Thermal output analysis of a designed parabolic trough solar field for moderate temperature industrial load

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Abstract—This paper presents an overview of the Parabolic Trough Solar Collectors, which is a fastest growing technology amongst concentrated solar power technologies. It is largely being used in developed countries; mainly in steam power cycles for electricity generation but its use is not limited to electric power generation. This technology is also being used for many other applications like refrigeration and air-conditioning, desalination of sea water, pumping of irrigation water and many other heating applications for process industry. Though this technology is already being used in many developed countries but there is barely any development in Malaysia. There is thus need for assessment of this technology to explore the potential industrial applications, under local environmental conditions. In this article basic design and development considerations for a parabolic trough collector system have been discussed. This paper also includes a thermal output analysis of a designed parabolic trough solar field to provide the baseline information for industrial applications feasibility study. System Advisor Model (SAM) has been used for this analysis, under environmental conditions of Ipoh, Malaysia. The results of simulation indicate that considerable amount of high temperature thermal energy can be obtained. The heat transfer fluid temperature reached up to 200 to 230°C, which can be used to operate an unfired boiler to produce steam or in some other industrial thermal application.

***Keywords*—**Solar Thermal Energy Utilization; Concentrated Solar Power; Parabolic Trough Collectors; Process Heating; Malaysian Climate

I. INTRODUCTION

Solar energy is the most abundantly available source of sustainable energy with a potential of satisfying future energy needs, in environment friendly way. Therefore, utilization of solar energy has got prime importance to mitigate with environmental challenges and energy scarcity scenario. Parabolic Trough Solar Collector is one of the most reliable concentrated solar power technologies. This technology has many applications but the most common is steam power cycles for electricity generation.

Parabolic Trough Collector (PTC) is actually a type of solar concentrators, used to produce high temperature thermal energy. A solar concentrator captures sunlight over a large aperture area and concentrates this energy onto a much small absorber area, multiplying intensity of the solar radiation by a concentration ratio in the range of 10–80 (for parabolic trough collectors) [1]. But to achieve such concentration, a concentrator needs to track the sun throughout the day.

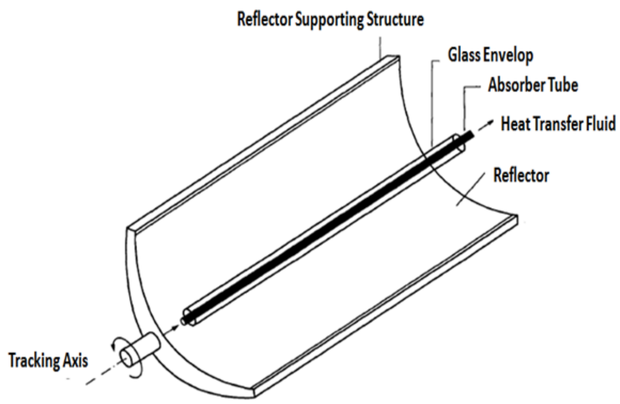

Fig 1: Schematic of a Parabolic Trough Collector [15]

A Parabolic Trough Solar Collector is a one-dimensional parabola that focuses solar beam radiation onto a line. Physically, this line is a tube (absorber) with a flowing liquid inside. The reflected radiation is absorbed and transmits heat to the liquid through the tube wall. The tube is jacketed with glass to prevent the convection loses. Primarily, a heat transfer fluid is heated by passing it through the concentrator's absorber tube and then this heated fluid exchanges absorbed heat with some thermal load, mostly with water for steam generation.

Though this technology is already developed and being used in many developed countries but there is barely any development in Malaysia (or tropical regions). There is thus need for assessment of this technology to explore the potential industrial applications, under the local environmental conditions.

The main objective of this research work is to perform thermal output analysis of a designed parabolic trough solar field for medium temperature loads, by using local environmental data. The results can further be used as feed for feasibility study of local industrial applications.

II. COMPARISON WITH OTHER TECHNOLOGIES

Basic philosophy behind development of all renewable energy technologies is to produce low cost energy while preserving the climate and natural resources (or) to produce energy from a renewable source with minimal impact on environment. Utilization of solar energy best qualify for this purpose. Acidification and Global warming potential are the key environmental impact indicators for power generation systems.

Actually, acidification is a process in which compounds like ammonia, nitrogen oxides and sulphur dioxides are converted into acidic substances that are harmful for environment, through a chemical reaction. Whereas, global warming is increase in atmospheric temperature due to gaseous emissions, having high heat capacity.

