SIMULATION OF DISH STIRLING SYSTEM FOR MALAYSIA ENVIRONMENT

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Bachelor of Electrical Engineering (Industrial Power)

June 2014

"I hereby declare that I have read this fully report entitled "**Simulation of Dish Stirling System for Malaysia Environment**" and found that is has achieve the requirement for awarding the Bachelor of Electrical Engineering (Industrial Power)"

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Simulation of Dish Stirling System for Malaysia Environment

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A report submitted to partial fulfilment of the requirement for the degree of Bachelor of Electrical Engineering (Power Industry)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

June 2014

I declare that this report entitle "**Simulation of Dish Stirling System for Malaysia Environment"** is the result of my own research except as cited in the references. The report has not been accepted for any degree and not concurrently submitted in candidature of any other degree.

Signature : ……………………………………………………………

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Date : ……………………………………………………………

Specially dedicated, in thankful appreciation for the support, encouragement and understanding for my beloved mother father, siblings, supervisor's and friends.

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In the name of Allah, The beneficent, The merciful

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ABSTRACT

Renewable energy has become an important source of global electricity generation. Tendency to lean towards renewable energy because it does not work out with use over time compared to conventional fuel electric generator. Another important factor is that renewable energy produces greenhouse gases and environmental pollution that little or none at all. On average, Malaysia receives about 6 hours of direct sunlight each day. The average annual daily solar radiation in Malaysia is in magnitude from 4.21 to 5.56 kWhm-2 and sunlight is more than 2200 hours per year. CSP technologies such as the Stirling dish systems can contribute to the development of a more sustainable energy system by converting solar energy into mechanical energy and then into electricity. Under Entry Point Energy programmed the target for Malaysia to build solar power capacity to 1.25 GW in 2020. The System Advisor Model was chosen to predict the performance of a dish stirling system in this project. The main objective of this project was to simulate and predict the performance of a dish stirling system by using SAM software. The input data to simulate dish stirling system are weather data from U. S. National Climatic Data Centre. The second objective is to analyse the electrical energy produced by a dish stirling system for four locations in Malaysia environment. The selected locations are George Town, Kota Baharu, Kuala Lumpur and Kuching. The highest solar to electrical energy conversion is in George Town. Found that the performance dish stirling system in George Town is better than the other location. All data and analysis in this project is hoped will be a good reference for further research and renewable energy technology development in Malaysia.

ABSTRAK

Tenaga boleh diperbaharui menjadi sumber penting dalam penjanaan elektrik global. Kecenderungan untuk menjurus kepada tenaga boleh diperbaharui adalah kerana ia tidak habis dengan penggunaan sepenuh masa berbanding dengan bahan api konvensional. Satu lagi faktor penting ialah tenaga boleh diperbaharui menghasilkan gas rumah hijau dan pencemaran alam sekitar yang sedikit atau tiada langsung. Secara purata, Malaysia menerima sebanyak 6 jam cahaya matahari setiap hari. Purata tahunan radiasi solar harian bagi Malaysia dalam magnitud 4.21-5.56 kWhm-2 dan cahaya matahari adalah lebih daripada 2200 jam setahun. Teknologi CSP seperti sistem piring Stirling boleh menyumbang kepada pembangunan sistem tenaga yang lebih mampan dengan menukar tenaga solar kepada tenaga mekanikal dan kemudian ke dalam elektrik. Di bawah Entry Point Tenaga, ditetapkan sasaran bagi Malaysia untuk membina kapasiti tenaga solar kepada 1.25 GW pada tahun 2020. Sistem Penasihat Model telah dipilih untuk meramalkan prestasi system piring Stirling dalam projek ini. Objektif utama projek ini adalah untuk merangsang dan meramalkan prestasi sistem piring Stirling dengan menggunakan perisian SAM. Data masukan untuk mensimulasikan sistem piring Stirling adalah data cuaca dari Pusat Data Iklim Kebangsaan, Amerika Syarikat. Objektif kedua adalah untuk menganalisa tenaga elektrik yang dihasilkan oleh sistem piring Stirling untuk empat lokasi di persekitaran Malaysia. Lokasi yang dipilih adalah George Town, Kota Baharu, Kuala Lumpur dan Kuching. Penukaran tenaga solar kepada elektrik yang paling tinggi adalah di George Town. Didapati, prestasi sistem piring Stirling di George Town adalah lebih baik daripada lokasi yang lain. Semua data dan analisis dalam projek ini diharapkan akan menjadi rujukan yang baik untuk penyelidikan lanjut dan untuk pembangunan teknologi tenaga boleh diperbaharui di Malaysia.

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INTRODUCTION

1.1 Overview

This chapter will elaborate about the Project Background, Project Motivation, Problem Statement, Objective, Scope of Project and Report Outline.

1.2 Project Background

Solar energy is one of the most attractive renewable energy sources that can be used as input to the heat engine such as stirling engines to generate electricity. The most common technologies used to harvest energy from the sun are photovoltaic (PV) and concentrated solar power (CSP). Photovoltaic method is based on light, meanwhile thermodynamic process in CSP system is based on heat. CSP systems use mirrors to concentrate solar sunlight and collect the thermal energy on the receiver. The thermal energy then uses to heat a working fluid or gas in receiver and generate super-heated steam to drive a generator through heat engine and then produce electricity. There are four types of CSP systems, namely linear Fresnel Reflectors, Parabolic Trough, Dish Stirling System and Solar Power Tower. Among these four CSP systems, dish stirling system has higher efficiency at converting thermal to electrical energy.

Dish stirling systems convert heat energy in solar radiation into mechanical energy by stirling engine and then into electricity. The dish stirling system recorded a world record in solar to electrical energy conversion efficiency of 29.4% in 1984 [1]. Since then, this system has gained widespread interest in producing cheap and reliable renewable electricity to the market in the near future. Another fact that increases the interest is the amount of sunlight reaching the earth's surface continuously at 1.05×10^5 TW [2]. The sunlight will produce about 4 times of the global energy needs for 2050 that are expected to be around 25-30 TW if only 1% power can be converted into electricity with an efficiency of 10% [2].

Countries around the world, including Malaysia are now focusing more towards green technology and renewable energy. Under Entry Point Energy programmed, the target for Malaysia to build solar power capacity is to 1.25 GW by 2020 [3]. On average, Malaysia receives about 6 hours of direct sunlight each day. Annual average daily solar radiation for Malaysia in magnitude from 4.21 to 5.56 $kWhm^{-2}$ and the sunlight is more than 2200 hours per year [3]. The dish stirling systems can contribute significantly to developing a more sustainable energy system.

1.3 Project Motivation

The key issue that motivates the drive towards exploring new renewable sources is that the world has a problem with decreasing of non-renewable energy source to generate electricity. Demand renewable energy has become an important issue for a global electricity generation. The high tendency to lean toward renewable energy because it does not depleted with use over time. Environmental issues and rising energy demand have increased interest in the use of renewable energy, especially in solar energy. As previous study of CSP only done outside Malaysia, there is slightly published paper of performance

CSP in Malaysia. So, it is motivated to study on performance CSP for Malaysia environment based on weather data by using System Advisor Model (SAM).

1.4 Problem Statement

The Parabolic dish Stirling engine systems have not been widely studied as other technologies such as photovoltaic solar in the Malaysian environment. Literature on these systems is also difficult to find and rarely organized in one cohesive report. Furthermore, data on the performance of dish stirling systems have typically not been accessible to the public and only a few Stirling dishes have been constructed to date [3]. Hence, the purpose of this project is to simulate and predict the performance Stirling dish system in Malaysia environment. In order to get the amount electrical energy produced in a year, all parameters include concentrator, receiver, stirling engine and parasitics parameter will be used. In this project, it is proposed to use SAM software as a tool to do the analysis of weather data. The weather data is about solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements information. The data use for SAM simulation comes in International Weather for Energy Calculation (IWEC) files that originally achieved at the U. S. National Climatic Data Centre. The IWEC are the result of ASHRAE research project 1025 by Numerical logics and Bodycote Materials Testing Canada. The IWEC data files are typical weather data that suitable for use with building energy simulation program for 227 locations outside the USA and Canada. The 227 locations include the location of George Town, Kuala Lumpur, Kota Baharu and Kuching. After the data is successfully simulated using SAM, then the analysis on energy produced by dish stirling system for Malaysia environment can be done.

1.5 Objectives

The objectives for this project are stated as follows:

1. To simulate and predict the performance of a dish stirling system by using SAM software.
2. To analyse the electrical energy produced by a dish stirling system for four locations in Malaysia environment.

1.6 Scope of Project

The main scope of this project is to simulate and predict the performance dish stirling system in Malaysia environment. The prediction of performance is based on energy produced within a year. The location of George Town is selected to simulate the performance because this area receives high solar radiation throughout the year in Malaysia. The weather data year 2012 from U. S. National Climatic Data Centre of George Town will be simulated by using SAM. The dish stirling engine use in SAM are based on the Wilkinson, Goldberg, and Associates, Inc. (WGA) model. This project also analyse the electrical energy produce by stirling system in four different locations in Malaysia. The selected locations are George Town, Kuala Lumpur, Kuching and Kota Baharu.

1.7 Report Outlines

The report consists of five chapters. Chapter 1 discusses the overview of project background, problem statement, objectives and scope of this project. Chapter 2 discusses the literature review on renewable energy, solar technology, and dish stirling system. The literature reviews will regarding on previous researchers work on Stirling dish system from Institute of Electrical and Electronics Engineers (IEEE) journal, articles, book, technical paper and others. Chapter 3 covers the methodology of the project and describe the flow chart of project activities. The result and discussions will be reviewed in chapter 4. This chapter will highlight the initial results achieved from data collection and simulation. Finally, the conclusion and recommendations on future research will be enlightened in chapter 5.

CHAPTER 2

LITERITURE REVIEW

2.1 Overview

This chapter will elaborate about the Concentrating Solar Power (CSP) parabolic which contain Solar Energy, Renewable Energy Technology, CSP Type, Principle of Stirling Engine, and a Preview of Related Previous Work. In this chapter, it starts with the introduction of renewable energy technology, four types of CSP system and its efficiency. Then, continues with the principle of alpha, beta and gamma type Stirling engine. The theory of important parts of the Stirling dish system which are concentrator, receiver, and power concentrating unit were also stated. The previous work is gathering from IEEE journals, thesis, book and also information from internet.

2.2 Solar Energy

Solar Energy is by far the most abundant energy source received by the earth. Solar energy received by the earth is in the form of solar radiation. Solar radiation is closely related to the duration of sunlight that’s been receiving by earth. Sunlight is the light and energy that comes from the sun. This energy that reaches the surface of earth is called insolation. Sunlight is also known as solar radiation. Solar radiation is the heat and radiation from the sun in the form of electromagnetic waves.

Malaysia naturally has an abundant sunlight received in a year. However, it is difficult to have a full day with clear sky. One of the main factors that cut a large sunlight is the presence of cloud. On average, Malaysia received about 6 hours of solar radiation a day. The annual average daily solar irradiation for Malaysia is between magnitude 4.21 – 5.56 $kWhm^{-2}$ and the sunlight duration is more than 2200 hours per years [3].Table 2.1 shows the solar radiation thought out the year in Malaysia location.

Table 2.1: Solar Radiation in Malaysia (average value throughout the year) [21].

Location	**Yearly Average Irradiance 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 Bharu	1705
Kuala Terengganu	1714
Ipoh	1739
Taiping	1768
George Town	1785
Bayan Lepas	1809
Kota Kinabalu	1900

Solar energy can be harvested from the sun basically divided into two categories which is photovoltaic (PV), and concentrated solar power (CSP) or solar thermal.

2.3 Renewable Energy Technology

Renewable energy is energy that comes from natural resources such as sunlight, wind, rain, tides, waves and geothermal heat [12]. The renewable energy can be harvest and converted into electricity.

2.3.1 Solar photovoltaic (PV)

Solar photovoltaic are technologies that convert solar energy into useful energy forms by directly absorbing solar photons. Solar photon is particles of light that acts as individual units of energy. That energy then converts to electricity through the solar PV panel. Solar PV-panels have efficiency around 10-20% [4]. These systems are used in large and small scale applications, for example on the rooftops, satellites, boats, solar farm and other remote system that need direct power. Figure 2.1 shows the example of PV-solar panel applications.

Figure 2.1: Photovoltaic solar panels [5]

2.3.2 Concentrated Solar power (CSP)

Concentrated Solar Power or solar thermal is systems where a large area of sunlight is concentrated on receiver using mirrors or lenses. There are four types of CSP systems, namely linear Fresnel reflectors, parabolic trough, dish Stirling concentrator and solar power tower.

2.3.2.1 Concentrating Linear Fresnel Reflectors

Concentrating Linear Fresnel reflectors as shown in Figure 2.2 use many thin mirror strips instead parabolic mirrors to concentrate sunlight onto two tubes with the working fluid. This system has the advantage of a flat mirror which can be used are much cheaper than parabolic mirrors and many reflectors can be placed in the same amount of space [18]. This technology uses modular flat reflectors to focus the sun's heat onto a receiver that consisting of a system of tubes through which water flows [18]. Concentrated sunlight boils the water in the tubes and generating high-pressure steam for direct use in power generation and industrial steam applications without the need for expensive heat exchangers. This system can generate power up to 150-200MW. The efficiency of this system is about 9-15% [17].

Figure 2.2: Linear Fresnel reflectors [4]

2.3.2.2 Parabolic Trough System

Parabolic trough system is where the parabolic mirrors focus the sunbeams to heat oil, which drives a steam turbine to produce electricity. Parabolic trough collectors are made by bending a sheet of reflective material into a parabolic shape, A metal black tube, covered with a glass tube to reduce heat losses is placed along the focal line of the receiver [19]. The efficiency of parabolic trough system is around 10-15 % [4]. The parabolic through solar farm is shown in Figure 2.3.

Figure 2.3: Parabolic Trough solar farm [4]

2.3.2.3 Solar Tower

The solar tower as shown in Figure 2.4 consists of an array of flat mirrors which are moveable to track the sun and focus the heat onto collector on the top tower. All of it is two axes to keep the sun’s reflected onto the receiver at the top of the tower. The receiver is heated by reflecting insolation thereby heating the heat transfer fluid pass through the tubes. These systems have a quite simple design and work, but have efficiency approximately 14-17% [4].

Figure 2.4: Solar tower plant [4]

2.3.2.4 Parabolic Dish Concentrator

Parabolic dish concentrators made up from mirrors reflect. It has a Stirling engine that located at the focal point of the dish reflector. Solar irradiation is concentrated onto a receiver and heat up the gas to generate electricity. The gas can be hydrogen, helium and air. This type of system has the highest efficiency of all solar technology, around 18-25% [4]. The dish stirling concentrator system is shown in Figure 2.5.

Figure 2.5: Dish Stirling concentrator system [4]

By comparing all four CSP technology, dish Stirling system is the system that has most efficiency in solar to electrical conversion. The dish Stirling system is suitable for small and large scale electricity generation. The difference between CSP systems is shown in Table 2.2.

Table 2.2: Different CSP Technology [7] [12].

Technology	**Focus**	**Temperature**	**Hybrid Operation**	**Cost ($/kW)**	**Efficiency**
Parabolic Trough	Line	400°C	Possible	4156	10-15%
Linear Fresnel	Line	270°C	Possible	2200	9-15%
Central Receiver	Point	1000°C	Possible	4500	14-17%
Parabolic Dish	Point	750°C	Still in R&D phase	6000	18-25%

2.4 Stirling Engine

A Stirling engine is a heat engine invented by Robert Stirling in 1918 [20]. It is based on the properties of gases and thermodynamic laws and principle. This engine uses an external heat source varies with the engine combust so there is no explosion in the cylinder during the work. The working gas is expended and compressed cyclically and continuously to produce motion to transforming energy. While the engine is running, the gas remains in the engine and it is displaced from the hot side to the cool side and vice versa. The Stirling engine works very quietly because there is no exhaustion like petrol engine [20].

The Stirling engine working gases can be air, hydrogen, helium, nitrogen or even vapour depending on the engine design [20]. Any heat source can be input to the engine, from solid coal to oil and solar energy. The Stirling engine was designed to be a safer alternative for steam engine when steam engine had poor quality and often caused an explosion because of the uncontrollable pressure elevation and primitive technology. Stirling engine have high efficiency with less exhaust emission in comparison to the internal combustion engine [20].

2.5 Operating Principle of Stirling Engine

Basically the Stirling engine consists of a cylinder containing a gas, a working piston and a Displacer piston. The regenerator and flywheel are often complimentary part of the engine. As shown in Figure 2.6, the temperature rises and gas expands proportional to the temperature of the heat side when heat part of cylinder is heated up by an external heat source [20]. The total working gas is constant in the cylinder and thus the expanded gas pushes the working piston down. The volume of the pressured gas increases in expanded state. In compression state, heat of gas is cooled and the gas loses its pressure and temperature [20]. Then, the working piston is back to the hot side and compresses the gas by the momentum force of the flywheel. When the working piston reaches its initial position, the Displacer piston also pushes the cooled gas to the hot side of the cylinder. The heat source again makes the gas expand and pushes the piston down again to produce mechanical energy for doing work. The cycle of the Stirling engine process is continued until the heat sources are unavailable [20].

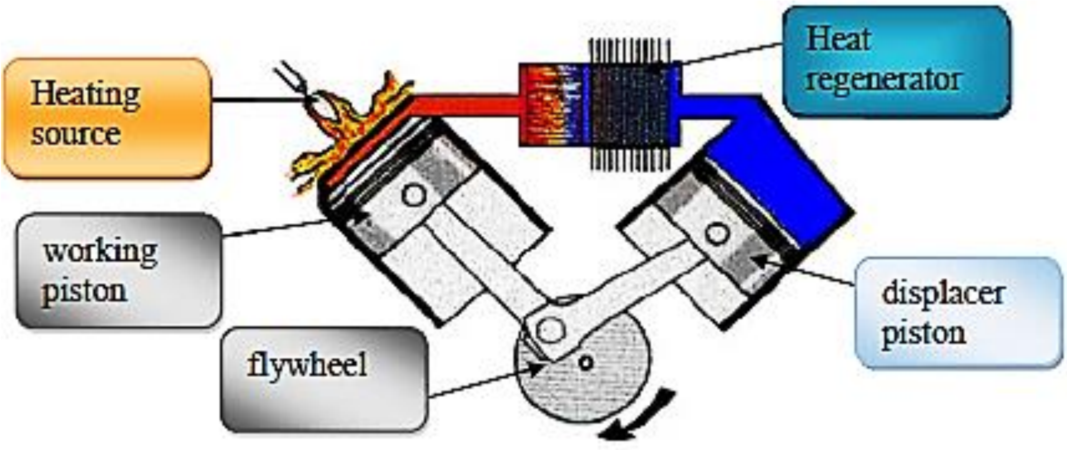


Figure 2.6: Stirling engine components [20]

The flywheel and regenerator has a big role in the performance of the engine as the flywheel converts the linear movement of a working piston to rotary movement. This gives a needed momentum for the cycle process [20]. While, generator improves the engine efficiency by takes heat from the gas in the expansion phase and give the recycle internal heat to the gas in the compression phase.

2.6 Stirling Cycle Phase

Stirling engine cycle has four phases which are heated, expansion, cooling and compression. The cycle is shown in Figure 2.7:

1. Heating (isovolumetric or isochoric): Heat source provides thermal energy to the engine to raise the temperature and pressure of working gas
2. Expansion (isothermal expansion): In expansion process, the volume of gas at hot side increases but the pressure and temperature decreases. During this phase the mechanical energy is produced from the heat energy

3. Cooling (isovolumetric or isochoric): The working gas is cooled in this process, thus the temperature and pressure decreases. The gas is prepared to be compressed during this cycle.
4. Compression (isothermal compression): The pressure of working gas increase where its volume decreases. The mechanical energy is used in this process because it needs an amount of work to be done.

