Solar Thermal Organic Rankine Cycle (STORC) power plant as an alternative to the steam power plant with a parabolic trough system in South Africa

O.Y. Odufuwa, K. Kusakana*

Abstract— This paper analyses the possibilities of incorporating the Organic Rankine Cycle (ORC) technology to a parabolic trough technology, reduces the cost of testing and optimisation by providing tools for the evaluation and optimisation of existing and proposed power plants. The thermodynamic potential for Solar-Thermal Organic Rankine Cycle (STORC) power plants was investigated by using Matlab Simulink ® and Thermolib library software. The methodology was implemented based on principles and specifications of some existing plant designs. The model basically considered four major elements: the solar resources model, the solar collector model, the fluid transfer and storage model and the ORC model. Based on the study outcome, the integrated model was created to analyse the variations in geographic, geometrical properties with thermo-physical properties for a specific period of the possible power output from the plant. Power output variation from the model results provided a tool for the case studies on the sensitivity and performance analysis and show that the plant will provide more power and higher efficiencies.

***Index Terms*— Direct Normal Irradiance, Organic Rankine Cycle, Solar Collectors, Heat transfer**

1 INTRODUCTION

Nowadays, there is a high demand for alternative modes of energy provision to reduce the potential for negative environmental impact [1-2]. Addressing the problem of sustainable energy supply is one of the major engineering challenges of the 21st century [3]. One potential means of overcoming this challenge lies in the development of renewable energy technology through a dedicated research effort. The effort includes, for example, exploration of biomass utilisation, waste heat energy recovery, wind energy and solar energy, among others. Among these alternative sources, renewable energy sources provide economical, safe and renewable energy technologies and create opportunities for the sustainability of power generation [4].

The exploration of renewable energy technologies in South Africa has 18 % of the total power generation capacity. The total power generation capacity is 52,811 MW with fossil fuel capacity of 43,485 MW and Low carbon capacity of (renewable, nuclear and imported hydro) 9,326 MW [5]. Moreover, renewable energy technologies have only recently achieved widespread adoption. Similar to conventional energy technologies, many of them are still to be tested and proven. One way of hastening the adoption of these technologies is to reduce the amount of field testing and field optimisation by using numerical models to optimise the technologies. Modelling of the specific renewable energy technology, such as the Organic Rankine Cycle (ORC) technology, reduces the cost of testing and optimisation by providing tools for the evaluation and optimisation of existing and proposed ORC plants [6].

Thermal power generation is a proven technology with several hundreds of plants in operation. Current large-scale systems rely on traditional steam-based Rankine cycles for power production. Most of these plants develop megawatts of electricity. On the other hand, ORC power plants are more compact and less costly than traditional steam cycle power plants and can better exploit lower temperature thermal resources. ORC develops kilowatts of electricity. The utilisation of ORC allows for solar-thermal power generation to become a more modular and versatile means of supplanting traditional fuels [7]. The Parabolic Trough Collectors incorporating a molten salt thermal with steam turbine storage power plant are currently being utilised for power generation and will generate up to 100 MW clean power supply to some areas in South Africa [8].

The objective of the study was to provide a tool, in the form of a computer simulation and modelling capability, for evaluating the output possibilities of incorporating a solar ORC system as an alternative to steam turbine system. Another objective of the study was to possibly compare the performance of components of an ORC solar-thermal power plant system into one numerical model that can be used to analyse entire system energy conversion processes for varying cases regarding the generation of electricity.

2 METHODOLOGY

A modelling approach was considered. Modelling the power plant considers the thermodynamic analysis of each component that transforms energy. The simulation program was developed using Matlab Simulink ® and Thermolib Simulink ® library. The steady state hourly variations of the parameter were considered for analysis of the STORC power plant. To achieve the main goals of this research, the following methodological steps of energy transfer elements was modelled:

2.1 Solar radiation resource model

Based on the study focus, which is on the South African weather, reliable data for the solar resource is available on a database of the Southern African Universities Radiometric

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Network (SAURAN) [9]. Weather data is also available from the South African Weather Service (SAWS) database, but there is no provision for any form of solar radiation data [10].

The main requirement in this part of the resource model is to read the specific meteorological data at a particular hour of a given day for the location of interest. This variable at the instance of the hour is the output to the collector model. The resource Simulink block looks for the required value from the given set of data. This flow chart is given in Fig.1.

