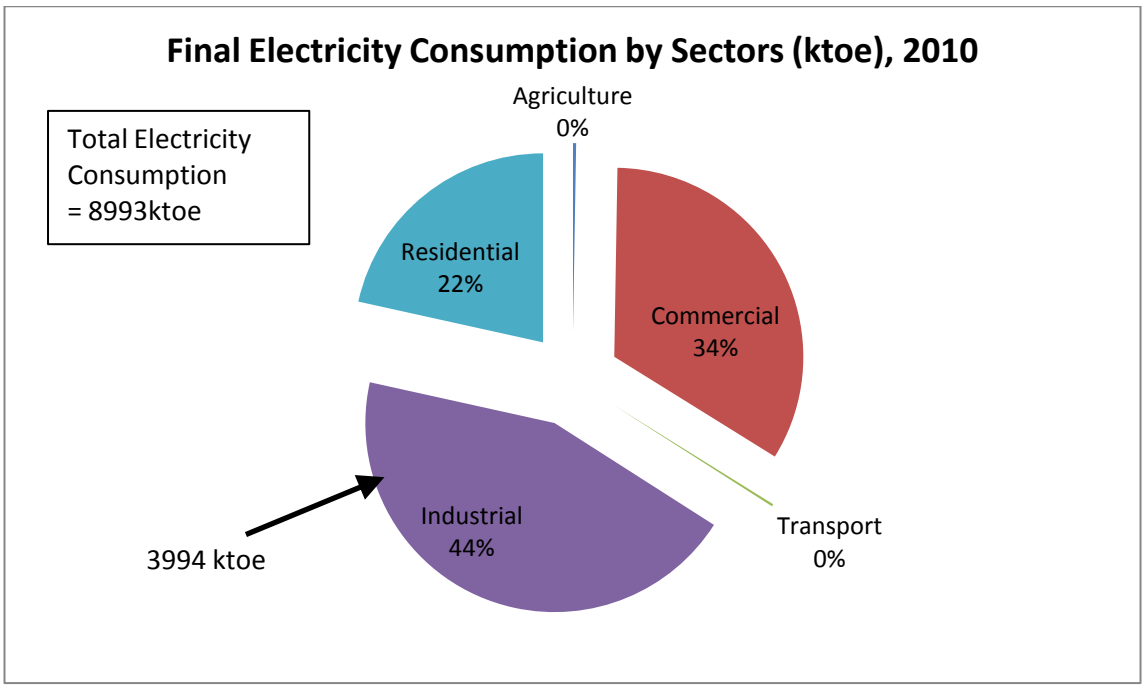


Figure 3.8 Final Electricity Consumption (ktoe), 2010. Source: MEIH, 2012.

From the figures, the industrial electricity usage is just 3994ktoe out of a total of 12,928ktoe, making grid electricity supply taking up just 26.4% of the energy mix. The contribution of non-grid electricity supply is not known from these figures. To estimate the energy mix distribution, the published works from the EU on the energy usage pattern in industries is referred, shown in Figure 3.9.

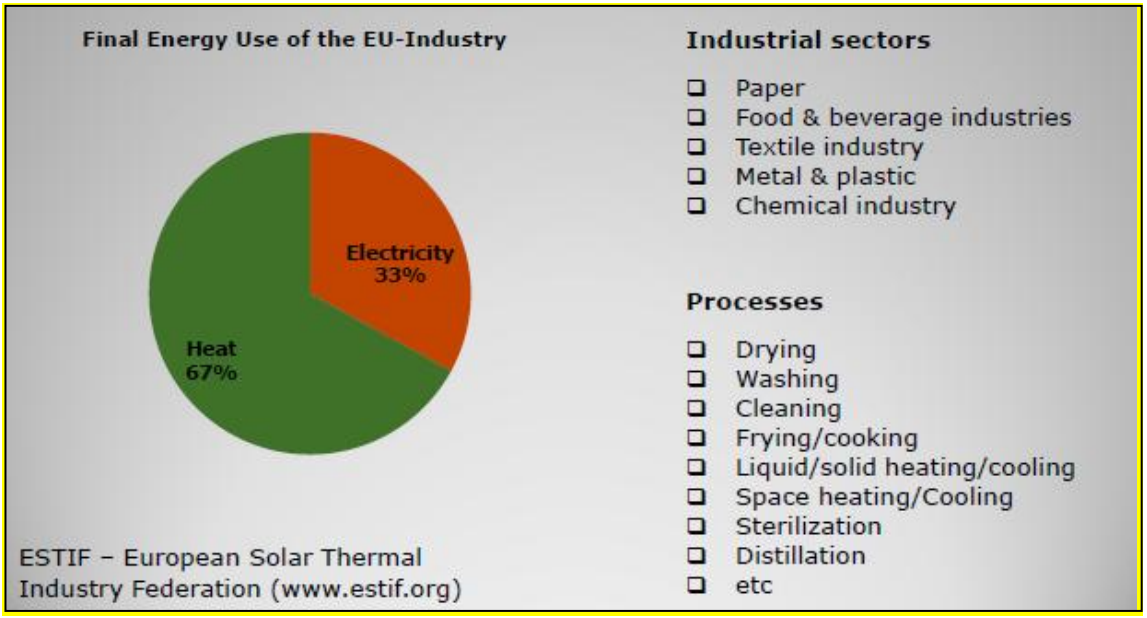


Figure 3.9 Final Energy use of the EU-Industry. Source: ESTIF, 2010.

Using Figure 3.9 as a guideline, it should be safe to assume that mostly the rest of the energy is in the form of thermal energy (74.6%, 8934ktoe, 104TWh) and the non grid electrical consumption is still marginal as compared to thermal energy.

In terms of quantitative demand, assuming Goyal's SIPH distribution, the heat demand per annum is as shown in Table 3.1

Table 3.1 Thermal Energy Demand for Malaysian Industries.

Temperature Range	% of Total Heat Demand	Malaysia Energy Demand (TWh)
≤100 ℃	13	13.52
100- 200 ℃	27	28.08
>200 ℃	60	62.4

Coupled with the strong growth rate shown in Figure 3.10, the potential of solar thermal energy in supplementing the industrial energy demand is enormous.

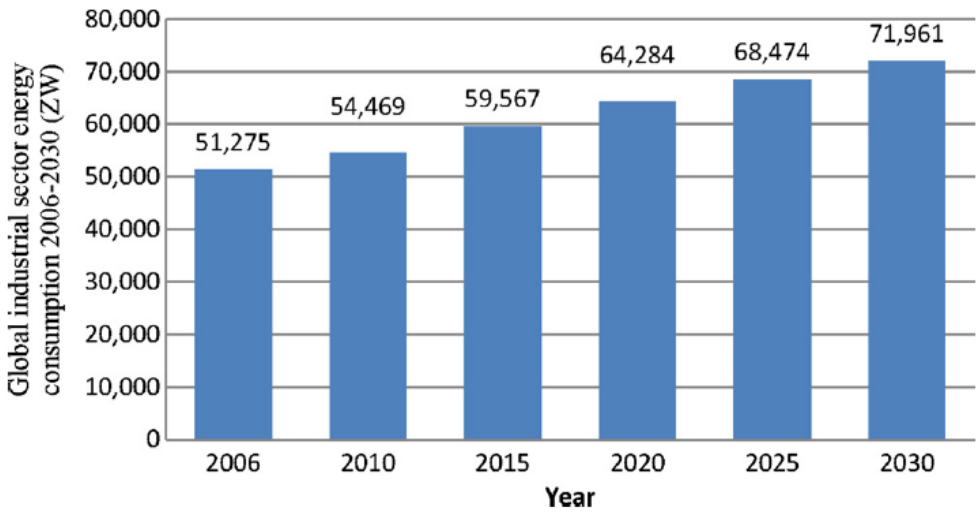


Figure 3.10 Global industrial sector energy consumption trend 2006-2030. Source: Abdelaziz et al, 2011.

3.4 Energy Consumption and Renewable Energies

We are all creatures of energy. Energy is our life sustenance. There will be no world as we know it without energy. As it stands today, world energy requirements is currently at 107,000 TWh/annum. It is predicted that global energy requirements will increase annually by 1.3 % until 2030. We consume around 13 billion litres of crude oil and approximately 14.7 million tonnes of hard coal and brown coal daily on this earth, most of this for the generation of electricity and heat, and for motor vehicles, airplanes and trains. Burning these fossil fuels causes approximately 25 billion tonnes of the greenhouse gas, carbon dioxide (CO_2), to be released each year into the earth's atmosphere (Technology Guide, 2009). Renewable energy sources will increase disproportionately, particularly wind and solar energy. However, as these currently only make up a small proportion of the primary energy supply, fossil energies will continue to dominate (Technology Guide, 2009), as shown in Figure 3.11. The environmental impact and scarce availability of fossil energy caused a shift for increased renewable energy utilization (IEA, 2006). Consumption of fossil fuels causes air and water pollution and also global warming. On the other hand, renewable energy can avoid these adverse impacts. Renewable energies do have their own negative influence to the environment but the magnitudes are much smaller and localized than fossil and nuclear energies (Union of Concerned Scientists, 2005).

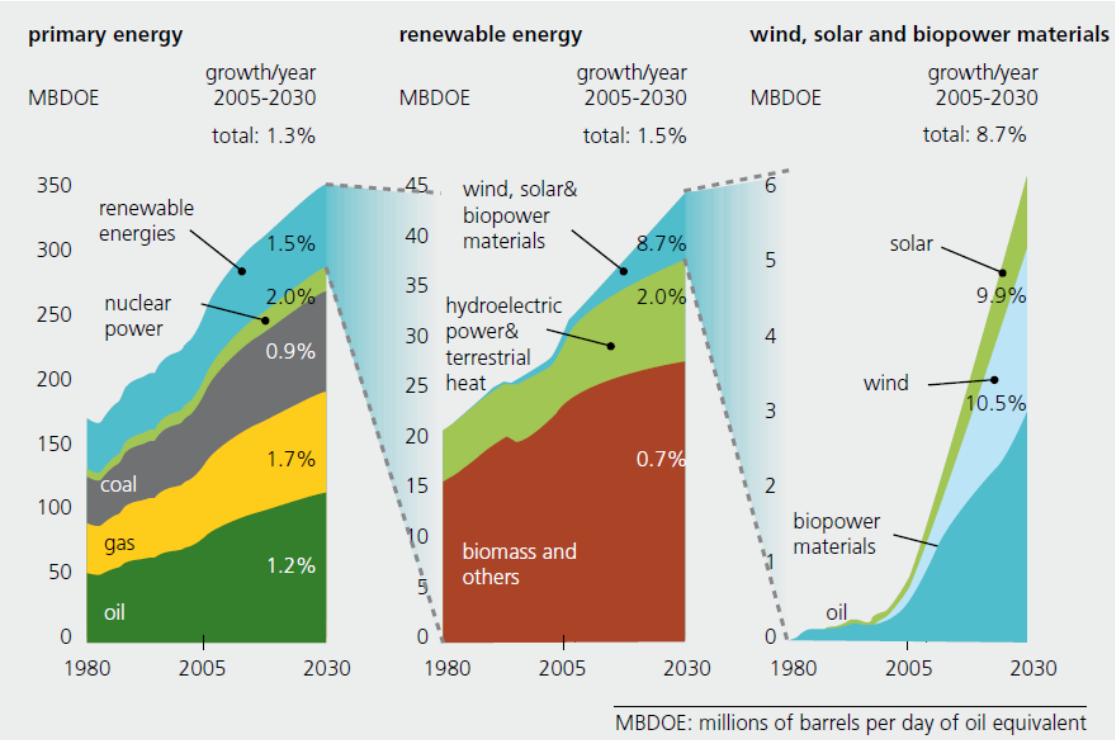


Figure 3.11 Global energy requirements by energy sources. Source: Exxon Mobil

From the International Energy Agency (2002), it is said that "Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources". The above statement stated two main direct sources of renewable energies, which are solar power and geothermal power, while other renewable energies are derivatives of them. Not forgetting tidal power is also a main direct source, but its contribution in relation to the other 2 main types is much smaller. Derivatives of solar energy go through at least one level of energy conversion state, increasing exergy and generating entropy in the process. Take for example biomass energy. Plant absorbs the solar energy and turns it into biological materials – branches, fruits and leaves. Unwanted materials are then collected and acted upon by bacteria, releasing combustible gasses. Another example would be fossil fuels. It is a form of energy

converted from dead animals or plants compressed in the earth crust over a period more than millions of years ago, through anaerobic decomposition. Solar energy is faced with the limitation of low exergy in the beginning. However, with the advent of different solar collection technologies able to produce high temperature outputs, low exergy is no longer an issue and its potential is very great, as demonstrated in the subsequent section.

3.5 Solar Energy and its potential

About 1000 PW of energy from the sun is received by earth every year which is 1000 times enough to cover the global energy demand (Amin, 2009). The sun is made of hot gaseous matter in a sphere with a diameter approximately of 1,390,000km, where continuous fusion of hydrogen into helium gives the sun an effective blackbody temperature of 5762K. Although the distance of the sun is 1.5 x 10^{11} m away from earth, its energy reaches our planet in 8 min and 20s. Energy output from the sun is 3.8 x 10^{20} MW, equivalent to 63 MW/m^2, radiating in all directions. Earth is only able to intercept a tiny fraction of 1.7 x 10^{14} kW, of the total radiation emitted (Kreith and Kreider, 1978). However, not all of the suns energy reaches the surface, as shown in Figure 3.12. Some of them are deflected and lost.

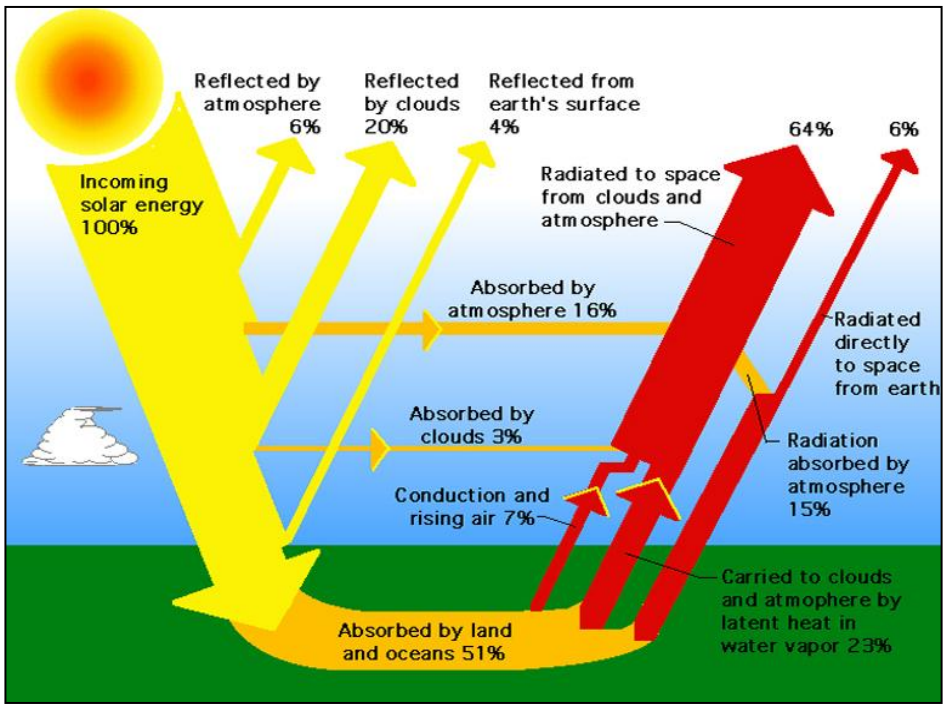


Figure 3.12 Solar energy distribution. Source: Four Peaks Technologies, 2010.

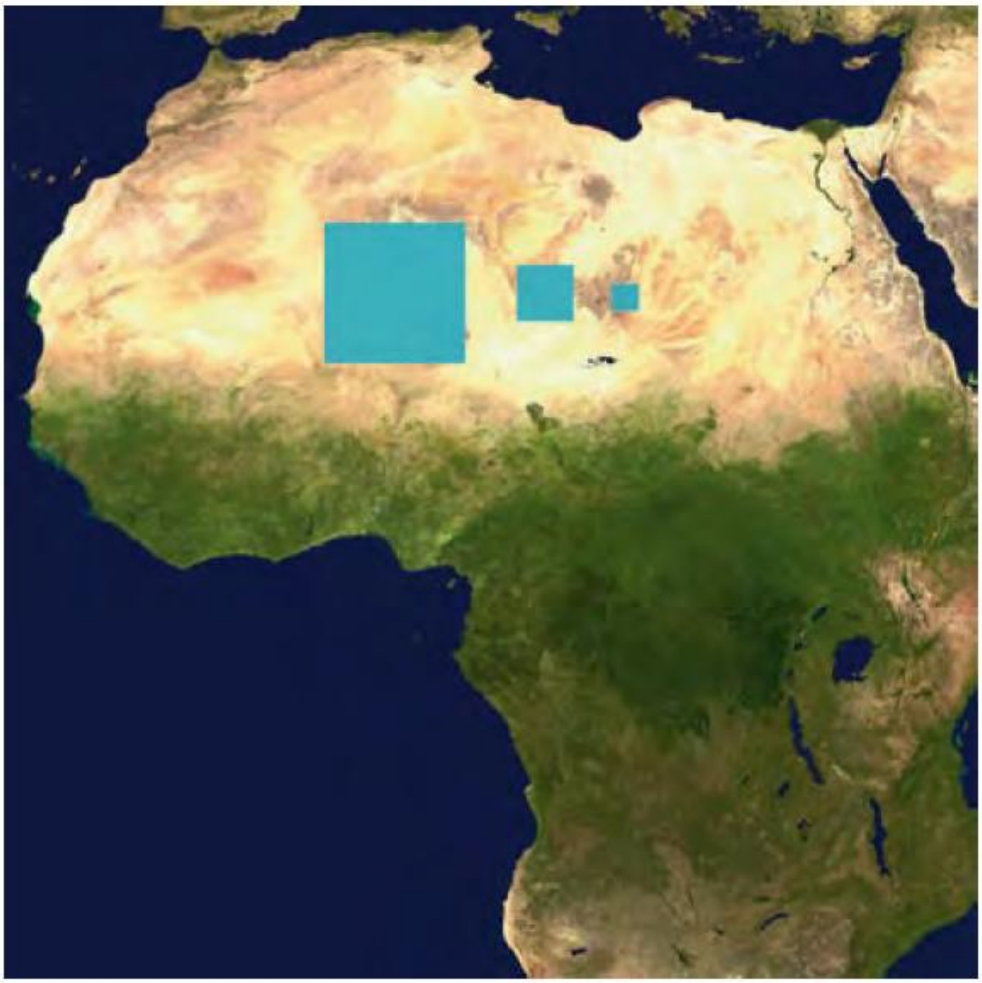


Figure 3.13 Solar radiation and energy requirements. Source: Technology Guide, 2009.

Figure 3.13 shows the power generation of the sun and the potential of solar energy in perspective. Assuming a 12% efficiency solar cell used in the Sahara, the big rectangle shows the surface area required to fulfill the energy demands throughout the world where the large square is approximately 910 km in length, medium size square for Europe's requirement and the smallest square for Germany (Technology Guide, 2009).

The electromagnetic radiation emitted by the sun is composed of a wide range of wavelengths which can be split into two major regions; ionizing radiation such as gamma and X-rays and non-ionizing such as infrared, visible light, and ultraviolet radiation. The damaging gamma and X-rays radiation is unable to penetrate the earth's atmosphere and can only be experienced in outer space. The solar energy imparted on earth consists of 8% ultraviolet, 47% visible light and 45% infrared (Arca, 1990). The

non-ionizing radiation is attenuated by our atmosphere before reaching Earth's surface. Through reflection, scattering, and absorption, our atmosphere changes or eliminates part of the incident energy by the sun. Almost all ultraviolet radiation and certain wavelengths in the infrared region are removed by our atmosphere (Encyclopedia of Science & Technology, 2001)

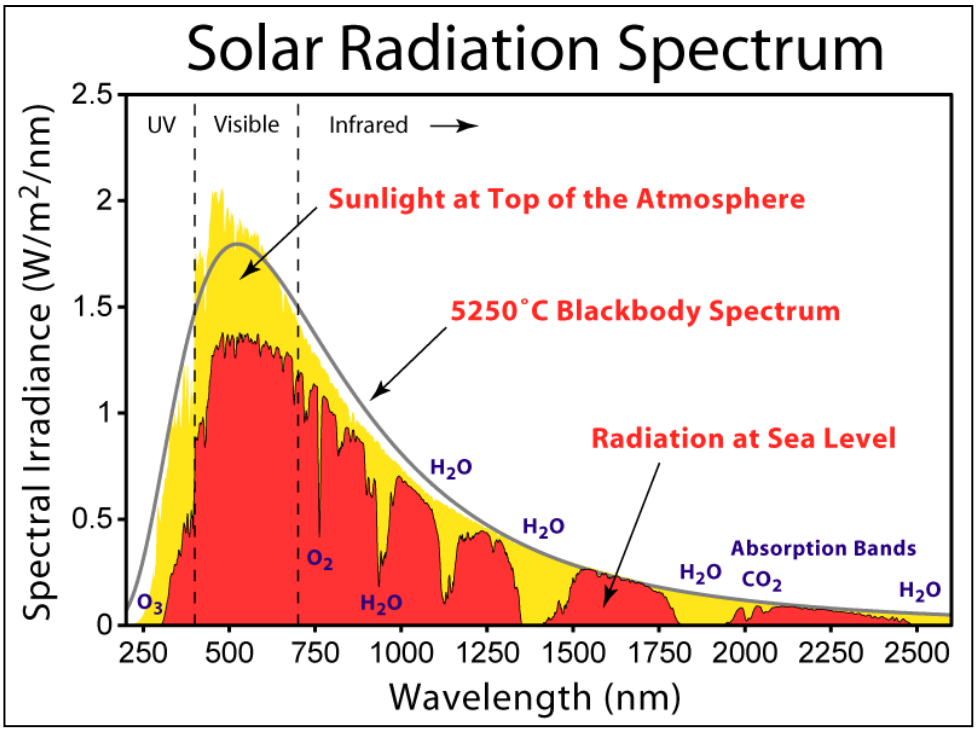


Figure 3.14 Typical Solar Radiation Spectrum. Source: ASTM, 2003.