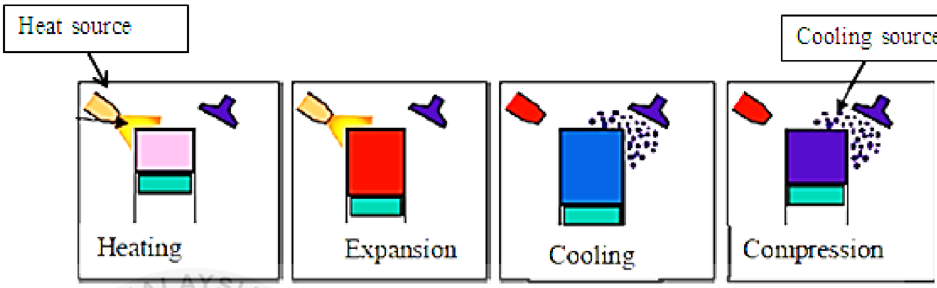


Figure 2.7: 4 phase of Stirling cycle [20]

PV graph in Figure 2.8 below shown the stirling cycle in stirling engine. The ideal stirling cycle consists of four thermodynamic processes acting on the working fluid.

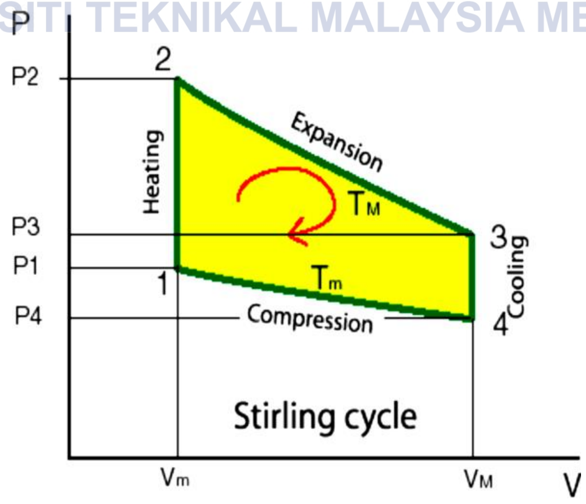


Figure 2.8: PV graph of Stirling engine [20]

Theoretical thermal efficiency Stirling engine is equal to the hypothetical Carnot cycle, which given by an equation;

$$\mu = 1 - T_3/T_1 \quad (2.1)$$

Where,

T_1 refers to the point 4 and in Figure 2.8.

The Carnot cycle efficiency is the highest efficiency can be attained by any heat engine. However, the actual efficiency of the Stirling engine is less than the ideal cycle.

2.7 Type of Stirling Engine

There is several types of Stirling engine have been introduced for different purposes. The most practical and known models are Alpha, Beta and Gamma type. These three types Stirling engine have the same basic working principle, but with different individual design. All those three type stirling engine working principle is derived from the thermodynamic laws [20].

$$E = PV = \eta RT \quad (2.2)$$

Where,

E= Energy (J)

P= Pressure (pa)

V=Volume (m^3)

n=Molar quantity of gas (Mol)

R= universal gas constant ($JK^{-1}Mol^{-1}$)

T= Temperature (K)

I. Alpha Type

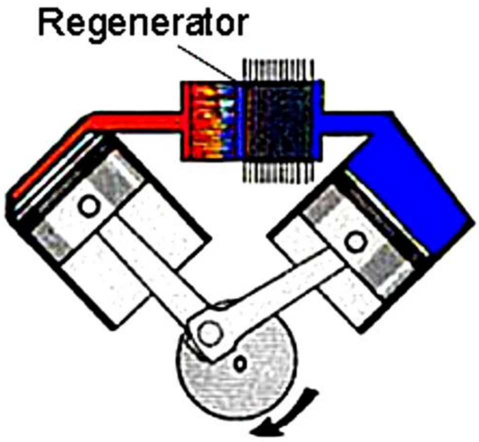


Figure 2.9: Alpha type Stirling engine [20]

Alpha type Stirling engine is the simplest design among these three types. Alpha type contains two power pistons in separate cylinders, one cold and one hot. The cold cylinder is situated in low heat exchanger and hot cylinder situated in the high temperature heat exchanger. Its advantage is easy to maintain and repair. It is useful for a stationary application or having large engines. However, the disadvantage of this design is it uses more material to build [20]. The typical alpha type stirling engine is shown in Figure 2.9.

II. Beta Type

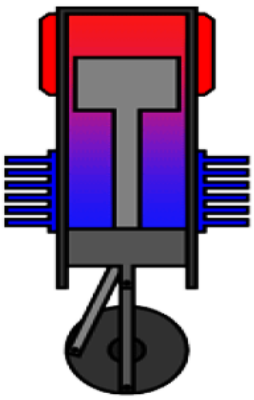


Figure 2.10: Beta Type Stirling engine [20]

A beta type Stirling engine as shown in Figure 2.10 has a single power piston and Displacer piston on the same shaft in one cylinder. The Displacer piston is a loose fit and not extracting any power, but it serves to shuttle the working gas between the hot and cold heat exchangers. When the hot end of cylinder is heated, the working gas expands and pushes the power piston. The gas contracts when pushed to the cold end and the momentum of the machine (flywheel) pushed the power piston to compress the gas. These Beta types have most complicated design and the most difficult to maintain or repair it compare to other Stirling engine design. But the main advantage is it has the highest efficiency in energy delivered by a machine to the energy needed in operating the machine. It also needs fewer components to build and most useful for mobile or small application [20].

III. Gamma Type

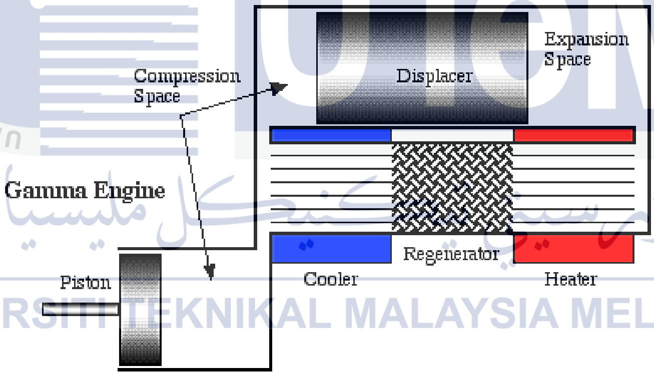


Figure 2.11: Gamma type Stirling engine [20]

Gamma type engine as shown in Figure 2.11 have a displacer/working and power piston similar to Beta type but in different cylinder. This model provides a convenient complete separation between the heat exchangers associated with the displacer cylinder and the compression and expansion work space associated with the piston. The gas in the two cylinders can flow freely between them and remains a single body. This designation produces a lower compression ratio, but mechanically is simpler and often used in multi cylinder Stirling engines [20].

2.8 Concentrator

Solar energy is concentrated by mirrors placed in a parabolic dish shaped frame onto the absorber in the receiver. The size of the concentrator depends on how much power input the power concentrating unit (PCU) can handle and the efficiency of the concentrator itself. Concentrator diameter needed for 10 kW and 25 kW systems is approximately 7.5 and 11 meters [16]. The efficiency of the concentrator without considering tracking of the sun and meteorological effects is determined by the reflectivity of the surface and the dish shape. Reflectivity losses increase with time as the debris is gathered onto the mirrors.

The solar reflectance for current stirling engine of the silvered mirrors are in ranges between 91 -95% [16]. The most durable mirror surfaces are using silver and glass mirrors. ReflecTech has success in develop a polymer reflective film that has high optical properties with 94.5% mirror reflectivity [16].

The intercept factor is the fraction of solar radiation reflected from the parabolic collector that enters the aperture. The intercept factor is influenced by the errors in the collector, size of aperture, the collector rim angle and nonparallel sunlight [16]. Increasing the intercept factor will increase the system performance and reduce error in parabolic reflecting collector surface.

The concentration ratio is the peak concentration of the system normalized by 1000 W/m^2. It good to have a high concentration ratio in concentrator system since aperture can be designed resulting in reduced thermal losses and intercept factor is large for a specified aperture diameter. The maximum concentration ratio can be obtained with a rim angle of 45 degrees [16]. Table 2.3 shows the concentrator system specifics by several manufacturers.

Table 2.3: Concentrator System for Several Manufacturers [16]

Concentrator	SAIC	SBP	SES	WGA
Glass area, m^2	117.2	60	91	42.9
Projected area, m2	113.5	56.7	87.7	41.2
Reflectivity	0.95	0.94	0.91	0.94
Focal Length, m	12.0	4.5	7045	5.45
Rim angle, ^{o}	29	52	40	37
Peak CR, sun	2500	12730	7500	>13000

2.9 Receiver

Receiver function is to absorb solar energy reflected by the concentrator as much as possible and transfer as heat to heating the working gas in the Stirling engine. Receiver often isolated to minimize the heat losses. The absorber is part of the receiver. The absorber captures the sunlight and transfer the heat to the working gas. The absorber consists of a mesh of tube connected to the top of the Stirling engine cylinders in PCU. The temperature of the absorber is important for the efficiency of the Stirling engine operation. The temperature maintained as high as possible while not exceeding the absorber and receiver materials thermal limit.

Another part of receiver is aperture. The aperture in stirling receiver is located at the focal point of the parabolic concentrator to reduce the convection and radiation loses. The aperture can have concentration ratio of over 1300 [16]. The size aperture must has diameters from 13 to 20 centimetres to ensure an appropriate fraction of the concentrator solar energy is intercept by the aperture. The intercept factor is often between 94 and 99 percent which is not blocked by the receiver housing [16].

An insulation thickness of 75 mm has been suggested as an effective width to minimize conduction in the receiver housing. The thickness was selected to minimize conduction and shading of the stirling dish mirror [16]. High temperature ceramic fiber insulation has been used with thermal conductivity ranging from 0.061 W/m-K at 550ºC to

0.094 W/m-K at 900 ºC [16]. Conduction losses should be less than 2% of the total receiver losses with effective insulator [16].

2.10 Regenerator

A regenerator consists of many metal mesh disks in stirling engine to improve the efficiency of the engine [16]. Regenerator absorbs thermal energy when working fluid passes from expansion space to compression space. The fluid is cooled before entering compression state. The regenerator then give thermal energy to the working fluid and it is pre-heated when the moves from compression to the expansion space. The efficiency of stirling engine can be more than 98% with the present of regenerator.

2.11 Power Concentrating Unit (PCU)

PCU includes the Stirling engine, external heat exchanger and generator. In the PCU, power conversion of solar energy to mechanical energy is done by Stirling engine. The drive shaft of the Stirling engine is connected to an electrical generator which converts the energy to electricity.

2.12 Parasitic power

Parasitic power is the electric power consumed to operate the dish stirling system. Parasitic power includes electrically driven cooling fan, cooling pumps, control system and tracking motors. In WGA system, the parasitic power is predict based on varying ambient conditions and operating speed. The optimal fan speed for cooling system for WGA is approximately 550 RPM [16].

2.13 System Advisor Model (SAM)

The system Advisor Model is software for people who involved in the renewable energy industry to facilitate decision making on performance and financial model. SAM makes performance prediction and cost of energy for grid-connected power projects. The prediction is based on system design parameters specify as input to the model. The project can be on customer side for utility meter, buying and selling electricity at retail rates or, or the utility side of meter, selling electricity as price negotiated through a power purchase agreement (PPA).

SAM represents the cost and performance of project using computer models developed at NREL, Sandia National Laboratories, and The University of Wisconsin. Each model represents a part of system and project financial structure. The model requires input data describing the renewable energy resource and weather conditions at the project location. The data can be choose from data file list, download from internet or create the file with real time data in its format. SAM user interface make it possible for inexperience people to build a model of a renewable energy project, and make the performance and cost prediction based on model result.

2.14 Review of Previous Related Works

From technical paper of Power Energy Conversion Symposium (PECs) 2012 on Concentrating Solar Power (CSP) In Malaysia environment. Researches have shown that Malaysia has a lot of solar energy with a magnitude of about 4.21 to 5.56 $kWhm^{-2}$ [3] for the average daily solar radiation and sunshine duration is more than 2200 hours per year.

CSP technologies require Direct Normal Irradiance (DNI) at least from 1900 to 2000 kWh/m^2/year to be economically feasible. An ideal location for CSP solutions are those that are exposed to high sunlight and low cloud cover, such as the southern states of the United States, Mexico, the Mediterranean Sea, Middle East, South Africa, parts of China, Pakistan, India , Australia and parts of South America [3]. Malaysia and other countries in tropical regions are not in high insolation zone with less than 1900 kWh/m^2/year. Clouds reduce annual production CSP plant to the extent that the plants may not have been viable in the tropics [3].

Due to weather conditions, it is believed that CSP systems cannot be used in tropical areas with relatively high diffuse fraction of the global radiation. However, no systematic study or research on developing CSP plants in Malaysia to prove that believe. Most CSP plants are located in areas with good solar resources with DNI higher than 1900 kWh/m2/year. Germany is located in an area with 902 kWh/m^2/year DNI, which is much lower than Malaysia [3]. However, in December 2008, the Germans launched their CSP plants use Tower system with a capacity of 1.5MW in Julich, Rhineland [3].

Thailand became the first country in the tropical regions have their own CSP plants. On January 25, 2012, Thailand's first CSP plant called TSE1 supplied 5MW of electrical power to public power grid Thailand for the first time. Therefore, this proves that CSP plants can work even in areas with lower DNI than 1900 kWh/m^2/year [3]. Malaysia still has the potential to develop CSP plant itself by taking consideration to the size of the collector field or design a new CSP technology to provide the same amount of heat or electricity in the region with the resources of a very good solar energy [3].

2.15 Summary and Discussion of the Review

In this chapter, there are two major sections included starting with theory and basic principle of the Stirling dish system and review of SAM software. Section one covers the renewable solar energy technology use which is photovoltaic (PV) and concentrated solar power (CSP). This project focuses on the performance of dish stirling system, thus the Stirling cycle and working principle are shown. Important part of the Stirling dish system such as concentrator, receiver, parasitic power and PCU were also shown in this section one. Section two covers the introduction to SAM and previous research on CSP in Malaysia environment. From the previous research, Malaysia has potential to develop this technology even in the tropical region area. Malaysian government need to take seriously in view of the CSP technology as one of the promising renewable energy for the future of Malaysia.

CHAPTER 3

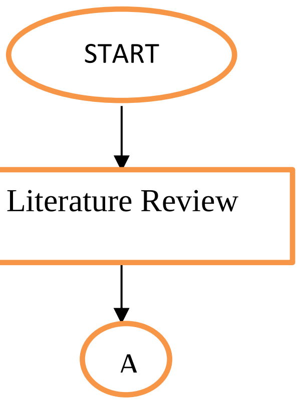
RESEARCH METHDOLOGY

3.1 Introduction

This chapter will describe the method of experimental procedure and task of planning in develop simulation on dish stirling system. In this project, SAM Software is used as the tool to develop dish stirling system block for measure and analyse the electrical energy produced by dish stirling system.

3.2 Flow Chart of Project Activities

The flow chart of project activities is shown in Figure 3.1



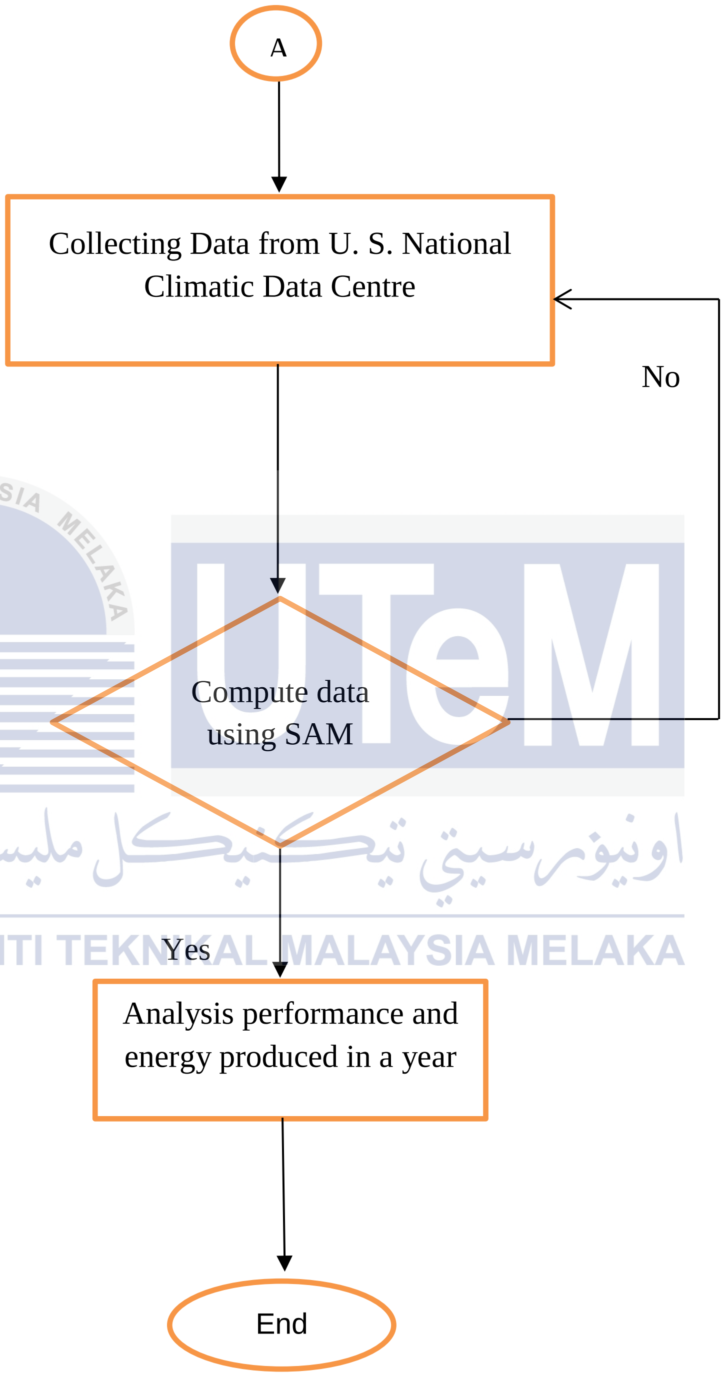


Figure 3.1: The flow chart of the methodology

3.2.1 Literature Review

The literature reviews will regarding on previous researchers work in identifying any important issues about Stirling dish system from IEEE journal, articles, newspaper, technical paper and others. Literature review part gives information about the performance dish stirling system,

3.2.2 Collecting Data from U. S. National Climatic Data Centre

Data used in this project is the actual data obtain from the U. S. National Climatic Data Centre and, was downloaded from U. S Department of Energy website. The data use comes in IWEC files are typical weather data include location of George Town, Kuala Lumpur, Kota Baharu and Kuching.

3.2.3 Compute Data Using SAM

Among the CSP technologies model in SAM, the Parabolic Dish has been selected in this project. The dish stirling system model that has been chosen are WGA type. WGA type has capacity 10 kW and smallest diameter for concentrator compare to other type in the SAM library system. The performance was simulated using Weather data from the U. S. National Climatic Data Centre. The analysis done on electrical energy performance based on four different locations in Malaysia. The data represented in graphical form, which show the monthly energy output in a year.

3.2.4 Analysis Performance and Energy Produced in a Year

The analysis will focuses on the energy produced in George Town location for duration one year. The graph energy output for parabolic dish in Figure 3.8, showed the highest and lowest energy output every month. Beside energy, the maximum Direct Normal Irradiance (DNI) for George Town was determined using SAM simulation. The maximum DNI value can show the efficiency of dish stirling system. Normal DNI value use of concentrator efficiency calculation is 1000 W/m^2 [13]. Performance comparison of dish stirling in a different location is compared based on monthly energy and DNI.

