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A SIMPLIFIED DESIGN PROCEDURE OF PARABOLIC TROUGH SOLAR FIELD FOR INDUSTRIAL HEATING APPLICATIONS

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ABSTRACT

This paper presents a stepwise approach for designing a Parabolic Trough Solar Collector system, which is the fastest growing technology amongst concentrated solar power technologies. This technology is mainly being used for electricity generation by steam power cycles, but there is huge potential for this technology to be used in industrial heating applications. Though this technology is already developed and successfully been used in many developed countries, but there is barely any development in Malaysia. The performance of parabolic trough collector system is highly dependent on geographic location and meteorological conditions. A parabolic trough solar heating system has been designed and simulated using meteorological data of Ipoh, Malaysia. Thermal performance of the designed system was evaluated for fixed load and without thermal energy storage. A unique set of conditions is required for designing the PTC system but the solar radiation and incident angle changes throughout the year. So, setting appropriate design point conditions is crucial in designing of PTC system. The effect of field size on capacity factor and dumped energy is also explained, using the concept of solar multiple. It was noted that increase in field size have very little impact on capacity factor for solar multiple values higher than 2. This study was conducted for solar-only system without thermal energy storage which resulted low annual capacity factor. So, it is not worth depending solely on solar energy, combination of solar with conventional fuel system can significantly contribute in reduction of fuel usage also the addition of thermal energy storage can add to its value even more.

Keywords: parabolic trough collectors, design point conditions, solar multiple, process heating, Malaysian climate.

INTRODUCTION

Basically, the sun is the ultimate source of energy for every life on earth and even fossil fuels including oil, coal and natural gas in a manner stores of solar energy, formed from the bodies of organisms that lived millions of years ago [1]. But direct utilization of solar energy got prime importance as it is the most abundantly available source of sustainable energy with no bad impacts on environment.

Solar energy has been used in a variety of applications which can be classified into two major categories: solar thermal applications and solar electrical power applications [2]. Many technologies have been developed for utilization of solar energy. This article focuses on Parabolic Trough Collector technology which is amongst the most successful thermal energy utilization technologies.

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 receiver area, multiplying intensity of the solar radiation by a concentration ratio in the range of 10–80 (for parabolic trough collectors) [3]. However, to achieve such concentration, a trough tracks the sun continually throughout the day.

Parabolic trough collectors are made by bending a sheet of reflective material into a parabolic shape. A metallic tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the collector (Figure 1). The concentrated radiation reaching the receiver tube heats the fluid that circulates through it, thus transforming the solar radiation into useful heat [4]. This high temperature heat energy produced in receiver can further be used to produce steam or for other thermal applications.

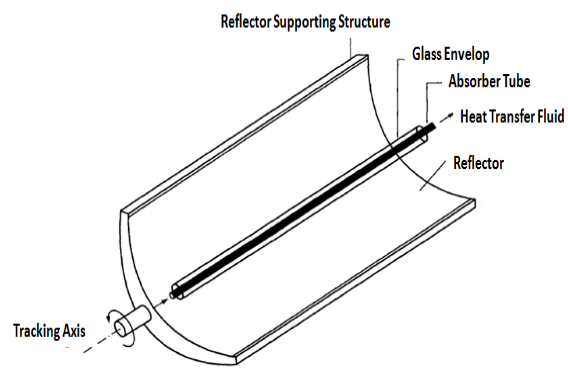

Figure-1. Schematic of a parabolic trough collector [17].

The main objective of this research work is to develop a simplified design procedure of a parabolic trough solar field for a specific thermal load. Thermal output patterns of designed solar field, under local environmental conditions, have been obtained through simulation using System Advisor Model (SAM). These patterns were used for parametric optimization of designed parabolic trough solar field. These results can further be used as baseline for feasibility study of local industrial applications.