Figure; 2 presents the global warming and acidification potential for different power generation systems and Concentrated Solar Power is one of the technologies having least footprints.

In addition to environmental aspects, Parabolic Trough Collector is one of most successful technologies for solar energy utilization. Its high reliability, operational compatibility, comparative low cost and high efficiency adds to its high value among other technologies [2].

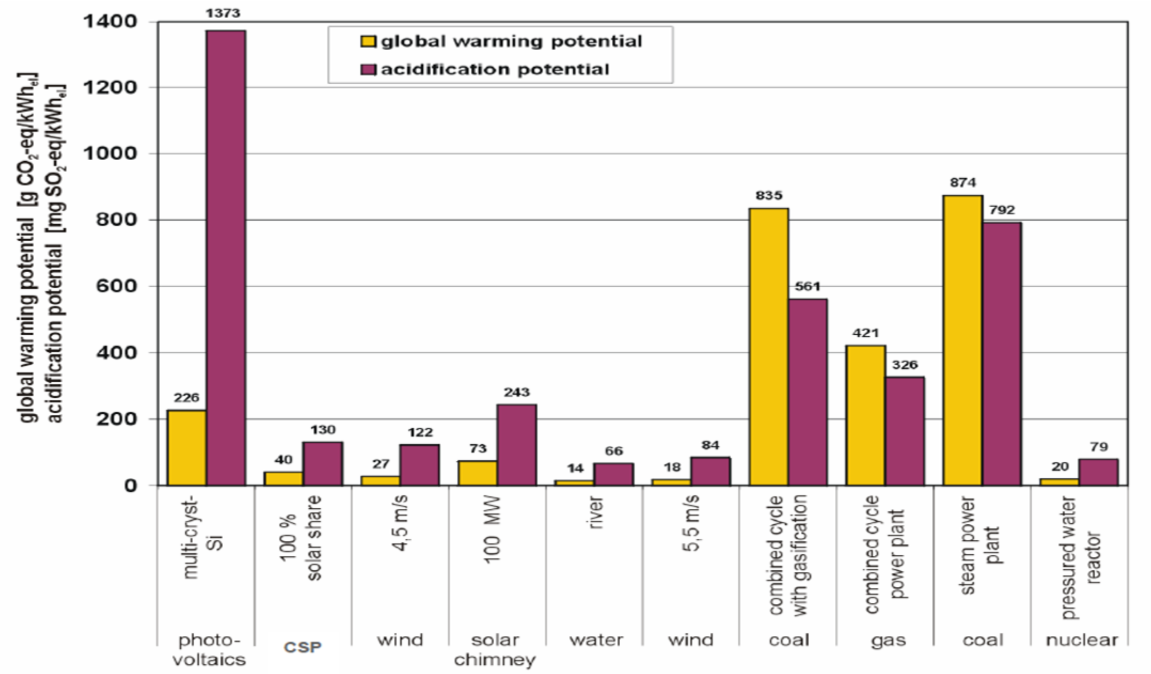

Fig 2: Environmental impacts of different power generation technologies [16]

A. Comparison with Photo-Voltaic Technology

Both Photo-Voltaic (PV) and Concentrated Solar Power (CSP) technologies are being used to generate electricity by utilizing solar energy, but CPS have some advantages that make this technology more reliable.

Solar energy is available only in day time but energy demand is for 24 hours a day. So, energy storage provides an option to increase grid reliability and there are many storage options available. The main difference between Concentrated Solar Power and Photo-Voltaic systems is energy storage efficiency. Heat storage is a far easier and efficient method compared to electrical energy storage. The ability of CSP to utilize high-efficiency Thermal Energy Storage systems makes this technology more attractive for large-scale energy production. The addition of thermal energy storage enables CSP systems to supply stored thermal energy during cloudy weather or at night, which eventually increases the reliability of the grid [3].

Concentrated Solar Power systems can also be used in direct applications where heat energy is required; on the other hand in Photo-Voltaic system electric energy need to be converted to thermal energy for such thermal applications that make the system less efficient.