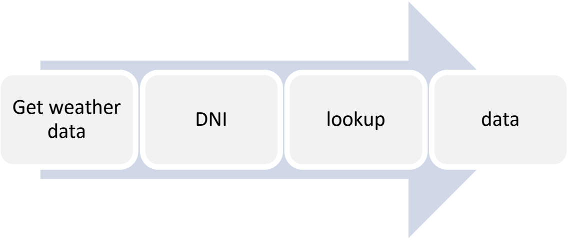

Fig. 1: Lookup hourly parameter flow chart

Table I. Input data for the Solar resources

Hour Number	Bloemfontein 01/01/2015			
	DNI (W/m²)	Temp ℃	P_{atm} mBar	WS m/s
6	0	18.89	853	3.503
8	658.728	19.65	854	2.712
10	872.391	22.28	855	4.853
12	741.312	24.68	854	6.756
14	402.63	25.33	854	6.486
16	518.025	27.82	852	5.385
18	876.21	28.09	852	3.88
20	500.332	27.22	852	2.821

Table I present a sample of the data required for input into the solar resource model. The model allows the change of data for different places and time periods. A 2-hour interval from 6 am to 8 pm was extracted.

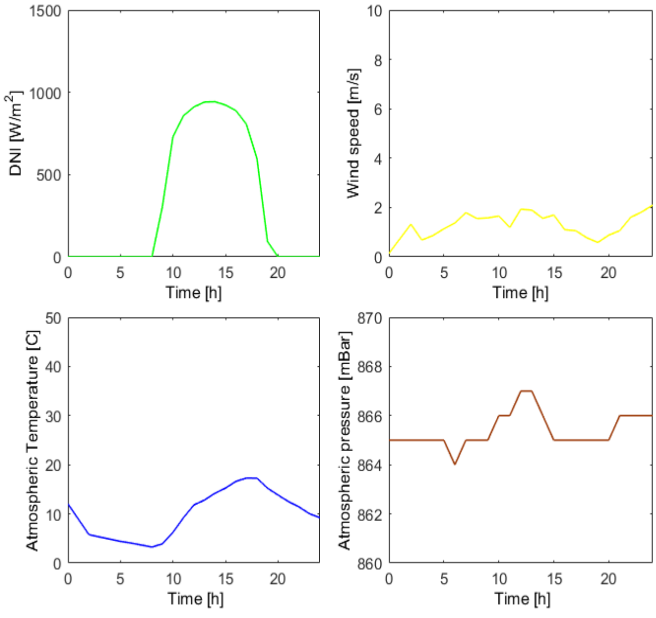

Fig. 2: Lookup hourly parameter flow chart Simulink plot of the meteorological data for Bloemfontein on 1 January 2015

The n-dimensional lookup block was adopted to determine the DNI, atmospheric temperature, atmospheric pressure, wind speed and relative humidity at a specific hour of a chosen location of interest. The model allows the change of data for different places and time periods. The lookup block made it easier to read the different meteorological data for any location for 24 hours during the various seasons of the year. The user is only required to modify the lookup table data for the measured data of the site, and periods and dates of the seasons of interest. Below is the Fig 2, which shows Bloemfontein's first 24-hour weather variations for January 1, 2015. Graphical outputs are presented in Fig. 2 showing the variation of meteorological data of interest over 24 hours.

2.2 Solar-thermal collectors

Utilisation of the energy from sunlight requires means to capture radiation from this source efficiently. The Parabolic Trough Collector (PTC) was modelled based on the choice of the existing power plant type of collector. PTC modelling involves thermodynamic analysis. Such analysis allows for the consideration of the thermo-physical properties, geometric parameters and other factors that determine the output of the collector unit of the power plant. The model applies to PTCs. The previous study was used for comparisons and validations. Flow chard of the model is given in Fig. 3.

Fig. 3: Lookup hourly parameter flow chart

$$Q_u = F_R A_a \left[S - \frac{A_r}{A_a} U_L \left(T_r - T_a \right) \right]; \; A_a = \left(x_w - D_{c\,o} \right) \quad (1)$$

$$T_{diff} = Q_u \left[\frac{1}{\pi D_{ro} L h_{f,ri}} + \frac{\ln\left({D_{ro}}/{D_{ri}} \right)}{2\pi L k_r} \right] \quad (2)$$

$$\eta_{col} = \left({Q_u}/{S A_a} \right) \times 100 \quad (3)$$

F_R considers the effects due to the heat capacity of the material and the heat loss effects is referred to as the heat removal factor. A_r and T_r represents the receiver area and temperature respectively. A_a, D_{co}, D_{ro}, D_{ri}, L, k_r, $h_{f,ri}$, and T_{diff}, represents the aperture's area and glass cover's outside diameter, receiver's outside diameter, receiver inside diameter, collector length, thermal conductivity of the receiver, heat transfer coefficient inside receiver, and temperature difference respectively. The absorber radiation is represented by S.