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Process heating applications

Parabolic Trough Collector applications can be distinguished in two major groups. The first and most common is Concentrated Solar Power (CSP) plants. There are currently several commercial CPS plants are working around the world. 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 [5].

The second group 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 to 10m and geometrical concentrating ratios are between 15 and 20[5].

There is a great potential of solar thermal energy utilization In Process Heating Applications. For typical process industries, 45–65%, of energy is used for heating applications below 300 ^{0}C, and 37.2% of these process heating applications are in the range of 92–204 ^{0}C [5]. Figure 2 presents a thermal energy and temperature requirements of typical process industry.

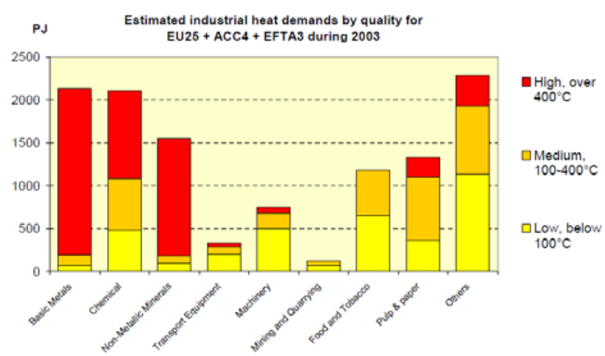

Figure-2. Heat energy requirements / industry wise [18].

DESIGN OF PTC HEATING SYSTEM

A stepwise approach has been adopted to design the Parabolic Trough Collector heating system. The design steps are mapped in Figure-3, following the explanation of important steps.

Establishment of design load basis

This system was aimed to provide heat for process industry heating applications. As discussed above the significant portion of heating applications lies between 92 – 200 ^{o}C, for typical process industries (like foods processing, textile, paper and pulp etc). So operating temperature of heat transfer fluid (HTF) for the parabolic trough collector system was set to 200 ^{o}C. The HTF will deliver 25 KW heat operate an unfired boiler to produce steam at 5 bar.

Selection of design point conditions

Performance of a parabolic trough collector solar field is evaluated for a set of conditions and geographical location, these set of conditions are known as Design Point Conditions.

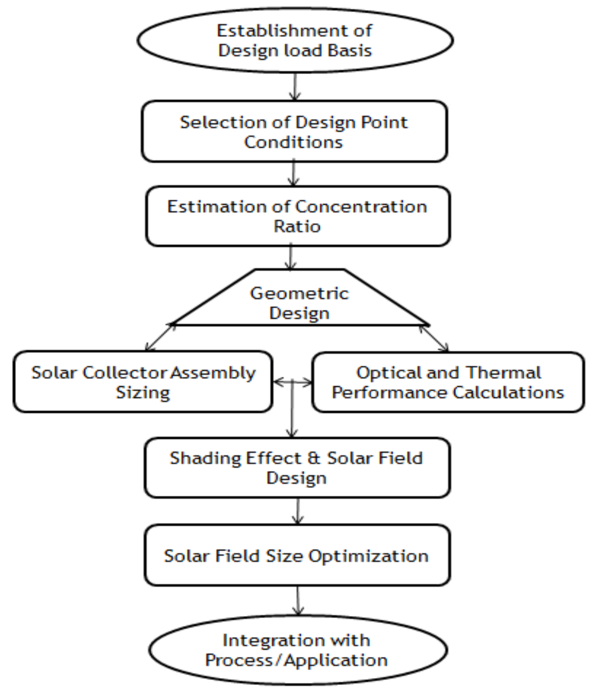

Figure-3. Design steps for PTC solar field.

Many studies on the design, analysis and optimization of PTC systems are available, but no clear criteria has been defined with consensus, for the choice of design point conditions [6]. It is mainly because of great diversity of meteorological data across the globe.