Figure 3.14 displays the solar radiation spectrum for direct light at both the top of the Earth's atmosphere and at sea level. These curves are known as Terrestrial Reference Spectra from the American Society for Testing and Materials (ASTM, 2003) and are the standard test condition used by the photovoltaic industry. The red field in the figure shows the wavelengths that reaches sea level while wavelengths of energy that reach the top of the atmosphere is shown by the yellow field. These radiations from the sun is filtered and reduced by different gases in specific wavelengths. Gases with specific absorption band residing in our atmosphere absorb some of the light. Additional light is redistributed by Rayleigh scattering, which gives our atmosphere the blue color sky.

Oxygen reduces infrared while our ozone filters out the ultraviolet rays in the shortest wavelength, known as UVB (Wikibooks, 2011).

Solar radiation can also be divided into two components, namely direct or diffuse radiation. Direct solar radiation can be concentrated with the optical devices while diffuse solar radiations are scattered direct solar radiation, which cannot be concentrated by with reflectors or lenses. During cloudy days, diffuse radiation predominates (Technology Guide, 2009). The amount of atmospheric absorption and scattering of solar radiation is a function of the effective distance (depending on atmospheric thickness and content) through which the radiation travels. At the outer atmosphere of Earth, the energy received is 1368W/m^2 and deviates in the region of ±1.7% because of the distance changes between the Earth and Sun, as shown in Figure 3.15 (Ahmad, 2011).

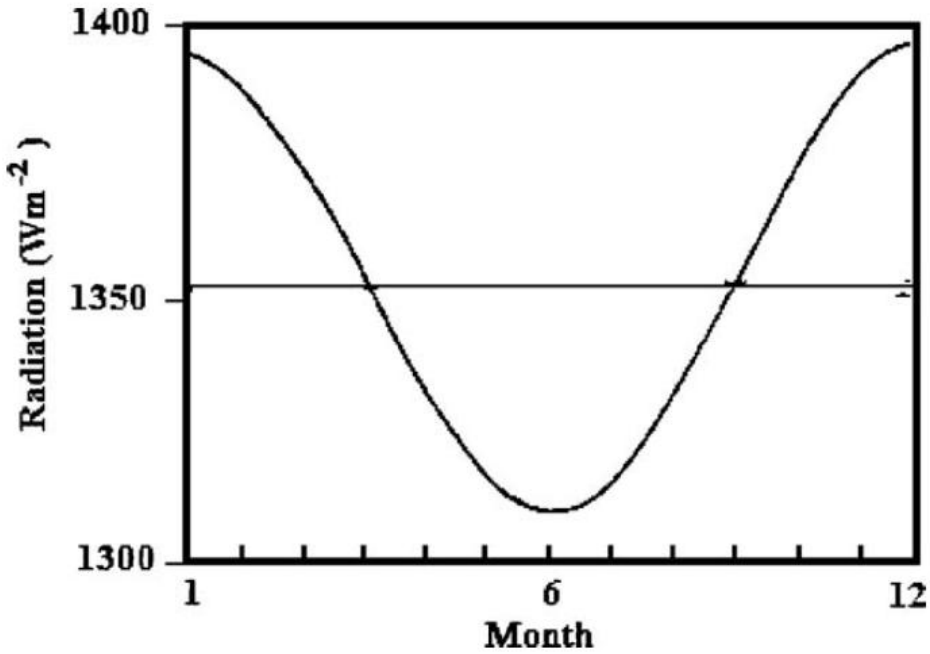


Figure 3.15 Yearly variation of the solar constant. Source: Ahmad, 2011.

The light of the Sun directly overhead at a 90° solar altitude, or zenith, at sea level provides an average peak intensity of 1 kW/m^2. As the Earth circles around the sun, the

angle between the Earth-Sun line and Earth's equatorial plane, known as solar declination varies accordingly, which affects the solar radiation coming to Earth. Intensity weakens at Sun angles approaching the horizon since the rays have more atmospheres to penetrate. Distributions of the solar irradiation depending on geographical locations are shown in Figure 3.16. The amount of solar energy incident on a horizontal surface at sea level ranges up to 7 kWh/m^2-day. At latitudes between 35 °N and 35 °S, the sites are exposed to around 2000 to 3500h of sunshine each year. At higher latitudes the solar energy imparted is less than on sea level (Encyclopedia of Science & Technology, 2007)

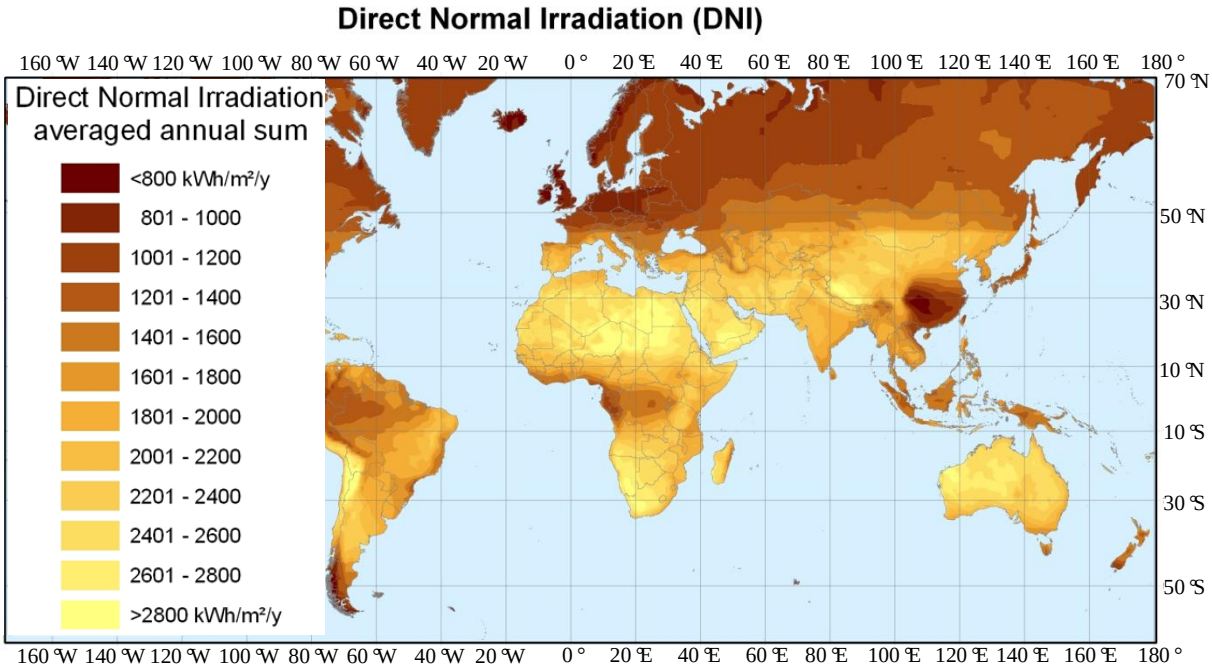


Figure 3.16 Worldwide direct normal solar irradiation. Source: DLR, 2008.

It can be seen that solar energy is also a relatively "fair" form of renewable energy. Most renewable energies are highly geographically dependent. For instances, wind energy works well offshore or near shore but weaken abruptly when we move towards inland; hydro energy needs rivers and dams at preferably higher level to have good

potential energy. While on the other hand, solar energy is best readied near the equator but through careful system design, it is available even in winter of seasonal countries.

On a side note, data collection of solar irradiation is normally done using solarimeters as illustrated in Figure 3.17. This device consists of a spherical glass cover under which contains thermoelectric elements as sensors. The total incident light energy will produce a proportional voltage from the thermoelectric element which is then recorded electronically (Everett, 2004).

Figure 3.17 A Solarimeter, also refer to as a "Pyranometer"

3.6 Malaysia – Solar Energy Perspective

Malaysia is positioned on the South China Sea and lies between 1° and 7° in North latitude and 100° and 120° in East longitude (Nugroho, 2010). The total land area is approximately 330,000km^2, of which 60% is made of Sabah and Sarawak and the remaining 40% Peninsular Malaysia. Malaysia is situated at the equator, surrounded by the sea. This results in a hot, high humidity and a relatively uniform climate all year round, typical of a tropical climate. The average daily is 26.5℃ and ranges between 22℃ to 33℃ throughout the year. Winds are generally light. There are 2 monsoon winds seasons in Malaysia. The Southwest Monsoon starts from May to September and the Northeast Monsoon is between November and March. The rainfall distribution pattern is determined by the monsoon winds and the local topographic features. In general, rainfall in Malaysia can be described as copious for the annual rainfall exceeds 2000mm. Heavy rainfall usually happens between the two monsoons. Rainfall usually happens in the afternoon or early evening, as compared to mornings. On average, Malaysia experiences more than 170 rainy days (Azhari, et al. 2008)

Heavy rains are experienced by exposed areas facing directly to the monsoon winds such as the east coast of Peninsular Malaysia, Western Sarawak and the northeast coast of Sabah. Whereas sheltered areas protected by mountain ranges are relatively independent from its influence. Most of the precipitation occurs as thunderstorm, with heavy falls in a short period of time. This indicates that western Peninsular Malaysia, Eastern Sarawak and Southwest coast of Sabah are better suited for solar energy utilization in comparison to the rest.

It is very unlikely to experience a completely clear sky for a full day or a few days with completely no sunshine, with the exception of during the northeast monsoon seasons (MMD, 2012). Solar radiation is closely related to the sunshine duration. Substantial

amount of sunshine and thus solar radiation is cut off by the ever changing presence of cloud. 6 hours of sunshine per day is the average expected in Malaysia (MMD, 2012). Due to the constant cloud shading and frequent rainfall, the potential of Malaysia in terms of solar energy is not as good as compared to arid desserts but still relatively good, as shown by Figure 3.18.

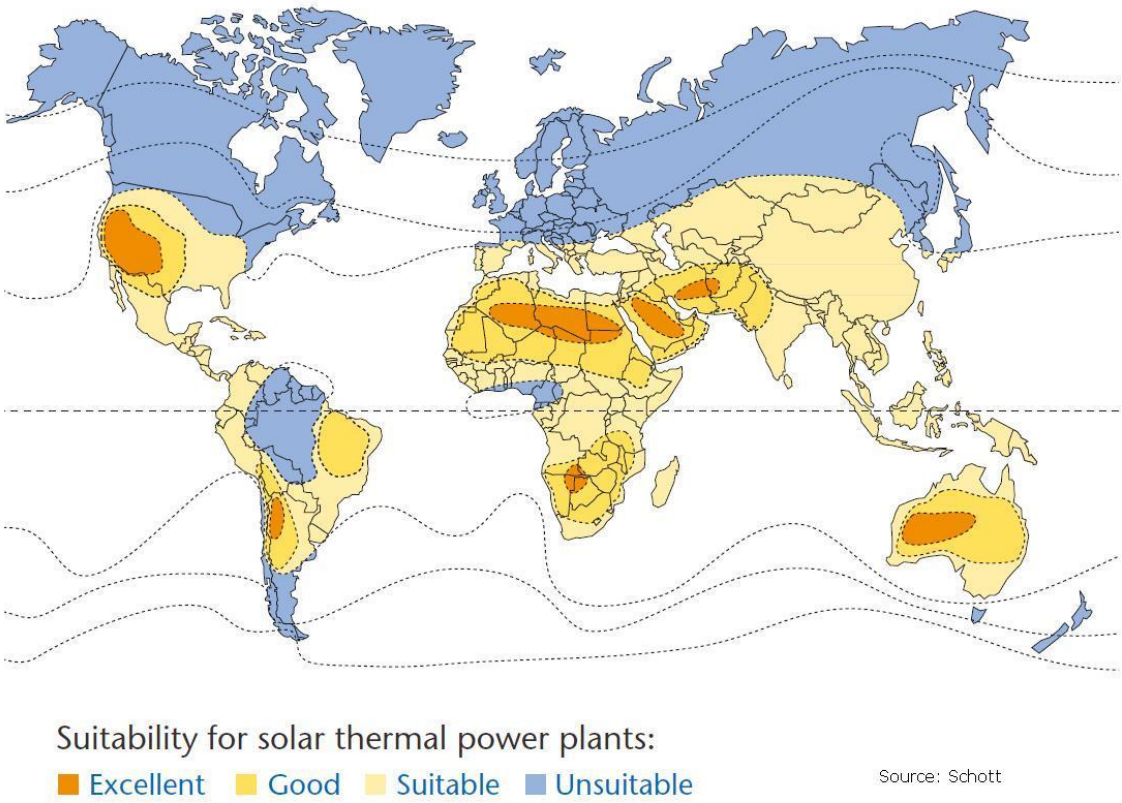


Figure 3.18 Suitability for solar thermal power plants. Source: Schott Ltd.

A distribution of the average solar radiation in Malaysia is shown in Figure 3.19. More than 10 years of measured data of direct and diffuse solar radiation exists only for Kuala Lumpur and Penang. The data shows that for Penang the amount of direct radiation as compared to the global values is normally less than 60% resulting in reduction in performance of solar concentrator, limiting the benefits of concentrators. East coast experiences a large standard deviation of daily global radiation while the peninsula experience more stable daily solar radiation variations (Shafiq, 2010).

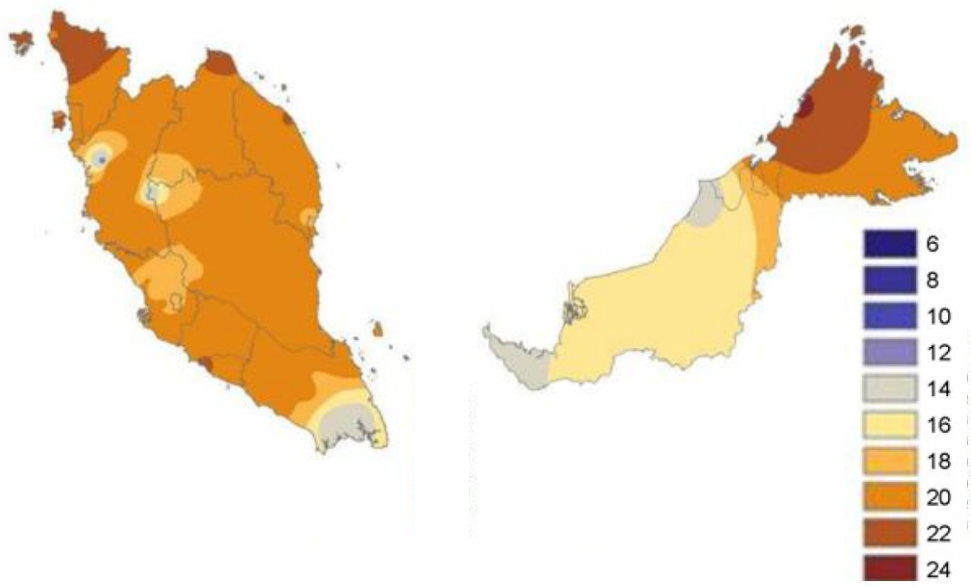


Figure 3.19 Annual average solar radiation (MJ/m2/day). Source: Maliman, M.N., 2005.

The average solar energy in Malaysia varies from paper to paper. Mekhilef et al. (2012) states that with an average of 12 hours of sunshine daily, the average solar energy received is between 1400 and 1900kWh/m^2 annually. Harris (2008) states that the solar insolation average at about 1643kWh/m^2 per year. Amin et.al (2009) finds that the sun hours in a day are more than 10. Yearly average solar radiation in various towns in the country is given by Table 3.1.

Table 3.2 Solar radiation in Malaysia (average value throughout the year). Source: Mekhilef et al., 2012.

Irradiance	Yearly average value (kWh/m^2)
Kuching	1470
Bandar Baru Bangi	1487
Kuala Lumpur	1571
Petaling Jaya	1571
Seremban	1572
Kuantan	1601
Johor Bahru	1625
Senai	1629
Kota Baru	1705
Kuala Terengganu	1714
Ipoh	1739
Taiping	1768
George Town	1785
Bayan Lepas	1809
Kota Kinabalu	1900

This works out to the monthly solar radiation in Malaysia to be around 400-600Mj/m^2 (Mekhilef, 2012). S.M. Shafie (2011) on the other hand states that Malaysia is exposed to an average daily solar radiation of 4500kWh/m^2 and average daily sunshine duration of about 12h, with an ambient temperature of between 27℃ and 33℃. Accordingly it was justified that the development of solar energy are favourable since the average daily solar insolation is 5.5kW/m^2. A.W.Azhari (2008) states that the range of annual average daily solar irradiance is from 4.21kWh/m^2 to 5.56kWh/m^2. 6.8kWh/m^2 is the highest estimated solar irradiation to be found in August and November. On the other hand, the lowest was estimated to be 0.61kWh/m^2 in December. These values were estimated from MTSAT-1R geostationary satellite images covering Malaysia, utilizing part of a system called RADMAP developed by Islam and Exell (1996). The results were correlated with data collected from several ground measuring stations in Malaysia and are found to be within acceptable limits. The monthly average daily solar irradiation of Peninsula Malaysia and Sabah and Sarawak are tabulated in Table 3.2 and plotted in Figure 3.20.

Table 3.3 Monthly average daily solar irradiation of Malaysia. Source: Azhari et. al, 2008.

Month	Min (kWh/m^2)	Max (kWh/m^2)	Average (kWh/m^2)
January	4.21	5.56	4.96
February	4.67	6.62	6.23
March	4.33	6.51	5.02
April	2.63	5.11	4.11
May	3.69	6.84	4.83
June	2.98	6.71	5.14
July	4.41	5.86	5.17
August	2.15	6.81	5.25
September	3.95	5.53	4.89
October	4.68	6.43	5.43
November	4.68	6.43	5.43
December	0.61	5.34	3.00

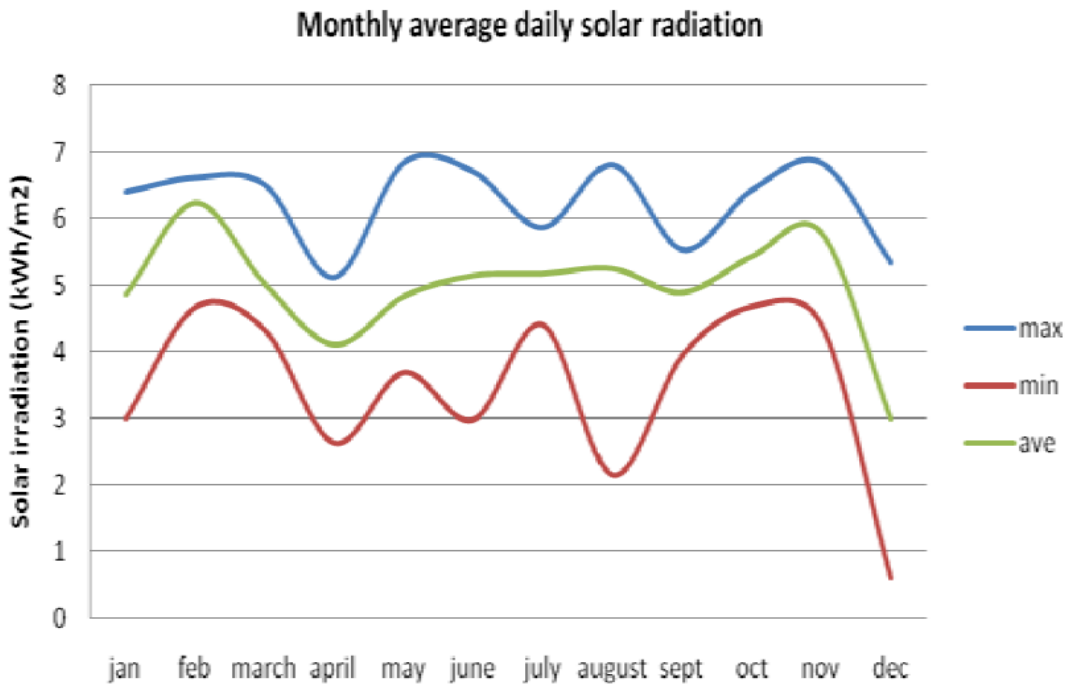


Figure 3.20 Monthly average daily solar radiation. Source: Azhari et. al, 2008.

A daily and preferably hourly variation of solar radiation is needed to have a better estimation of the performance of a solar thermal system. The Malaysian Meteorological Services do provide such data for weather stations distributed across Malaysia. However, typical performance or long-term average of a system would require many years of data, which results in long computational time. To overcome this, the simulation can be performed using 1 year of typical weather data (TWD), which produces faster results. Employing Finkelstein-Schafer statistics and 19 years of meteorological data, I.A.Rahman (2007) has complied a set of typical weather data as the test reference year for Subang, Malaysia. The data are shown in Figures 3.21, 3.22, 3.23 and 3.24.

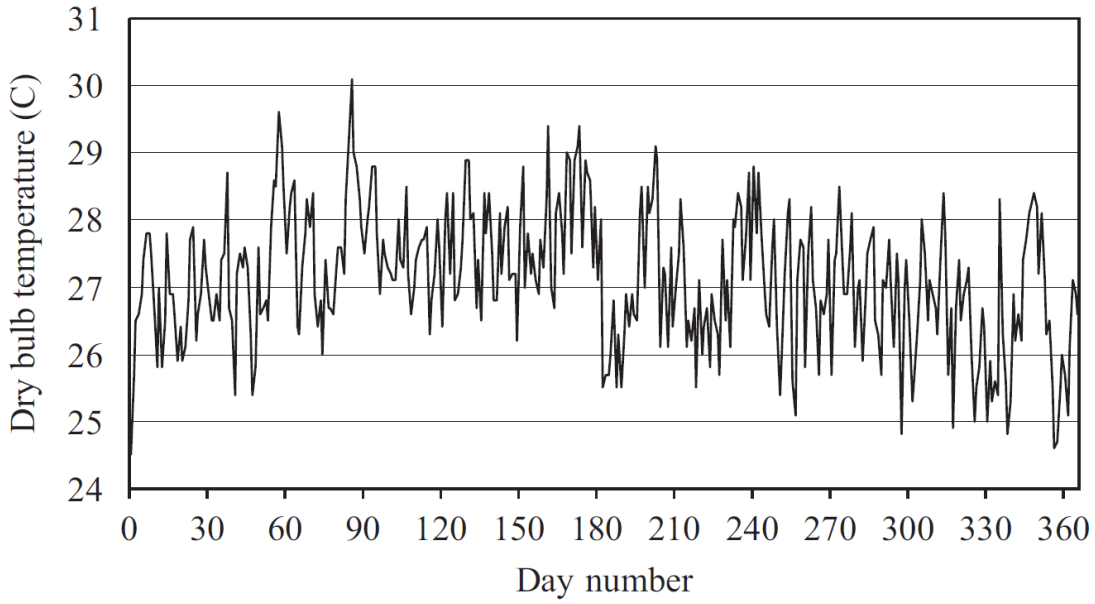


Figure 3.21 Daily mean dry-bulb temperature for equal weightings test reference years. Source: I.A. Rahman et. al, 2006.