3.3 SAM Methodology

The method used in this project is simulation method. The output data determined using the SAM software. There are several steps to simulate the performance when using SAM:

1. Opening SAM software

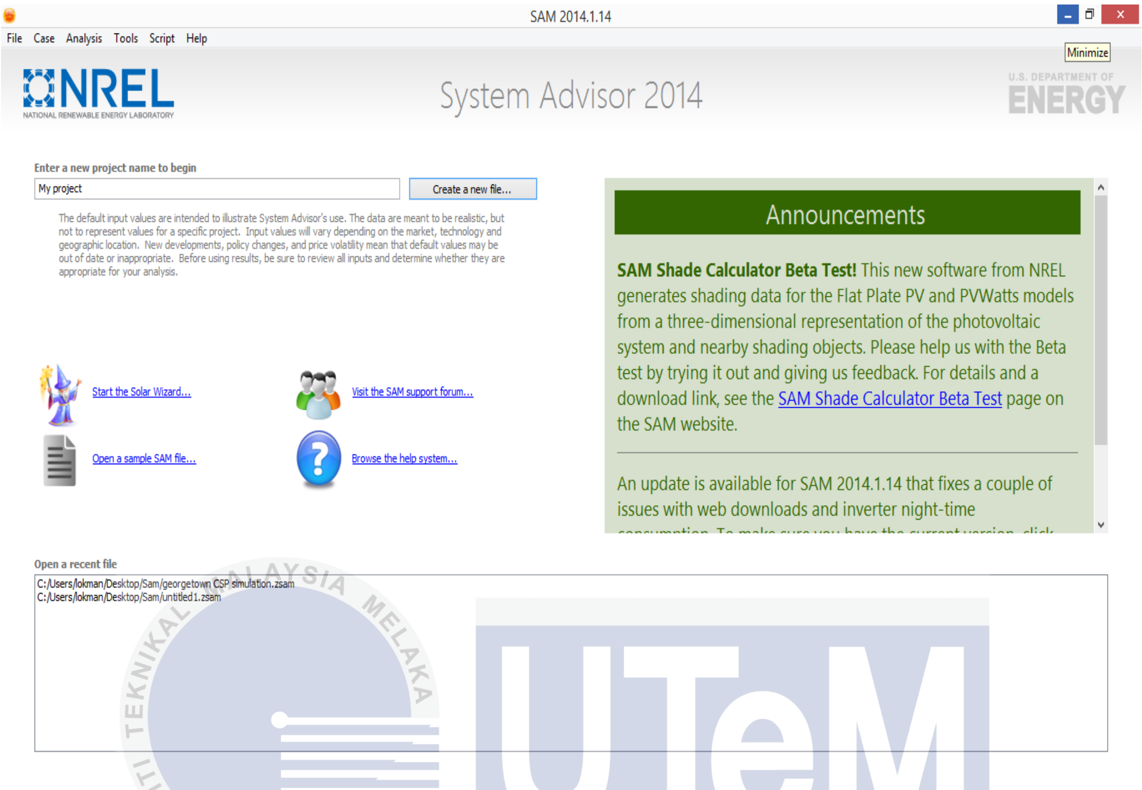


Figure 3.2: Opening SAM software

After opening SAM software version 2014.1.14, window will show the software as in Figure 3.2. Enter a new project name and then click “create a new file”.

After create a new file, a pop-up window will show as in Figure 3.3. The pop-up window showed a selection of renewable technology such as Photovoltaic, Concentrating Solar Power, Generic System, Solar Water Heating, Wind Power, Geothermal and Biomass Power.

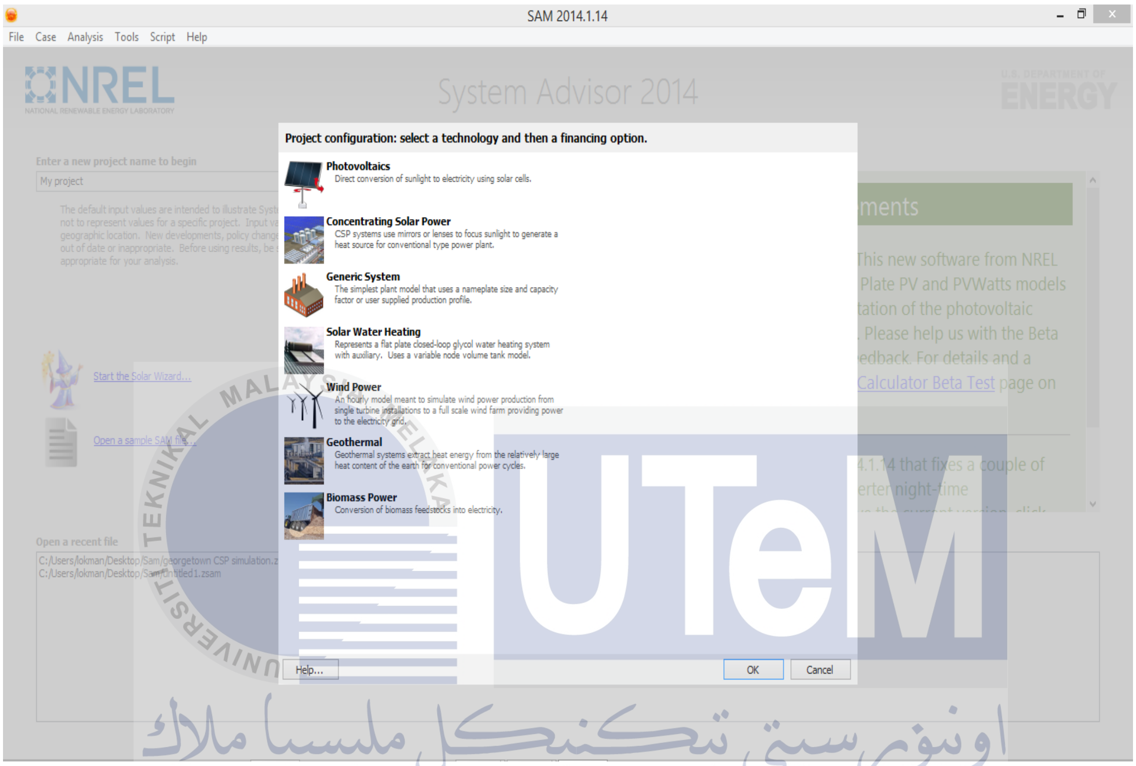


Figure 3.3: Project technology configuration

Select "Concentrating Solar Power" and choose the "Dish Stirling" system. Select any of the financial option on the right side and click "ok" to start a new project as shown in Figure 3.4.

Figure 3.4: CSP type and financial plan

2. Entering Data

The window will appear as shown in Figure 3.5. Choose weather data file for any desired location to run the simulation.

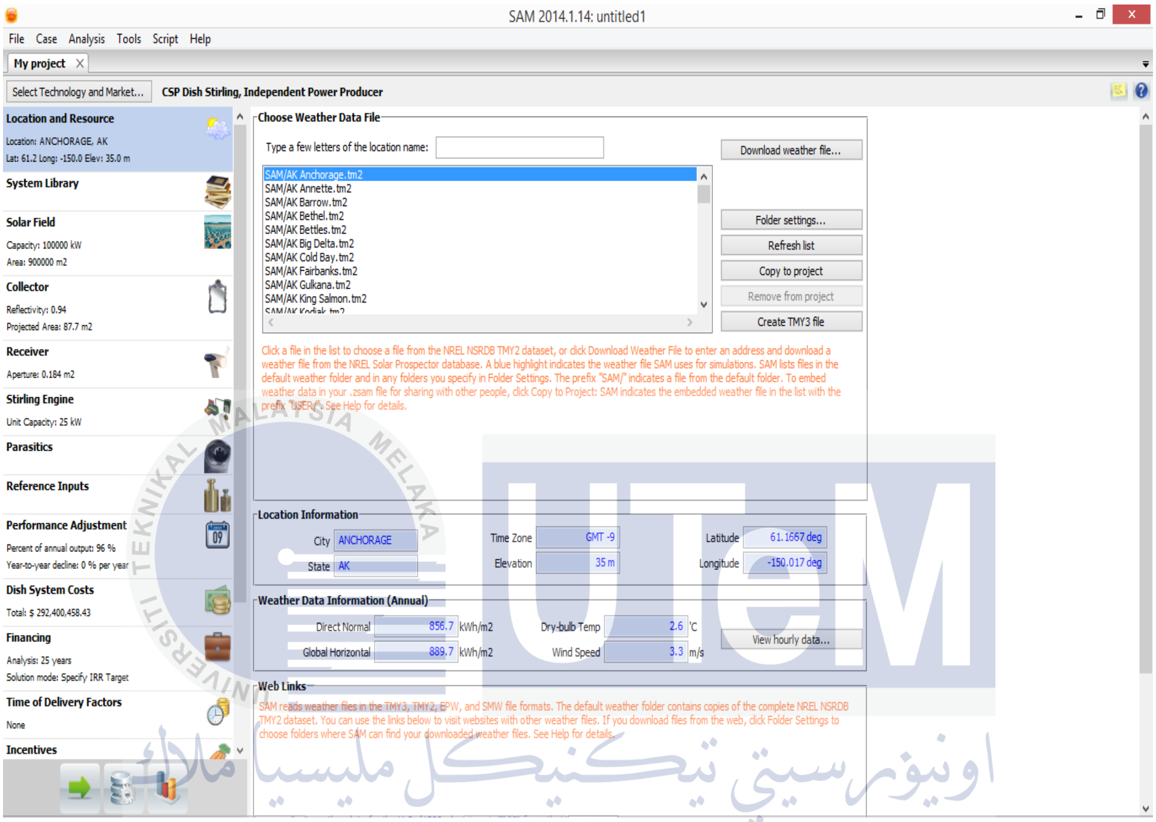


Figure 3.5: Main page of SAM

For weather data on Malaysia environment, click “Best weather data for international location (in EPW format)”.

The weather data is downloaded from U. S Department of Energy website as shown in Figure 3.6.

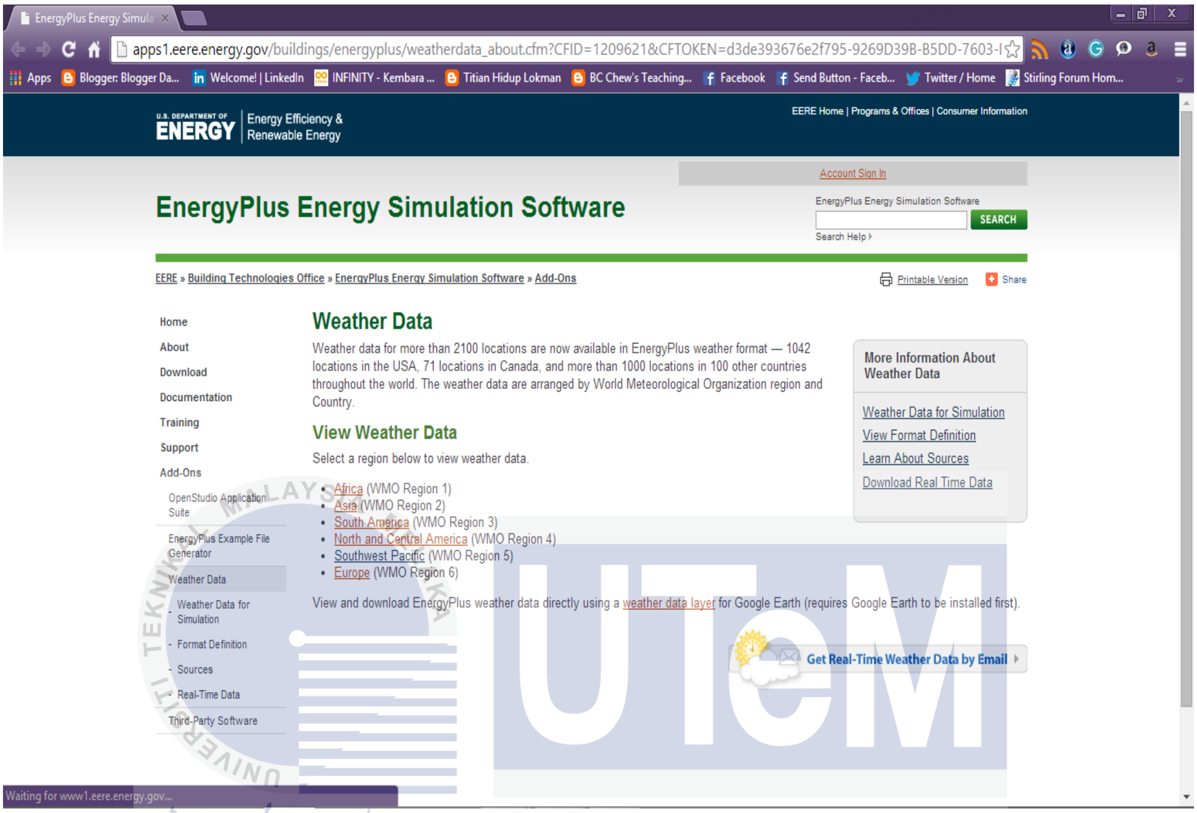


Figure 3.6: U. S Department of Energy website

Save the weather data on a folder in desktop or laptop. The weather data is in zip file, copy the EPW file to another folder so that SAM can add the downloaded weather data.

Click “Folder settings…” to add the file as shown in Figure 3.7 and click “ok”.

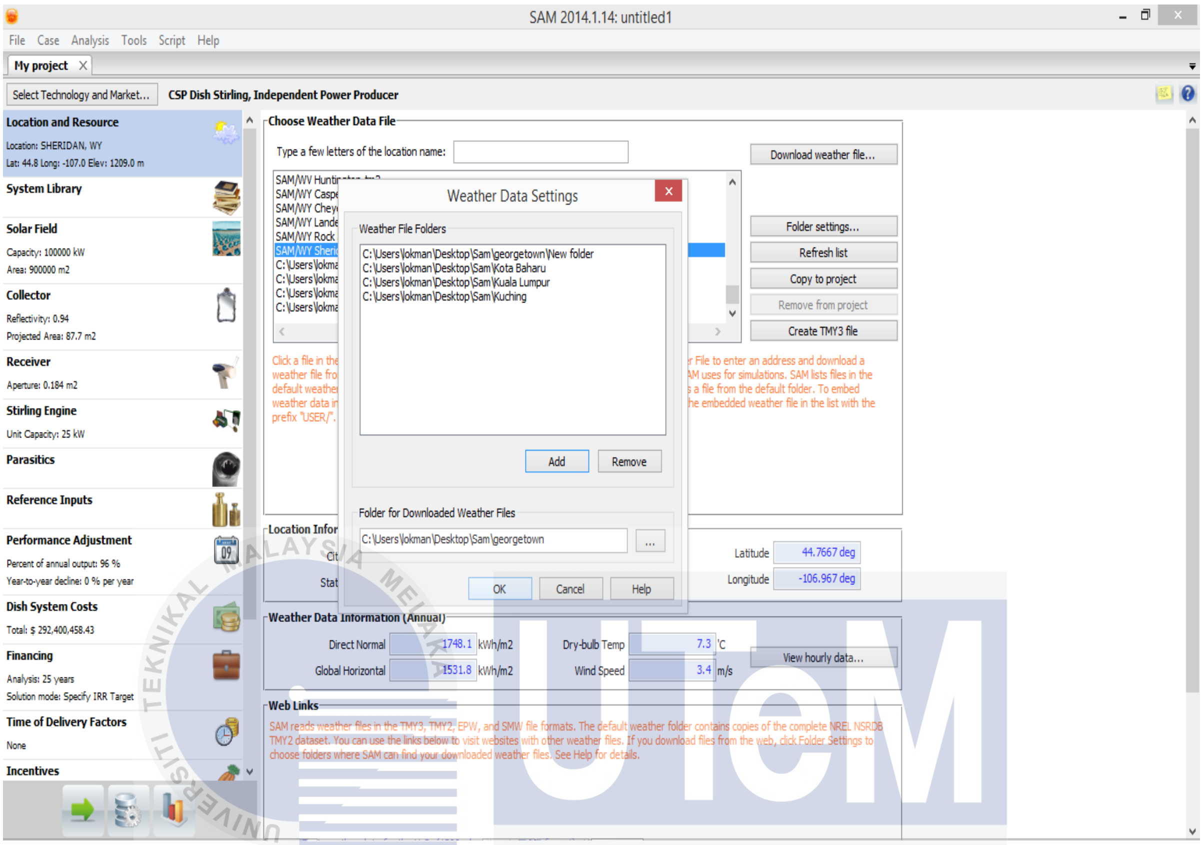


Figure 3.7: Add weather file to SAM software

The weather data will appear as shown in Figure 3.8 below. Select the weather file and run the simulation.

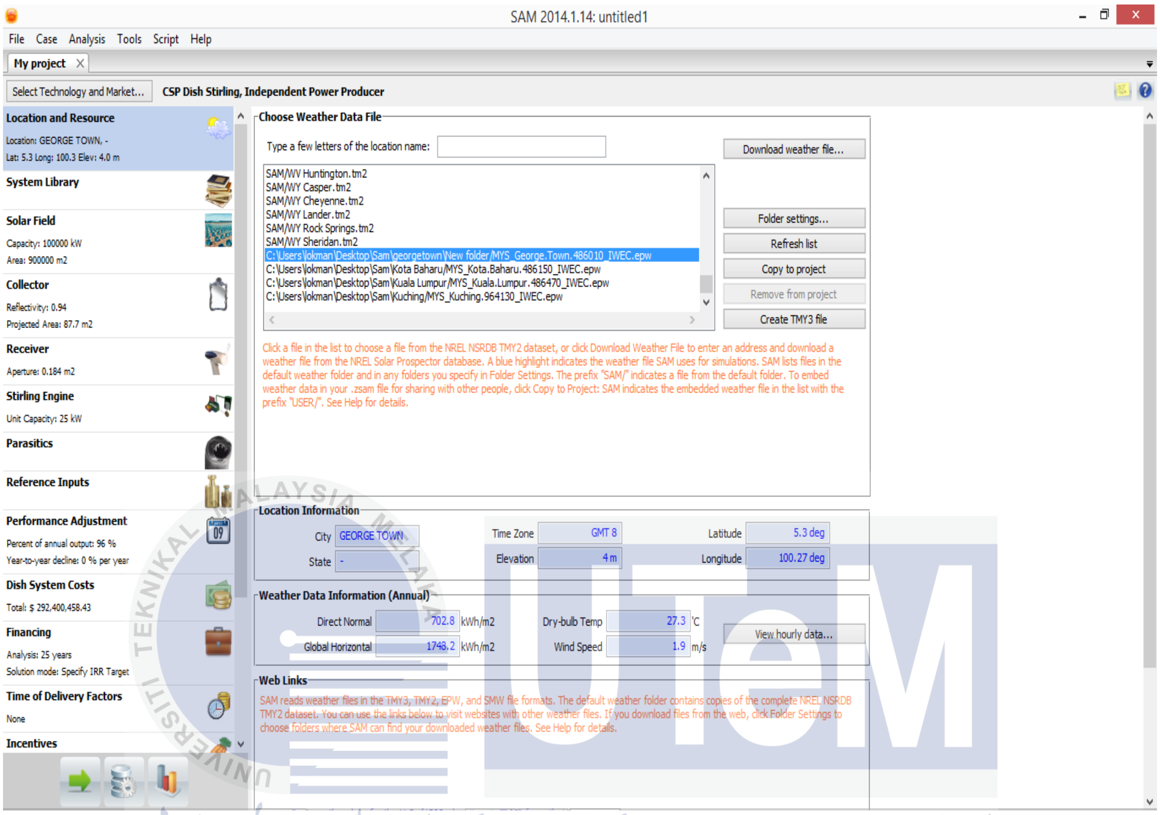


Figure 3.8: Run simulation

3. Monthly Energy Produced

Simulation on weather data shows in Figure 3.9 is the monthly energy in kWh from January to December.