In our case the most crucial design point parameter is direct normal irradiance (DNI). On analysis of metrological data of Ipoh, Malaysia it was found that DNI value ranges from 0 to 855 W/m^2 [7]. The goal of this step is to carefully set a suitable DNI value that can predict the entire year performance. In 2013 Wirz *et al.* compared PTC field efficiencies, calculated at different design points DNI, with yearly average efficiencies (simulated). He concluded that design point determined through the weighted average of effective DNI yield results that agree very well with the yearly average efficiency values [6].

Since a minimum solar power input is necessary to run a CSP plant, values with a DNI below 250 W/m^2 are not considered. The weighted average of DNI data above 250 W/m^2 is 475 W/m^2, which is also the design point value of DNI for our system.

Estimation of concentration ratio

First step in 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 [8], under different environmental conditions. On the basis of

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difference in beam radiation data the concentration ratio value can be calculated by extrapolation, which resulted to 21 for operating temperature 200 ºC.

Geometric design, sizing and performance

The diameter of absorber tube is important in defining concentration ratio. The smallest diameter of commercially available solar evacuated solar tube is 40 mm. So, to achieve the desired concentration ratio 2.6 m aperture width is required.

Next geometry defining parameter for parabolic trough collector is the rim angle. A small rim angle makes relatively flat trough but with a longer focal length [9]. Normally the rim angle ranges from 70-115º. The higher rim angles require more reflecting surface for same aperture area, consequently increased cost and weight of collector. There are many factors need to be considered while selecting a rim angle but the most important is concentration ratio, Higher concentration ratios need larger rim angles [10]. The value of rim angle was selected 72.5º after considering the key parameters.

After geometric design, size (dimensions) selection of PTC assembly is important. Ideal size of assembly was decided by considering operational and manufacturing constrains. The dimensions of designed Parabolic Trough Solar collector are shown in Figure-4.

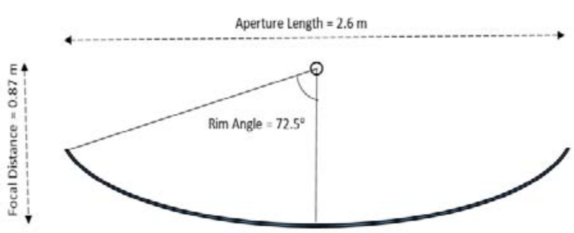

Figure-4. Geometry of designed parabolic trough.

The geometry and dimensions of PTC assembly significantly affect the thermal and optical performance of solar field. So these three steps are interlinked and simultaneously completed. The overall efficiency of a parabolic trough collector depends on optical and thermal performances.

Optical performance depends on the fraction of solar radiation absorbed per unit area of un-shaded aperture (S), which can be calculated by equation 01 [3]

$$S=I_b\rho(\gamma\tau\alpha)\,K_{\gamma\tau\alpha} \tag{1}$$

Where I_b is effective incident beam radiation on the plane of aperture, ρ is the reflectance of the collector, γ is intercept factor, τ is transmittance, and α is absorptance. $K_{\gamma\tau\alpha}$ is an incidence angle modifier.

Whereas thermal performance of collector can be calculated by the actual useful energy gain per unit area (Q_u), given by equation 02 [3].

$$Q_u = A_a F_R\left(S - \frac{A_r U_L}{A_a}\left(T_i - T_a\right)\right) \tag{2}$$

Where A_a is the un-shaded area of the collector aperture and A_r is the area of the receiver, S is the absorbed solar radiation per unit of aperture area, T_i and T_a are inlet fluid temperature and ambient temperature F_R is the collector heat removal factor.

Solar field design

Two field orientations are common in PTC field design one is east-west mounting and this orientation does not require continuous tracking. Other orientation is south-north mounting and trough will track sun from east to west throughout the day [3]. South-North mounting orientation is more efficient and was chosen for this system.

In designing the south-north parabolic trough solar field the row spacing got prime importance. This is because the shading effect of each trough row on next trough is dependent on spacing between the rows.