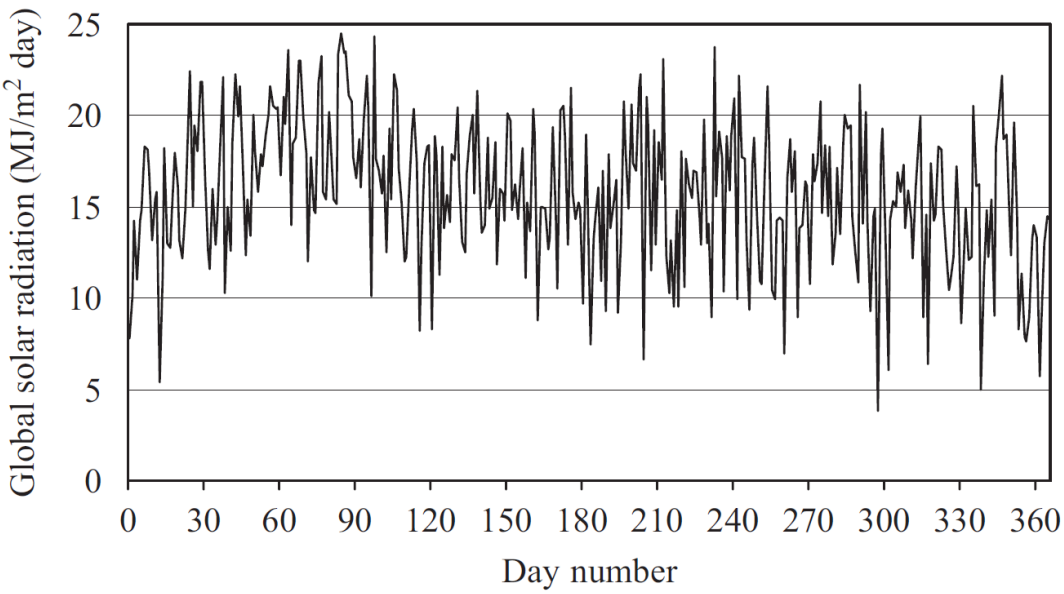


Figure 3.22 Daily global solar radiation for equal weightings test reference years. Source: I.A. Rahman et. al, 2006.

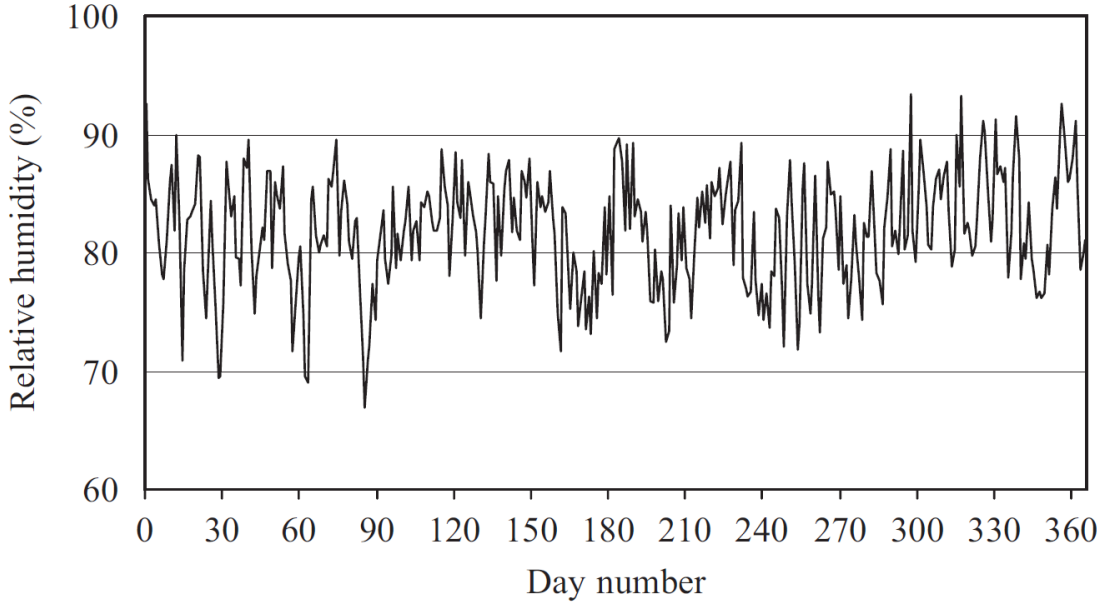


Figure 3.23 Daily mean relative humidity for equal weightings test reference years. Source: I.A. Rahman et. al, 2006.

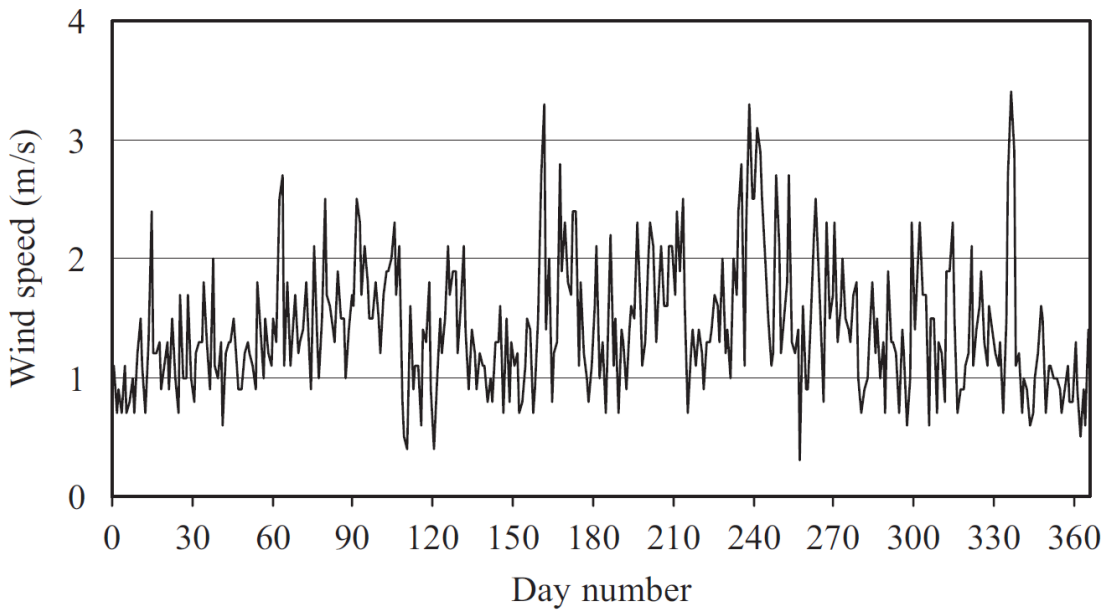


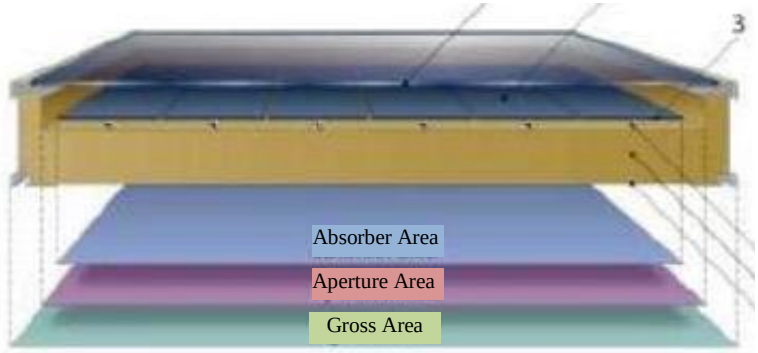
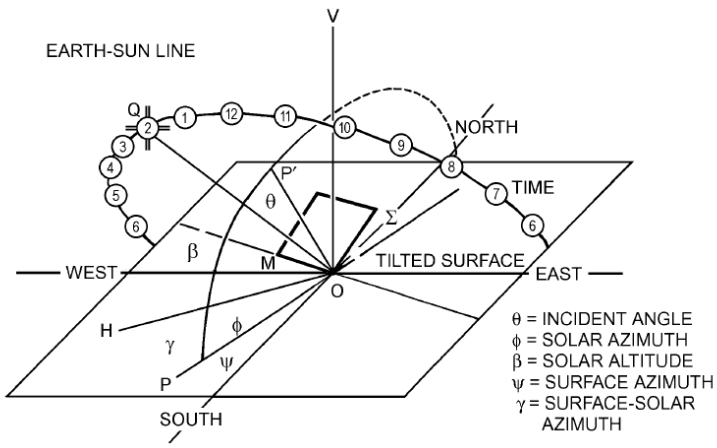
Figure 3.24 Daily mean wind speed for equal weightings test reference years. Source: I.A. Rahman et. al, 2006.

3.7 Solar Thermal Collectors

To begin the introduction to solar collectors, it is helpful to keep the following terms and explanation shown in Table 3.3 in mind to ease in the comprehension of the subject matter.

Table 3.4 Commonly used terms and definition for solar collectors.

Terms	Description
Irradiation /Insolation, G	Radiation flux incident on a surface from all directions.
Direct Irradiance	Sunshine directly coming from the sun, without being blocked by clouds.
Diffuse Irradiance	Scattered light that appears to come from the whole sky and cannot be concentrated by lenses or reflectors.
Black body	A perfect emitter and absorber of radiation.
Emissivity	The ratio of the radiation emitted by the surface at a given temperature as compared to a same temperature blackbody.

Terms	Description
Aperture Area, Absorber Area, Gross Area	Total area available for the absorption of solar radiation Actual area of black absorber, which is exposed to the sun. Total size of the collector array  **Figure 3. 25 Area definitions of a solar collector.**
Incident Angle	The angle between the line normal to the irradiated surface (OP') and the earth-sun line QQ. This incident angle affects the intensity of the direct component of solar radiation striking the surface and the surface's ability to absorb, transmit or reflect the sun's rays (ASHRAE Chapter 33, 2007)  **Figure 3.26 Solar Angles with Respect to a Tilted Surface. Source: ASHRAE, 2007.**

Terms	Description
IAM (Incidence Angle Modifier)	Output performance variance of a solar collector as the angle between the collector and of the sun changes.
Solar Fraction (%)	Measures the percentage of energy consumption being fulfilled by solar renewable energy.

A solar thermal collector is a solar device used to absorb sunlight, be it direct or diffuse solar radiance and transform it into useful heat. When the Sun's shortwave radiation impinges upon a blackened surface, much of the incoming radiant energy can be absorbed and converted into heat. The temperature that results is determined by: the intensity of the solar irradiance; the ability of the surface to absorb the incident radiation; and the rate at which the resulting heat is removed (McGraw Hill Encyclopedia of Science and Technology, 2007). The various dynamics present in a solar collector is shown in Figure 3.27.

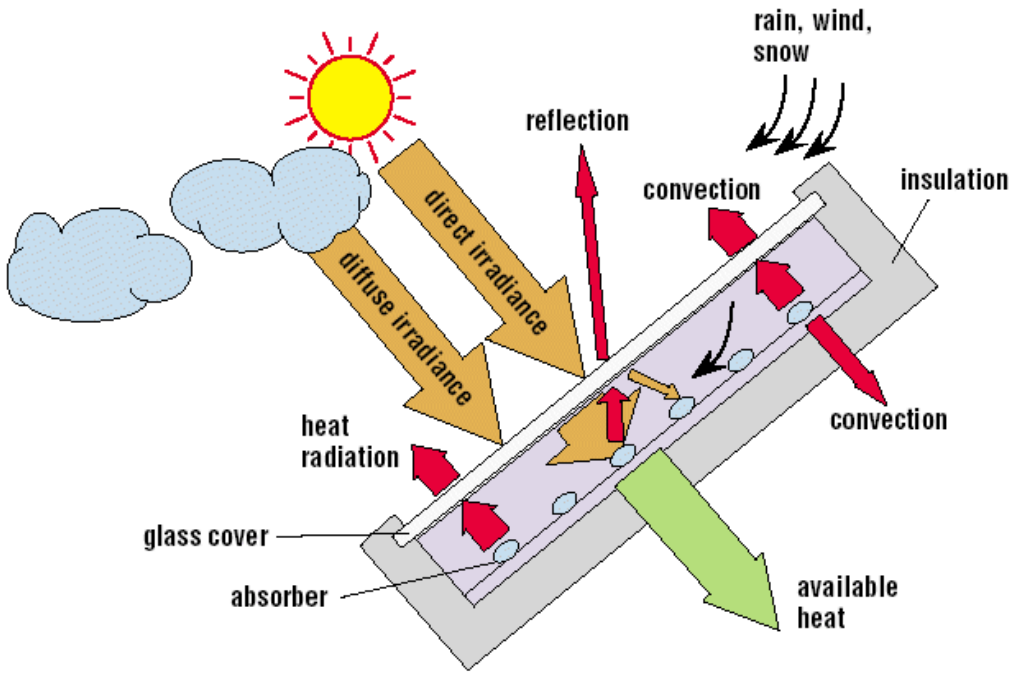


Figure 3.27 Processes at a solar collector. Source: Renewable Energy World, 2004.

The energy inputs are denoted by the yellow arrows, namely direct irradiance and diffuse irradiance; the useful thermal energy is denoted by the green arrow while the various losses by the red arrow, namely reflection, convection, conduction and radiation losses.The fraction of irradiation absorbed by the surface is called the absorptivity α, the fraction reflected by the surface is called the reflectivity ρ, and the fraction transmitted is called the transmissivity τ (Cengel, 2004) That is,

Absorptivity: $$\alpha = \frac{Absorbed\ Radiation}{Incident\ Radiation} = \frac{G_{abs}}{G} \quad (3.1)$$

Reflectivity: $$\rho = \frac{Reflected\ Radiation}{Incident\ Radiation} = \frac{G_{ref}}{G} \quad (3.2)$$

Absorptivity: $$\tau = \frac{Transmitted\ Radiation}{Incident\ Radiation} = \frac{G_{tr}}{G} \quad (3.3)$$

Where G is the radiation energy incident on the surface, and G_{abs}, G_{ref} and G_{tr} are the absorbed, reflected and transmitted portion of it, respectively. From the 1st Law of thermodynamics,

$$G_{abs} + G_{ref} + G_{tr} = G \quad (3.4)$$

And

$$\alpha + \rho + \tau = 1 \quad (3.5)$$

For opaque surfaces, τ=0 and thus

$$\alpha + \rho = 1 \quad (3.6)$$

The selective coating on the evacuated tubes possesses a high absorptivity up to 94%. Combined with the low emissivity and good insulation, it is very efficient in harnessing the energy of the sun. This is the reason why all solar collectors are opaque and black.

The efficiency and temperature obtained of a solar thermal system are determined by the following factors:

1. Intensity of solar radiation
2. Location and orientation of the collectors
3. Aperture area of solar collectors
4. Efficiency of the solar collectors
5. Type of system to which it is connected (size of water heater etc)
6. Rate at which heat is removed, either for useful work or as losses.

To suit the various requirement of the industry, a myriad of systems or type of collectors are devised to cater for different needs, as shown in Table 3.4. The major differences in the systems are the means used to concentrate the solar rays to achieve higher solar irradiation per unit area.

Table 3.5 Types of solar energy collectors. Source: Kalogirou, 2003.

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (℃)
Stationary	Flat plate collector (FPC)	Flat	1	30 – 80
	Evacuated tube collector (ETC)	Flat	1	50 – 200
	Compound parabolic collector (CPC)	Tubular	1 – 5	60 – 240
			5 – 15	60 – 300
Single-axis tracking	Linear Fresnel reflector (LFR)	Tubular	10 – 40	60 – 250
	Parabolic trough collector (PTC)	Tubular	15 – 45	60 – 300
	Cylindrical trough collector (CTC)	Tubular	10 – 50	60 – 300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100 – 1000	100 – 500
	Heliostat field collector (HFC)	Point	150 – 2000	150 – 2000

3.8 Solar Evacuated Tubes Collector

Evacuated tubes collector refers to the housing and the method it uses to minimize radiation loss. A cross section of the tube and optical processes is shown in Figure 3.28.

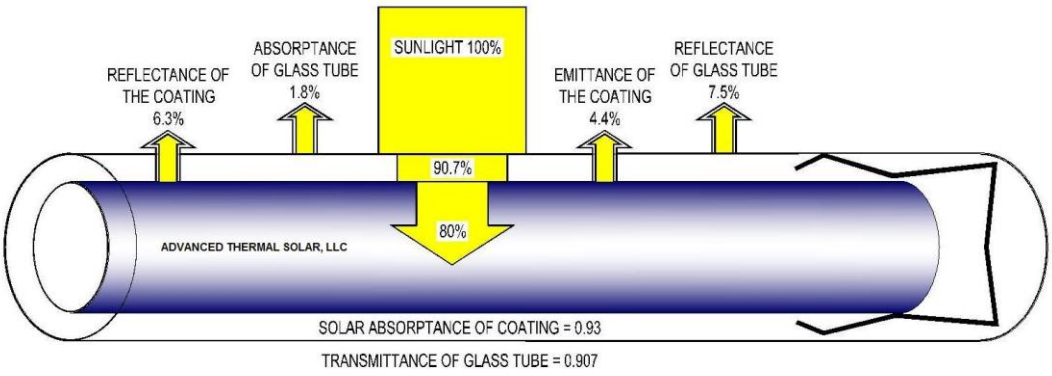


Figure 3.28 Optical processes for evacuated tube. Source: advthermalsolar.com, 2012

The vacuum inside each tube gives good insulation for conductive and convective heat transfer and therefore limits the losses of the system from outside influences, such as low temperature, high wind or high humidity. The most popular type are the Sydney tube, or commonly known as “thermos flask tube”, shown in Figure 3.29.

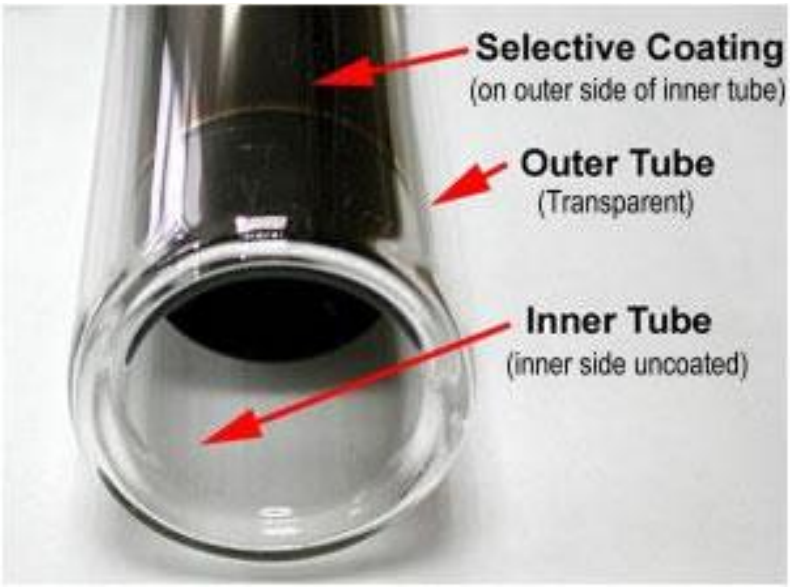


Figure 3.29 Sydney Tube. Source: B&ES, 2012

Each tube is normally made from borosilicate glass and consists of one glass tube inside of another glass tube, fused at the top. The free air in the space between the two tubes evacuated giving a Thermos flask similar vacuum-tube jacket. The transparent outer tube houses while the inner tube which is coated with a selective coating optimized to absorb the solar radiation and turns it into heat (REIA, 2007). The absorbed heat is transferred by an aluminium fin to a central piping, where the working fluid flows through. The working fluid carries the thermal energy and converges into a manifold on the top of the solar collector.

Often a CPC reflector is placed under the tube to utilize the absorber area not facing directly to the sun and to capture the sunlight which was passed between each collector tube. If damaged, each tube can be removed individually for easy replacement. There are 2 major competing technologies in transporting out the absorbed thermal energy from evacuated tubes, namely heat pipe or U-pipe (IEA SHC, 2008).

3.8.1 Evacuated Heat Pipe Collectors

A heat pipe consists of a hollow pipe with a low pressure inside. The low pressure is to lower the temperature required to alter the state of the liquid into gaseous state. Purified water in a small amount with some additives is sealed inside the tube. The water vapourizes when the heat pipe is heated above an adjustable temperature, rising to the top of the heat pipe. The top of the heat pipe is also known as a condenser and possesses a much larger diameter than the providing for a larger surface over which heat can be transferred to the working fluid. The vapour transfers its thermal energy to the working fluid and condenses back to its liquid form, which flows back to the bottom of the heat pipe. The process repeats in a loop. To ensure circulation, a heat pipe collector has to be tilted at a minimum angle of operation, typically about 20°. The quality and quantity of the fluid residing in a heat pipe is very crucial. Water scale and tube exposition will not happen as no water flows in the evacuated tube (IEA SHC, 2008). A schematic is shown in Figure 3.30.