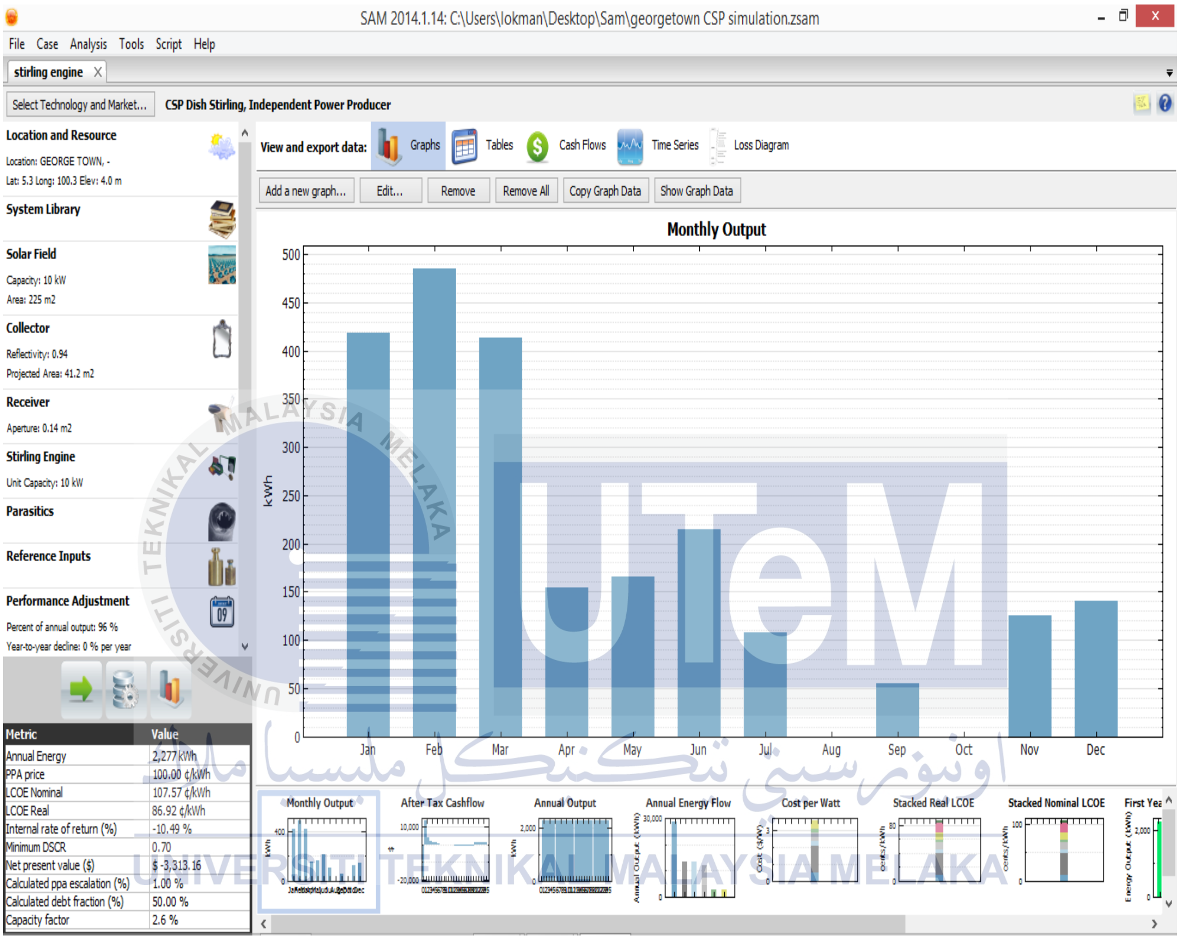


Figure 3.9: Monthly Output Graph

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Meanwhile, the DNI versus total field net power output is shown in Figure 3.10. The analysis on energy and DNI graph will be discussed further in Chapter 4.

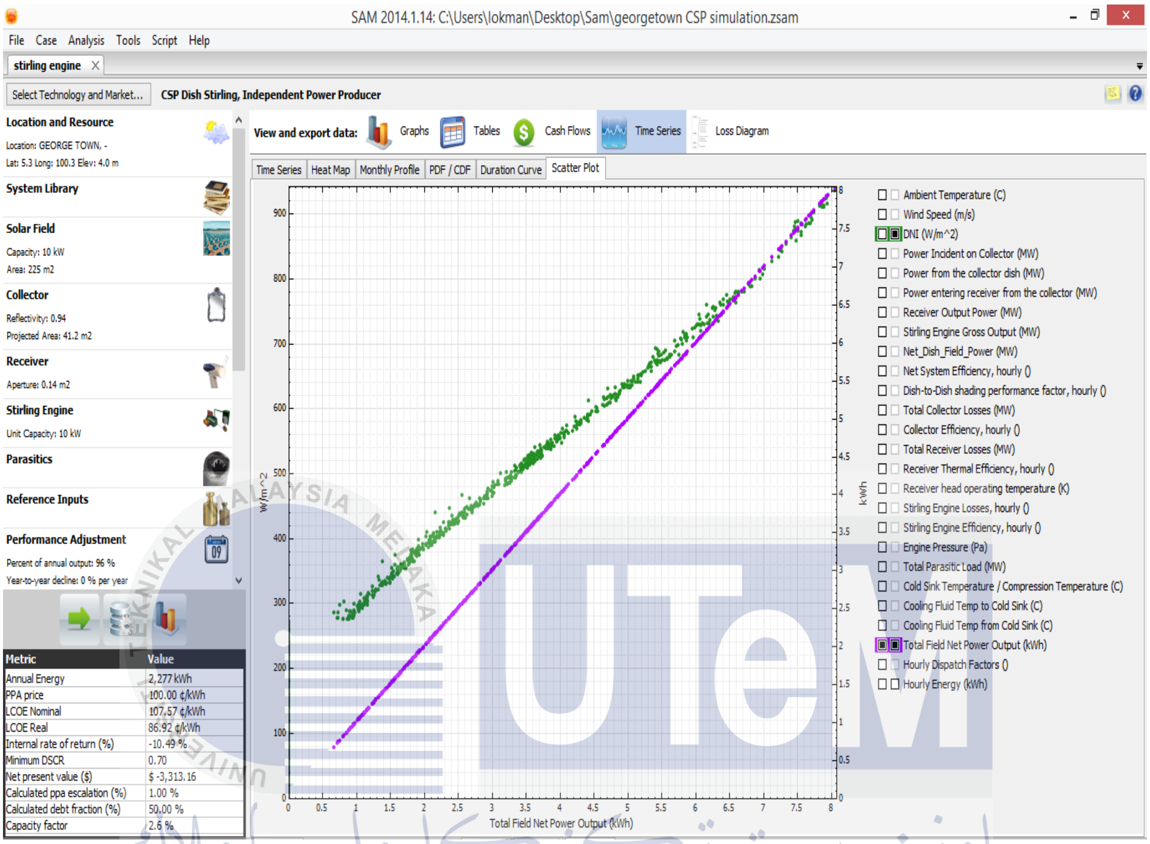

Figure 3.10: DNI versus Total Field Net Power Output Graph

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter will include the result and analysis of the project. On top of that, the results were directly corresponding to the objective of the project, which has been stated in the chapter 1.

4.2 Project Result

A dish stirling system that has been chosen for the simulation is Wilkinson, Goldberg, and Associates, Inc. or (WGA). WGA dish stirling system has capacity to produce 10 kW [16]. The number of dish stirling system in the field is one unit. Therefore, the total capacity of dish stirling system is 10 kW. The collector separation in the field is 15 m, and it takes 225 m^2 for total solar field area [16].

The collector parameter used in this simulation is the projected mirror area, total mirror area and the reflective material. The projected mirror area for WGA type is 41.2 m^2. The total mirror area is 42.9 m^2, and the reflective material is 0.94. Most of concentrator depends on the reflective surface to concentrate the sunlight. Under laboratory condition, the highest reflectance of metal is polished silver, which is almost 98%. Back surface silvered glass has a solar reflectance about 95%, while silvered plastic film have 96% reflectance [6]. In this simulation, WGA model use collector of mirrors with laminated glass type which have the highest reflectance among the others dish in SAM library [16]. The input collector parameter can be referred from Figure 4.1.

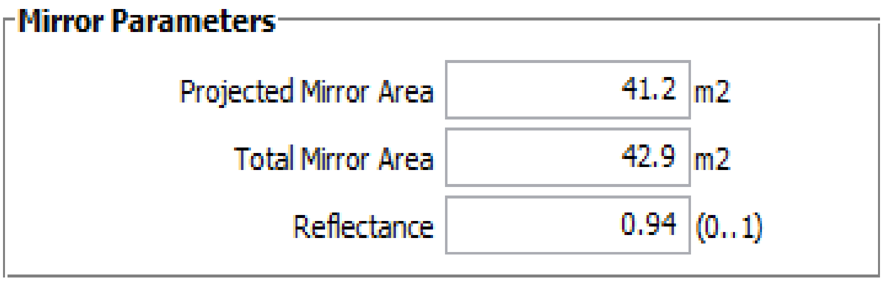

Figure 4.1: Collector parameter for WGA type

The receiver aperture diameter for the WGA type system is 0.14 m. An insulation of thickness 75 mm has been used as an effective width. High temperature ceramic fiber insulation has been used in receiver with dependent thermal conductivity 0.061 W/m-K. The absorber absorptance is 0.9 with a surface area of 0.15 m^2. The input receiver can be referred from Figure 4.2.

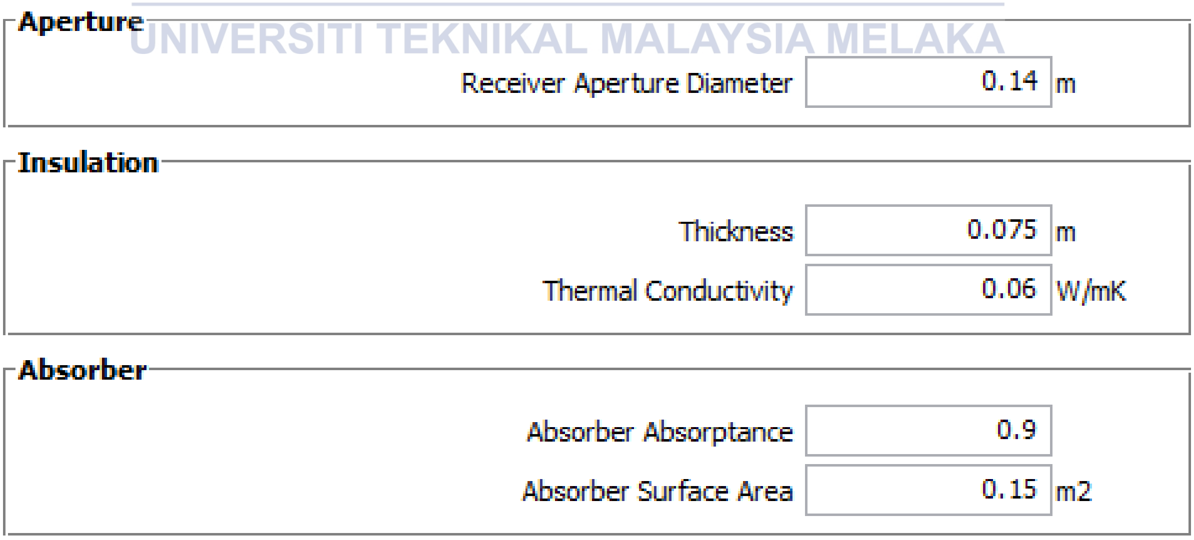

Figure 4.2: Receiver input for WGA type

4.2.1 Dish Stirling System Performance in Selected Area

Weather data from George Town is selected to be a reference for predicting the performance of a dish stirling system by using SAM software. Referring to Figure 4.3, **S**imulation of performance in George Town by using SAM show the highest monthly energy produced is in February, which is 485.323 kWh. On August and October, there are no productions of energy for a whole month. The lowest monthly outputs that can generate energy are in September with 54.782 kWh.

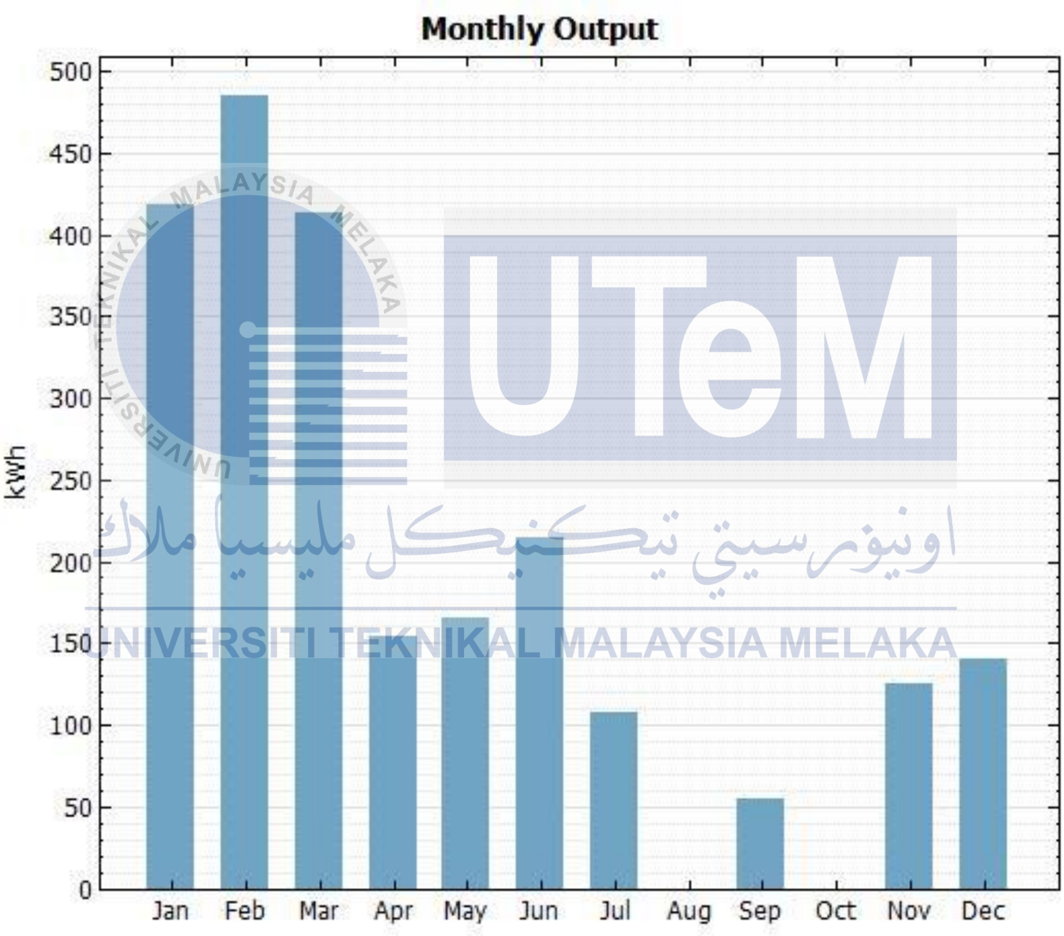

Figure 4.3: Monthly output of dish stirling system in George Town.

At three months earlier, the performance of dish stirling engine is the highest for that year. After three months, the energy output drop drastically start in April and increases slightly for three months later. Five months after that is where the dish stirling engine is in poor performance, with two month zero energy production.

The energy production graph shows that for first three months, solar radiation on George Town is high. In April, the performance drop due to decreases of solar radiation by formation of cloud and rain [22]. Start on July, George Town experiences heavy rain and low solar radiation, thus affect the performance of a dish stirling system [22]. The monthly energy output can be seen clearly in Table 4.1.

Table 4.1: Table of Monthly Energy in George Town

Month	Monthly Energy (kWh)
1	418.022
2	485.323
3	413.419
4	153.613
5	165.848
6	214.204
7	107.185
8	0
9	54.782
10	0
11	124.917
12	139.879

The dish stirling system performance can be predicted more efficient by referring the annual DNI for George Town which show in Figure 4.4. The simulation result show that the maximum DNI value reached over 900 W/m^2 in March and DNI value drop below 200 W/m^2 in December and January. The DNI value for August and October is below than 200 W/m^2, and at once explain why the energy production in that two month is zero. The minimum requirement of DNI, for dish stirling engine to produce energy with high efficiency was around 200 W/m^2.

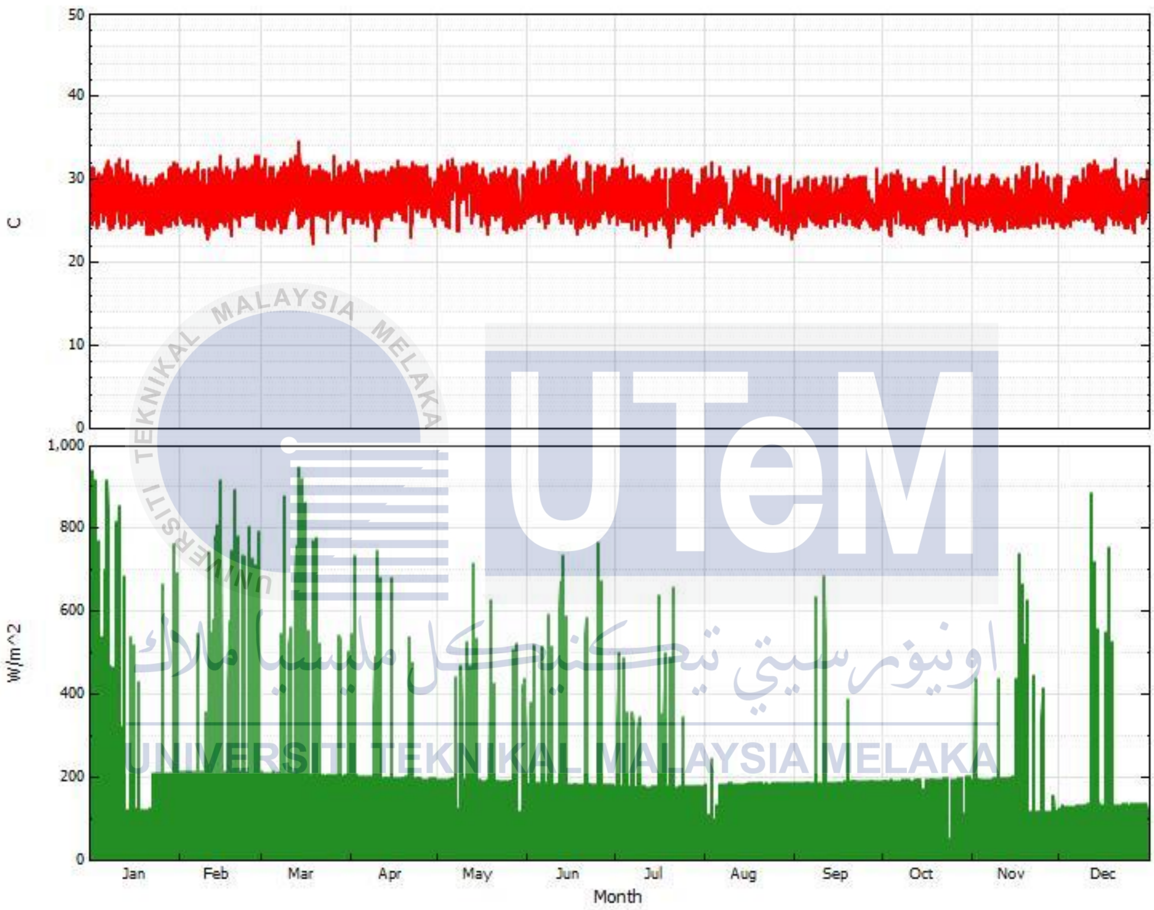

Figure 4.4: Annual DNI and ambient temperature

Figure 4.5 shows DNI versus the Total Field Net Power Output. From the graph, it can be observed that the total generated power is linearly increasing with the increase of the DNI.

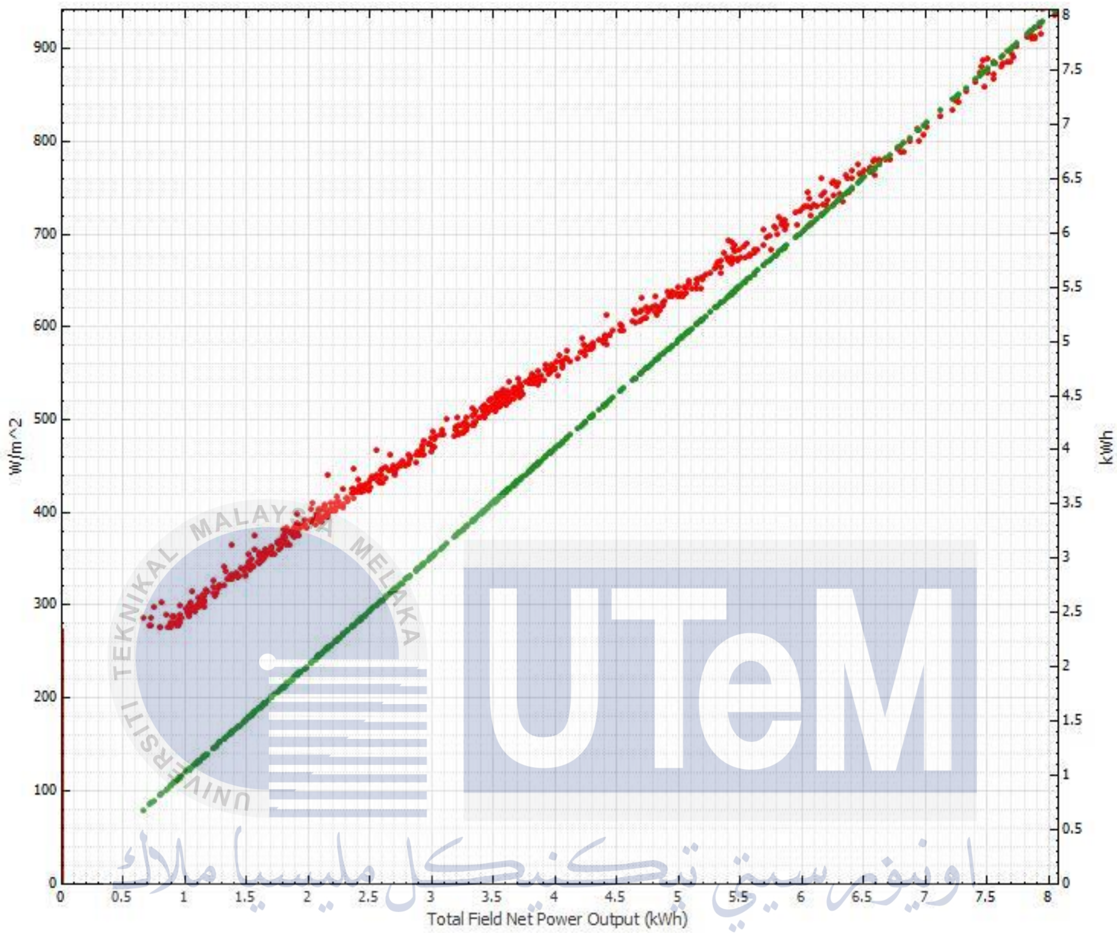

Figure 4.5: DNI vs total field net power output

Based on Figure 4.5 above, the power output of dish stirling engine can be achieved up to 8kWh at maximum value DNI of 938 W/m^2. The collector efficiency up to 94% can be achieved if the DNI value is higher than 200 W/m^2. If DNI value is lower than 200 W/m^2, the efficiency will be zero. Overall, the average annual energy produced in George Town is 194.3012 kWh. In one day, the energy can produce as much as 64.77 kWh.