Figure-5 shows the aperture planes of two successive rows placed at p distance apart when seen along their axis

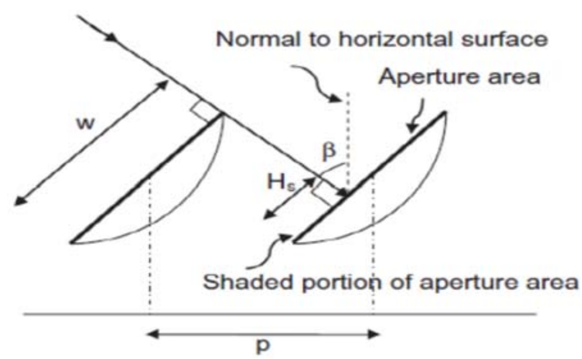

Figure-5. Shading effect of successive rows [11].

of rotation. Height of the shadow cast by one row on the other at any time can be calculated by Equation 3 [11].

$$H_s = \left[w - p\cos\beta\right]^+ \tag{3}$$

Figure-6 presents the effect of row spacing on shading for designed PTC dimensions. The spacing between consecutive troughs was calculated on the base of zero shading for daily eight hours of operation (four hours on both side of solar noon). The distance between the rotation centers of consecutive trough was set to be 5 m.

The next important consideration is heat transfer fluid selection and design of circulation system. HTF operating temperature, pressure drop, heat and pressure losses are some of the important aspects at this stage. In the designed

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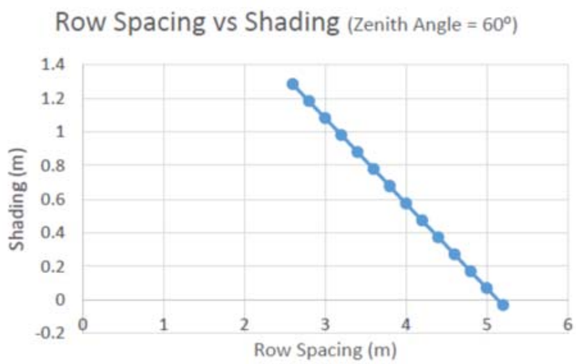

Figure-6. Shading effect of successive rows.

system Therminol VP I was used as heat transfer fluid and all the troughs were connected in series (single loop).

Solar field sizing

Correctly deciding solar field size is very important for the success of system. A very large field size will result excessive useless thermal energy (to be dumped or defocus) under high solar irradiance values whereas, a small field will not be able to produce sufficient thermal energy [12]. The aim is to select optimum solar field size for a solar-only parabolic trough collector field, using neither hybridization nor thermal storage. Two methods have been used for the solar field.

One method for sizing a field is to calculate the field area at maximum value of solar irradiance, commonly fixed on the 21st June at solar noon. This will give the solar field area at Solar Multiple =1. Solar multiple (SM) is defined as the ratio of the actual aperture area of the mirrors to the reference mirror aperture area [13]. As the field design point solar irradiance is annual maximum value so at SM=1 the field will be able to provide full thermal load for very short interval hence shall result in low annual capacity factor. Whereas, the greater values of SM will increase the annual capacity factor but will cause the more energy wastage (dumped or defocus). After analyzing the effect of SM on annual capacity factor and wasted energy, an optimum field size can be selected.

The second method of field sizing is to calculate the field area on the basis of weighted average of effective irradiance (the geometric design point). The simulation results of both methods are presented in next section.

Integration with load application

Integration with the application is also an important step in solar thermal energy utilization system. Depending on application, hybridization and storage can add value to the system. As mentioned earlier this system was designed on solar-only basis and without storage. The heat energy absorbed by the field was delivered to operate an unfired boiler to produce steam at 5 bar.

SIMULATION

In this study System Advisor Model (SAM) [14] software has been used for thermal analysis of a designed parabolic collector system. SAM's parabolic trough performance model is 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 [15].