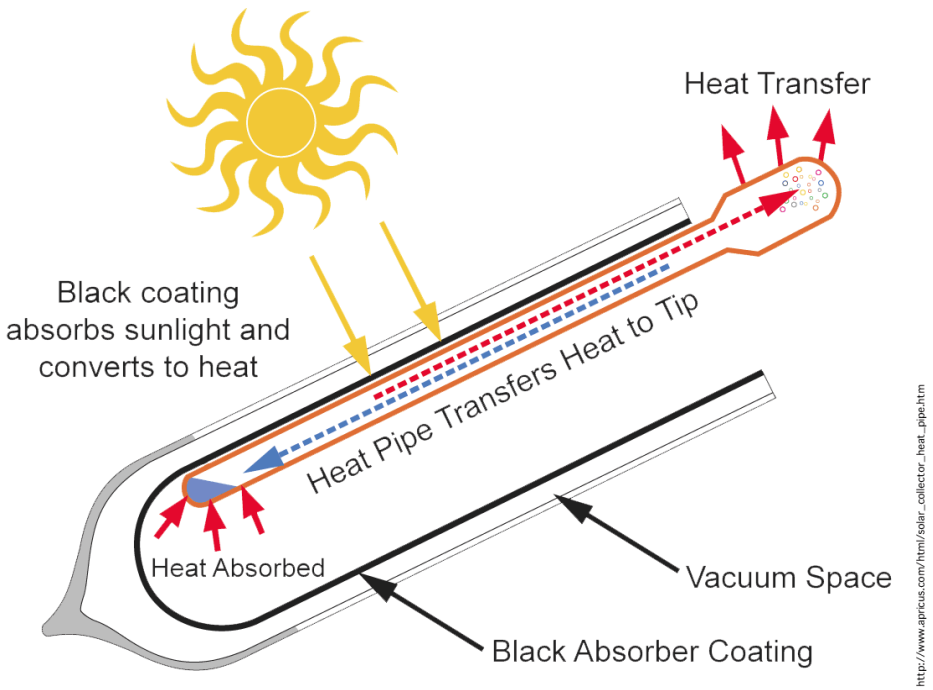


Figure 3.30 Heat pipe evacuated tube collector. Source: B&ES, 2012

3.8.2 Evacuated U-pipe Collectors

A U pipe collector differs in its mechanism in transporting useful thermal energy out. It is comprised of a manifold and many vacuum tubes each containing one U-shaped copper pipe. Aluminium fins transfer the heat absorbed to the copper pipes and working fluid are pumped through it to obtain hot water. A pictorial representation is shown in Figure 3.31 and Figure 3.32.

Figure 3.31 Picture of an U-pipe cross section

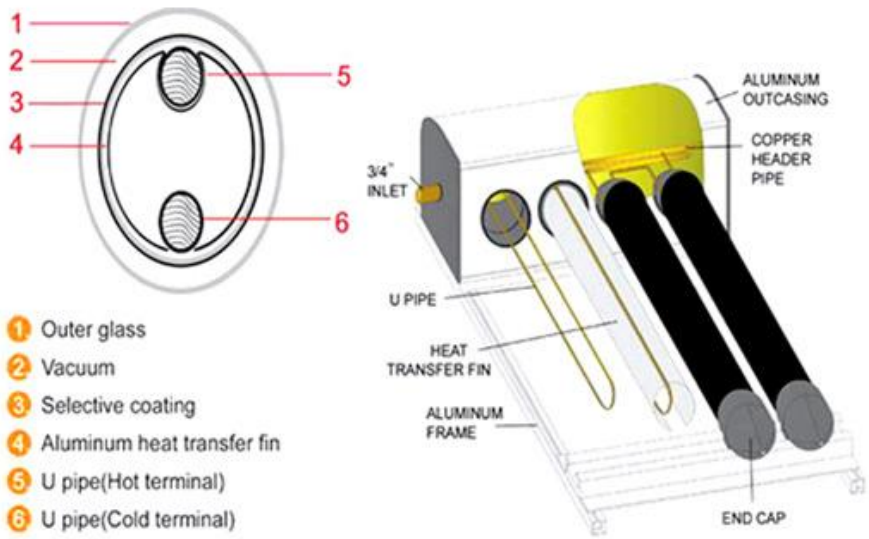


Figure 3.32 A U-pipe solar collector

3.9 Medium Temperature Solar Thermal System

A typical solar thermal system shall consist of an array of collector, a heat transfer circuit which includes the heat exchanger, the pump and circulation fluid and lastly a storage system, usually a tank filled with liquid and a heat exchanger, as shown in Figure 3.33.

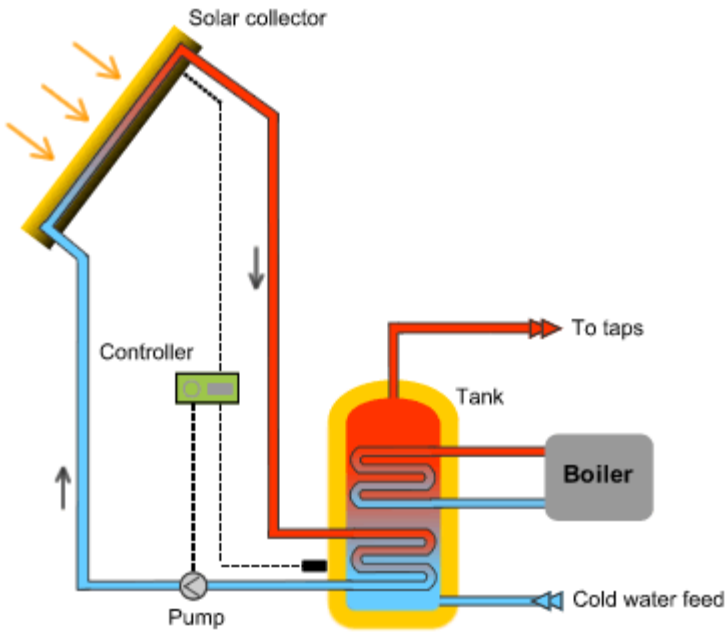


Figure 3.33 Basic components in a solar thermal system.

It is clear that this is a very simple system. The simplicity involved is an advantage of this kind of system.

The integration of solar collectors to an industrial thermal powered system can be as a pre-heater for make-up water in boiler operations, directly for a process, or to generate steam by itself, as shown in Figure 3.34.

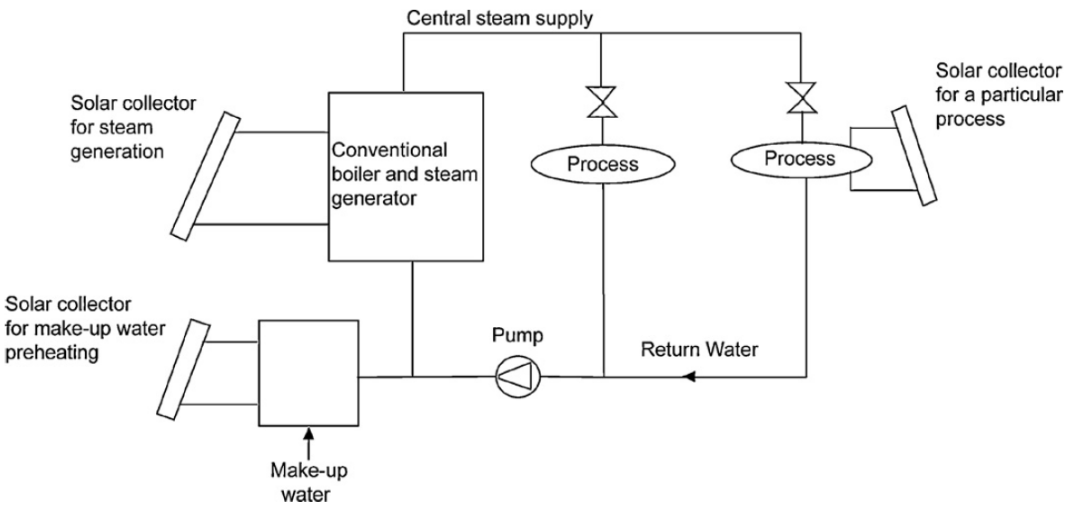


Fig. 5. Integration of solar collectors to an industrial thermal powered system [15].

Figure 3.34 Integration of solar collectors to an industrial thermal powered system. Source: Kalogirou, 2003.

It is important before the deployment of the solar thermal system to take note of the following criteria before deployment, namely orientation, angle of inclination and shading. These are parameters that would affect the output of the collector. Orientation and angle of inclination is related to the collector's angle to the moving sun, which should be optimized to achieve the highest output year round. Shading is to avoid any shadows casting on the collectors at any time of the year. This is to ensure maximum output and to avoid any thermal stress imbalance.

CHAPTER 4: METHODOLOGY

4.1. Overview

The methodology used to conduct this study is shown in Figure 4.1.

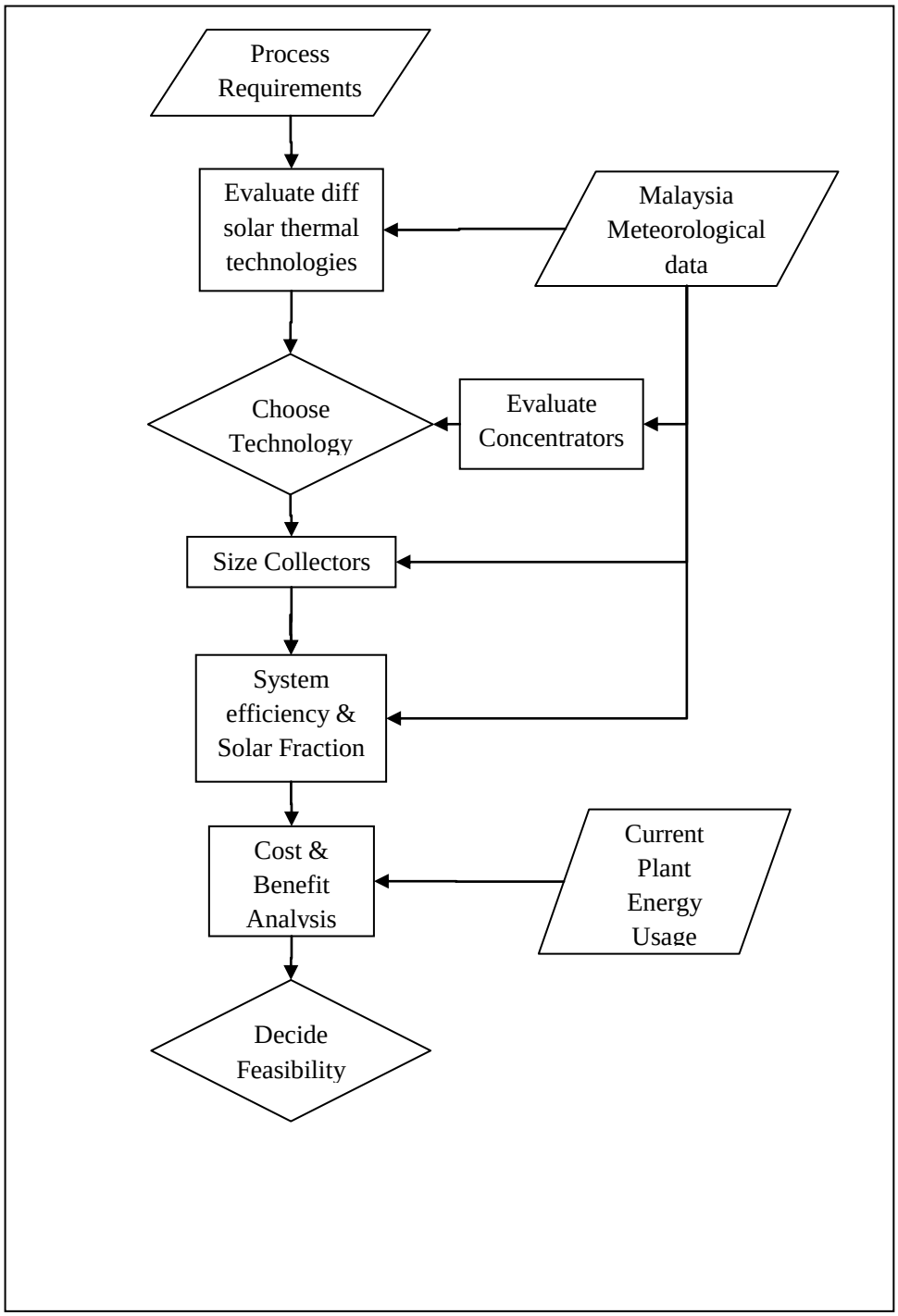


Figure 4. 1 Methodology flow chart.

The study is initiated by a choosing a process relevant to most industrial processes, such as boiler feed water pre-heater or high pressure wash down system. Using the Malaysian meteorological data, different solar thermal technologies are evaluated and decided on one. Then, the system is sized based on the collectors that are available in the market. A simulation is carried out on the system output using Malaysia typical weather year data with the solar fraction as the final output. Various case scenarios are then carried out to study the sensitivity and reaction of the system .This solar thermal system is then compared with other means of generating thermal energy and a cost & benefit analysis done.

The various calculations involved are explained subsequently.

4.2. Theory and Calculations

Different theoretical evaluation of the long-term performance is studied (Oliveira, 2007). A more simplistic approach is selected as to be explained subsequently. The calculation of the system performance is divided into 4 parts:

a) Solar collector performance and output

b) Heat Exchanger output

c) Design and Sizing for Open loop Direct System

d) Design and Sizing for Closed Loop Drain Back System

4.3. Solar Collector Performance

A cross section of an evacuated tube and its associated parts is shown below in Figure 4.2.

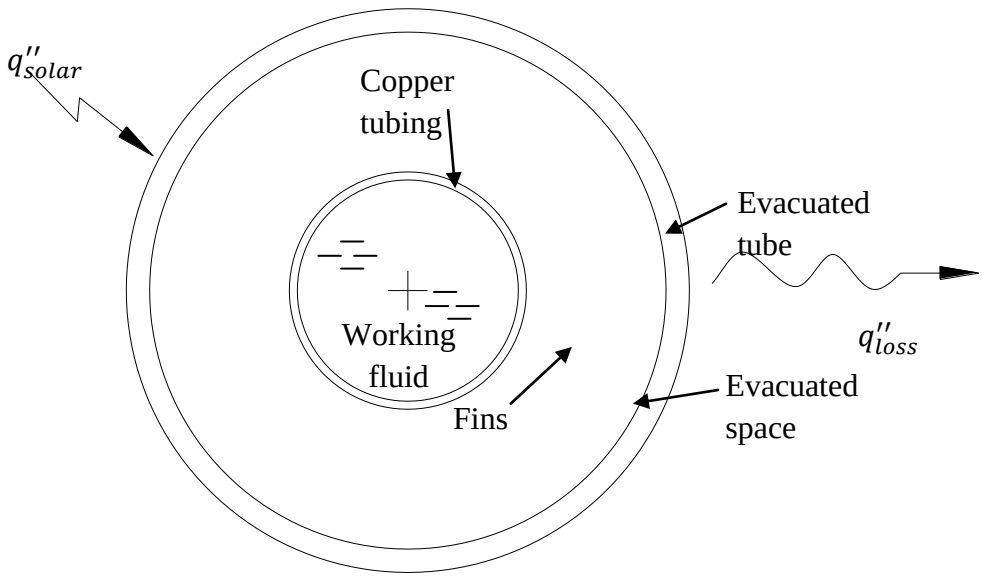


Figure 4. 2 Evacuated tube cross section

An evacuated tube can be modeled as in Figure 4.3.

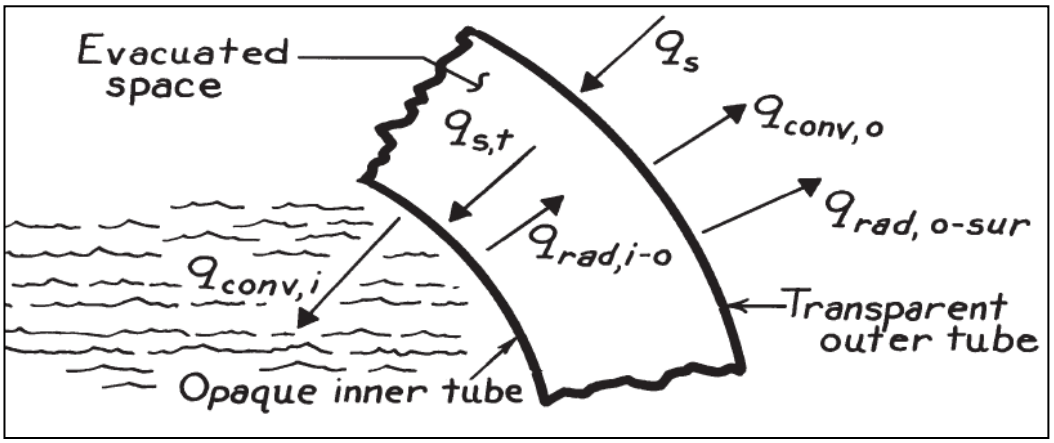


Figure 4. 3 Relevant heat transfer processes for an evacuated tube collector. Source: Incropera, 2007.

The relevant heat transfer processes are as follows (Incropera, 2007):

q_s	Incident solar radiation including contribution due to reflection off panel (most is transmitted),
$q_{conv,o}$	Convection heat transfer from outer surface to ambient air,
$q_{rad,o-sur}$	Net rate of radiation heat exchange between outer surface of outer tube and the surroundings, including the panel,
$q_{s,t}$	Solar radiation transmitted through outer tube and incident on inner tube (most is absorbed),
$q_{rad,i-o}$	Net rate of radiation heat exchange between outer surface of inner tube and inner surface of outer tube, and
$q_{conv,i}$	Convection heat transfer to working fluid.

There is also conduction heat transfer through the inner and outer tube walls. If the walls are thin, the temperature drop across the walls will be small. Also, since the thermal conductivity of copper and aluminium fin is very much better than the working fluid and through the evacuated tube, both of the thermal resistance is ignored.

It can be seen that is not a simple equation to solve, especially when radiative heat transfer is involved. Recognizing the difficulty in achieving an exact solution to the above heat transfer processes, an experimental method is employed, as the equation shown below.

$$\%\eta = \eta_0 - a_1 \frac{(T_m - T_a)}{G_k} - a_2 \frac{(T_m - T_a)^2}{G_k} \tag{3.7}$$

Where,

Symbol		Description	Unit
$\%\eta$	=	Solar Collector Efficiency	%
η_0	=	Optical efficiency of the collector. It measures the ability of the collector is at absorbing sunshine.	%
a_1	=	Liner loss co-efficient. It is a measure of how much heat is lost mainly by conduction as the collector temperature rises relative to ambient temperature.	W/m^2K
a_2	=	Quadratic loss co-efficient. It is a measure of how much heat is lost mainly by convection and radiation as the collector temperature rises relative to ambient temperature.	W/m^2K^2
T_m	=	Mean temperature of the collector	℃
T_a	=	Surrounding ambient temperature	℃

The coefficient a_1 and a_2 is determined by experiment and is unique to each type of collector. T_m is the arithmetic mean of the inlet and outlet temperature. This approximation yields reasonably accurate results (O'Keefe, 1985).

Applying Newton's Law of cooling, the required mass flow rate to maintain the temperature difference would be

$$\dot{m} = \frac{\%\eta \times q_s'' \times A_{aperture}}{c_p \times (T_{out} - T_{in})} \tag{3.8}$$

4.4. Heat Exchanger

For the performance calculation, the number of transfer units, NTU and heat capacity ratio, C_r value will need to be computed and subsequently the heat exchanger effectiveness, ε is then determined, either from the equation below

$$\varepsilon = 1 - e^{\left\{\frac{1}{C_r} \times NTU^{0.22} \times e^{\left(-C_r \times NTU^{0.78} - 1\right)}\right\}} \tag{3.9}$$

or from the chart in Figure 4.4 for single pass, cross flow flat plate heat exchanger with both fluid unmixed.

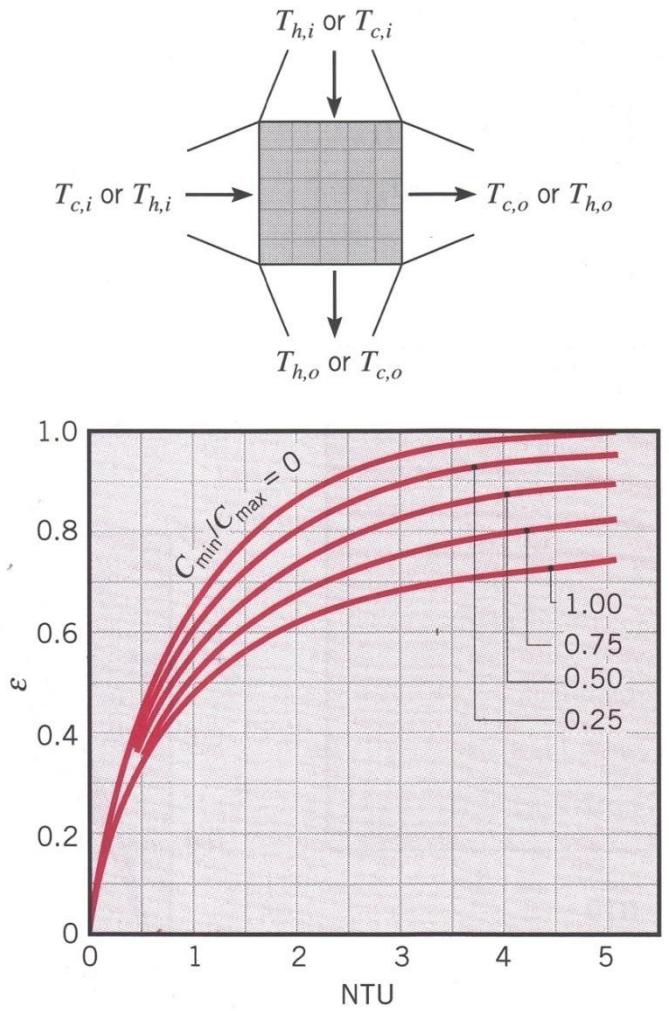


Figure 4. 4 Effectiveness of a single-pass, cross-flow heat exchanger with both fluids unmixed. Source: Incropera, 2007.

Determination of NTU is given by

$$NTU = \frac{U_h \times A_h}{C_{min}} \tag{3.10}$$

Where U_h is the Overall Heat Transfer Co-efficient, C_{min} is equal to C_c or C_h, whichever is smaller. C_c and C_h are the cold and hot fluid heat capacity rates, respectively, given by the formulation:

$$C_{cold/hot} = \dot{m_{c/h}} \times c_{p,c/h} \tag{3.11}$$

Also,

$$C_r = \frac{C_{min}}{C_{max}} \tag{3.12}$$

With the obtained effectiveness, ε, the heat transfer rate is given by

$$q = \varepsilon \times C_{min} \times \left(T_{hot,in} - T_{cold,in}\right) \tag{3.13}$$

The heat transfer rate of the heat exchanger will be the determining factor in sizing the temperature of collector input and output.