4.2.2 Energy Produced by Dish Stirling System at Four Locations in Malaysia

The simulation for dish stirling system at four locations was done just like the first objective. The selected location is George Town, Kota Baharu, Kuala Lumpur, Kuching, The energy output graph for George Town is already discussed in sub-topic 4.1.1. The energy output graph for Kota Baharu, Kuala Lumpur and Kuching is shown in Figure 4.6, Figure 4.7 and Figure 4.8.

Figure 4.6 shows that the highest monthly energy produced is in March with 119.446 kWh. The lowest energy produced is in January, which is 10.2858 kWh. On August, there is no production of energy for a month.

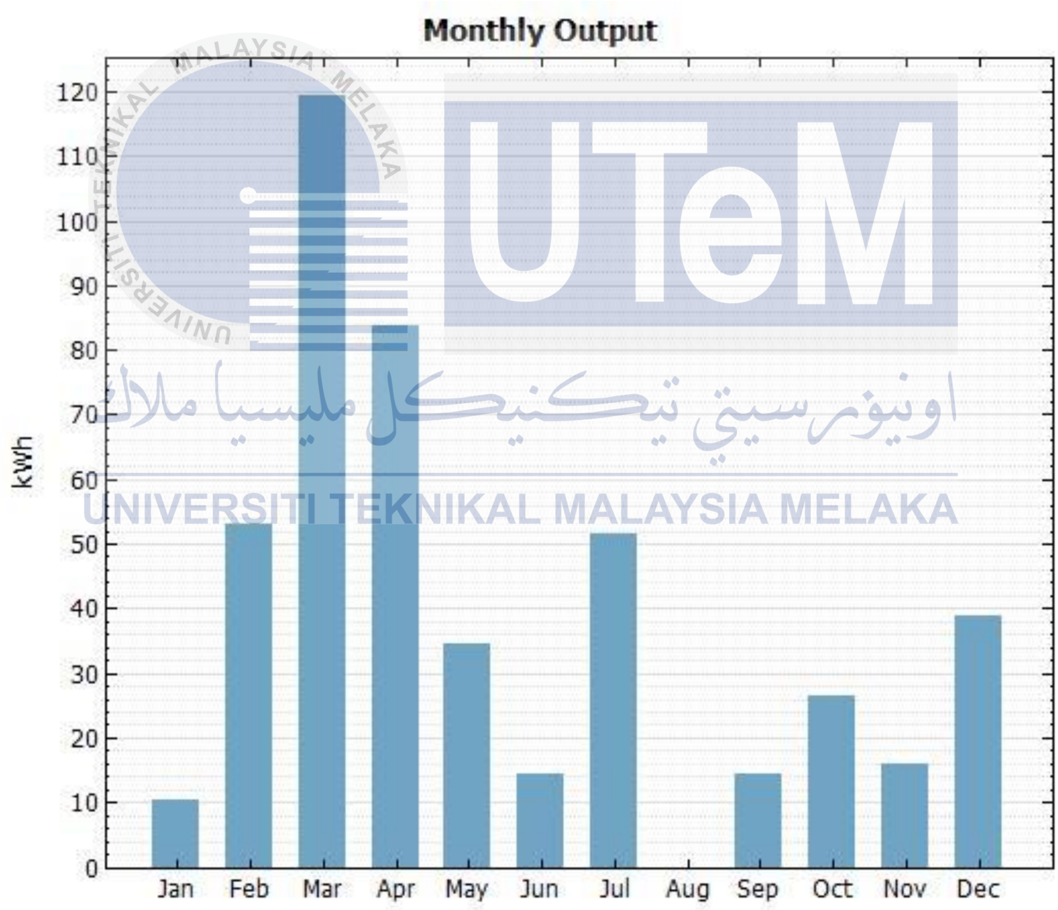

Figure 4.6: Monthly output of dish stirling system in Kota Baharu

Energy production in Kuala Lumpur is shown in Figure 4.7. In March, dish stirling recorded the highest energy produced, which is 96.6134 kWh. The lowest energy recorded is in December with value 1.03506 kWh. Dish stirling system produce zero energy in May.

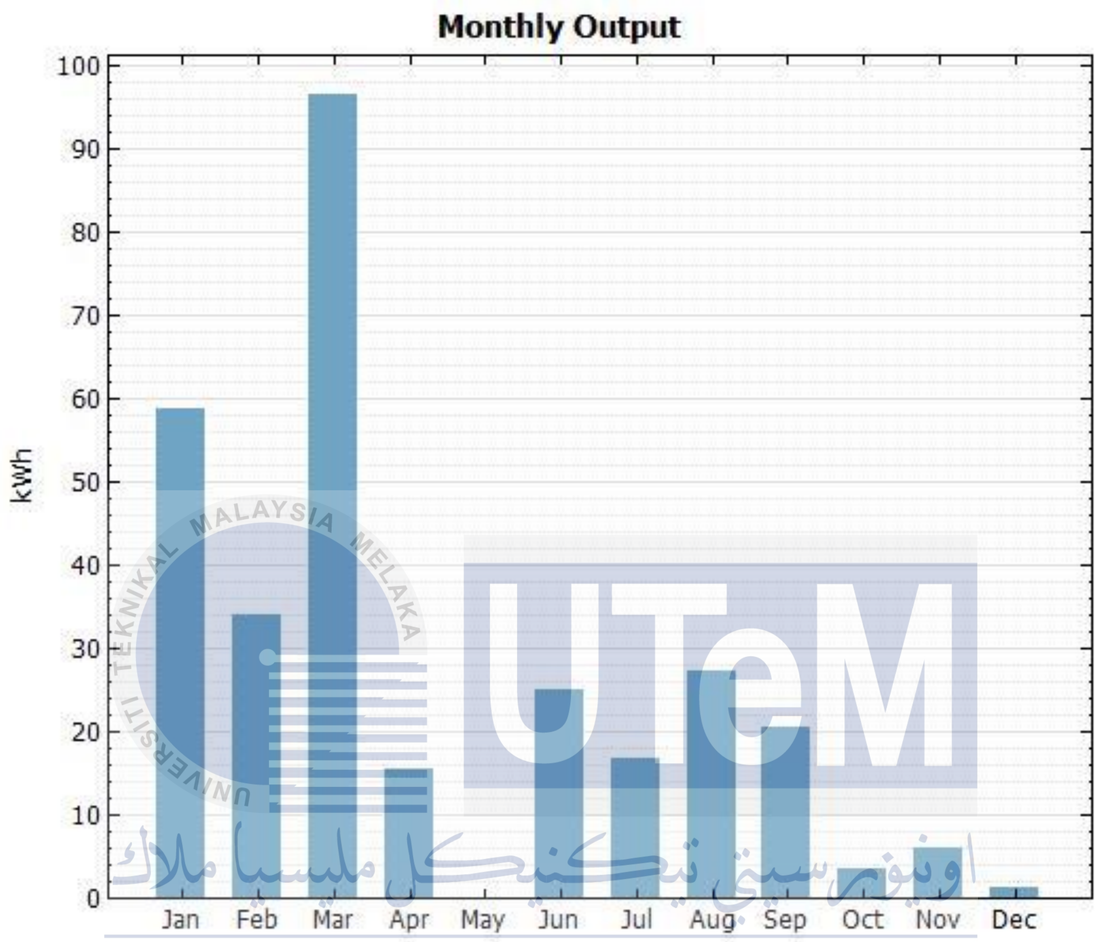

Figure 4.7: Monthly output of dish stirling system in Kuala Lumpur

Refer to Figure 4.8 shows the monthly output of a dish stirling system in Kuching. The highest energy produced is in May, which recorded value 221.55 kWh. The lowest energy produced in Kuching is 10.3821 kWh.

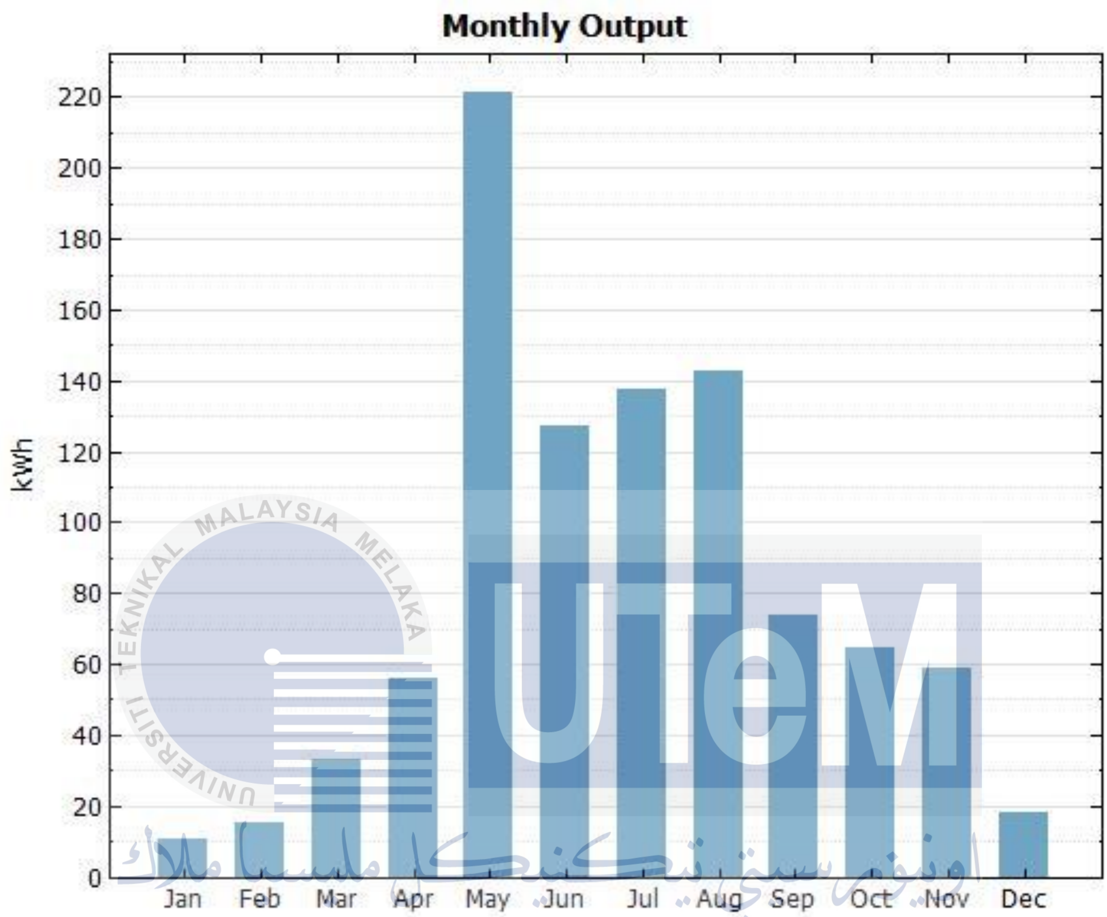

Figure 4.8: Monthly output of dish stirling system in Kuching

Table 4.2: Table of Monthly Energy in Four Locations in Malaysia

Month	Monthly Energy (kWh) at George Town	Monthly Energy (kWh) at Kota Baharu	Monthly Energy (kWh) at Kuala Lumpur	Monthly Energy (kWh) at Kuching
1	418.022	10.2858	58.6866	10.3821
2	485.323	53.1279	34.0447	15.2843
3	413.419	119.446	96.6134	32.8045
4	153.613	83.8553	15.4237	55.994
5	165.848	34.4193	0	221.55
6	214.204	14.3502	25.0446	126.949
7	107.185	51.5952	16.6966	137.687
8	0	0	27.2045	142.907
9	54.782	14.5111	20.5203	74.0623
10	0	26.3873	3.49738	64.7812
11	124.917	15.8187	5.76468	59.1163
12	139.879	38.9472	1.03506	17.8191
Average	189.766	38.562	25.37763	79.94473

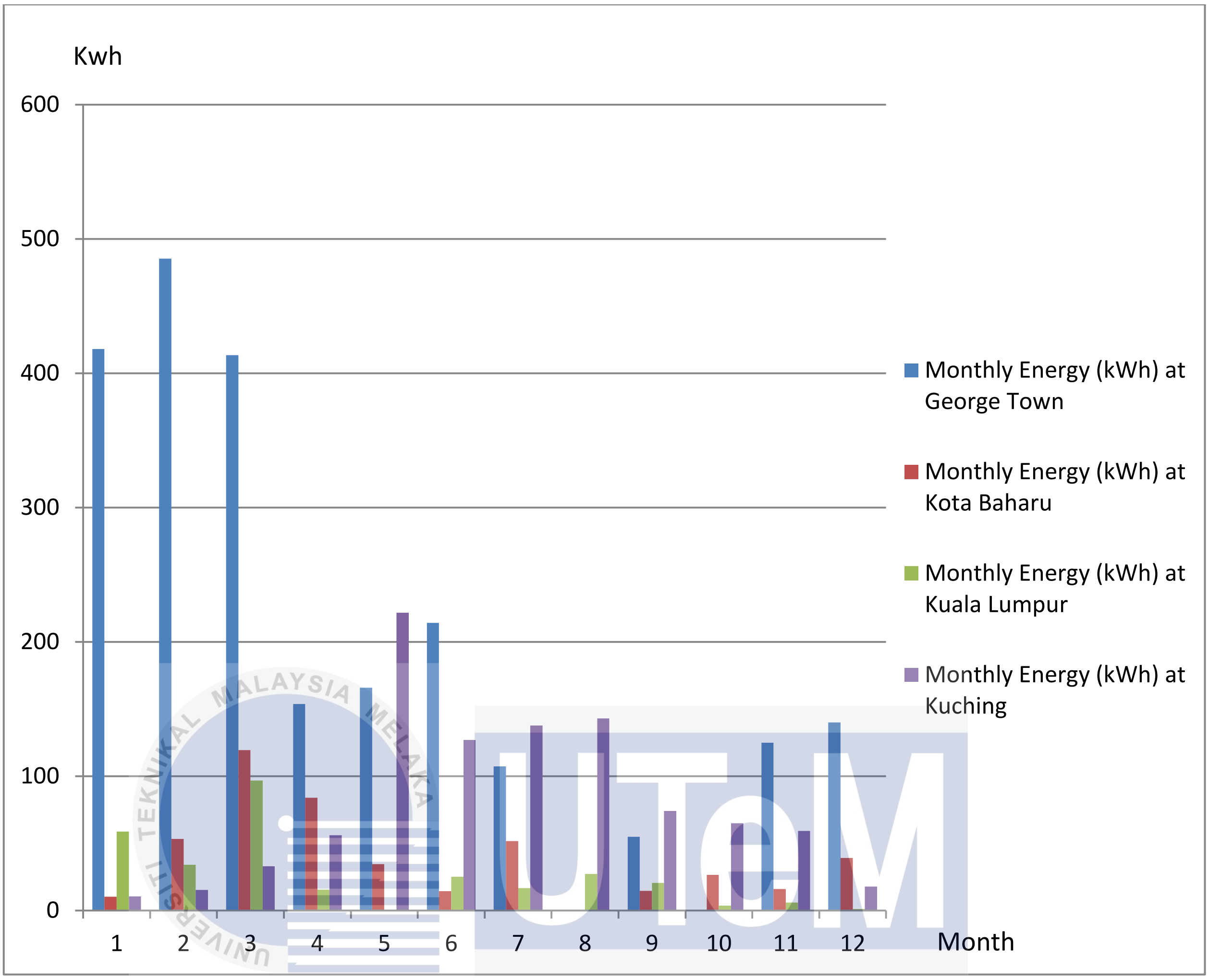

Figure 4.9: Performance comparison in four locations

Based on monthly output of four locations in Malaysia, George Town has the highest energy produce in a month, which is 485.323 kWh, compare to the other location. Refer to Figure 4.9, the annual energy for George Town is 189.766 kWh. While, the lowest energy produced by a dish stirling system is in Kuala Lumpur, with energy 1.03506 kWh. The annual energy for Kuala Lumpur is 25.3776 kWh. The second highest annual energy production is 79.9447 kWh in area Kuching. Whereas, Kota Baharu has an annual energy output about 38.562 kWh.

Figure 4.10 shows the graph for DNI and Total Field Net Power Output in area George Town. From the graph, it showed that if the DNI is high, then the Net power and monthly energy also high. The graph clearly shown the net power is zero for DNI less than 200 W/m^2.

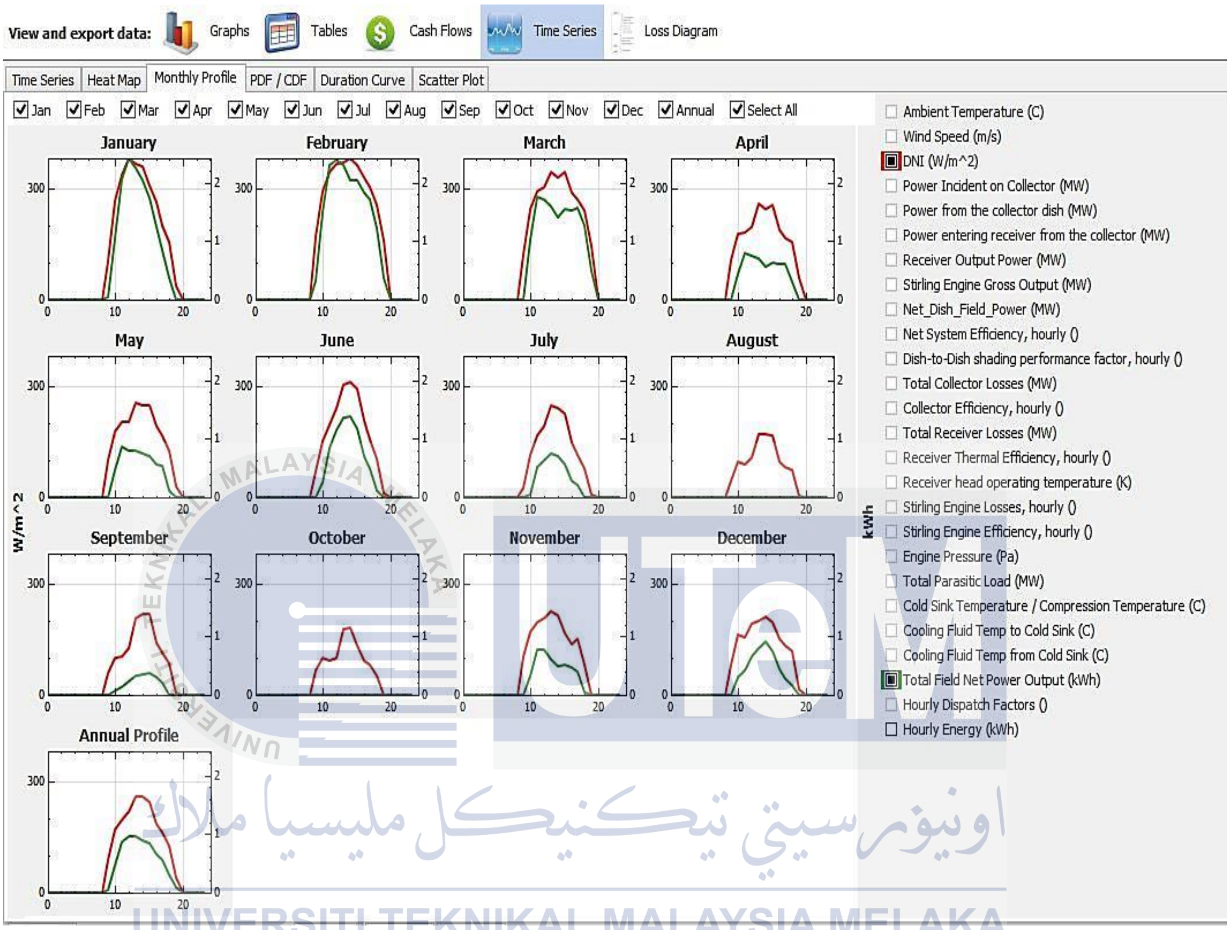

Figure 4.10: DNI and Total Field Net Power Output in George Town

Figure 4.11 shows the DNI and Total Field Net Power Output in Kota Baharu. The monthly DNI in Kota Baharu is less than George Town. Surprisingly, the net power on December month is zero even though the DNI is more than 200 W/m^2.