B. Comparison with other Solar Thermal Technologies

Parabolic Trough Collector system is the most successful industry-scale solar energy utilization technology available today. It is because of high reliability, operational compatibility, low cost (comparatively) and high efficiency. There are many developed technologies that convert solar energy into high temperature heat energy, which further converted to electrical energy through steam power cycle. Solar-to-electricity conversion efficiencies of different Concentrated Solar Power technologies are shown in Table; 1

TABLE I. EFFICIENCIES OF CSP SYSTEMS [4]

Technology	***Peak Solar to Electricity conversion Efficiency %***	***Annual Solar to Electricity Efficiency %***
Parabolic Trough	23 – 27	15 – 16
Linear Fresnel System	18 – 22	8 – 10
Solar Tower (Central Receiver System)	20 – 27	15 – 17
Parabolic Dish	20 – 30	20 - 25

It is not only efficiency that matters in adopting a technology but cost, operational complexity and flexibility are also evenly important. Distinguishing between parabolic trough, linear fresnel, solar tower and parabolic dish systems, 94% of installed solar power plants are based on parabolic trough systems, with an overall capacity of around 1.8 GW till March 2012[5]. Rest all has a share of only 6%. The proportion of parabolic trough system in under construction plants is almost the same.

III. Potential Applications

Parabolic Trough Collector system is used in a variety of applications which can be classified into two main categories, concentrated solar (electrical) power and solar thermal applications [6].

The first category is most common, most of the commercial concentrated solar power (CSP) plants are working on parabolic trough collector system. Normally operating temperatures in parabolic trough CSP plants are between 300 to 400 ^{o}C. To achieve these temperatures aperture widths vary between 6 to 9m, trough lengths are between 100 to 150m and geometrical concentration ratios are between 20 and 30 [7].

The second category of applications requires temperatures between 100 and 250 ^{o}C. These applications are mostly moderate-temperature applications with high consumption rates. Typical aperture widths are between 1 to 3m, trough lengths vary between 2 and 10m and geometrical concentration ratios are between 15 and 20 [7] .

If we look into energy consumption of typical process industries, 45–65%, of energy is used for heating applications below 300 ^{o}C, and 37.2% of these process heating applications are in the range of 92–204 ^{o}C [8].

Following are some of the proven applications of parabolic trough collector system [7] [9] [10].

- Unfired boilers for steam generation
- industrial heating applications
- Domestic hot water and space heating
- Air-conditioning and refrigeration
- Pumping irrigation water
- Desalination of sea water

IV. Solar Radiation Data For Ipoh, Malaysia

In this study Ipoh city weather data is used. The metrological data contain 5 (five) parameters, recorded hourly for whole year. The parameters are solar radiation, ambient temperature, relative humidity, speed and direction of the wind. In solar concentrators only beam solar radiations are considered but in available metrological data global solar radiation data is provided, which is sum of diffused and beam radiation.

In 2011, Mr. Dimas Firmanda Al Riza et al. calculated beam and diffused radiation for Ipoh by developing the correlation between RH, clearness index and beam transmittance[11], [12].These calculated values of solar radiations have been used in this study.

V. Simulation For Small industrail Unit

In this study System Advisor Model (SAM) [13] software has been used for thermal analysis of a designed parabolic collector system. SAM's parabolic trough performance model is implementation of a TRNSYS based model. SAM offers two models for performance evaluation, Empirical Trough Model and Physical Trough Model. The physical trough model is based on principles of heat transfer and thermodynamics. On the other hand empirical values of some experimental measurements are used in the empirical trough system model. Physical model is more flexible than the empirical model [14].

Both trough performance models consist of three modules. Each module calculates energy output value based on the relevant parameters [14].

- The solar field module calculates the solar field thermal output.
- The storage and dispatch module calculates energy flow into the thermal energy storage system and thermal energy delivered to the power block
- The power block module calculates the system's net electric output.

In this study Physical Trough Model is used and only thermal output of a designed solar field is analyzed.

A. Design Details

The purpose of this study is to evaluate the performance of a parabolic trough collector system for moderate temperature (180-230 ^{o}C) industrial heating applications. First step for designing the collector is selection ideal concentration ratio for desired operating temperature.

There is no experimental data available for calculation of an ideal concentration ratio to meet our desired operating temperature, under local environmental conditions. However, the optimum concentration ratio curves are available for various operating temperatures [9], under different environmental conditions. On the basis of difference in beam radiation data the concentration ratio value is calculated by extrapolation (Concentration Ratio =20).

The diameter of absorber tube is important in defining concentration ratio for collectors. The smallest diameter of commercially available solar evacuated solar tube is 40 mm. For selecting aperture length, the absorber tube diameter and operability are considered. So, to achieve the desired concentration ratio 2.6 m aperture width is selected.