The major outputs required from the collector models are the collector useful heat gain, Q_u determined using (1). Equations (2) was used for relative temperatures computations. The collector efficiency, η_{col} was estimated using (3) [11-12].

The most important output parameters (collector efficiency, heat gain and HTF exit temperatures) are considered for three cases. The first instance will review the variation for these important output parameters over 24 hours. The second instance is the change of the output with the dimension and HTF in the collector system. Lastly, the model investigated the variations of the output parameters with the location of interest. The model considers the thermal efficiency of the collector in some cases by assuming the optical efficiency ranges from 60-100%. Matlab Simulink ® and Thermolib library were used to develop the models.

2.3 Solar-thermal storage

Storage of solar energy to stabilise the periodic fluctuations in the radiation is required for the solar plant system. Reasonable performance could be achieved in the system taking into consideration the relative function of its components. Load requirements, capacity and condition of the source of energy to the system determine the expectation of the system. Analysis of the capacity and rate of inputs and outputs provides a reasonable tool towards system optimisation.

The storage was modelled using the Simulink ® Thermolib library. Considering the Thermolib, the mass and energy balance of the liquid storage tank input and output flows will be based on (4), used to calculate the mass balance using the molar fraction (at an instance *i*) n_i and the molar flow rate, *dni/dt* (per time from inlet to outlet) of the fluid in the system molar fraction and the molar flow rate of the fluid in the system. The energy balance is done by considering the enthalpy rate, dH/dt at the inlet, H_{in} and outlet, H_{out} of the components. Hence, energy balance is expressed in (5).

$$\frac{dn_i}{dt} = n_{i,in} - n_{i,out} \tag{4}$$

$$\frac{dH}{dt} = H_{in} - H_{out} \tag{5}$$

2.4 Organic Rankine Cycle

The operation of the Simple Rankine Cycle still applies to an Organic Rankine Cycle. The difference is based on the type of transport fluid used in the system. The ORC uses a high molecular mass organic fluid which allows heat recovery from a low-temperature source such as industrial waste heat and solar-thermal collectors. The study is centered on an ORC type applicable to Parabolic Trough Collectors (PTCs).

The thermodynamic analysis follows the first law of thermodynamic of non-flow and steady flow processes for the components of the system.

The model is composed of the evaporator to the turbines, and a pump coupled to the WF storage tank. The block determines the power output and thermal efficiency of the plants at the endpoint. A double stage turbines and air cooled condenser were used in the system. On the other hand, the pump and evaporator are set up for pumping and counter flow heat exchange respectively.

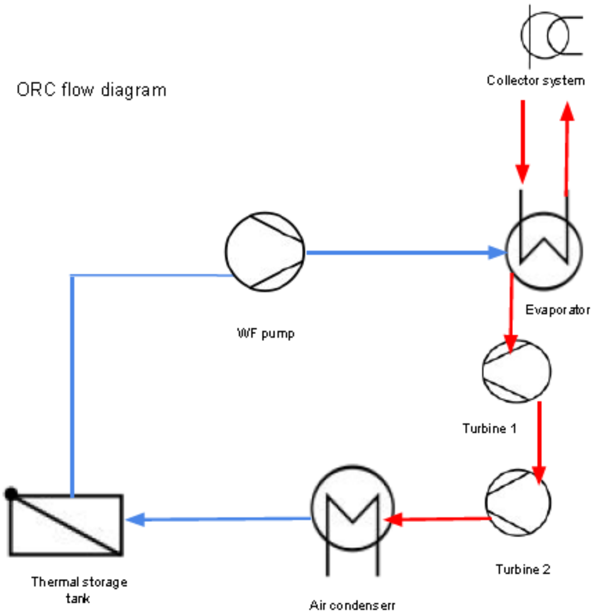

Fig. 4: ORC flow diagram

$$Energy = m_f(\Delta h) \tag{6}$$

Equation (6) was used to determine the output energy of the component where m_f is the mass of WF and Δh is the specific enthalpy change.

$$\dot{W}_{Turbine} = \dot{m}_{WF}(h_{in} - h_{out}) \tag{7}$$

Turbine power is expressed in (7) where $\dot{m}_{WF}$ is the mass flow rate of the working fluid. h_{out} is the actual specific enthalpy at the outlet and h_{in} is the specific enthalpy at inlet.