4.5. Design and Sizing for Open loop Direct System

A fixed ΔT condition is imposed on the system, which is 75°C outlet temperature of the solar collector and 27 ℃ as the water inlet temperature to the collector. It is sized to provide 100% solar fraction for the sunniest day in Malaysia. It is designed without taking into consideration of any heat storage facility and the transient behavior of the system due to changes in solar insolation. With these constraints, the panels required are determined.

With the designed arrangement, the Malaysia typical weather data is used to calculate the solar fraction in a year. This is achieved by first computing the mass flow rate required to maintain the desired differential temperature in the inlet and outlet of the collector, followed by the power output of the system.

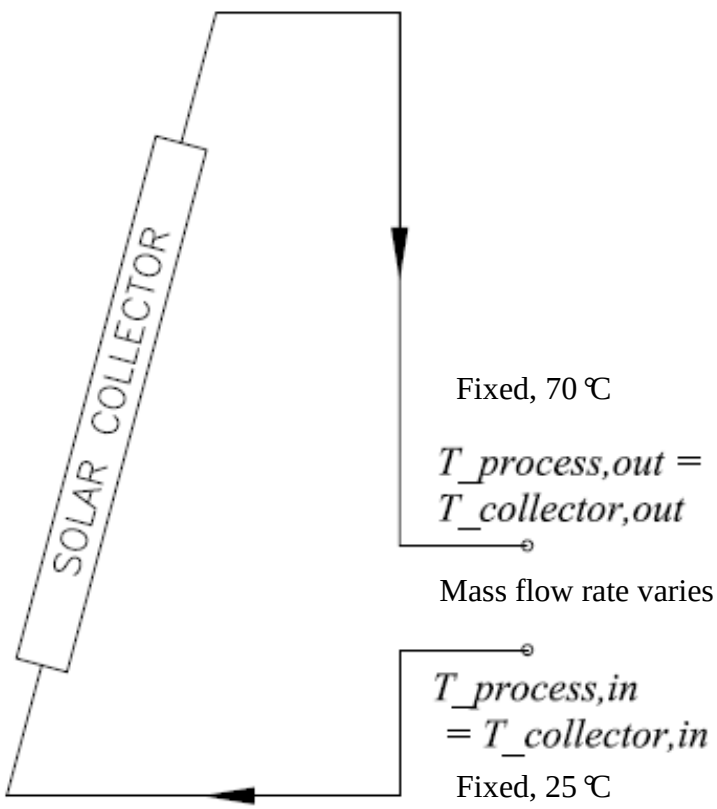


Figure 4. 5 Schematics for Open Loop Direct System

4.6. Design and Sizing for Closed Loop Drain Back System

This system is complicated by the presence of the heat exchanger, which is dealt with accordingly.

First, a fixed ΔT condition is imposed on the cold side of the heat exchanger, which is 25 ℃ as the water inlet temperature to the heat exchanger and 70 ℃ for the Cold side outlet temperature. The process requirement of 470kW is used to determine the mass flow rate required on the cold side, which uses water as the process fluid.

The design criteria is set that on the sunniest day, the mass flow rate of the collector loop, which is on the heat exchanger hot side needs to be equal to the cold side mass flow rate. This would give a heat capacity of unity to the system. Subsequently, the cold side heat capacity is determined followed by the heat exchanger NTU. Using these 2 values, the effectiveness of the heat exchanger is computed.

The hot side heat exchanger input and output temperature is calculated using the knowledge of the effectiveness and process requirement. Assuming no heat loss, these temperatures will correspondingly be the solar collector in and out temperatures. The solar collector efficiency for the said input and output temperatures are determined and the number of panels required sized.

For the performance calculation of the system, the overall heat transfer coefficient of the heat exchanger will change during changes in the mass flow rate or if different working fluids are used. However, Data on thermal performance are not readily available because of the proprietary nature of the machines (Plant Design Handbook, 2001). Consequently, during these calculations, the overall heat transfer coefficient is assumed to be constant. The bottleneck in the system is set on the ability of the collector to produce the required output, rather than the heat exchanger capacity to transfer the

required power output. The heat exchanger performance is assumed to be able to handle the system requirements, regardless of the flow rate.

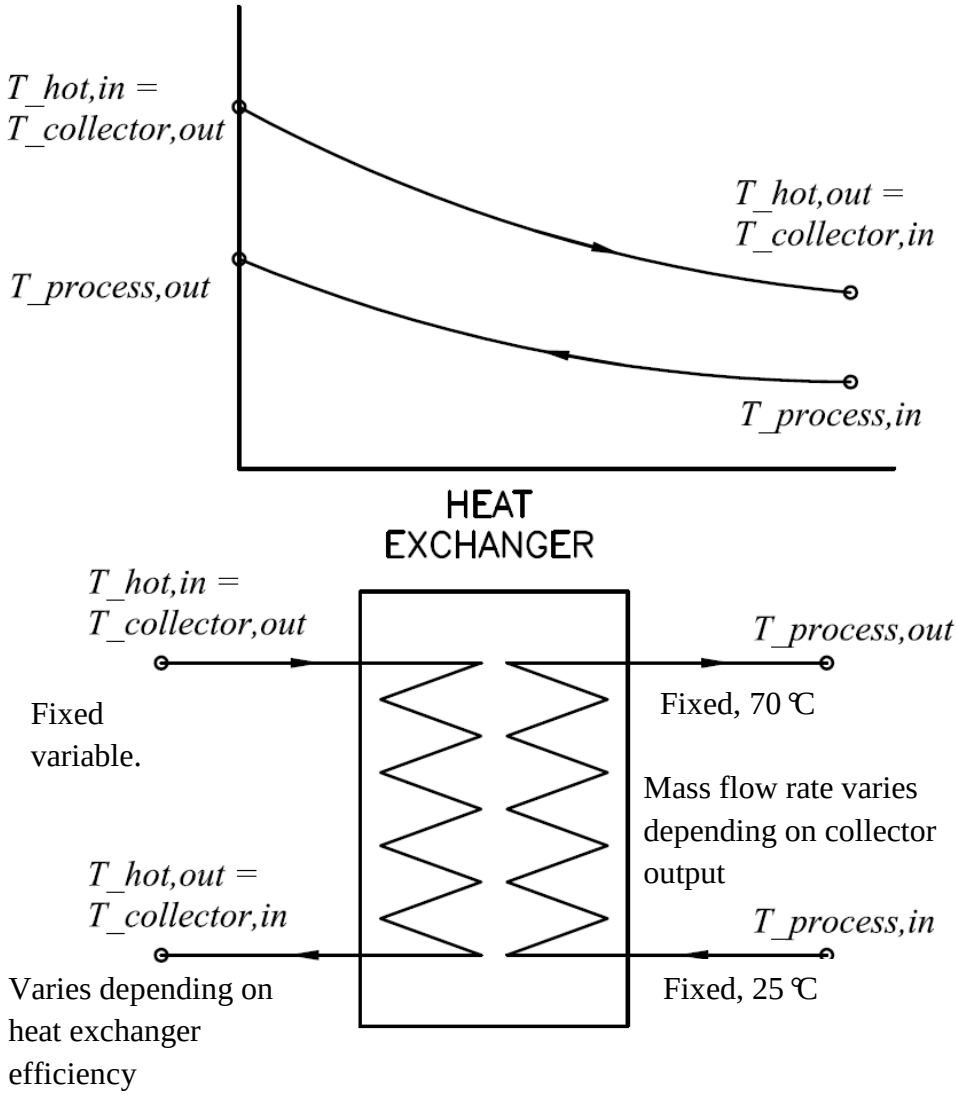


Figure 4. 6 Schematic of closed loop drainback system and temperature profile of heat exchanger.

4.7. Software Assisted Analysis

To calculate the overall solar fraction in a year, and its hourly variation, spreadsheet software is needed. Microsoft Excel is selected for its built-in library of functions and the ease of programming through the use of macro. The input, calculations involved and output are shown in Figure 4.7.

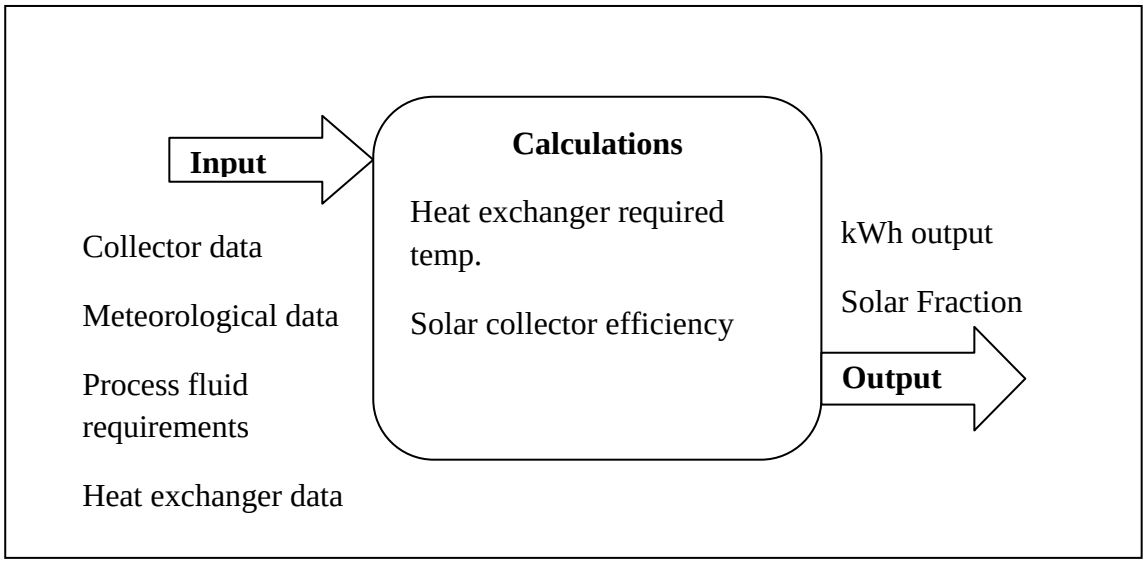


Figure 4. 7 Excel block diagram.

The steps in obtaining the overall year result for an open loop direct system is as follows:-

1. Input process requirements and fluid properties.
2. Input evacuated tube collector data.
3. Input 365 days Malaysian typical meteorological year data on solar insolation.
4. Input collector input and output temperature
5. Convert the daily average insolation into hourly insolation following a normal distribution.
6. From the hourly solar insolation, choose the highest value as the basis for system sizing.

7. Calculate the efficiency of the collector panel at that hour.
8. Determine the mass flow rate of working fluid through the panel.
9. Calculate the number of panels required to produce 100% solar fraction for that hour.
10. Using the number of panels obtained, calculate the output from the panels on each and every hour.
11. Get monthly average solar fraction.

For a closed loop drain back system, the only difference is the existence of a heat exchanger, which raises the solar collector input and output temperature in order to maintain the process fluid requirements. The calculation steps are the same as previous with an additional step to first determine the raised temperature required. The prerequisite steps are:-

1. Input heat exchanger active area, overall heat exchanger efficiency.
2. Input working fluid heat capacity.
3. Calculate solar collector input and output temperature.

CHAPTER 5: PROJECT BACKGROUND AND SIZING DESCRIPTION

To study the applicability of medium solar thermal technology, a particular process in the industry is chosen. Since most plants would have long operating hours and a preferred production flow, it is unrealistic to depend solely on solar insolation for a particular process's thermal energy needs. It is a requirement that energy is supplied on demand. To overcome this, a solar thermal system would need to be supplemented by another system, such as electrical heater, heat pumps or boilers.

Subang is the location with the most meteorological data availability as it is where our nation's first airport is situated. Incidentally, there are a few industrial estates in Subang. For these reasons, the factory chosen is situated within Subang area.

One process which is mostly used in all industries is high pressure wash down systems. This system is used for cleaning purposes. The system requirements are listed in Table 5.1.

Table 5.1 Solar thermal system requirements.

Criteria	Value	Unit
Power	470	kW
Fluid Out temperature	80	℃
Fluid In Temperature	25	℃
Fluid used	Water	-
Fluid heat capacity	4.18	$kW/m^2.K$
Required flow rate	2.044	kg/s

5.1 Solar Collector Selection

As the collector heats up, more heat is loss to the surrounding. The main mechanism are Conduction loss at the front, side and back of the panel, Convective losses at the front of the panel and most importantly radiative loss at the front of the panel., described by the equation below, repeated for convenience:-

$$\%\eta = \eta_0 - a_1 \frac{(T_m - T_a)}{G_k} - a_2 \frac{(T_m - T_a)^2}{G_k} \tag{3.7}$$

Where,

Parameter		Description	Unit
$\%\eta$	=	Solar Collector Efficiency	%
η_0	=	Optical efficiency of the collector. It is a measure of how good the collector is at absorbing solar energy.	%
a_1	=	Liner loss co-efficient. It is a measure of how much heat is lost mainly by conduction as the collector temperature rises relative to ambient temperature.	W/m^2K
a_2	=	Quadratic loss co-efficient. It is a measure of how much heat is lost mainly by convection and radiation as the collector temperature rises relative to ambient temperature.	W/m^2K^2
T_m	=	Mean temperature of the collector, $(T_{outlet}+T_{inlet})/2$	℃
T_a	=	Surrounding ambient temperature	℃

The equation above would yield an efficiency graph as in Figure 5.1.

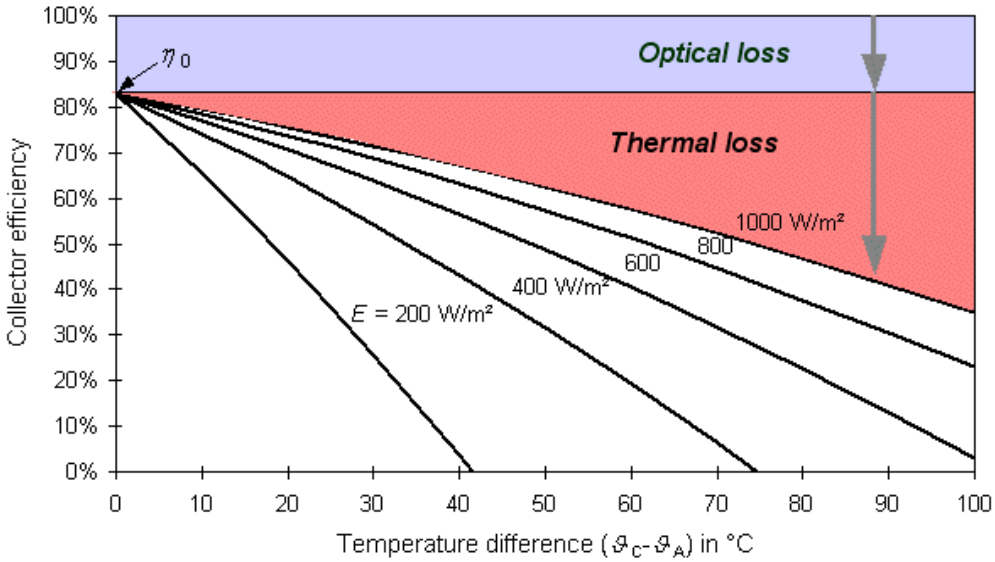


Figure 5.1 Efficiency of solar collector as the collector temperature rises. Source: Renewable Energy World, 2004.

Generally, flat plate collector has a lower linear loss coefficient but higher quadratic loss co-efficient as compared to an evacuated tube collector. This would result in a higher heat loss when the difference in collector and ambient temperature is higher, as shown in Figure 5.2

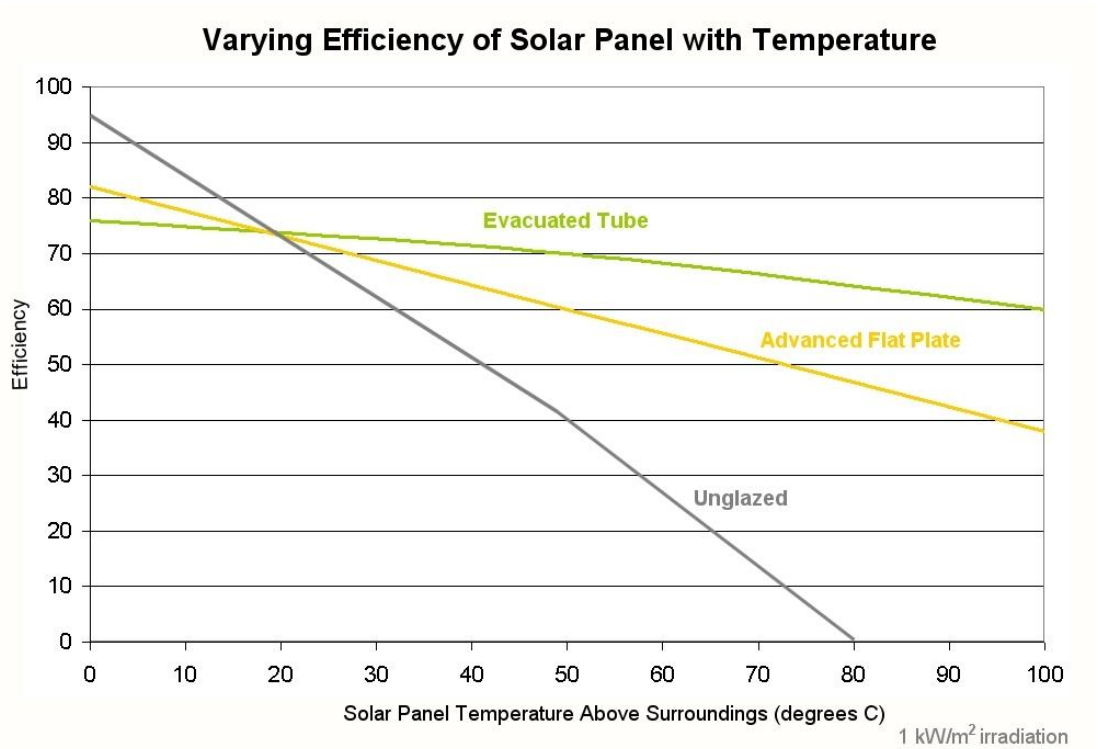


Figure 5.2 Comparison of flat plate and evacuated tube collector.

Due to our intention of utilizing the solar thermal energy for industrial usage, which is in the medium temperature region, and the simplicity of a stationary collector, the evacuated tube collector is chosen for this study since it yields a higher efficiency. This would be

the reason why evacuated tubes are more popular, as show in Figure 5.3 of the market share of various solar collectors.

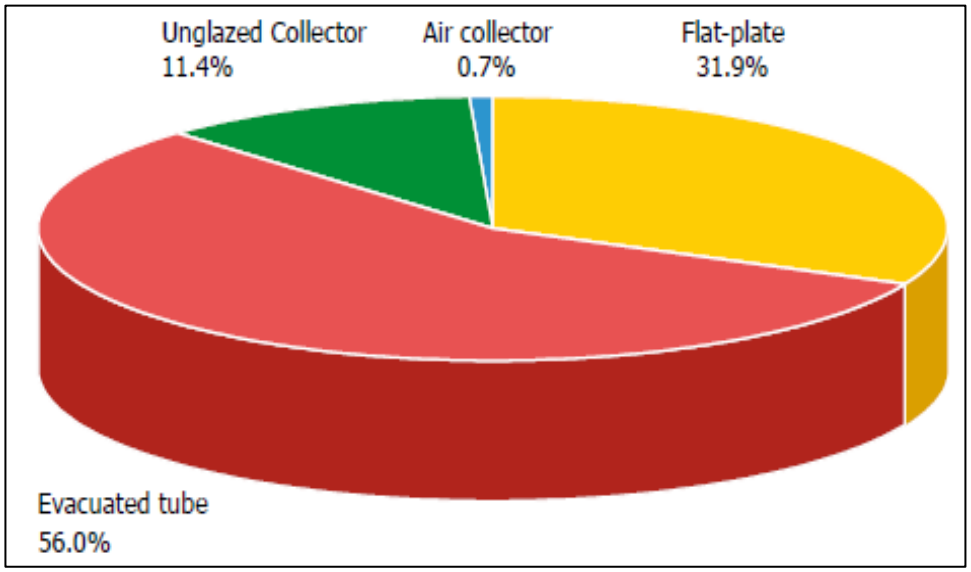


Figure 5.3 Distribution of the total installed capacity in operation by collector type in 2009. Weiss and Mauthner, 2011.

In general, the two collectors have nearly identical efficiency ratings and the differentiating advantages of U-pipes are:

- Lower price
- Installation versatility – there are no requirements on inclination of the panels.
- Smaller size for easier placement in tight locations.

A comparison of the two technologies was undertaken by SuMaxx, as shown in Table 5.2.

Test Models: SunMaxx-30 Heat Pipe, and SunMaxx-30U-Pipe

Testing Report: Solar Keymark Certification Testing

Table 5.2 Comparison of heat pipe and u-pipe evacuated tube collectors. Source: SuMaxx, 2008.

Model	**SunMaxx-30U**			**SunMaxx-30**		
Collector Type	U-Pipe			Heat Pipe		
Aperture Area	2.67 m^2 (28.74 ft^2)			2.79 m^2 (30.03 ft^2)		
Conversion Factor (efficiency η_0)	0.650			0.734		
Heat Transfer Coefficient (a_1)	1.585 $W/(m^2K)$			1.529 $W/(m^2K)$		
Temperature Dependent Heat Transfer Coefficient (a_2)	0.002 $W/(m^2K^2)$			0.012 $W/(m^2K^2)$		
Typical Power Output/Collector						
$T_m - T_a$ (K)	@ 400 W/m^2	@ 700 W/m^2	@ 1000 W/m^2	@ 400 W/m^2	@ 700 W/m^2	@ 1000 W/m^2
10	649	1172	1693	772	1387	2001
30	562	1083	1510	650	1264	1879
50	469	990	1510	490	1105	1719
Power Output ($BTU/h/m^2$ – Aperture Area) based on 1000W/m^2 Irradiance	2163 $BTU/h/m^2$ of Aperture Area 201 $BTU/h/ft^2$ of Aperture Area			2446 $BTU/h/m^2$ of Aperture Area 227 $BTU/h/ft^2$ of Aperture Area		
Total BTU/h	5923 BTU/h			6824 BTU/h		
BTU/h/$ Invested (Value of Collector)	BTU/h/$ 4.76			BTU/h/$ 3.90		

The result shows that the conversion efficiency of Heat Pipe technology is better than U-Pipe. However, in pure dollar value – BTU/h/$ invested –U-Pipe Solar Evacuated

Tube Solar Collectors is more cost effective because of their lower price and comparable performance rating.