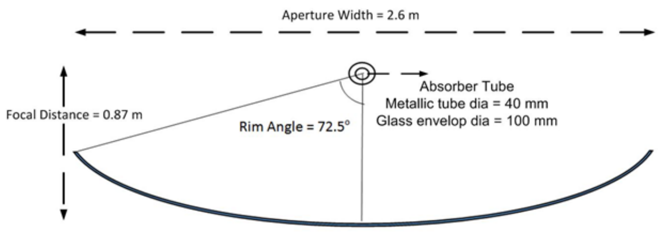

Fig 3: Geometry of the Parabolic Trough Collector

The geometry and optimum size (dimensions) of trough have been decided by considering operational and manufacturing constrains. The dimensions of designed Parabolic Trough Solar collector are shown in Figure; 3. Solar field has five modules of 6 m long troughs. These troughs are connected to make a 30 m long assembly, to be operated in single loop.

B. Simulation Inputs

The solar field is designed to measure the thermal output for process heat loads. The simulated system is based on Heat Transfer Fluid (HTF) cycle, without thermal energy storage. It is assumed that the high temperature HTF delivers the absorbed heat to an unfired boiler producing saturated steam at 5 bar. Therminol VP-1 is used as Heat Transfer Fluid.

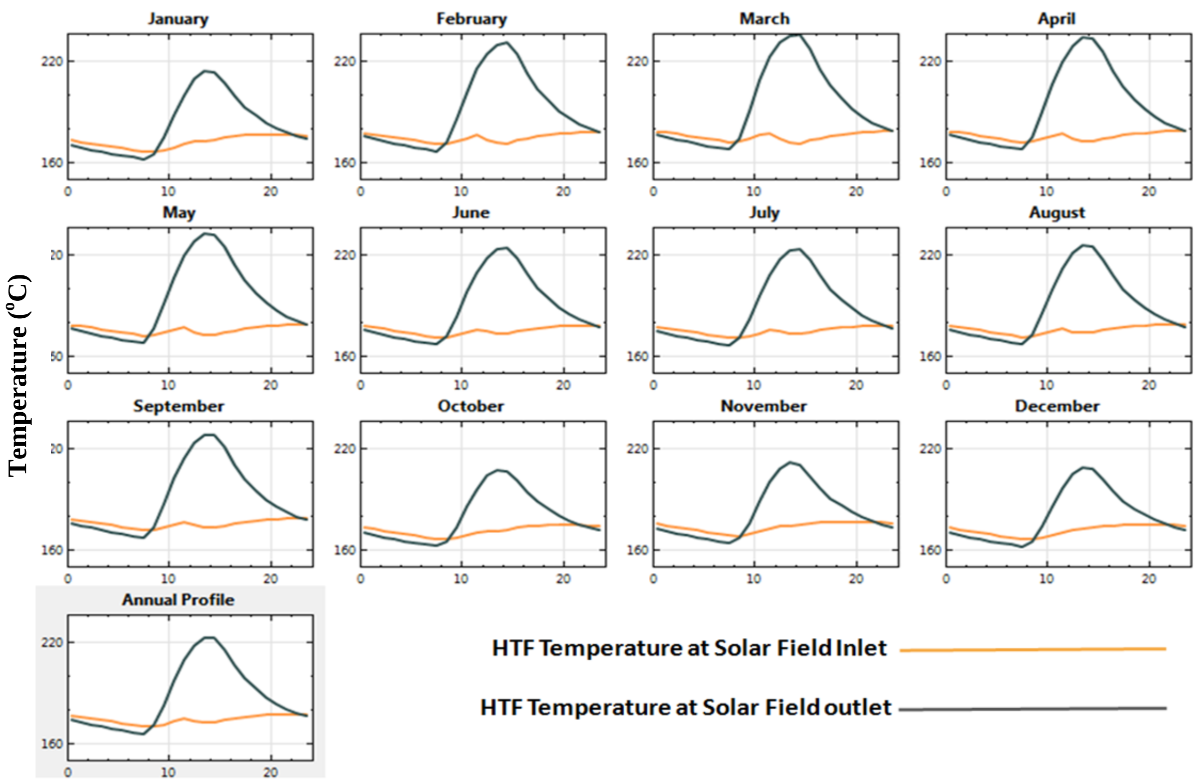

Fig 4: Average daily HTF temperature profile (time of the day along x-axis and HTF temperatures along y-axis)

The first input required is weather file for specific location. The key constituents of this data file are site geographical coordinates, hourly wet and dry bulb temperatures, beam and diffused radiations, wind speed and direction.