Both trough performance models consist of three modules. Each module calculates energy output value based on the relevant parameters [15].

- 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.

Simulation inputs

The solar field is designed to measure the thermal output for different field sizes. 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 steam at 5 bar. Therminol VP-1 is used as Heat Transfer Fluid.

The first input required is weather data 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 [16].

The optical performance of a parabolic trough collector mainly depends on the reflectance of mirror material and absorptance of absorber tube. 0.65 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 170°.

Simulation results

The simulation was run for different solar field areas calculated on basis of solar multiple. For maximum annual irradiance (SM=1), four trough assemblies were required. For every increment of 0.25 in solar multiple one trough assembly was added to the system. Figure-7 represents the effect of solar multiple on critical parameters.

Figure-7 shows that as we increase the solar multiple, thermal energy production and utilization got increased, meanwhile the amount of wasted (dumped)

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energy also increased. Initially the energy utilization increased rapidly

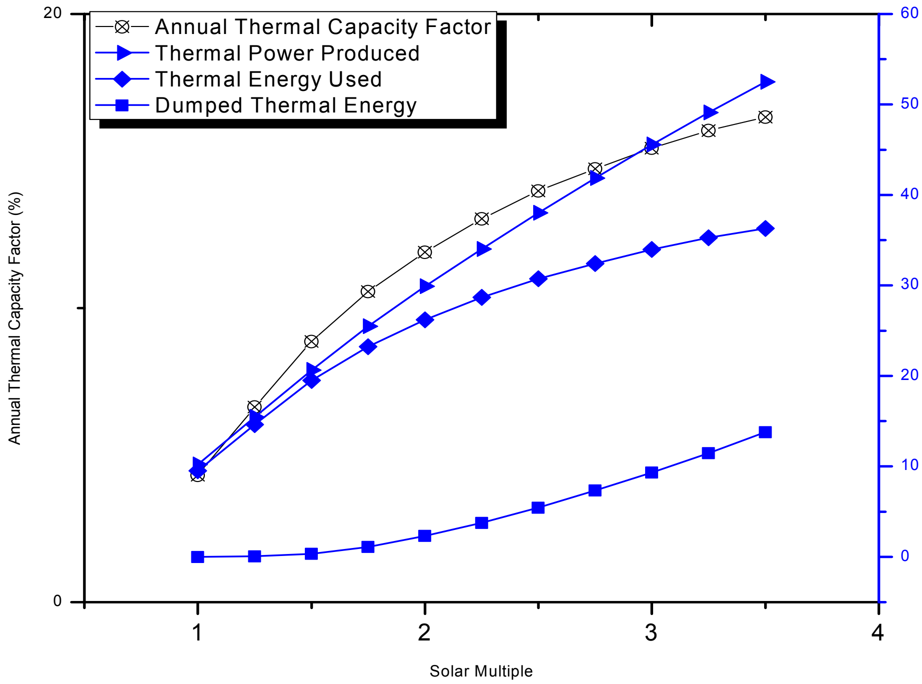
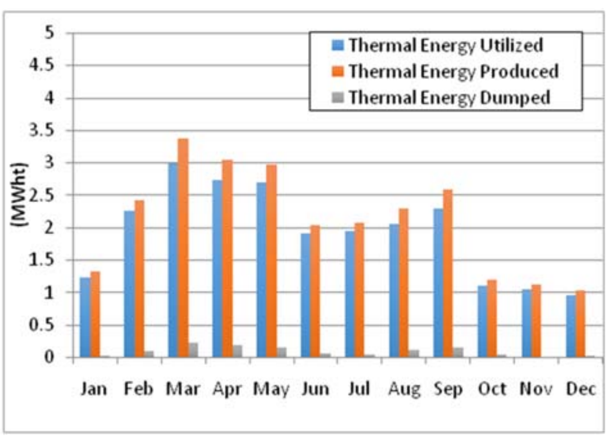
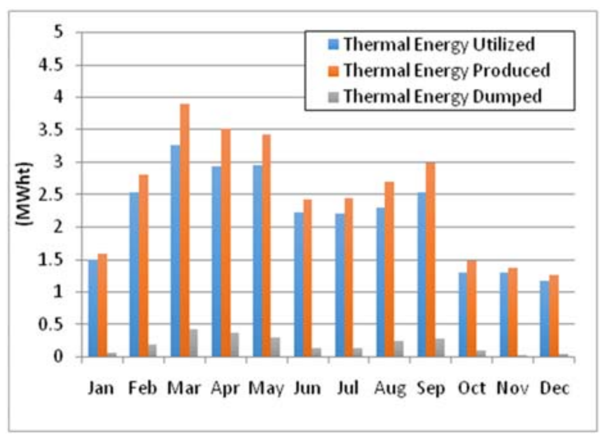