Also, compared to the flat solar panel, solar tube is designed to collect the energy from the daylight at all angles, as illustrated in Figure 5.4. The rays are all absorbed perpendicularly to the tube. Therefore, solar tube collector is more efficient in absorbing solar energy.

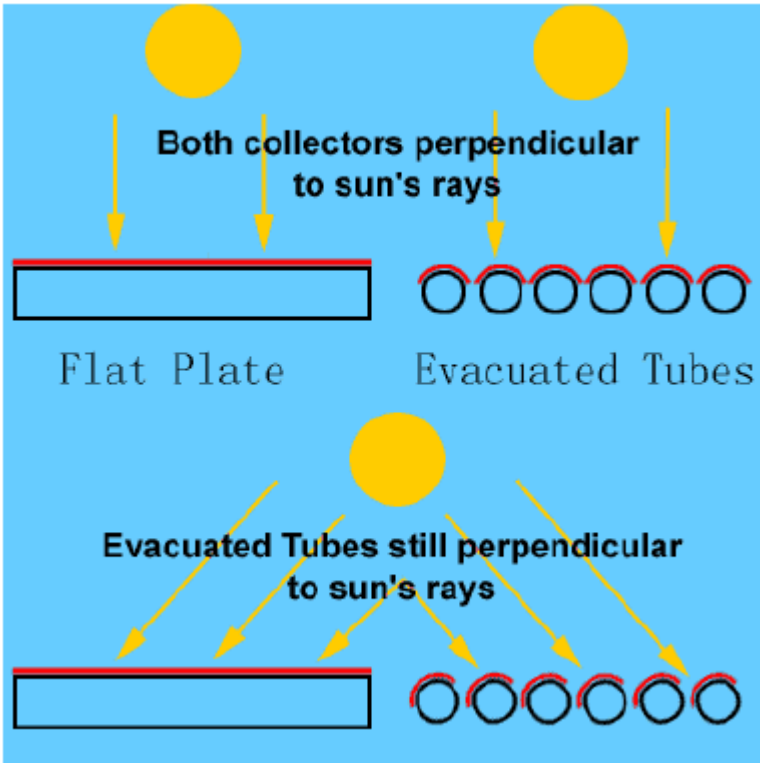


Figure 5.4 Solar ray angle. Source: Himin Ltd., 2012

Due to the simplicity and the proven nature of the technology used in a U-pipe solar collector, it is chosen for further study for the higher possibility of implementation in the industrial world.

From the market, a solar collector vendor is chosen, which is Himin Ltd from China. The solar collector used has the parameters listed in Table 5.3. The parameters are tested by German Fraunhofer research institute and are obtained directly from the manufacturer.

Table 5.3 Himin Solar Collector HUJ16/1.8

Paramater	Value	Unit
D_tube	58	mm
D_Copper	8	mm
U-pipe thickness	0.5	mm
Length	1800	mm
Collector Joint	15	mm
Outline Dimension	1978x1636x134	mm x mm x mm
No of tubes	16	-
Weight	61.65	kg
Rated working pressure	0.6	MPa
a1	2.103	$W/(m^2K)$
a2	0.0107	$W/(m^2K^2)$
n_0	0.779	-
Aperture Area	1.51	m^2
Gross Area	3.24	m^2

Figure 5.5 Himin u-pipe collector. Source: Himin Ltd, 2012.

5.2 System Description

The philosophy of design is that this system is meant to be a secondary system. Its function is to supplement a primary system, which is able to supply the full heat load requirement by itself. It is the intent to avoid thermal overload in the system. As such, the solar thermal system is sized such that the solar fraction will be 1 for the sunniest day. Two systems are evaluated, namely the Open-Loop Direct and Closed Loop Drain Back system.

5.3 Open-Loop Direct Systems

This is the simplest of the active systems. The transfer fluid acts also as the intended working fluid for a process and is passed through the collector, gaining heat energy in the process. A solar storage tank acts as an expansion tank and is the reservoir of the heated fluid. The heated fluid is then passed to a secondary heater where if the temperature is insufficient, it will be heated by other means such as boiler or electrical heater. An air vent is required at the high point of the solar thermal collector for initial air purging. A pump is used to circulate the working fluid and can be thermostatically controlled to give a variable flow rate to maintain the output temperature.

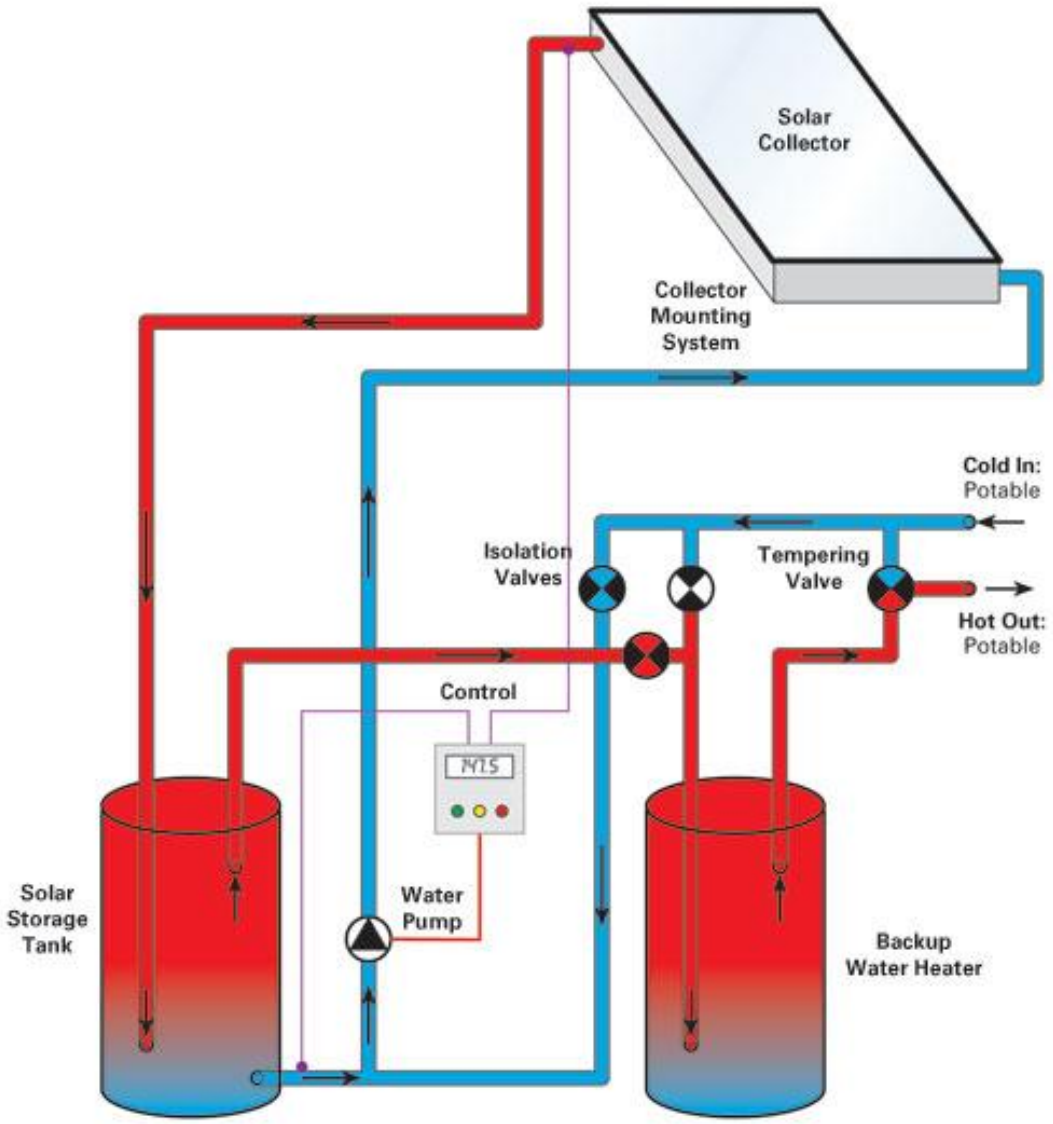


Figure 5.6 Open-Loop Direct Systems. Source: Homepower.com, 2012.

5.4 Closed-Loop Drainback Systems

The closed-loop drainback system is attractive because of the least amount of routine service required of any active system. The heat-transfer working fluid is circulated in a closed loop, making no direct contact with the outer environment and thus eliminating the risk of contamination. When the system is not in use, either because of over capacity or maintenance, the solar collector is emptied of the working fluid which is stored in a reservoir tank.

The operation of the system is when the pump is running; the working fluid is pumped from the reservoir to the collector and then the heat exchanger, transferring heat energy to the process fluid in the solar tank. If the pump is off, the working fluid will drain back by gravity to the reservoir. As such, there must be a continuous slope in the piping for efficient draining and the collector must therefore always be situated above the storage tank. Drainback systems are able to avoid overcapacity and freezing and are effective and reliable. They can operate twenty years without servicing typically.

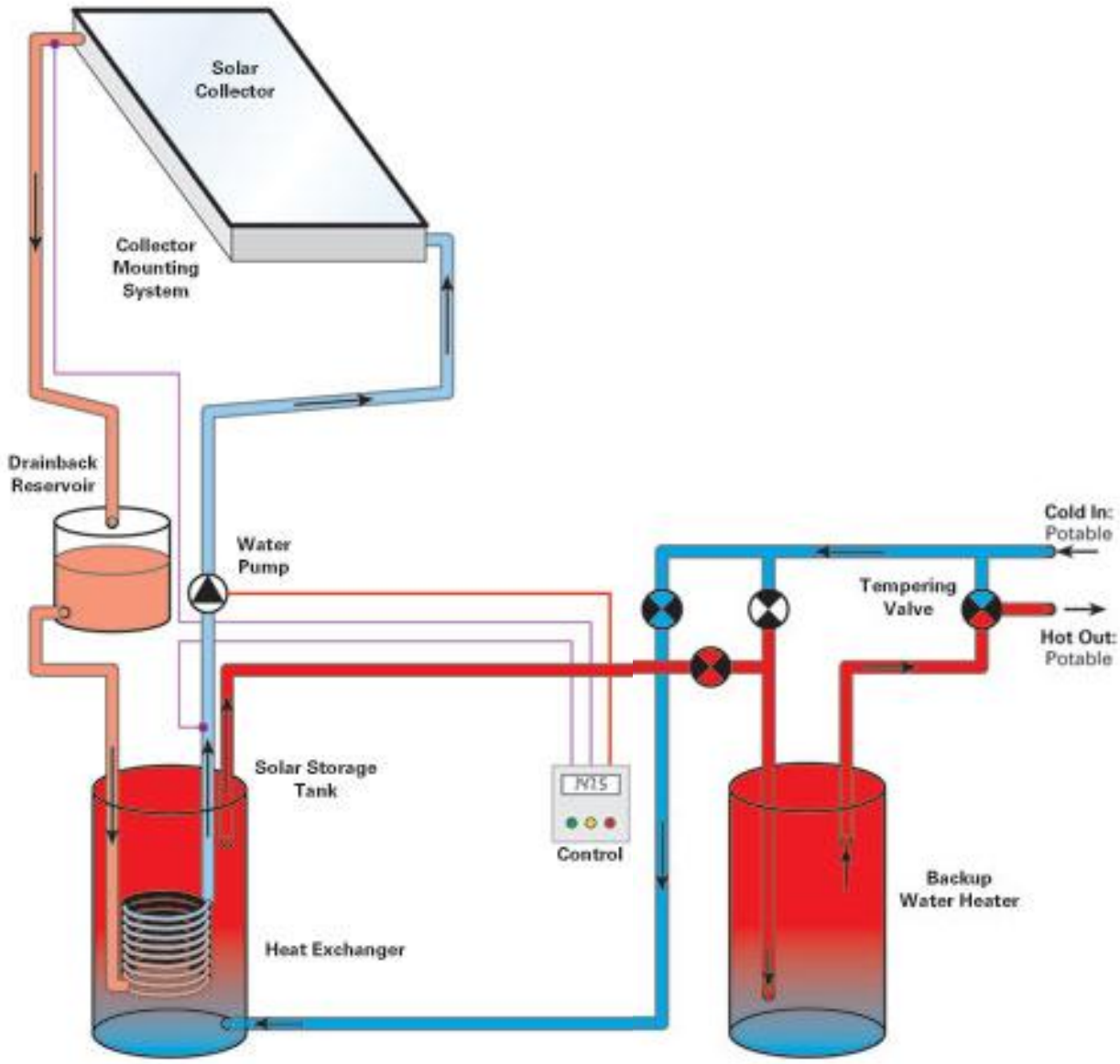


Figure 5.7 Closed loop drain back systems. Source: Homepower.com, 2012.

A plate type heat exchanger is used in the simulation and have the specifications as shown in Table 5.4. The Overall Heat Transfer Co-efficient obtained for the rated heat transfer rate is assumed to be constant for the whole range of different mass flow rate of fluid across the heat exchanger.

Table 5.4 Heat exchanger parameters.

Paramater	Value	Unit
Type	Plate	-
Channels x Pass (Hot & Cold)	25 x 1	-
Total Active Area, A_h	19.11	m^2
Overall Heat Transfer Coefficient, U_h	3000	$W/(m^2K)$
Heat Exchanger Rate	470	kW
Net Weight	584	kg

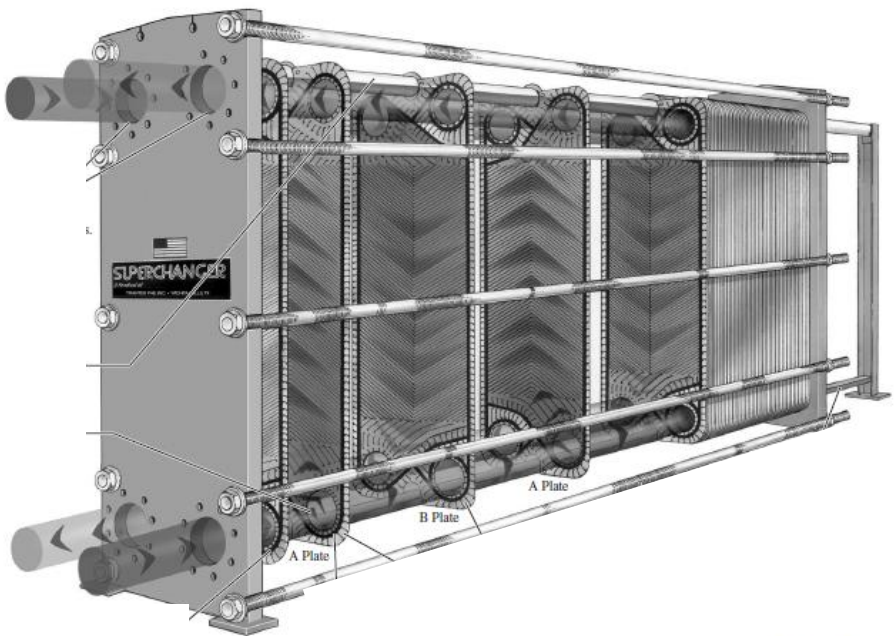


Figure 5.8 Plate type heat exchanger. Source: Tranter PHE, Inc.

CHAPTER 6: RESULTS & DISCUSSIONS

The requirement and component properties used for the simulations are repeated here for reader convenience purposes.

Table 6. 1 Solar thermal system requirements

Criteria	Value	Unit
Power	470	kW
Fluid Out temperature	80	C
Fluid In Temperature	25	C
Fluid used	Water	-
Fluid heat capacity	4.18	$kW/m^2.K$
Required flow rate	2.044	kg/s

Table 6. 2 Himin Solar Collector HUJ16/1.8

Paramater	Value	Unit
D_tube	58	mm
D_Copper	8	mm
U-pipe thickness	0.5	mm
Length	1800	mm
Collector Joint	15	mm
Outline Dimension	1978x1636x134	mm x mm x mm
No of tubes	16	-
Weight	61.65	kg
Rated working pressure	0.6	MPa
a1	2.103	$W/(m^2K)$
a2	0.0107	$W/(m^2K^2)$
n_0	0.779	-
Aperture Area	1.51	m^2
Gross Area	3.24	m^2

Table 6. 3 Heat exchanger parameters.

Paramater	Value	Unit
Type	Plate	-
Channels x Pass (Hot & Cold)	25 x 1	-
Total Active Area, A_h	19.11	m^2
Overall Heat Transfer Coefficient, U_h	3000	$W/(m^2K)$
Heat Exchanger Rate	470	kW
Net Weight	584	Kg

6.1 Open Loop Direct System

The open loop direct system is sized with parameters shown in Table 6.4 below:-

Table 6. 4 Sizing parameters for open loop system.

Paramater	Value	Unit
Max solar insolation	1304.1	W/m2
Collector input temperature	25	℃
Collector output temperature	80	℃
Panels required	323	
Each panel efficiency at max solar insolation	73.86	%

With the application of Malaysia Typical Weather Year data, the resulting output and solar fraction is shown in Figure 6.1 and Table 6.5.

Table 6. 5 Open loop direct system solar fraction of system for a typical year (80 ℃)

Month	Min (kWh/m^2)	Max (kWh/m^2)	Average (kWh/m^2)	Average kW Output	Solar Fraction, %
January	4.21	5.56	4.96	134,117	28.54
February	4.67	6.62	6.23	152,868	32.53
March	4.33	6.51	5.02	174,584	37.15
April	2.63	5.11	4.11	152,262	32.40
May	3.69	6.84	4.83	141,180	30.04
June	2.98	6.71	5.14	137,755	29.31
July	4.41	5.86	5.17	139,457	29.67
August	2.15	6.81	5.25	134,493	28.62
September	3.95	5.53	4.89	127,682	27.17
October	4.68	6.43	5.43	133,376	28.38
November	4.68	6.43	5.43	121,804	25.92
December	0.61	5.34	3.00	115,809	24.64

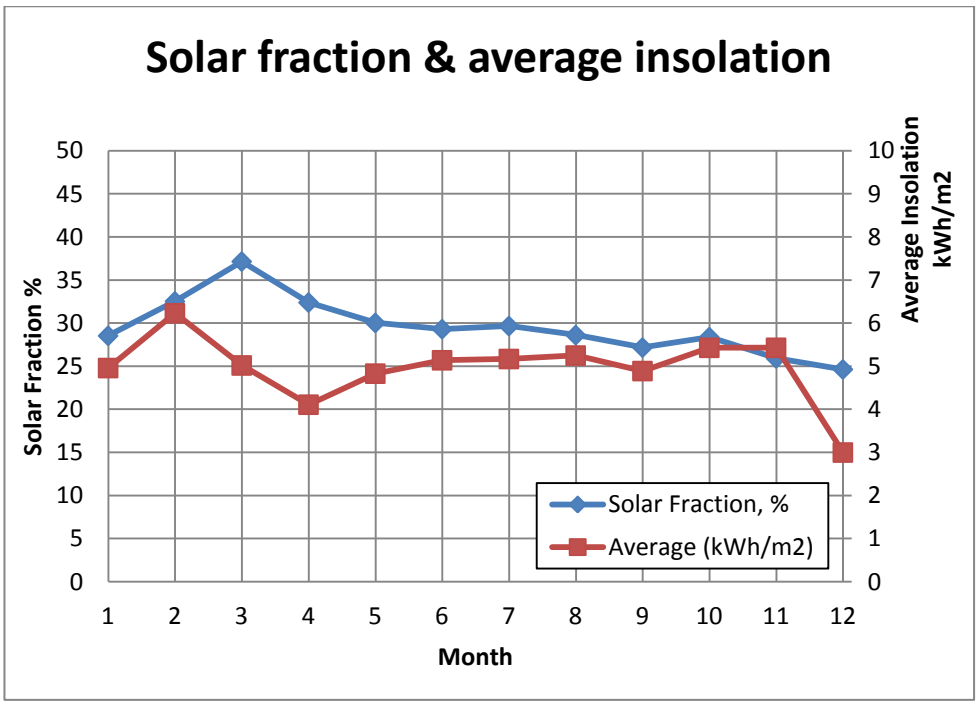


Figure 6. 1 Open Loop Direct System Solar fraction and average insolation (80 ℃)

This first attempt from the outset would give a false impression that the solar thermal system is unable to provide a good enough solar fraction, of just 37.97% maximum. However, this is due to our sizing intention of no overloading at any day in a year. Instead, we should look at how the variation in solar fraction behaves in a year, rather than the total contribution it has to the system. The variation in this case is 12.46% using 323 panels. If 960 panels are used, the maximum solar fraction would be 114.28% and gives a variation of 37.5%. Despite the multitude of equation used, the result is just a direct scaling of the original 323 panels. This also demonstrates that it is unrealistic to rely on solar alone as the provider of process heat, due to the huge variation in output, unless clever ways of solar storage is designed.

Since it is the intent that the solar thermal system is used as a fuel saver, it should be sized with no wastage at anytime. If the design is to maximize solar fraction, during periods of over capacity, the excess thermal energy will have to be discarded, which can be seen as a waste. Due to this, the original design philosophy of no overload in any one day is retained.

6.2 Closed Loop Drainback System

The closed loop drainback system is sized with parameters shown in Table 6.6 below:-

Table 6. 6 Sizing parameters for open loop system.

Paramater	Value	Unit
Process Flow Output & Input Temperature	25 & 80	℃
Max solar insolation	1304.1	W/m^2
Collector input temperature	40.76	℃
Collector output temperature	95.76	℃
Panels required	338	-
Each panel efficiency at max solar insolation	70.53%	%

With the application of Malaysia Typical Weather Year data, the resulting output and solar fraction is shown in Figure 6.2 and Table 6.7.