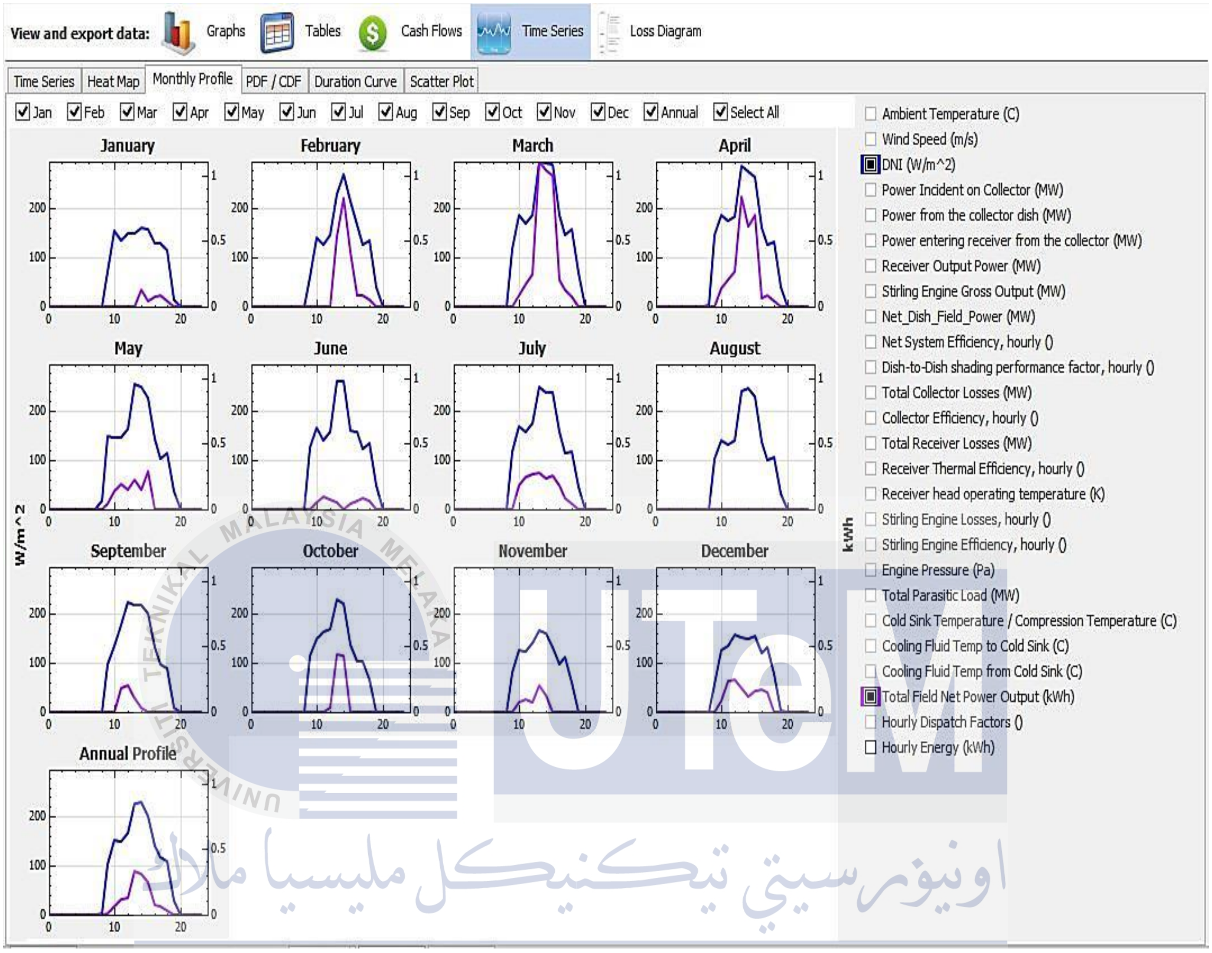

Figure 4.11: DNI and Total Field Net Power Output in Kota Baharu

Figure 4.12 shows the DNI and Total Field Net Power Output in Kuala Lumpur. Area in Kuala Lumpur has the lowest DNI value over a year. The dish stirling system still can operate in Kuala Lumpur with low DNI, below than 200 W/m^2. The system operates with poor performance in converting solar to electrical energy.

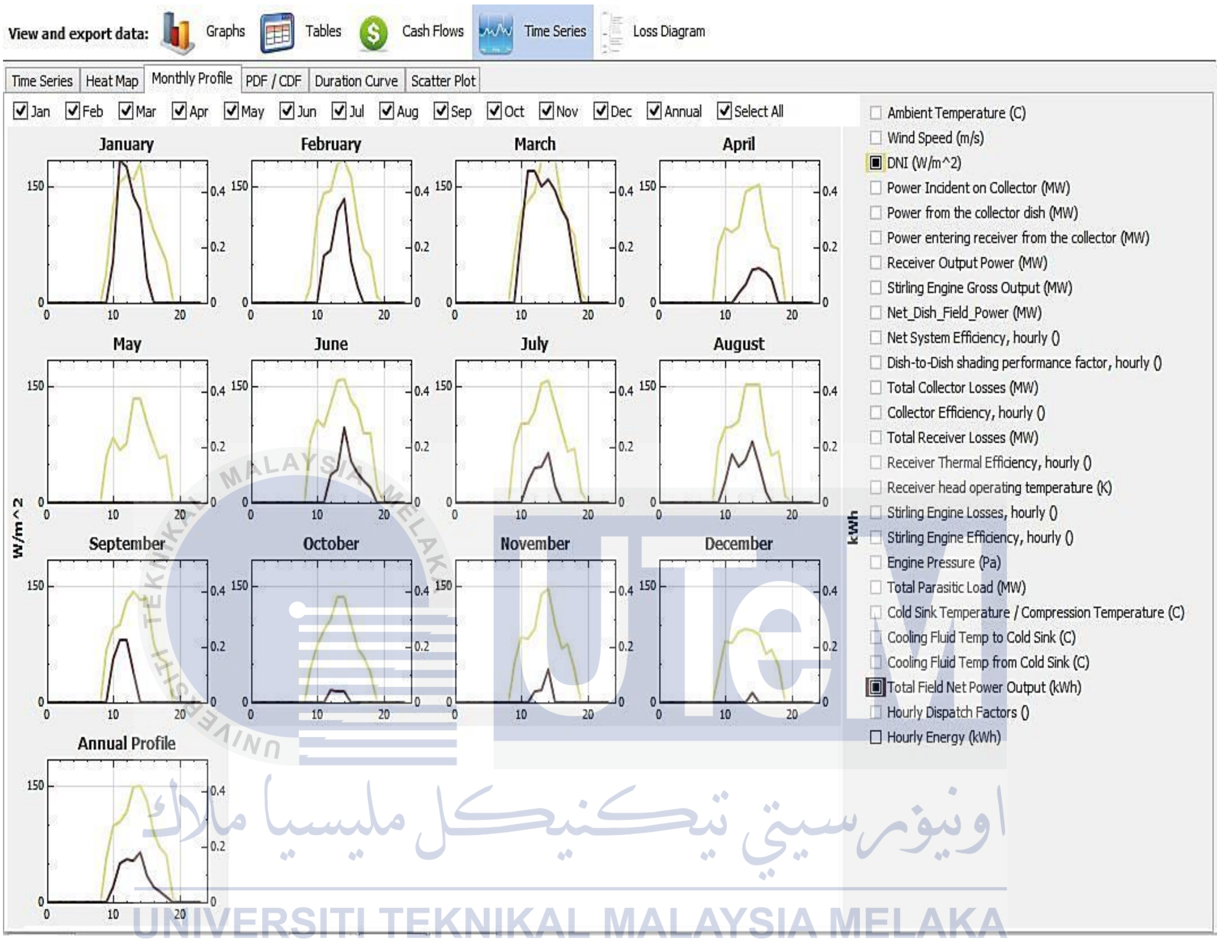

Figure 4.12: DNI and Total Field Net Power Output in Kuala Lumpur

Figure 4.13 shows the DNI and Total Field Net Power Output in Kuching area. The annual DNI is below than 200 W/m^2. This dish stirling system also in poor performance with low DNI and Net power output. The main advantages of this area are the solar energy is reliable through a year. The dish stirling engine gives the energy output ever month.

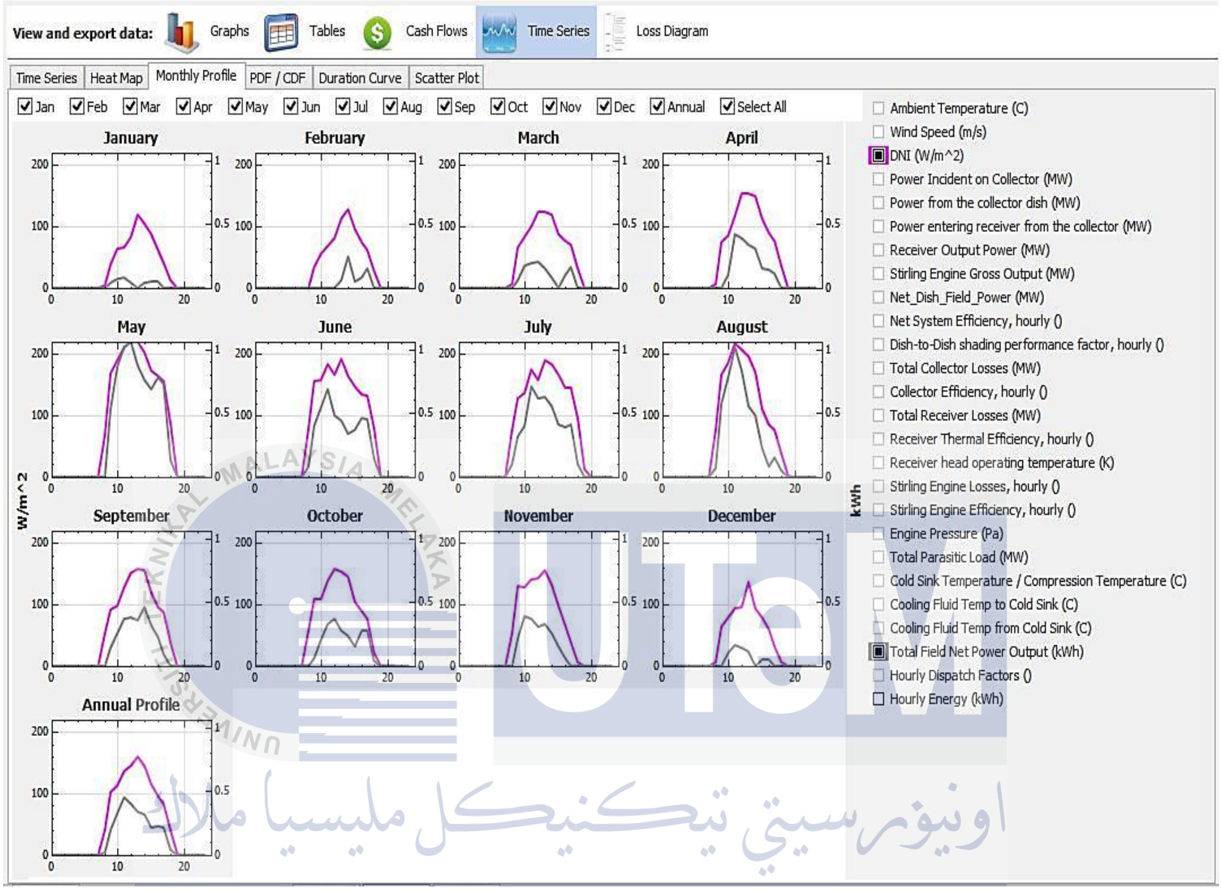

Figure 4.13: DNI and Total Field Net Power Output in Kuching

4.3 Result Analysis

Based on the simulation result, it shows that George Town have high DNI compare to area Kota Baharu, Kuala Lumpur and Kuching. Dish stirling system in George Town can produce high energy output with high efficiency. The minimum requirement for dish stirling system to operate with high efficiency in that area is DNI higher than 200 W/m^2. However, the dish stirling system in another area still can operate and give energy in DNI lower than 200 W/m^2. Dish stirling system operate in low DNI area has low efficiency. Despite that, performance of dish stirling system still low in Malaysia location. Moreover, Malaysia is a tropical climate with such heavy rainfall, high value of cloud cover, high wind speed and high value of humidity [22]. This climate affects the ambient temperature, solar to electrical conversion efficiency and power generation of dish stirling system on Malaysia environment.

CSP technologies require Direct Normal Irradiance (DNI) at least from 1900 to 2000 kWh/m^2/year to be economically feasible [3]. Even though Malaysia has DNI value of 759.2 kWh/m2, Germany has broken the statement when their CSP plants use Tower system with a capacity of 1.5MW in Julich, Rhineland [3]. Thus, the CSP technology may possible to implement in Malaysia environment.

CHAPTER 5

CONCLUSIONS

5.1 Introduction

This chapter will discuss conclusion for this subject and give recommendations for future research about this topic.

5.2 Conclusion

After doing an analysis of the performance of the dish stirling engine in Malaysia environment, it can be said that all the objectives of this project are accomplished. The prediction of performance of a dish stirling system by using System Advisor Model (SAM) are determined. The electrical energy produced for four locations, George Town, Kota Baharu, Kuala Lumpur and Kuching was analysed by simulating the weather data from U. S. National Climatic Data Centre.

The weather data are the input data for the CSP model in SAM. This data used to calculate the monthly output produce by dish stirling system. The data include ambient temperature, wind speed, and DNI start from 1 January to 31 December. The output data from SAM simulation is represented in monthly.

Analysis on the performance of dish stirling engine is done by analysing the monthly output, with the dish stirling system principle. The monthly data are related to the DNI value in that selected area and total field net power output. From the analysis, it is known that the performance of a dish stirling system is depend on the total solar radiation receive by the concentrator. The higher DNI values in that area, the higher performance of dish stirling system.

From this project, the uses of SAM software are recommended for performance prediction of CSP system model. This software is easy to use, but the limitation is on the weather data. It is hoped that, there are people who can produce weather data of every state in Malaysia. This weather data will help the growth of using the SAM software for renewable technology design.

5.3 Recommendation

As a recommendation, the analysis of renewable technology, performance can be more effective by using real data of dish stirling system in Malaysia environment. The weather data must collect as many as possible for different locations in Malaysia. The real data of dish stirling system and weather data can be used to improve renewable technology, efficiency and thus can be the trigger to project manager, technology developers and researchers to implement this technology in Malaysia.

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APPENDICES A – Weather Format

Weather Format

The following information was published at the “Building Simulation ‘99” conference in September 1999. The paper was entitled “Improving the Weather Information Available to Simulation Programs” by D. Crawley, J. Hand, and L. Lawrie.

INTRODUCTION

All building simulation programs employ some means of representing local climatic conditions relative to the building models. For example, Radiance (Ward 1996) needs a description of sky conditions and illuminance values to calculate solar distribution through a window and within a space. Three of the widely used energy simulation programs in the UK and US, ESP-r (ESRU 1999), BLAST (UI 1998), and DOE-2 (Winkelmann et al. 1993) also use weather conditions to simulate the response of a building. But even after 30 years of significant development advances in simulation capabilities, these programs use the same climate representations as in the past—a simple set of hourly temperature, humidity, wind speed and direction, and atmospheric pressure and solar radiation or cloud cover data. These data are often ‘typical’ data derived from hourly observations at a specific location by the national weather service or meteorological office. Examples of these typical data include TMY2 (NREL 1995) and WYEC2 (ASHRAE 1997) in the United States and Canada and TRY (CEC 1985) in Europe. The TMY2 and WYEC2 typical weather years contain more solar radiation and illumination data than older formats such as TMY (NCDC 1983), WYEC (ASHRAE 1985), and TRY (NCDC 1981) in the U.S. Crawley (1998) demonstrated that the methods used to select data for the TMY2 and TRY data sets better fit the long-term climate patterns.

Radiation and illumination data are becoming increasingly necessary in simulation programs. Anyone who has ever attempted to measure daylight factors will be familiar with the fluctuations in lighting levels under partly cloudy conditions. The expansion and contraction of lightweight building components also shares sensitivity to rapid fluctuations in solar radiation. Single-sided ventilation is dependant on wind pressure fluctuations and pedestrians in many cities are acquainted with the disarming tendency of the wind to guest and change direction. It is increasingly the case that design questions touch on such issues.

In a research context, the advent of tools such as LabVIEW (National Instruments Corporation 1999) have made it possible for increasing numbers of researchers to acquire and process test-cell data. The increasing use of building energy management systems (BEMS) has also provided high frequency information from which simulation could be used as a predictive tool for future control strategies. Other issues of control, particularly of advanced daylighting control require sub-hourly illumination data to ensure that possible control regimes are tested under realistic conditions. Janak (1997) observed that the differences between 5 minute and hourly illumination data could result in prediction variations approaching 40%.

Thus far, projects that mix empirical and simulation-based work have had to store and access such data via temporal database facilities (ESRU 1999). As the number of high quality datasets increases so does the need to encapsulate such information in a form that can be broadly distributed. The simulation community must also consider the uncertainty in high frequency performance predictions that are based on boundary conditions that have been sampled at one or two magnitudes less temporal resolution.

The simulation community must also consider practitioner demands and issues of quality assurance. Someone who is not a native of Copenhagen may not know that there are three or four recognizable patterns of winter weather that should be included in detailed assessments. A data set that lacks documentation or is dependent on separately held lists of assumptions can be effectively useless.

In the absence of data within the weather data format, the simulation programs must calculate these data often with older calculation methods. As the simulation programs have become more capable, data at hourly resolution is no longer enough—interpolating between hourly observations does not accurately represent weather conditions that change much more frequently such as illumination.

We have developed a new, generalized weather data format for use by energy simulation programs has been developed and adopted by both ESP-r (in the UK) and EnergyPlus (in the US). Anticipating the need for data at time steps less than one hour, the format includes a minute field to facilitate the use of sub hourly data. The data include basic location identifiers such as location name, data source, latitude, longitude, time zone, elevation, peak design conditions, holidays, daylight savings period, typical and extreme periods, ground temperatures, period(s) covered by the data and space for descriptive comments. The time step data include dry bulb and dew point temperature, relative humidity, station pressure, solar radiation (global, extraterrestrial, horizontal infrared, direct, and diffuse), illuminance, wind direction and speed, sky cover, and current weather.

NEW WEATHER FORMAT FOR SIMULATION PROGRAMS

For these reasons, we developed a new generalized weather data format for use with two major simulation programs—ESP-r and EnergyPlus (Crawley et al. 1999). All the data are in SI units. The format is simple, text-based with comma-separated data. It is based on the data available within the TMY2 weather format but has been rearranged to facilitate visual inspection of the data. The TMY2 data are a strict, position-specific format—filling missing data with nines and zero values with zeroes. The new weather data format contains commas to facilitate data reading and analysis with spreadsheet programs. By eliminating redundant 'fill' values, the size of each file is only slightly larger than the original TMY2 format.