Figure-7. Effect of solar multiple on critical parameters.

with every 0.25 increment in solar multiple but after solar multiple value reaches to 2, the increment effect on energy utilization became very minor. On the other hand, the dumped energy started increasing rapidly after SM=2. The annual thermal capacity factor is defined as the ratio of energy utilized to the annual load requirement based on 24



a) SM = 1.75



b) SM = 2

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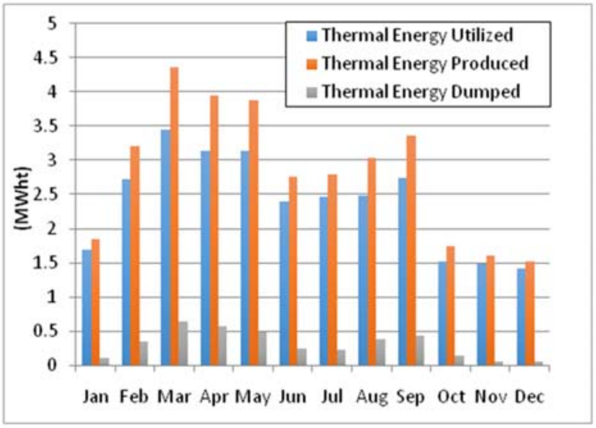

c) SM = 2.25

Figure-8. Monthly energy profiles for different solar.

hrs and 365 days. Initially, the capacity factor increased rapidly with the increase in SM, but after SM=2 the increment effect on capacity factor became negligible. The values of capacity factor calculated were low because this system was simulated without storage and sun is available only in day time.

Alternatively, the solar field area was calculated on the basis of annual weighted average of effective solar irradiance (475 W/m^2). The calculated area (118.3 m^2) was very close the area calculated on the basis of solar multiple=2 (124 m^2).

Figure-8 presents the monthly values of thermal energy produced, energy utilized and dumped for (a) SM=1.75, (b) SM=2, and (c) SM=2.25. In March, April and May solar field have highest thermal energy output but the dumped energy is also high in these months. On the other hand, thermal output is very low in months of October, November, December and January; it is because of high cloudy/rainy days.

While comparing values of dumped energy presented in Figure-8 a, b and c, It is visible that considerable amount of energy has been dumped at SM=2, (Figure-8-b) in the low irradiance months i.e. Oct, Nov, Dec and Jan. it is visible in Figure 8-c, that the dumped energy started to increase rapidly in all months. So, every increment in SM will cause exponential increase in dumped energy.

CONCLUSIONS

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.

Two solar field sizing techniques were discussed. On the basis of simulation results it could be concluded that annual weighted effective irradiance could be used not only to accurately predict the round year performance of parabolic trough collector, but it could also give the optimum field area.

Solar multiple based optimization method provides a broader insight of system output behavior. This technique can be very helpful in sizing the solar heating system with thermal energy storage. The dumped energy can be stored and used at no-sun times, which will increase the capacity factor of the system.