Table 6. 7 Closed Loop System Solar Fraction of system for a typical year (80 ℃)

Month	Min (kWh/m^2)	Max (kWh/m^2)	Average (kWh/m^2)	Average kW Output	Solar Fraction, %
January	4.21	5.56	4.96	122,180	26.00
February	4.67	6.62	6.23	141,175	30.04
March	4.33	6.51	5.02	163,301	34.74
April	2.63	5.11	4.11	140,582	29.91
May	3.69	6.84	4.83	129,418	27.54
June	2.98	6.71	5.14	125,836	26.77
July	4.41	5.86	5.17	127,606	27.15
August	2.15	6.81	5.25	122,380	26.04
September	3.95	5.53	4.89	115,548	24.58
October	4.68	6.43	5.43	121,565	25.86

Month	Min (kWh/m^2)	Max (kWh/m^2)	Average (kWh/m^2)	Average kW Output	Solar Fraction, %
November	4.68	6.43	5.43	109,601	23.32
December	0.61	5.34	3.00	103,636	22.05

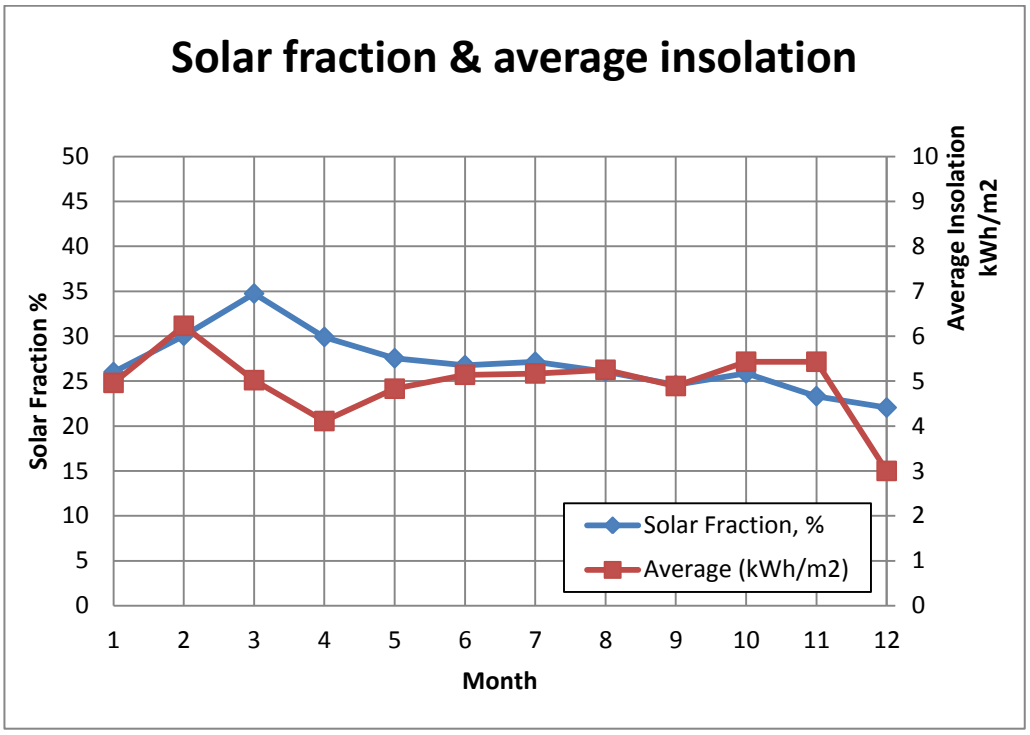


Figure 6. 2 Closed Loop Direct System Solar fraction and average insolation (80 ℃)

6.3 Comparison of Open Loop and Closed Loop Drainback System

The two systems results are tabulated in Table 6.8.

Table 6. 8 Open loop and close loop solar fraction at 80 ℃ output temperature.

Parameter	Open Loop Direct System	Closed Loop Drainback System
Maximum Solar Fraction	37.15	34.74
Minimum Solar Fraction	24.64	22.05

The difference between open loop and closed loop is around 2.4%, coming to approximately 11.33kW. A further sensitivity analysis on output temperature on system efficiency is done. A summary of different output temperature, between open loop and closed loop system is shown in Table 6.9.

Table 6. 9 Open loop and close loop system performance at various output temperatures.

Output Temp	Open Loop			Closed Loop			Difference % between Closed and Open Loop	
	Average Solar Fraction, Open Loop	Average Collector Efficiency, Open Loop	Panels used	Average Solar Fraction, Closed Loop	Average Collector Efficiency, Closed Loop	Panels Used	Solar Fraction	Average Collector Efficiency,
70	31.19	57.43	319	28.86	44.92	332	8.07	27.85
80	30.32	52.10	323	27.8	41.00	338	9.06	27.07
90	29.55	47.87	328	26.8	37.18	346	10.26	28.75
100	28.70	44.50	332	25.65	33.56	353	11.89	32.60
110	27.98	41.46	338	24.61	30.30	362	13.69	36.83
120	27.12	38.46	343	23.54	27.4	371	15.21	40.36
130	26.27	35.51	349	22.52	24.86	381	16.65	42.84
140	25.38	32.71	355	21.46	22.53	391	18.27	45.18
150	24.53	30.17	362	20.43	20.31	403	20.07	48.55

The resulting information is plotted in a graph form as shown in Figure 6.3.

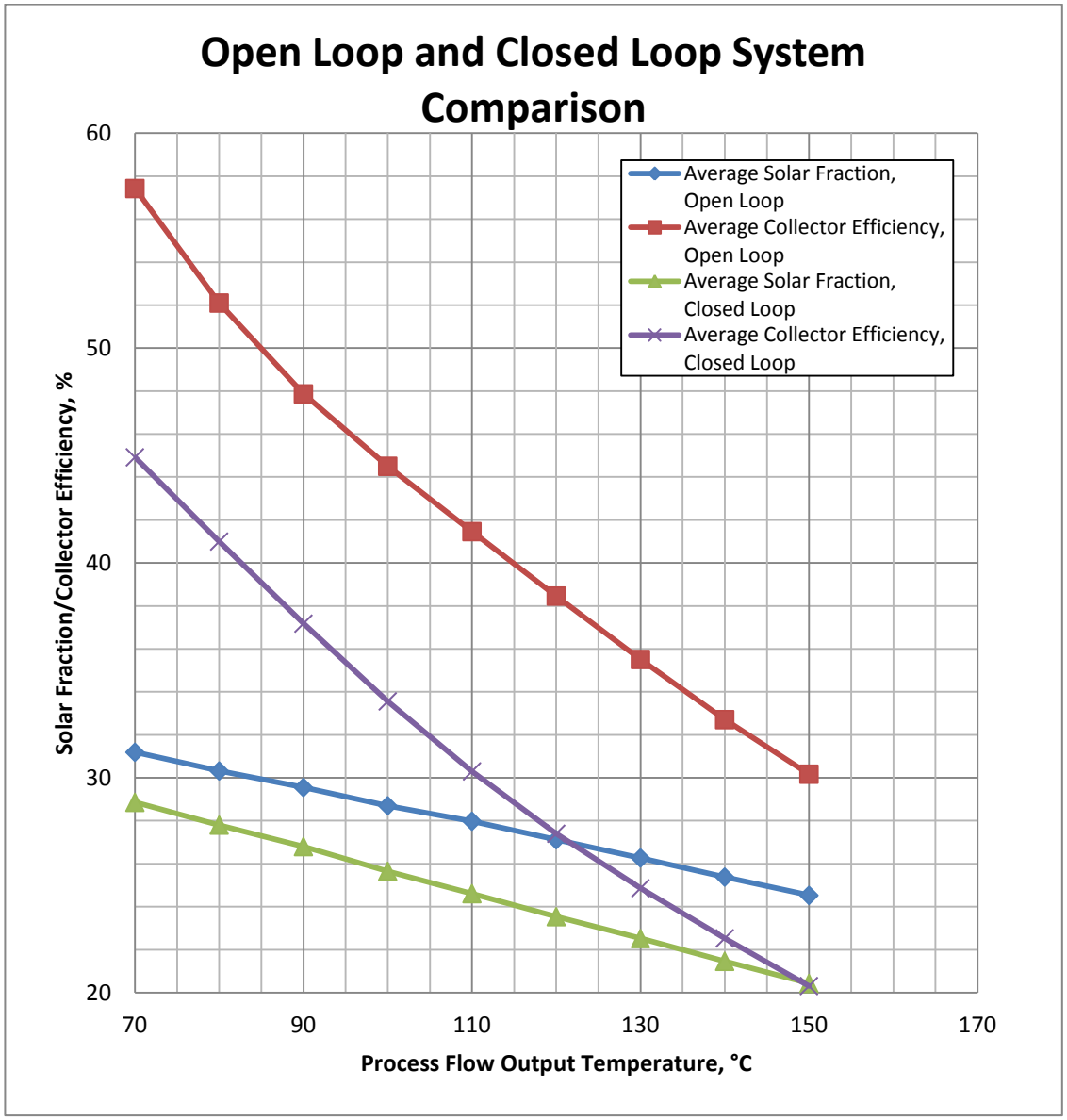


Figure 6. 3 Open loop and closed loop system performance at various output temperatures.

It shows that for a higher output temperature, greater loss is experienced by both systems. It is observed that as the output temperature grows so will the difference between the performance of an open loop and closed loop system. This signifies that if possible; try to use a direct system as much as possible. The presence of a heat exchanger device would mean a higher collector output requirement and thus lower efficiency.

6.4 Cost and Benefit Analysis

The system for output of 70 ℃ hot water is used for the cost analysis. This is because to give a fair comparison, the performance comparison was downgraded to the limitation of the heat pump sourced which can only go to a maximum of 70 ℃. Table 6.10 summarizes the cost of various methods in generating thermal energy.

Table 6. 10 Consumption Cost and Overall Cost for 70 ℃ output temperature

No	Method	Consumption Cost RM cents /kWh_{th}	Overall Cost /Profit RM Cents/kWh_{th}
1	Medium Temperature Solar Thermal System (Open Circuit)	0	3.54
2	Medium Temperature Solar Thermal System (Closed Circuit)	0	(5.27)
3	Electric Heater	(28.3)	(28.76)
4	Steam Boiler	(24.565)	(25.11)
5	Solar PV driven electric heater	94.7	0
6	Heat Pump	(8.09)	(10.63)

Consumption cost refers to the cost of fuel. Overall cost takes into consideration of the installation cost of the systems. The economical analysis is done for an assumed useful life of 10 years, although it can be reasonable expected that the well maintained equipment will be able to be in service for 20 years or more. There are no considerations of maintenance costs in the calculation. Refer Appendixes for detailed calculations.

From the cost and benefit analysis, it can be seen that open circuit solar thermal system is the most attractive, giving a return of 3.54 ¢ per kWh_{th}. This is followed by Solar PV

driven electric heater breaking even the investment cost at the 10th year through selling the electricity generated to TNB and using the proceeds to purchase grid electricity for heaters, giving 0 ¢ per kWh_{th}. Subsequently, closed circuit solar panel system is at the 3rd position, costing 5.27 ¢ per kWh_{th} followed by Heat pump system at 10.63 ¢ per kWh_{th}; Steam Boiler at 25.11 ¢ per kWh_{th} and finally pure electric heater, at 28.76 kWh_{th}.

Solar PV system is ranked high because of the heavy subsidies the Government has provided through the Feed-in-Tariff. The other alternatives such as diesel and grid electricity are also subsidized by the government. Even without subsidies, the return of solar thermal system can be on par, making it an economically viable solution. The attractiveness of this system will be greatly felt when the subsidies for fuel is removed by the government and mass adoption by the industry pushes down component and installation cost.

The downside of solar thermal system is the real estate needed for the deployment of the panels, which in this case stands at around 34m x 34m of space. Part of the solar panels can be integrated into the building roof, generating useful energy while acting as an insulator to lower radiative heat gain to the building, reducing cooling cost. Also, the system is limited to low temperature applications, given the government subsidized cheap alternatives available currently in Malaysia.

The big initial cost would be a deterrent for implementation of solar thermal as compared to conventional boilers. It is observed that a big chuck of the system cost is spent on transportation of collector panels from China. If there is a manufacturing plant in Malaysia, we can expect that the cost to be lower and would make the system more acceptable to the industry.

Maintenance cost for the different system is not included into the cost and benefit analysis. The inclusion of these costs would provide a better estimate of the attractiveness of solar thermal systems. Qualitatively, it should be noted that solar thermal system involves minimal moving parts. It is foreseen that the maintenance involved would be much less than boiler/heat pump technologies.

CHAPTER 7: CONCLUSIONS

Malaysia's solar energy potential and SIPH demand has been explored and found attractive. Technology to achieve SIPH is available and improving. Also, installed system around the globe is a good source for reference for deployment in Malaysia. Finally, the cost and benefit analysis has shown that SIPH is the cheapest among the other alternatives. It is demonstrated that Solar Industrial Process Heat is technically feasible and economically feasible. The research objectives have been achieved.

Policy makers in Malaysia should have a closer look at the benefits of SIPH as a means to achieve greater renewable energy utilization. Support and direction from the government is always a good catalyst for wider acceptable by the industry.

Lastly, in my opinion there should be a common glass screen for each collector panel, rather than having each evacuated tube exposed to the environment by its own. This is because with the frequent rain in Malaysia, the glass surface of the tubes will be easily dirtied by the elements. A common glass screen will ease the cleaning of the panels and is much more practical.

BIBLIOGRAPHY

A. Acra, M. Jurdi, H. Mu'allem, Y. Karahagopian, and Z. Raffoul,1990. *Water Disinfection by Solar Radiation, Assessment and Application*. [Online] Available at: <http://almashriq.hiof.no/lebanon/600/610/614/solar-water/idrc/01-09.html.> [Accessed 11 May 2012]

Abdelaziz EA, Saidur R, Mekhilef S. *A review on energy saving strategies in industrial sector*. Renewable and Sustainable Energy Reviews 2011;15(1): 150 – 68.

Advanced Thermal Solar, LLC, 2012. *Sizing your system.* [Online] Available at: <http://www.advthermalsolar.com/sizing-your-system.php> [Accessed 15 April 2012]

AGO. (2006). *Vacuum tube solar thermal collector. Fact Sheet No 05, Solar Thermal*. Canberra, Australia Greenhouse Office.

Amin, N.,Lung,C.W.,Sopian,K. 2009. *A practical field study of various solar cells on their performance in Malaysia*. Renewable Energy, 34(8), 1939–1946.

Appleyard D. 2009. *Action Plan for 50% :how solar thermal can supply Europes energy*. Renewable Energy World, March-April 2009: 100-5.

Aschoff Solar, 2012. *Solar Energy-easy and efficient.* [Online] Available at: <http://www.terramar.com.vn/aschoff_solar.html>[Accessed 1 May 2012]

Ayu Wazira Azhari, Kamaruzzaman Sopian, Azami Zaharim, Mohamad Al Ghoul. 2008. *A new approach for predicting solar radiation in tropical environment using satellite images – case study of Malaysia*. WSEAS Transaction on Environmental Development 2008, 4, 373-378.

Beath A.C. (2012). *Industrial energy usage in Australia and the potential for implementation of solar thermal heat and power*. Energy, 43, 261-272.

Building and Engineering Services Association (B&ES). Solar Thermal. [Online] Available at :<http http://www.b-es.org/sustainability/solar-thermal-guidance/> [Accessed 15 April 2012]

Chandran VGR, Sharma S, Madhavan K. *Electricity consumption-growth nexus: the case of Malaysia*. Energy Policy 2010;38:606 – 12.

Claudia Vannoni, Riccardo Battisti and Serena Drigo (2008). *Potential for Solar Heat in Industrial Processes*. CIEMAT, Madrid.

EarthTrends. Energy and resources; 2010. Malaysia.earthtrends.wri.org.

Economic Transformation Programme: A roadmap for Malaysia. (2010). PEMANDU.

Encyclopedia Article. (2008). *Solar Energy*. McGraw-Hills Access Science Encyclopedia of Science and Technology Online.

Everett, B. (2004). Solar Thermal Energy. In *Renewable Energy – Power for A Sustainable Future* (2nd ed.) (pp. 17-64). New York: Oxford University Press.

Firdaus Muhammad-Sukki, Roberto Ramirez-Iniguez,Siti Hawa Abu-Bakar,Scott G. McMeekin,Brian G.Stewart. (2011). *An evaluation of the installation of solar photovoltaic in residential houses in Malaysia: Past, present, and future*. Energy Policy, 39, 7975–7987.

Fuller R.J. (2010). *Solar industrial process heating in Australia – Past and current status*. Renewable Energy, 36, 216-221.

Goyal R.K., Tiwari G.N. (1999). *Performance of a reverse flat plate absorber cabinet dryer: a new concept*. Energy Conversion Management 1999;40(4):385 – 92.

Hans-Jörg Bullinger (Editor) (2009). *Technology Guide - Principles, Applications, Trends*. Springer-Verlag Berlin Heidelberg, 316.

Harris, A.H. (2008). *MBIPV Project: Catalyzing Local PV Market, Finance & Investment Forum on PV Technolgy, Kuala Lumpur, Malaysia.*

IEA. (2006). *International energy annual 2004*. Energy Information Administration

IEA SHC. (2008). *Process Heat Collectors State of the Art within Task 33/IV* .AEE INTEC, Gleisdorf, Feldgasse 19, Austria.

Islam, MD. Radiqul & Exell, R.H.B. (1996). *Solar radiation mapping from satellite image using a low cost system*. Solar Energy 56(3):225-237.

Jingyi Han, Arthur P.J. Mol, Yonglong Lu. (2009). *Solar water heaters in China: A new day dawning*. Energy Policy, 38, 383–391

Kalogirou Soteris A. (2004) *Solar thermal collectors and applications*. Progress in Energy and Combustion Science, 30(3), 231–95.

Kalogirou, S. (2003). *The potential of solar industrial process heat applications*. Applied Energy, 76(4), 337–361.

Keong CY. (2005) *Energy demand, economic growth, and energy efficiency – the Bakun dam-induced sustainable energy policy revisited*. Energy Policy, 33, 679 – 89.

Koh SL, Lim YS. (2010) *Meeting energy demand in developing economy without damaging the environment – a case study in Sabah, Malaysia, from technical, environment and economic perspectives.* Energy Policy , 38, 4719 – 28.

Kulkarni Govind N, Kedare Shireesh B, Bandyopadhyay Santanu. (2008). *Design of solar thermal systems utilizing pressurized hot water storage for industrial applications.* Solar Energy, 82, 686–99.

Liu SY, Li LD. (2000). *Application researches of solar drying and their applications in industry and agriculture.* New Energy Res, 22(1):9–15 [in Chinese].

Luo, Z. (2008). *China solar water heater market report.* Solar Thermal Utilization Committee in China Association of Rural Energy Industry,Beijing.

Malaysian Meteorological Department. General Climate of Malaysia [Online] Available at :<http://www.met.gov.my/index.php?option=com_content&task=view&id=75&Itemid=1089&lang=English> [Accessed 15 April 2012]

Nancy Cannon. (2007). *Encyclopedia of Science & Technology*, 10th Edition, Volume 16 (S-SON), McGraw-Hill.

Malaysia Energy Information Hub. Statistics of Energy Usage [Online] Available at: , http://meih.st.gov.my/statistics;jsessionid=D46B33627FBB560232814BE4809A369F> [Accessed 3rd April, 2012]

Meyer J.P. (2009). *Solar thermal: large scale installations- gaining ground across the globe.* Sun and Wind Energy, 5, 68-81.

Mohd Zainal Abidin Ab Kadir, Yaaseen Rafeeu, Nor Mariah Adam. (2010). *Prospective scenarios for the full solar energy development in Malaysia*. Renewable and Sustainable Energy Reviews, 14, 3023-3031.

Shafiq, Nik Mohd Qamarul. (2010). *Performance Evaluation of Solar Flat Plate Collector*. University Malaysia Pahang.

Nowshad Amin, Chin W.L. & K. Sopian. (2009) *A practical field study of various solar cells on their performance in Malaysia*. Renewable Energy. 34, 1939-1946.

Nugroho AM. (2010). *The impact of solar chimney geometry for stack ventilation in Malaysia's single storey terraced house*. Malaysia's Geography 2010;(January):163–77.

Oliveria A.C. (2007). *A new look at the long-term performance of general solar thermal systems.* Solar Energy, 81, 1361-1368.

Pacheco, J.E. (2001). *Demonstration of solar-generated electricity on demand: The Solar Two project*. Journal of Solar Energy Engineering-Transactions of the ASME, 123(1), 5-5.

Patterson, John, n.d. *Solar hot water basics.* [Online] Available at:<http://homepower.com/basics/hotwater/> [Accessed 13 April 2012]

Proctor D, Morse RN. (1977). *Solar energy for the Australian food processing industry*. Solar Energy 1977;19:63 – 72.

Qamarul Shafiq, N.M. (2010). *Performance Evaluation of Solar Flat Plate Collector.* Faculty of Mechanical Engineering, Universiti Malaysia Pahang

R. Keith Mobley Ed. (2001). *Plant Engineer's Handbook.* Butterworth-Heinemann

Rahman I.A., J. Dewsbury. (2007). *Selection of typical weather data (test reference years) for Subang, Malaysia*. Building and Environment, 42, 3636–3641.

Renewable Energy Industries Academny. (2007) *Solar Hot Water version 2.0*, Installer Training Manual.

Renewable Energy World 02/2004 pp. 95-99

S. Mekhilef, A. Safari, W.E.S. Mustaffa, R. Saidur, R. Omar, M.A.A. Younis. (2012). *Solar energy in Malaysia: Current state and prospects*. Renewable and Sustainable Energy Reviews, 16, 386-396.

Saidur R, Ahmed JU, Masjuki HH. (2010). *Energy, exergy and economic analysis for industrial boilers for Malaysia*. Energy Policy 2010;38(5):2188–97.

Saidur, R., Leong, K.Y., & Mohammad, H.A. (2011). *A review on applications and challenges of nanofluids*. Renewable and Sustainable Energy Reviews, 15, 1646-1668.

Salsabila Ahmad, Mohd Zainal Abidin Ab Kadir, Suhaidi Shafie. (2011). *Current perspective of the renewable energy development in Malaysia*. Renewable and Sustainable Energy Reviews, 15, 897-904.

Schnitzer H, Christoph B, Gwehenberger G. (2007). *Minimizing greenhouse gas emissions through the application of solar thermal energy in industrial processes*. Approaching zero emissions. Journal of Cleaner Production 2007;15(September (13 – 14)):1271 – 86.