The traditional distribution of data source and uncertainty flags within the raw data fields carries with it not only the need for many field separators, it obfuscates the relationships between non-numerical data. In a set of minute data, which could easily require hundreds of thousands of records, the space penalty is considerable. In the E/E file format, all data source and uncertainty fields have been clumped together as a single field immediately following the day and time stamp. For applications where uncertainty is not an issue such data can be easily ignored. When it is important, a single text field is conceptually and computationally easy to parse.

Another difference between the EnergyPlus/ESP-r (E/E) format and TMY2 is the addition of two new data fields—minute and infrared sky. The minute field facilitates use of data observed at intervals of less than one hour such as measured data from a research study of energy efficiency for a particular building. This will allow easier and more accurate calibration of a simulation model to measured data than possible in the past. The infrared sky field allows the programs to calculate the effective sky temperature for re-radiation during nighttime.

The last difference is that a full year of data (such as 8760 hours) is not required—subsets of years are acceptable. Which periods are covered by the data is described in the files. Periods of typical weather patterns based on analysis of the data are also included within the format. A side-by-side comparison of data included in the E/E weather format with data previously used by ESP-r, DOE-2, and BLAST is shown in Table 1. A deficiency noted within ESP-r for example is the lack of correcting air volumes for elevation change—many of the users of ESP-r are in relatively low elevations. For DOE-2 and BLAST, neither program used illumination data in daylighting calculations or infrared sky temperatures—it was always recalculated at time of use.

By including the uncertainty and data source information found in TMY2, users now can evaluate the potential impact of weather variability on the performance of the building.

Table 1. Comparison of E/E with ESP-r,DOE-2, and BLAST Weather Data Formats

Data Element	**DOE-2**	**BLAST**	**ESP-r**	**E/E**
Location (name, latitude, longitude, elevation, time zone)	X	X	X	X
Data source				X
Commentary			X	X
Design conditions				X
Typical/extreme periods				X
Data periods				X
Holiday/Daylight Savings		X		X
Solar Angles/Equation of Time Hours		X		
Degree Days		X		X
Year	X	X	X	X
Month	X	X	X	X
Day	X	X	X	X
Hour	X	X	X	X
Minute				X
Data source and uncertainty flags				X
Dry bulb temperature	X	X	X	X
Wet bulb temperature	X	X		X
Dew point temperature	X			X
Atmospheric station pressure	X	X		X
Humidity ratio	X	X		X
Relative humidity			X	X
Enthalpy	X			
Density	X			
Wind Speed	X	X	X	X
Wind Direction	X	X	X	X
Infrared Sky Temperature		X		X
Solar Radiation (global, normal, diffuse)	X	X	X	X
Illuminance (global, normal, diffuse)				X
Sky cover (cloud amount)	X			X
Opaque sky cover				X
Visibility				X
Ceiling height				X
Clearness (monthly)	X			
Ground temperatures (monthly)	X			X
Present weather observation and codes (rain, snow)		X		X
Precipitable water				X
Aerosol optical depth				X
Snow depth				X
Days since last snowfall				X

McDonald and Strachan (1998) are introducing uncertainty analysis into ESP-r.

We use the EnergyPlus data dictionary format to describe the E/E weather data set. (See the end of this document). Each line in the format is preceded by a keyword such as LOCATION, DESIGN CONDITIONS, followed by a list of variables beginning either with A or N and a number. A stands for alphanumeric; N for numeric. The number following A/N is the sequence of that number in the keyword list. Commas separate data. (Refer to the IDD Conventions document in “Getting Started” for further explanation of the format). The header information consists of eight lines (keywords): LOCATION, DESIGN CONDITIONS, TYPICAL/EXTREME

PERIODS, GROUND TEMPERATURES, HOLIDAYS/DAYLIGHT SAVINGS, COMMENTS 1, COMMENTS 2, and DATA PERIODS. This is followed by the time step data.

The first eight lines or header within each E/E weather file define basic location information such as longitude, latitude, time zone, elevation, annual design conditions, monthly average ground temperatures, typical and extreme periods, holidays/daylight savings periods, and data periods included. There is also space for users to document any special features or information about the file such as sources of data. The data then follows—8760/8784 lines if hourly data for a year. The specific data elements in the E/E format include:

- Location (City, State Province Region, Country, Data Source, WMO Number, Latitude, Longitude, Time Zone, Elevation)
- Design Conditions (Annual Extreme Daily Mean, Mean Maximum Dry Bulb Temperature and Standard Deviation, Mean Minimum Dry Bulb Temperature and Standard Deviation, Heating Dry Bulb Temperature (99.6%, 99%, 98%), Cooling Dry Bulb Temperature/Mean Coincident Web Bulb Temp (0.4%, 1.0%, 2.0%), Cooling Dew Point Temperature, Mean Coincident Dry Bulb Temp (0.4%, 1.0%, 2.0%), Coincident Humidity Ratio and Relative Humidity (0.4%, 1.0%, 2.0%), Daily Range of Dry Bulb Temperature, Heating Degree Days Base Temperature, Heating Degree Days, Cooling Degree Days Base Temperature, Cooling Degree Days)
- Typical/Extreme Periods (Number of Typical/Extreme Periods (up to 8), Description of each Typical/Extreme Period, Start Month/Day, End Month/Day)
- Ground Temperatures (Number of Ground Temperature Depths (up to 3), Depth for each Ground Temperature set, Soil Conductivity, Soil Density, Soil Specific Heat, Monthly Average Ground Temperatures)
- Leap Year indicator, Daylight Savings Periods, Holidays
- Comments
- Time Step Data Periods, #Number, #Number Records/Intervals in an hour, Description, Start Day of Week, Start Month/Day, End Month/Day)
- Time Step Data (Year, Month, Day, Hour, Minute), Data Source and Uncertainty Flags,
- Time Step Data (Dry Bulb Temperature, Dew Point Temperature, Relative Humidity, Atmospheric Station Pressure, Radiation (Extraterrestrial Horizontal, Extraterrestrial Direct Normal, Horizontal Infrared Radiation from Sky, Global Horizontal, Direct Normal, Diffuse Horizontal), Illuminance (Global Horizontal, Direct Normal, Diffuse Horizontal, Zenith Luminance), Wind (Direction, Speed), Sky Cover (Total, Opaque, Visibility, Ceiling Height), Present Weather (Observation, Codes), Precipitable Water, Aerosol Optical Depth, Snow (Depth, Days Since Last Snowfall))

Tables 2, 3, 4, 5, and 6 describe the codes for the sixth field in the time step data—Data Source and Uncertainty Flags. Table 2 describes the flags in order they are presented within the sixth data field—each flag is a single letter or number. Tables 3, 4, 5 and 6 provide a description of each of the codes. An example header and first and last days of an E/E data file for Washington, DC (Dulles Airport, Sterling, Virginia) is shown following the IDD description at the end of this document.

The E/E Weather Utility automatically generates the Typical/Extreme periods. daylight savings periods and number of holidays and holiday dates are country- and site-specific. The number of holidays is variable and entered by the user. We included daylight savings and holidays in the format so that users will only have to find those data once, not each time they run the simulation program. In both EnergyPlus and ESP-r, these design conditions, holiday, daylight savings, other data are defaults and can be overridden by user input.

UTILITY

We developed a utility for the E/E format to read standard weather service file types such as TD1440 and DATSAV2 and newer ‘typical year’ weather files such as TMY2 and WYEC2.

The utility translates and extends typical weather data into the E/E format. The processor makes the calculations necessary for interpolating data (when data is missing) and calculates the illumination data—not typically currently an observed value reported by the meteorological offices through the world. The utility also prepares an interactive summary of the weather data set that the user can browse and save.

Table 2. Key to Data Source and Uncertainty Flags

Data Flag	Flag Values
Dry Bulb Temperature Data Source	A-F
Dry Bulb Temperature Data Uncertainty	0-9
Dew Point Temperature Data Source	A-F
Dew Point Temperature Data Uncertainty	0-9
Relative Humidity Data Source	A-F
Relative Humidity Data Uncertainty	0-9
Atmospheric Station Pressure Data Source	A-F
Atmospheric Station Pressure Data Uncertainty	0-9
Horizontal Infrared Radiation Data Source	A-H, ?
Horizontal Infrared Radiation Data Uncertainty	0-9
Global Horizontal Radiation Data Source	A-H, ?
Global Horizontal Radiation Data Uncertainty	0-9
Direct Normal Radiation Data Source	A-H, ?
Direct Normal Radiation Data Uncertainty	0-9
Diffuse Horizontal Radiation Data Source	A-H, ?
Diffuse Horizontal Radiation Data Uncertainty	0-9
Global Horizontal Illuminance Data Source	I, ?
Global Horizontal Illuminance Data Uncertainty	0-9
Direct Normal Illuminance Data Source	I, ?
Direct Normal Illuminance Data Uncertainty	0-9
Diffuse Horizontal Illuminance Data Source	I, ?
Diffuse Horizontal Illuminance Data Uncertainty	0-9
Zenith Luminance Data Source	I, ?
Zenith Luminance Data Uncertainty	0-9
Wind Direction Data Source	A-F
Wind Direction Data Uncertainty	0-9
Wind Speed Data Source	A-F
Wind Speed Data Uncertainty	0-9
Total Sky Cover Data Source	A-F
Total Sky Cover Data Uncertainty	0-9
Opaque Sky Cover Data Source	A-F
Opaque Sky Cover Data Uncertainty	0-9
Visibility Data Source	A-F, ?
Visibility Data Uncertainty	0-9
Ceiling Height Data Source	A-F, ?
Ceiling Height Data Uncertainty	0-9
Precipitable Water Data Source	A-F
Precipitable Water Data Uncertainty	0-9
Broadband Aerosol Optical Depth Data Source	A-F
Broadband Aerosol Optical Depth Data Uncertainty	0-9
Snow Depth Data Source	A-F, ?
Snow Cover Data Uncertainty	0-9
Days Since Last Snowfall Data Source	A-F, ?
Days Since Last Snowfall Data Uncertainty	0-9

Table 3. Solar Radiation and Illuminance Data Source Flag Codes

Flag Code	Definition
A	Post-1976 measured solar radiation data as received from NCDC or other sources
B	Same as "A" except the global horizontal data underwent a calibration correction
C	Pre-1976 measured global horizontal data (direct and diffuse were not measured before 1976), adjusted from solar to local time, usually with a calibration correction
D	Data derived from the other two elements of solar radiation using the relationship, global = diffuse + direct ´ cosine (zenith)
E	Modeled solar radiation data using inputs of observed sky cover (cloud amount) and aerosol optical depths derived from direct normal data collected at the same location
F	Modeled solar radiation data using interpolated sky cover and aerosol optical depths derived from direct normal data collected at the same location
G	Modeled solar radiation data using observed sky cover and aerosol optical depths estimated from geographical relationships
H	Modeled solar radiation data using interpolated sky cover and estimated aerosol optical depths
I	Modeled illuminance or luminance data derived from measured or modeled solar radiation data
?	Source does not fit any of the above categories. Used for nighttime values and missing data

Table 4. Solar Radiation and Illuminance Data Uncertainty Flag Codes

Flag	Uncertainty Range (%)
1	Not used
2	2 - 4
3	4 - 6
4	6 - 9
5	9 - 13
6	13 - 18
7	18 - 25
8	25 - 35
9	35 - 50
0	Not applicable

Table 5. Meteorological Data Source Flag Codes

Flag	Definition
A	Data as received from NCDC, converted to SI units
B	Linearly interpolated
C	Non-linearly interpolated to fill data gaps from 6 to 47 hours in length
D	Not used
E	Modeled or estimated, except: precipitable water, calculated from radiosonde data; dew point temperature calculated from dry bulb temperature and relative humidity; and relative humidity calculated from dry bulb temperature and dew point temperature
F	Precipitable water, calculated from surface vapor pressure; aerosol optical depth, estimated from geographic correlation
?	Source does not fit any of the above. Used mostly for missing data

Table 6. Meteorological Uncertainty Flag Codes

Flag	Definition
1- 6	Not used
7	Uncertainty consistent with NWS practices and the instrument or observation used to obtain the data
8	Greater uncertainty than 7 because values were interpolated or estimated
9	Greater uncertainty than 8 or unknown.
0	Not definable.

CONCLUSIONS

We have developed a generic weather format for use by EnergyPlus and ESP-r. The new data set covers data that are increasingly needed for simulations of complex building designs such as sub-hourly data and illumination data. By extending the weather data available to developers of energy simulation models, we believe that the new format will also encourage developers to actually use the data available rather than forcing them to create data within their modules. Several advantages for this weather data format include:

- Measured data with time-steps of less than one hour can be easily translated into the format
- Data are easily shared among major energy simulation programs
- Specialized weather data sets, e.g., hot sunny, cold cloudy, high wind, etc—can be developed for the same location
- Uncertainty associated with global climate change can be evaluated

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WEB RESOURCES

Building Energy Tools Directory, a directory of information on more than 160 energy tools from around the world.

http://www.eren.doe.gov/buildings/tools_directory/

Energy Systems Research Unit, University of Strathclyde, authors of ESP-r, up-to-date information on ESP-r and other energy systems research and software development.

http://www.strath.ac.uk/Departments/ESRU

EnergyPlus, up-to-date information on the current status of EnergyPlus and working with the team, and documentation such as input data structure, output data structure, and licensing opportunities. A more detailed description of the EnergyPlus/ESP-r weather format is also included with sample weather files.

http://www.eren.doe.gov/buildings/energy_tools/energyplus.htm

WEATHER DATA IDD FORMAT

```
!ESP-r/EnergyPlus Weather Format
!22 November 1999

LOCATION,
  A1, \field city
  \type alpha
  A2, \field State Province Region
  \type alpha
  A3, \field Country
  \type alpha
  A4, \field Source
  \type alpha
  N1, \field WMO
   \type integer
  N2 , \field Latitude
     \units deg
     \minimum -90.0
     \maximum +90.0
     \default 0.0
     \note + is North, - is South,
     \note degree minutes represented in decimal (i.e. 30 minutes is .5)
     \type real
  N3 , \field Longitude
     \units deg
     \minimum -180.0
     \maximum +180.0
     \default 0.0
     \note - is West, + is East,
     \note degree minutes represented in decimal (i.e. 30 minutes is .5)
     \type real
  N4 , \field TimeZone
     \units hr (decimal)
     \minimum -12.0
     \maximum +12.0
     \default 0.0
     \note  Time relative to GMT.
     \type real
  N5 ; \field Elevation
     \units m
     \minimum -1000.0
     \maximum< +9999.9
     \default 0.0
     \type real

DESIGN CONDITIONS,
   N1, \field Annual Extreme Daily Mean Maximum Dry Bulb Temperature
      \units C
   N2  \field Annual Extreme Daily Mean Minimum Dry Bulb Temperature
      \units C
   N3, \field Annual Extreme Daily Standard Deviation Maximum Dry Bulb Temperature
      \units C
   N4, \field Annual Extreme Daily Standard Deviation Minimum Dry Bulb Temperature
      \units C
   N5  \field 99.6% Heating Dry Bulb Temperature
      \units C
   N6, \field 99% Heating Dry Bulb Temperature
     \units C
   N7, \field 98% Heating Dry Bulb Temperature
     \units C
   N8, \field 0.4% Cooling Dry Bulb Temperature
     \units C
   N9, \field 0.4% Mean Coincident Wet Bulb Temperature
     \units C
```

```
    N10, \field 1.0% Cooling Dry Bulb Temperature
      \units C
    N11, \field 1.0% Mean Coincident Wet Bulb Temperature
      \units C
    N12, \field 2.0% Cooling Dry Bulb Temperature
      \units C
    N13, \field 2.0% Mean Coincident Wet Bulb Temperature
      \units C
    N14, \field 0.4% Cooling Dew Point Temperature
      \units C
    N15, \field 0.4% Mean Coincident Dry Bulb Temperature
      \units C
    N16, \field 0.4% Humidity Ratio {?}],
    N17, \field 1.0% Cooling Dew Point Temperature
      \units C
    N18, \field 1.0% Mean Coincident Dry Bulb Temperature
      \units C
    N19, \field 1.0% Humidity Ratio
       \units {?}
    N20, \field 2.0% Cooling Dew Point Temperature
      \units C
    N21, \field 2.0% Mean Coincident Dry Bulb Temperature
      \units C
    N22, \field 2.0% Humidity Ratio
       \units {?}
    N23, \field Daily Range of Dry Bulb Temperature
      \units C
    N23, \field Heating Degree Days Base Temperature
      \units C
    N24, \field Heating Degree Days
    N25, \field Cooling Degree Days Base Temperature
      \units C
    N26; \field Cooling Degree Days

TYPICAL/EXTREME PERIODS,
    N1, \field Number of Typical/Extreme Periods
    A1, \field Typical/Extreme Period 1
    N2, \field Period 1 Start Date
    N3, \field Period 1 End Date
    A2, \field Typical/Extreme Period 2
    N4, \field Period 2 Start Date
    N5, \field Period 2 End Date
   --- etc ---

GROUND TEMPERATURES,
    N1, Number of Ground Temperature Depths
    N2, \field Ground Temperature Depth 1
       \units m
     N3, \field Depth 1 Soil Conductivity
       \units W/m-K,
     N4, \field Depth 1 Soil Density
       \units kg/m3
     N5, \field Depth 1 Soil Specific Heat
       \units J/kg-K,
     N6, \field Depth 1 January Average Ground Temperature
      \units C
     N7, \field Depth 1 February Average Ground Temperature
      \units C
     N8, \field Depth 1 March Average Ground Temperature
      \units C
     N9, \field Depth 1 April Average Ground Temperature
      \units C
     N10, \field Depth 1 May Average Ground Temperature
      \units C
     N11, \field Depth 1 June Average Ground Temperature
      \units C
     N12, \field Depth 1 July Average Ground Temperature
```

\units C
N13, \field Depth 1 August Average Ground Temperature
\units C
N14, \field Depth 1 September Average Ground Temperature
\units C
N15, \field Depth 1 October Average Ground Temperature
\units C
N16, \field Depth 1 November Average Ground Temperature
\units C
N17, \field Depth 1 December Average Ground Temperature
\units C
-- etc ---

HOLIDAYS/DAYLIGHT SAVINGS,
A1, \field LeapYear Observed
\type choice
\key Yes
\key No
\note Yes if Leap Year will be observed for this file
\note No if Leap Year days (29 Feb) should be ignored in this file
N2, \field Daylight Savings Start Day
N3, \field Daylight Savings End Day
N4, \field Number of Holiday definitions following
A2, \field Holiday 1 Name
N5, \field Holiday 1 Date
-- etc --

COMMENTS 1, A1; \field Comments 1]

COMMENTS 2, A1; \field Comments 2]

DATA PERIODS,
N1, \field Number of Data Periods
N2, \field Number of Records per hour
A1, \field Data Period 1 Name/Description
A2, \field Data Period 1 Start Day of Week
\type choice
\key Sunday
\key Monday
\key Tuesday
\key Wednesday
\key Thursday
\key Friday
\key Saturday
N3, \field Data Period 1 Start Date
N4, \field Data Period 1 End Date
-- etc --

! Actual data does not have a keyword
N1, \field Year
N2, \field Month
N3, \field Day
N4, \field Hour
N5, \field Minute
A1, \field Data Source and Uncertainty Flags
N6, \field Dry Bulb Temperature
\units C
N7, \field Dew Point Temperature
\units C
N8, \field Relative Humidity
N9, \field Atmospheric Station Pressure
\units Pa
N10, \field Extraterrestrial Horizontal Radiation
\units Wh/m2
N11, \field Extraterrestrial Direct Normal Radiation
\units Wh/m2
N12, \field Horizontal Infrared Radiation from Sky

```
  \units Wh/m2
N13, \field Global Horizontal Radiation
  \units Wh/m2
N14, \field Direct Normal Radiation
  \units Wh/m2
N15, \field Diffuse Horizontal Radiation
  \units Wh/m2
N16, \field Global Horizontal Illuminance
  \units lux
N17, \field Direct Normal Illuminance
  \units lux
N18, \field Diffuse Horizontal Illuminance
  \units lux
N19, \field Zenith Luminance
  \units Cd/m2
N20, \field Wind Direction
  \units degrees
N21, \field Wind Speed
  \units m/s
N22, \field Total Sky Cover
N23, \field Opaque Sky Cover
N24, \field Visibility
  \units km
N25, \field Ceiling Height
  \units m
N26, \field Present Weather Observation
N27, \field Present Weather Codes
N28, \field Precipitable Water
  \units mm
N29, \field Aerosol Optical Depth
  \units thousandths
N30, \field Snow Depth
  \units cm
N31; \field Days Since Last Snowfall
```