The optical performance of a parabolic trough collector mainly depends on the reflectance of mirror material and absorptance of absorber tube. 0.91 and 0.96 are the values of reflectance and absorptance used in simulation, respectively. The stow angle (angle that trough have to track in one day) is kept 160°. Total solar field aperture is 78 m^2. The maximum operating temperature of heat transfer fluid is set to 250 °C.

C. Results

The solar field's yearly average thermal energy output is 60 KWh per day, which can be delivered to some thermal load of moderate temperature. Figure 4 shows the simulated results of heat transfer fluid temperatures at solar field inlet and outlet against the daily time. The temperature profiles are based on monthly and yearly average values. March, April and May are the most efficient months for operation, HTF solar field outlet temperature reaches to 240^{o}C in peak sun hours. The yearly average HTF solar field outlet temperature in peak sun hours is around 220^{o}C.

A similar pattern has been observed in simulated values of monthly thermal energy output of solar field. Figure; 5 presents the monthly values of thermal power produced. In March, April and May solar field have highest thermal energy output. The thermal output is very low in months of October, November, December and January; it is because of high cloudy/rainy days.

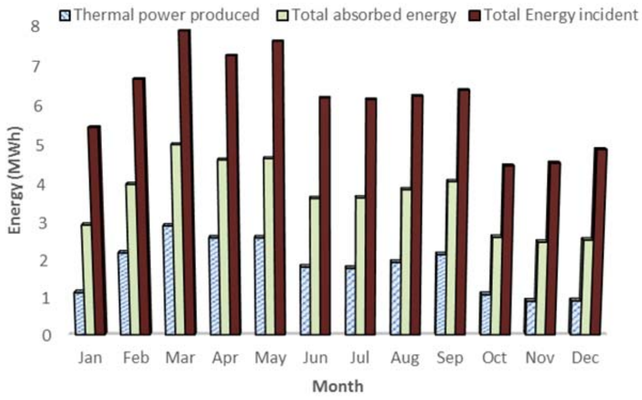

Fig 5: Monthly Energy Profiles

Figure; 6 presents the monthly average Optical and thermal efficiencies of solar field. Solar field has peak efficiency in March and in months of October, November, December and January the thermal efficiency is very low.

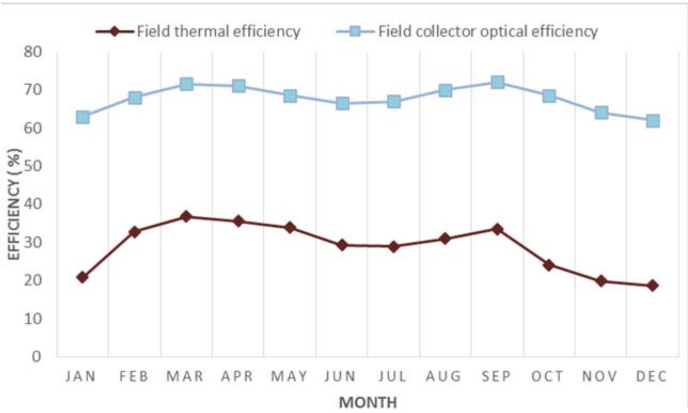

Fig 6: Monthly Solar Field Efficiency Profiles

VI. Conclusion

The focus on using parabolic trough solar systems for delivering heat energy to the industrial thermal loads is not only because of a huge amount of energy is consumed in industrial heating applications, but also for reduction in industrial emissions produced by the fossil fuel burning.

Though this study is performed on a tropical climate area with high number of cloudy/rainy days but on the basis of simulation results, the author believes that a huge potential is available for utilizing solar energy for moderate temperature industrial applications. However, it is not worth depending solely on solar energy due to the high percentage of inactive time. The combination of (PTC) solar with conventional fuel system can significantly contribute in reduction of conventional fuel usage and addition of thermal energy storage can add to its value even more.

Unfired boiler appears to be the best option for transporting and delivering the solar thermal energy to industrial loads, by transferring the absorbed solar energy (heat) to water to produce steam. This system can produce steam of 150 to 170 ^{o}C, which can be used in different process industries like; textile, food processing, tanneries, pulp & paper etc. This steam can also be used to operate steam driven water pumps for irrigation purpose.

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