Tenaga Nasional Berhad. (2012). Tenaga Nasional Electricity Tariff Rates for Industries.

The Malaysia Economic in Figures 2010. Economic planning unit. Prime Minister Department, 2011. [Online] Available at: <http://www.epu.gov.my/malaysianeconomyfigures2009>[Accessed 5 May 2012]

UK Solar Energy, n.d. *How does my new solar system works?*. [Online] Available at:<http://www.uksolarenergy.org.uk/solar-system.html> [Accessed 30 April 2012]

Union of Concerned Scientists, 2005. Benefits of renewable Energy Use. [Online] Available at:<www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/public-benefits-of-renewable.html> [Accessed 10 May 2012]

Wang Zhifeng. (2009). *Prospectives for China's solar thermal power technology development*. Energy, 35, 4417-4420.

Xiao C, Luo H, Tang R, Zhong H.(2004).*Solar thermal utilization in China*. Renew Energy, 29, 1549–56.

Yunus A. Cengel. (2004). *Heat Transfer; A practical approach*. 2nd ed. New York:Mc Graw Hill.

Zhi-qiang Liu, Ai-xiang Xu, Yuan-yuan Lv, Xiao-xiao Wang. (2011). *Promoting the development of distributed concentrated solar thermal technology in China.* Renewable and Sustainable Energy Reviews, 16, 1174– 1179

APPENDIX A - TENAGA NASIONAL ELECTRICAL PRICING AND TARIFF – INDUSTRIAL

Table A1 Tenaga Nasional Electricity Tariff Rates for Industries. Source: TNB, 2012

TARIFF CATEGORY		UNIT	RATES
1	**Tariff D - Low Voltage Industrial Tariff**		
	For Overall Monthly Consumption Between 0-200 kWh/month		
	For all kWh	sen/kWh	34.5
	The minimum monthly charge is RM7.20		
	For Overall Monthly Consumption More Than 200 kWh/month		
	For all kWh (From 1kWh onwards)	sen/kWh	37.7
	The minimum monthly charge is RM7.20		
	Tariff Ds – Special Industrial Tariff (for consumers who qualify only)		
	For all kWh	sen/kWh	35.9
	The minimum monthly charge is RM7.20		
2	**Tariff E1 - Medium Voltage General Industrial Tariff**		
	For each kilowatt of maximum demand per month	RM/kW	25.3
	For all kWh	sen/kWh	28.8
	The minimum monthly charge is RM600.00		
	Tariff E1s – Special Industrial Tariff (for consumers who qualify only)		
	For each kilowatt of maximum demand per month	RM/kW	19.9
	For all kWh	sen/kWh	28.3
	The minimum monthly charge is RM600.00		

TARIFF CATEGORY		UNIT	RATES
3	**Tariff E2 - Medium Voltage Peak/Off-Peak Industrial Tariff**		
	For each kilowatt of maximum demand per month during the peak period	RM/kW	31.7
	For all kWh during the peak period	sen/kWh	30.4
	For all kWh during the off-peak period	sen/kWh	18.7
	The minimum monthly charge is RM600.00		
	Tariff E2s – Special Industrial Tariff (for consumers who qualify only)		
	For each kilowatt of maximum demand per month during the peak period	RM/kW	27.7
	For all kWh during the peak period	sen/kWh	28.3
	For all kWh during the off-peak period	sen/kWh	16.1
	The minimum monthly charge is RM600.00		
4	**Tariff E3 - High Voltage Peak/Off-Peak Industrial Tariff**		
	For each kilowatt of maximum demand per month during the peak period	RM/kW	30.4
	For all kWh during the peak period	sen/kWh	28.8
	For all kWh during the off-peak period	sen/kWh	17.3
	The minimum monthly charge is RM600.00		
	Tariff E3s – Special Industrial Tariff (for consumers who qualify only)		
	For each kilowatt of maximum demand per month during the peak period	RM/kW	24.4

	For all kWh during the peak period	sen/kWh	26.7
	For all kWh during the off-peak period	sen/kWh	14.7
	The minimum monthly charge is RM600.00		

Notes: SIT has a 2% higher increase than normal Industrial tariff in line with the Government's effort to gradually phase out the SIT subsidy

Top-Up and Standby

"Co-generator" means a generator who uses a single primary energy source to generate sequentially two different forms of useful energy for its own use at an efficiency rate of more than 70%. Services offered to co-generators are:

Top-up supply:

The additional supply required by a Co-generator who does not produce sufficient electricity for its own use.

Standby supply:

The supply that TNB provides to a Co-generator in the event that the Co-generator does not generate electricity due to plant failure or planned shutdown for maintenance. The Co-generator has a choice of firm or non-firm supply. Non-firm standby means that TNB does not guarantee that supply can be given when the Co-generator fails or is shutdown for maintenance.

Notes:

This new Standby rate (as of 1 June 2011) is applicable to the following customers:

All new co-generation customers; and

Existing co-generation customers who wish to migrate to this new Standby rate

For existing co-generation customers who wish to maintain the previous Standby (Firm & Non-Firm) rates, the previous Standby (Firm & Non-Firm) rates together with the new Top-Up rate (as of 1 June 2011) will be applicable

1% as Feed-in-Tariff (FiT) for RE Fund will be imposed on consumers' monthly bill (excluding Domestic consumers with monthly consumption of 300kWh and below) effective 1st December 2011.

The industrial tariff rate used in the comparison is based on “Tariff E1-Medium Voltage General Industrial Tariff”. The tariff rate for each kilowatt of maximum demand per month is not included.

As such, the tariff rate for each kWh is 28.8 ¢.

APPENDIX B – BOILER THERMAL ENERGY GENERATION COST

Typical fuel properties are listed as below:

Table B1 Typical fuel properties. Source: Mark's Handbook 11th Ed

Fuel	Typical Density	High Calorific Value	Low Calorific Value	Fuel Pump Prices	Price ¢/kWh (HCV)
Petrol (RON95)	740kg/ m^3	46.89MJ/kg	43.71MJ/kg	RM1.90/litre	19.71
Diesel	860kg/ m^3	45.97MJ/kg	43.17MJ/kg	RM2.49/litre*	22.67
Diesel (Automotive)	860kg/ m^3	45.97MJ/kg	43.17MJ/kg	RM1.80/litre	16.39
Natural Gas		36.38MJ/m^3	32.75MJ/m^3	RM0.62/ m^3	6.14

The price for industrial use diesel is obtained through the Department of Statistics Malaysia, as shown in Figure B1.

Jadual 2: Harga unit purata bagi bitumen, minyak bahan api dan diesel
Table 2: Average unit prices for bitumen, fuel oil and diesel

Item	Tempoh *Period*	Semenanjung Malaysia *Peninsular Malaysia*
(1) Minyak Bahan Api *Fuel Oil*		**RM Seliter** *RM Per Litre*
Sederhana *Medium*	**2011 Dis**	2.34
	2012 Jan	2.49
	Feb	2.49

Figure B1 Diesel price for industrial use. Source: Department of Statistics Malaysia

A typical boiler is obtained through the widely used industrial yellow pages "Alibaba.com". The boiler chosen is shown in Table B2.

Table B2 Typical Boiler Data. Source: Alibaba.com, Henan Sitong Boiler Co., Ltd.

Items	WNS0.5-0.7-Y(Q)
Nominal Capacity (t/h)	0.5
Nominal Working Pressure (Mpa)	0.7
Saturated Steam Temperature (℃)	170
Thermal Efficiency of Boiler (%)	92
Nominal Oil and Gas Consumption (Nm3/h)	34.5/42
Power Consumption (KW)	2.96
Applicable Fuel	Light oil or heavy oil Natural gas or city gas
Power Supply (AC)	380v 50Hz
Weight and Size of maximum transport thing (m)	3.1×1.9×1.9
Approx. Weight of maximum transpoirting kg	4000
Exhaust Gas Temperature (℃)	230
Combustion way	Pressure atomized Micro positive pressure combustion
Regulating mode	Automatic

The displayed price is USD 10,000, FOB. It is estimated that the price should be around USD 15,000 DDP + Installation + Startup & Commissioning. The total Estimated Price = RM105, 000.00.

Knowing that the heat of vaporization of steam is 2257kJ/kg, the boiler chosen is able to output 1,128.5kW of thermal energy. This is suitable for our requirement of 470kW. Ignoring the power consumption since it is small relative to the output and utilizing the thermal efficiency given, the cost of thermal energy generation through a boiler is tabulated in Table B3.

It is assumed the useful life is 10 years and without consideration of maintenance cost. Assuming again an average utilization of 10 hours per day, 365 days a year, the overall cost of boiler output is tabulated in Table B3.

Table B3 Typical cost of thermal energy generation through boilers

Fuel	Price ¢/kWh (HCV)	Boiler Output ¢/kWh	Boiler Ouput (Including cost of ownership)
Diesel	22.67	24.65	25.11
Natural Gas	6.14	6.67	7.14

APPENDIX C – ELECTRIC HEATER

Price quote was obtained from rs-component for a domestic usage immersion tank heater. The datasheet is as below. The price is RM137.50 including delivery for a 3000kW unit. It is assumed that an industrial unit will need to be of a higher quality of construction and as such will command double the price. A calculation of the final price is shown in Table C1.

Table C1 Electric heater installation price

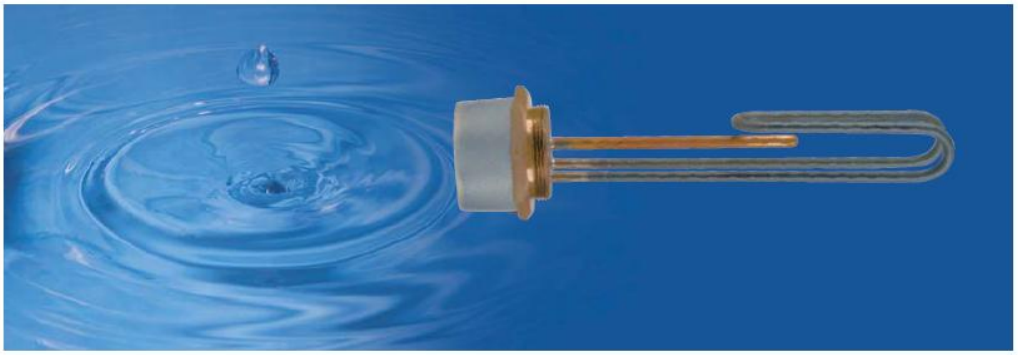
Item	RM
Unit Price for domestic use	137.50
Unit Price for industrial use	275.00
Total price for 470kW	44,000.00
Total price including installation & startup	103,125.00

The efficiency is chosen to be 1. It is assumed the useful life is 10 years and without consideration of maintenance cost. Assuming again an average utilization of 10 hours per day, 365 days a year, the overall cost of electrical heater output is tabulated in Table C2.

Table C2 Typical cost of thermal energy generation through electric heater

Fuel	Price ¢/kWh	Heater Output ¢/kWh	Heater Ouput (Including cost of ownership)
Electric	28.3	28.3	28.76

Immersion Heaters



The Range

Redring have introduced a new range of Dual cut-out immersion heaters to comply with the European safety standard, EN 60335-2-73 for fixed immersion heaters.

All Redring dual cut-out immersion heaters are supplied complete with rod thermostat, and are manufactured with a separate, 'secondary manual reset safety cut-out' fitted directly to the immersion heater head.

This ensures that all Redring immersion heaters are compliant, and do not rely on the fitting of a combined rod thermostat with cut-out to meet the safety requirement. Dual cut-out immersion heaters are available in standard copper or Aqualoy variants for use in more aggressive water areas.

Approvals

WRAS Approved Product BEAB Approved CE

Guarantee

3 YEAR GUARANTEE

Specification for Domestic Dual cut-out Immersion Heaters

Catalogue No.	Short Code	Length Inches
2 1/4" BSP Copper with fitted STAT & CUT-OUT - (1 year guarantee)		
33324501	P11DC	11
33324502	P14DC	14
33324503	P27DC	27
33324504	P30DC	30
33324505	P36DC	36
2 1/4" BSP Aqualoy with fitted STAT & CUT-OUT - (3 year guarantee)		
33324601	A11DC	11
33324602	A27DC	27
2 1/4" BSP Twimerser Copper with fitted STAT & CUT-OUT - (1 year guarantee)		
30302801	TS27DC	10/27
1 3/4" BSP Unvented Aqualoy with fitted STAT & CUT-OUT - (3 year guarantee)		
33324701	GU11DC	11

Specification for Industrial Immersion Heaters

Catalogue No.	Short Code	Loading kW	Phases	Immersed Length	Thermostat
2 1/4" BSP Incoloy 825 with fitted stat					
60391301	RY211	2	1 only	11	Yes
60391302	RY311	3	1 or 3	11	Yes

Figure C1 Immersion heater datasheet. Source: rs-component.com.my

APPENDIX D – SOLAR PV THERMAL ENERGY GENERATION COST

The cost of implementing solar PV is available abundantly, although mostly dealt with domestic usage. The works of Firdaus Muhammad-Sukki, et al. (2011) is shown in Table D1.

Table D1 Cost of PV electricity generation for a 2.5kWp PV panel. Source: Muhammad-Sukki, 2001

The cost-benefit analysis of implementing the FiT in the UK and in Malaysia.

Item	Unit	United Kingdom	Malaysia (a	Malaysia (b)
Yearly solar insolation	kWh/m^2	1000.00	1400.00	1643.00
Installation cost	MYR	60,000.00	47,800.00	47,800.00
Electricity generated from the 2.5 kWp PV panel	kWh	2500.00	3500.00	4107.50
Contract period	Year	25.00	21.00	21.00
FiT rate	MYR/kWh	2.2224[a]	1.23	1.23
Income from FiT scheme				
Generation and exportation of electricity	MYR	5556.00	4305.00	5052.23
Maintenance per year	MYR	600.00	478.00	478.00
Annual revenue	MYR	4956.00	3827.00	4574.23
Total revenue at the end of contract year	MYR	123,900.00	80,367.00	96,058.73
Investment analysis				
Total profit	MYR	63,900.00	32,567.00	48,258.73
Payback period	Year	12.11	12.49	10.45
Average annual return on investment	%	4.26	3.24	4.81

[a] This value is a combination of generation tariff of MYR2.0784 and exporting tariff of MYR0.144, as ment

It is assumed that the scaling up to 470kW is directly proportional. A calculation of the price of installation is shown in Table D2.

Table D2 PV panel installation price

Item	RM
Unit Price a 2.5kWp PV panel system	47,800
Price for a 470kWp PV panel system	8,986,400

The output of the 470kWp PV system is scaled to be 772,210 kWh per year. It is assumed the useful life is 10 years and without consideration of maintenance cost and the feed-in tariff rate from Kettha for a system of 75kWp – 1MWp is RM1.14. The

output from the PV is assumed to be sold back to the grid and using the proceeds to pay for the thermal energy generation. The useful life of the whole system is 21 years. The cost of output of this system is tabulated in TableD3.

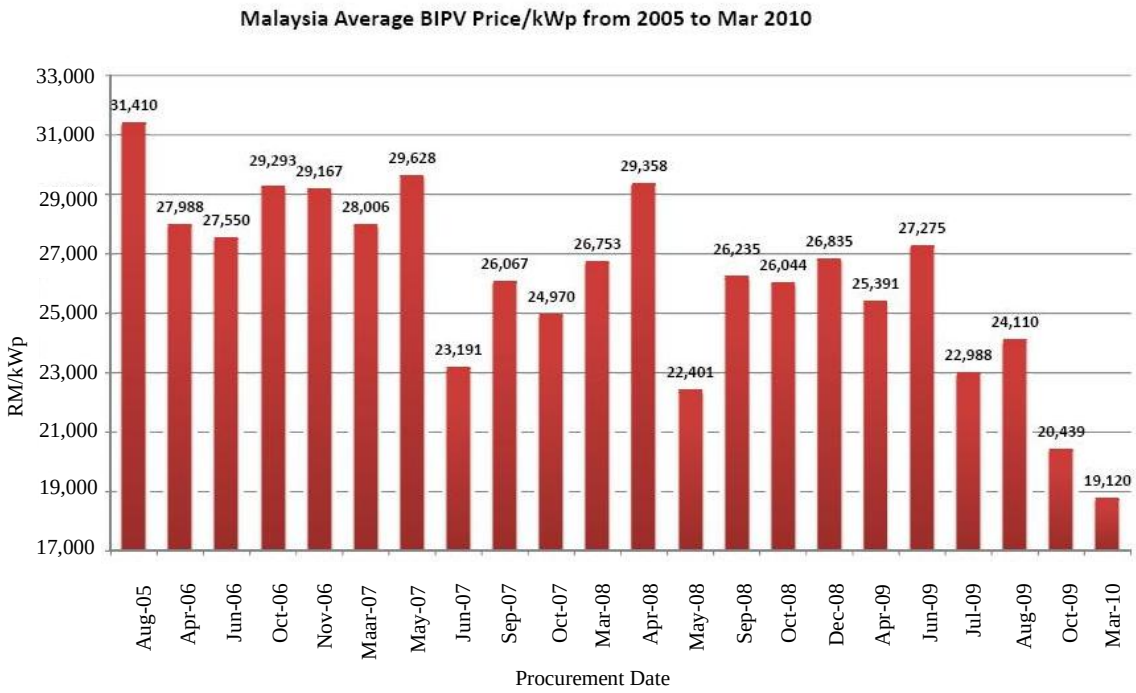


Figure D1 Malaysia Average BIPV Price/kWp from 2005 to 2010. Source: www.mbipv.net.my

Table D3 Cost of electricity generation

Item	Value	Unit
Feed-in Tariff Price	1.23	RM/kWh
TNB Electricity Price	0.283	RM/kWh
Net Profit	0.947	RM/kWh
Total Electricity Generation	722,210	kWh
Payback period	10	Years
Cost of Electricity generation for 10 years	0.283	RM

Since the payback period is 10 years, the first 10 years when the system is installed is used to payback for the cost of the system itself, and the cost of electricity is the same as using the electricity straight from TNB grid. As such, the cost of a system out of the picture and only the consumption cost is of concern, as tabulated in Table D4.

Table D4 Typical cost of PV thermal energy generation through electric heater

Fuel	Price ¢/kWh
Electricity bought from TNB while PV generated is sold back.	28.3

APPENDIX E – HEAT PUMP ENERGY GENERATION COST

High-temperature Air Source Heat Pump Water Heater					
MODEL			CAR-40	CAR-50	CAR-80
Outlet water temperature		℃	70℃		
Rated heating capacity		KW	26.6	32	53
		BTU	90759	109184	180836
Rated heating input power		KW	8.3	9.7	16.5
Rated heating input current		A	15.2	17.8	30.4
COP			3.2	3.3	3.2
Power Supply		V/Hz			
Noise		dB(A)	63	64	66
Dimension	Width	mm	1450	1450	1700
	Depth	mm	780	780	900
	Height	mm	1050	1050	1215
Unit weight		KG	280	320	570
Environmental temperature control range		℃	-10℃~43℃		
Throttling type			Electronic expansion valves/thermal expansion valves		
Refrigerant type			R417A, R407C,R410A optional		
Compressor	Type		Copeland, Sanyo, Dakin optional		
	Quantity	pcs	2	2	4
	Security functions		Built-in protection device overheating protection, sequence protection, undervoltage protection and delay protection.		
Air source heat exchanger	Type		Finned heat exchanger		
	Motor power	KW	0.6	0.6	1.5
Hot water side heat exchange	Type		Efficient tube in tube heat exchanger		
	Water flow	m^3/H	4.57	5.5	9.11
	Water pressure down	kPa	20	23	25
	pipe size	DN	32	32	50
	water side max working pressure	kPa	1000	1000	1000
Rated hot water working condition: Air source side dry bulb temp is 20℃. wet buld temp is 15℃. Initial temp of hot water is 20℃ and termination hot water temp is 70℃.					

Figure E1 Heat pump datasheet

A reference price from Alibaba.com indicates that the cost is around USD 150/kW.

For 470kW = USD 70,500
= RM 218,550
Per kWh = RM218,550/(470kW × 10 hours × 365 days/yr × 10 years)
ownership = RM 0.0127/ kWh × 2 (including installation etc)
cost = RM 0.0254

Assuming a COP of 3.5,
Cost per kWh = RM0.283/kWh /4 + RM 0.0254 = RM 0.1063

APPENDIX E – SOLAR THERMAL ENERGY GENERATION COST

Open Loop

Table E1 Solar Thermal System Costs – Open Loop

Item	RM
Solar Collector/unit	1240
Solar Collector Transportation/unit	2464
Total Units required	319 Nos
Containers required	8 Nos
Estimated Transportation Cost	250,000
Collectors cost	400,000
Other components, Installation, Commissioning and etc	450,000
Total Cost	1,100,000

The savings incurred by using this system is translated to boiler fuel saving, which stands at RM0.2465/kWh. Although there needs to be input to keep the circulating fluid moving, the pump used is less than 5kW. As such, the pump presence is ignored.

System total kWh per year = 521,184kWh/year

Cost Saving per year = 521,184kWh × RM 0.2465/kWh
= RM 128,471

10 years service = RM 1,284,717

Payback period = 9 years

ROI, 10 years = 1.68%

Per kWh cost/ profit = (RM 1,284,717 – RM 1,100,000)/5,211,848kWh
= 3.54 cents

Closed Loop

Table E2 Solar Thermal System Costs – Closed Loop

Item	RM
Solar Collector/unit	1240
Solar Collector Transportation/unit	2464
Total Units required	332 Nos
Containers required	9 Nos
Estimated Transportation Cost	300,000
Collectors cost	420,000
Other components, Installation, Commissioning and etc (including HE)	720,000
Total Cost	1,440,000

The savings incurred by using this system is translated to boiler fuel saving, which stands at RM0.2465/kWh. The inclusion of the flat plate heat exchanger has increased the cost of the system by RM270,000.

System total kWh per year = 481,228kWh/year

Cost Saving per year = 481,228kWh × RM 0.2465/kWh
= RM 118,623

10 years service = RM 1,186,230

Payback period = 13 years

ROI, 10 years = -1.76%

Per kWh cost/profit = (RM 1,186,230 – RM 1,440,000)/4,812,288kWh
= -5.27 cents