SAMPLE WEATHER FILE (first few lines)

```
LOCATION,Boulder,CO,United States,TMY2 94018,724699,40.02,-105.25,-7,1634
DESIGN CONDITIONS,header line 2 (design conditions)
TYPICAL/EXTREME PERIODS,0
GROUND TEMPERATURES,0
HOLIDAYS/DAYLIGHT SAVINGS,No,0,0,0
COMMENTS 1,Boulder CO weather data taken from TMY2 data
COMMENTS 2,
DATA PERIODS,1,1,TMY2 Year,Sunday,1,365
1970,01,01,01,60,B8E7B8B8?9?0?0?0?0?0?0B8B8B8B8?0?0F8F8A7E7,-7.0,-
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```

APPENDICES B – Introduction to WGAssociates and Solar Dish/Stirling Power System

INTRODUCTION TO

WGAssociates

and

SOLAR DISH/STIRLING

POWER SYSTEMS

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WGAssociates Product Description

1. INTRODUCTION

WGAssociates (WGA) is a small company incorporated in Texas as Wilkinson, Goldberg, and Associates, Inc. It was formed in 1983 to provide engineering services to government and to industry. From its inception WGA has been extensively engaged in the design and construction of solar concentrators with their attendant control systems, in both the thermal and photovoltaic arenas. As examples, WGA engineers designed two Test Bed Concentrators (11 Meter diameter dish solar collectors), as shown in Figure 1. These have been operating at Sandia for almost 20 years. The 25 kW_e faceted Stretched-Membrane Concentrator shown in Figure 2, was also designed and built for Sandia as part of their dish/Stirling program.

Figure 1 Test Bed Concentrator

Figure 2 Stretched-Membrane Concentrator

WGA designed and fabricated the high performance 25 kW_e glass-metal mirrored dish/Stirling concentrator for Cummins Power Generation (CPG) shown in Figure 3 with an Aisin Stirling Cycle engine installed. Recently, WGA completed design, fabrication, and installation of the WGA-500, a 10 kW_e glass-mirror surfaced dish/Stirling system for use in on-grid applications. This system, shown in Figure 4 was installed, tested, and is presently operating at Sandia Albuquerque. This design is presently being adapted for remote off-grid applications.

Figure 3 WGA-1500 25 kW_e Concentrator

Figure 4 WGA-500 10kW_e Collector

WGAssociates personnel are experienced in the design and construction of various types of antenna structures and control systems, including satellite communications, tropospheric scatter, radar, and radio telescopes up to 91 m (300 ft) in diameter. These structures were, for the most part, efficient, high strength-to-weight ratio space frames designed to meet exacting performance requirements under high wind loads and other adverse environmental conditions. The wealth of experience gained in the development of such antenna technology was, and is, directly transferable to the development of solar concentrators.

2. SOLAR COLLECTOR PRODUCTS

Currently WGAssociates has three principal Solar Collector products. These are:

1. A parabolic dish solar concentrator system, Model No. WGA-500, sized to produce 10 to 15 kWe of electrical power.
2. A parabolic dish solar concentrator system, Model No. WGA-1500, for electrical power production in the range of 30 to 45 kWe.
3. Collector control systems, Model No. WGA-CCS, for control and monitoring of solar collector systems.

Significant characteristics of these products are described in Section 3.

The Model WGA-1500 concentrator design is based on the earlier 25 kWe concentrators designed and built by WGA in 1995 and successfully tested by CPG. The structure design has been upgraded to reduce weight and cost. It has been successfully subjected to finite element analysis. The reflector panel fabrication methods have been considerably refined and made more cost effective. Samples made with the new fabrication methods have been tested both before and after accelerated life testing by Sandia National Laboratories with excellent results (end of life slope errors less than 1.5 milliradians). The CPG dish delivered 94% or the reflected energy into a focal plane aperture of 13 inches (0.33 meters) diameter as shown in Figure 5.

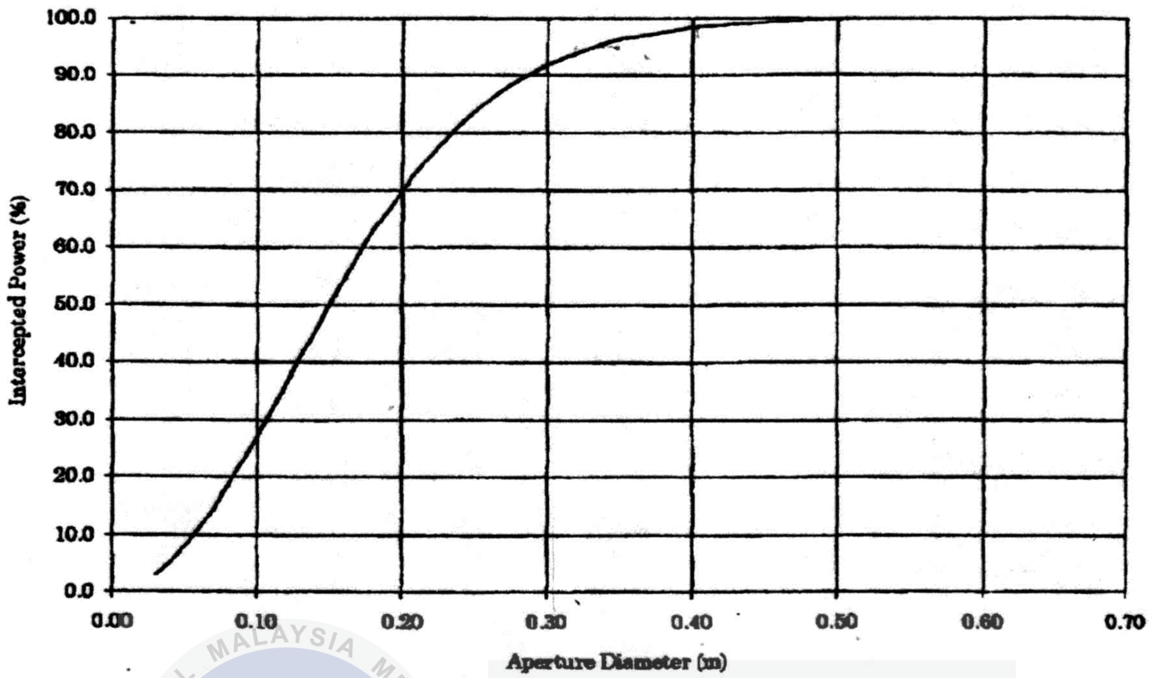

Figure 5 Power Intercept for the WGA-1500 Concentrator

The Model WGA-1500 concentrator is compatible with a number of existing Power Conversion Systems (PCS) including the Stirling Thermal Motors STM 4-120 Stirling Engine, United Stirling Motors USAB 4-95 Stirling Engine, and the Allied Signal Brayton Cycle Engine. All of these PCS's are capable of operating in a hybrid mode using solar energy when available or burning some form of fossil fuel or bio-gas in periods of no sun.

The design of the Model WGA-500 concentrator currently operating at Sandia is being upgraded for increased cost effectiveness and fabrication of two additional systems is currently under contract. The Model WGA-500 is designed for integration with the Schlaich Bergermann und Partner SOLO 161 Stirling Cycle PCS. The concentrator is, however, readily adaptable to other PCS units. The concentrator has demonstrated a high stiffness-to-weight ratio. The improved second generation mirror panels, as tested by the National Renewable Energy Laboratories (NREL), have a proven 1 milliradian RMS slope Error. As a result, the concentrator has extreme optical accuracy, delivering 100% of the reflected energy from the dish into a 6 inch diameter focal plane aperture (see Figure 6).

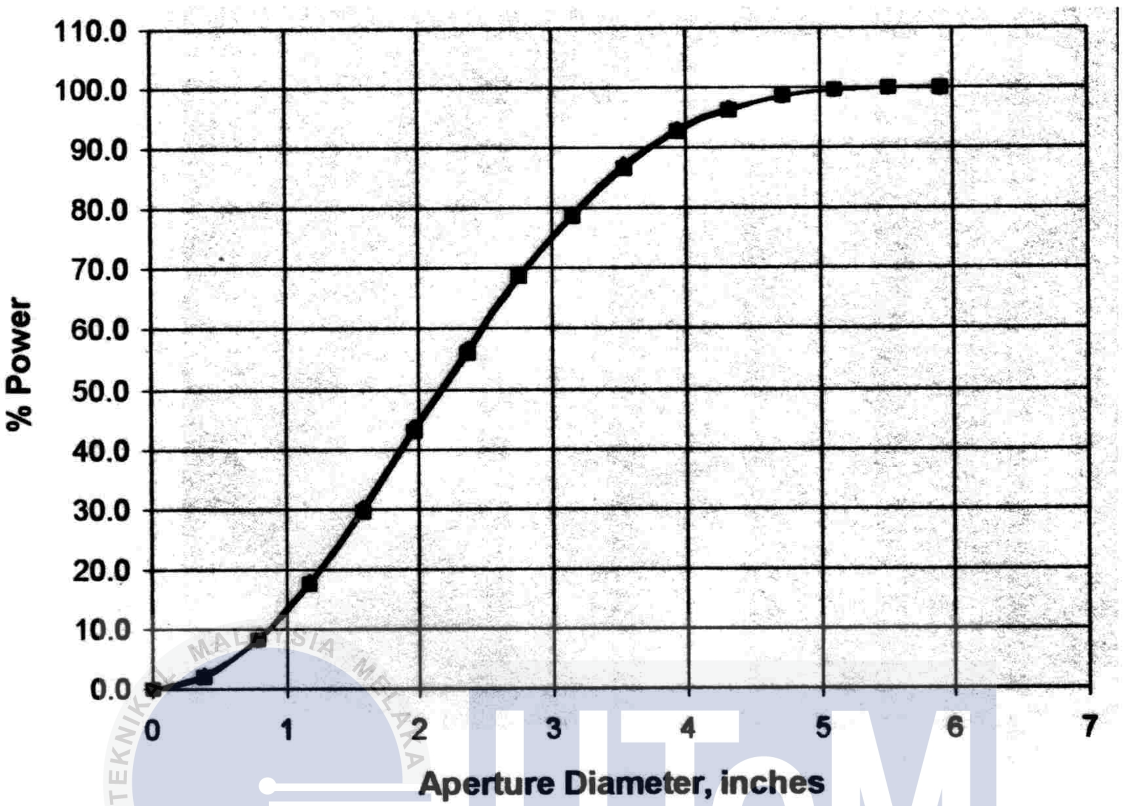

Figure 6 Power Intercept for the WGA-500 Concentrator

The WGA-CCS control system is an advanced design of a system that has operated successfully for some 15 years. It is a fully integrated system that includes off-the-shelf hardware operating with custom software, providing control and monitoring of a concentrator and a power conversion system. It provides unattended operation with automatic start-up, sun acquisition, sun tracking, shutdown, fail safe fault monitoring and response, etc. It provides tracking accuracy within 1 milliradian, rms. The system is described in greater detail below.

3. COLLECTOR FEATURES

The WGA dish/Stirling Collector Systems comprises three major sub-systems - the Concentrator System, the Power Conversion System (PCS), and the Collector Control System (CCS).

3.1. CONCENTRATORS

The WGA-1500 30 kW_e (nominal) concentrator is a second generation version of the successful 25 kW_e dish concentrator shown in Figure 3 above, originally designed and constructed for Cummins Power Generation, a division of Cummins Engine, Inc. The WGA-500, a 10 kW_e (nominal) concentrator, shown in Figure 4 above, employs similar technology to that used in the WGA-1500.

Both concentrators are paraboloidal point-focusing, full tracking dish concentrators in an elevation-over-azimuth axis arrangement. The concentrator designs are configured to meet the requirements of the commercial marketplace, in both power grid connected and remote (off-grid) applications.

Each concentrator consists of five major subassemblies - the tracking structure, the reflector surface, the base structure, the azimuth drive and the elevation drive.

The tracking structure for support of the reflector surface is a fully triangulated space frame constructed primarily of structurally efficient thin wall tubing. Virtually all joints are pinned to eliminate bending moments. The resulting assembly is lightweight and exhibits an extremely high stiffness-to-weight ratio.

In each concentrator, the dish is surfaced with an array of glass-metal composite mirror panels. Each panel consists of a 1-mm silver/glass mirror laminated to a thin-gage steel sheet, which is backed by a lightweight structural core and another thin steel sheet. The "sandwich" is fully bonded with structural adhesives. The completed panels exhibit extraordinarily low slope errors and high structural stability. The mirror panels, when installed on the tracking structure, are fully adjustable for alignment purposes.

The base structure, or pedestal, is made from standard pipe with welded flanges at both ends for integration with the foundation and the azimuth drive, respectively.

The tracking drives are sized to fit the specific load conditions for each concentrator. In each case the azimuth drive trains use a commercial, field-proven, planocentric gear reducer with a ratio of approximately 16,000:1. The elevation drive trains employ off-the-shelf ball screw linear actuators. The 10 kW concentrator is configured to allow the dish to depress in elevation to 25 degrees below horizontal for engine maintenance convenience. This option can be included readily in the 30 kWe dish.

Optical performance of these concentrators is significantly better than is possible with present stretched membrane reflectors. The WGA systems yield an intercept factor of better than 95%, leading to a net thermal efficiency of at least 89%. The concentrator design lends itself to low cost, conventional fabrication and installation processes.

The salient characteristics of the concentrators are shown below.

3.1.1 WGA-1500 CONCENTRATOR CHARACTERISTICS

Aperture Diameter	15.6 m (51.2 ft)
Focal Length	9.37 m (369 in)
Focal Ratio, f/d	0.6
Rim Angle	45°
Projected Area (Aperture)	140 m^2 (1510 ft^2)
Peak Concentration Ratio	>5000:1 at 1000 W/m^2 insolation
Reflector Surface Contour	Paraboloidal per $Y^2 = 4fZ$
Facet Construction	1-mm silvered glass mirrors bonded to a composite substrate of two thin steel sheets separated by a lightweight structural core
Reflectivity	94%
Slope Error	1.5 mrad, rms
Mirror Support Structure	Thin-wall tubular space frame
Tracking Axis Configuration	Elevation over Azimuth
Pedestal Configuration	Standard pipe, flanged both ends
Slew Rates	38 deg/min, each axis
Weight (less Engine)	
• On Elevation Axis	6,071 kg (13,357 lbs)
• Pedestal & Az Drive	1,727 kg (3,800 lbs)
Design Focal Point Load	909 kg (2,000 lbs)
Wind	
• Operating	15.6 m/sec (35 mph)
• Drive to Stow (Any dish Attitude)	24.6 m/sec (55 mph)
• Stow	40.2 m/sec (90 mph)
Thermal Output	123.8 kW_t at 1000W/m^2 insolation
Optical Efficiency	89%

3.1.2 WGA-500 CONCENTRATOR CHARACTERISTICS

Aperture Diameter	8.7 m (28.5 ft)
Focal Length	5.33 m (209.83 in)
Focal Ratio, f/d	0.6
Rim Angle	45°
Projected Area (Aperture)	43.5 m^2 (468 ft^2)
Peak Concentration Ratio	>11,000:1 at 1000 W/m^2 insolation
Reflector Surface Contour	Paraboloidal per $Y^2 = 4fZ$
Facet Construction	1-mm silvered glass mirrors bonded to a composite substrate of two thin steel sheets separated by a lightweight structural core
Reflectivity	94%
Slope Error	1.0 milliradian, rms
Mirror Support Structure	Thin-wall tubular space frame
Tracking Axis Configuration	Elevation over Azimuth
Pedestal Configuration	Standard pipe, flanged both ends
Slew Rates	38 deg/min, each axis
Weight (less Engine)	
• On Elevation Axis	1675 kg (3,686 lbs)
• Pedestal & Az Drive	546 kg (1,200 lbs)
Max Focal Point Load	546 kg (1,200 lbs)
Wind	
• Operating	15.6 m/sec (35 mph)
• Drive to Stow (Any dish Attitude)	24.6 m/sec (55 mph)
• Stow	40.2 m/sec (90 mph)
Thermal Output	41 kW_t at 1000W/m^2 insolation
Optical Efficiency	89%

3.2 - WGA-CCS COLLECTOR CONTROL SYSTEM

The WGA-CCS Collector Control System provides control and monitoring of a Concentrator and a Power Conversion System (receiver/engine/generator). It can also provide a power grid interface. Each Collector System possesses the intelligence for all aspects of normal operation, with a network data link used only for supervisory monitoring and control. It provides for unattended collector operation with automatic startup and shutdown. Sun tracking uses a hybrid approach consisting of both passive and active tracking. The use of active tracking allows for automated structural alignment error detection and correction and automated clock drift correction, while passive (program) tracking allows tracking of the sun during periods of cloud cover.

There are control system versions available for both power grid applications and for remote off-grid applications.

The control system uses an off-the-shelf industrial grade embedded PC single board computer and I/O cards. The software is written in the C++ language. Software is developed and debugged on a PC using standard PC based compilers and debuggers. The software can be readily adapted for different system configurations and to run with another vendor's embedded PC and/or I/O cards as hardware availability changes. The present C++ software has amassed over a hundred thousand hours of operation on solar collectors with great success.

A summary of significant characteristics of the WGA-CCS Collector Control System follows.

3.2.1 WGA-CCS COLLECTOR CONTROL SYSTEM FEATURES

Unattended operation:

- Automatic start-up, sun acquisition, and both passive and active sun tracking.
- Automatic control and monitoring of the engine/generator or the engine/generator controller.
- Automatic control of the power grid interface.
- Automatic stowing with excessive wind speed and/or end of day.
- Automatic escape from the sun when insufficient insolation exists and/or when automatically detected fault conditions (including power grid failure) exist.
- Automatic shutter, brake, alternative fuel control for collector systems so equipped.
- Automatic alignment error correction and controller clock drift correction.
- Automatic recovery from grid power failure or power down mode.
- Automatic performance data collection with download on-command.

Fully integrated, standalone control system:

- Integrated Control System concept features control cabinets located at each dish that connect to all sensors and actuators on that dish.
- Integrated engine/generator interface maximizes system performance.
- Integrated performance data acquisition enables recording of valuable operating data.

Well proven, fully automatic dish tracking control:

- Closed loop capture range of 10 to 20 milliradians allows for lower cost structures and structural alignment methods compared to traditional open loop tracking methods.
- Hybrid tracking methodology - clock time based calculations that determine the current location of the sun, with adjustments then being made to that position by the active sun tracking algorithms (closed loop tracking). Closed loop tracking is based on either Flux Tracking or on Insolation Tracking (User's choice).
- Tracking accuracy is better than 1.0 milliradian, rms, with a WGA concentrator.
- Automated Self-Alignment uses tracking error analysis to measure and correct for all critical dish mounting alignment errors and clock time errors to insure calculated positioning stays within the closed loop capture range.
- Automatic fault monitoring and controlling an appropriate response.
- Readily adapted to any concentrator axis system (Az/El, Polar, Roll/Tilt, etc.) with capability for major deviations from normal coordinates. For example, a polar mount designed for 45° latitude can be used effectively at 30° latitude.

Built in monitoring and control:

- Monitoring and control capability provided remotely via dial-up modem, the Internet, and a local network connected to a PC.
- Local monitoring capability provided by a hand held input and display unit.
- Remote downloading of system software into nonvolatile Flash EPROM memory.
- Networking allows sharing of sensors such as high wind speed sensors in a multiple unit field or solar farm application.

User friendly interfaces:

- Menu driven handheld terminal control and monitoring.
- Command line driven mode for extensive technician diagnostics.
- DOS and WINDOWS based PC remote user interfaces.

Hardware Implementation:

- Contained in a weather-proof enclosure to be installed at the concentrator.
- Operates on either 50 or 60 Hz.
- Optional transformer to match engine/generator output voltage to power grid voltage.
- Utilizes off-the-shelf, industrial temperature range components.
- Computer with both digital and analog I/O is an embedded PC compatible platform with a PC/104 bus for expansion capability.
- Concentrator Axis Drive Motors may be either AC or DC.
- Position Sensors - Solid state Hall Effect sensors are magnetically actuated.
- Flux Tracking Sensors, if used - Four high temperature thermocouples (1/4" dia., Type K or N) mounted around the engine receiver aperture.
- Insolation Tracking, if used - photovoltaic cells in a shadow box mounted on the concentrator structure.