By comparing both solar field sizing techniques, the weighted average method seems better, as it can save substantial amount of computational effort in designing the solar heating system, using neither hybridization nor thermal storage. But this method can't predict system performance with thermal energy storage.

Though this study has been conducted for a tropical climate area with high number of cloudy/rainy days, resulting low annual capacity factors. However, on the basis of simulation results, the author believes that a substantial potential is available for utilizing solar energy for moderate temperature industrial applications. Normally the industrial thermal loads need uniform energy so; 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.

REFERENCES

[1] S. A. Kalogirou, "Solar thermal collectors and applications," Prog. Energy Combust. Sci., vol. 30, no. 3, pp. 231–295, 2004.

[2] M. Jradi and S. Riffat, "Medium temperature concentrators for solar thermal applications," Int. J. Low-Carbon Technol., pp. 1–11, 2012.

[3] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes: Third Edition. John Wiley and Sons, 2007.

[4] S. A. Kalogirou, "A detailed thermal model of a parabolic trough collector receiver," Energy, vol. 48, pp. 298–306, 2012.

[5] A. Fernández-García, E. Zarza, L. Valenzuela, and M. Pérez, "Parabolic-trough solar collectors and their applications," Renew. Sustain. Energy Rev., vol. 14, pp. 1695-1721, 2010.

[6] A. Steinfeld, M. Wirz, and M. Roesle, "Design Point For Predicting Year-round Performance Of Solar Parabolic Trough Concentrator Systems," in International Conference on Energy Sustainability ES2013, 2016, pp. 1-8.

[7] D. F. Al Riza, S. I. U. H. Gilani, and M. S. Aris, "Hourly Solar Radiation Estimation Using Ambient

Temperature and Relative Humidity Data," Int. J. Environ. Sci. Dev., vol. 2, no. 3, pp. 188–193, 2011.

[8] K. Frank and G. D. Yogi, Handbook of Energy Efficiency and Renewable Energy. CRC Press, 2007.

[9] W. B. Stine and M. Geyer, Power From The Sun. J.T. Lyle Center for Regenerative Studies California, USA, 2008.

[10] G. Pierucci, D. Fontani, P. Sansoni, and M. De Lucia, "Shape Optimization for Parabolic Troughs Working in Non-ideal Conditions," Energy Procedia, vol. 57, pp. 2231–2240, 2014.

[11] V. M. Sharma, J. K. Nayak, and S. B. Kedare, "Shading and available energy in a parabolic trough concentrator field," Sol. Energy, vol. 90, pp. 144-153, 2013.

[12] M. J. Montes, A. Abánades, J. M. Martínez-Val, and M. Valdés, "Solar multiple optimization for a solar-only thermal power plant, using oil as heat transfer fluid in the parabolic trough collectors," Sol. Energy, vol. 83, no. 12, pp. 2165-2176, Dec. 2009.

[13] N. S. Suresh, N. C. Thirumalai, B. S. Rao, and M. A. Ramaswamy, "Methodology for sizing the solar field for parabolic trough technology with thermal storage and hybridization," Sol. Energy, vol. 110, pp. 247-259, Dec. 2014.

[14] N. National Renewable Energy Laboratory, "System Advisor Model Version 2015.1.30 (SAM 2015.1.30)."

[15] N. National Renewable Energy Laboratory, "Solar Advisor Model Reference Manual for CSP Trough Systems," 2009.

[16] D. F. Al Riza, "Sizing Optimization of Standalone Photovoltic System for Residential Lighting," Universiti Teknologi Petronas, 2011.

[17] [17] A. Thomas, "Solar steam generating systems using parabolic trough concentrators," Energy Convers. Manag. vol. 37, no. 2, pp. 215-245, Feb. 1996.

[18] [18] Ecoheatcool and Euroheat and Power, "The European heat market, work package 1. Final Report," Brussels, 2006.