2.5 Heat transfer fluids and working fluids

Heat transfer fluid is the transport medium at the high-temperature zone. Glycol compound mixture (Ethylene Glycol) found in car antifreeze fluids and other HTF candidates (Steam and N-Propane) were simulated. Different combination of the HTF in the collector and WF in the ORC (Ethylene Glycol as HTF and R245fa as WF, N-Propane as HTF and R245fa as WF and steam as HTF and R410a as WF) was considered. ORC is suitable for low temperature applications, which is an advantage over the steam thermal system. Unlike steam turbine system that requires high temperature mostly ORC allows operation at low temperature (solar and waste heat) system. Ethylene Glycol mixture was chosen as a conceptual candidate for HTF because of the chemical properties to retain the low heat operation [13].

The working fluid is utilised at the turbine region for transport to work output areas. The choice of transport fluid is also relevant to optimisation of the system. The simulation software Matlab Simulink ® and Thermolib Simulink ® library allows flexible modelling of the proposed plant [14].

3 RESULTS

3.1 Solar-thermal collectors Model outputs

The collector efficiency for different types of HTF (Steam, Ethylene Glycol and N-Propane) in the collector was plotted in Fig. 5. The heat gained at the various locations revealed that the heat gain varies with the site of interest as plotted in Fig. 6. Fig. 7 shows the variations of heat gain with the length of the collector. The HTF exit temperature was also considered as shown in Fig. 8, and it was seen that the fluid exit temperature stays constant for different lengths of the collector.

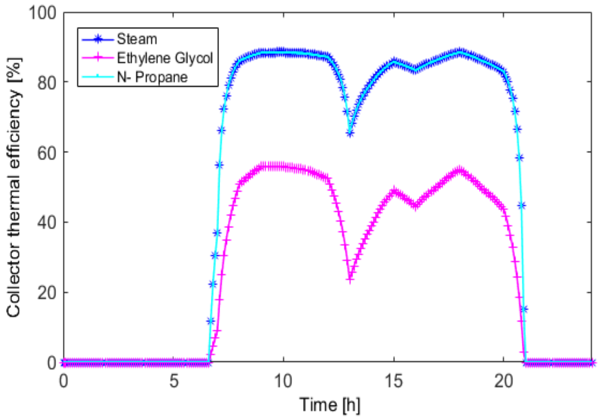

Fig. 5: Variation in collector efficiency over the same day with different HTF in the system power

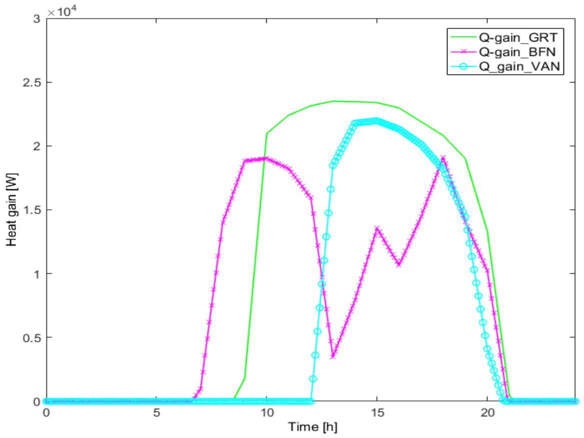

Fig. 6: The hourly heat gained for different locations

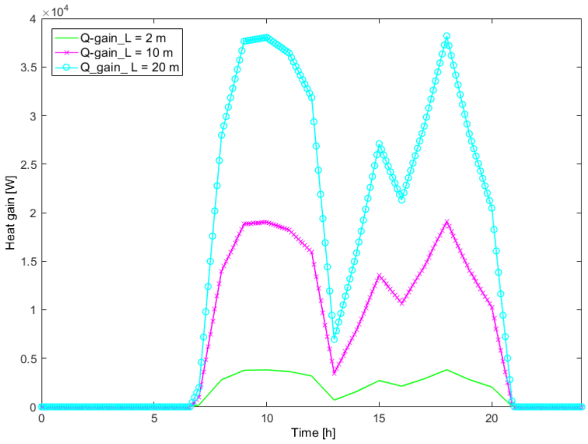

Fig. 7: The hourly heat gained for various lengths of the collector at a chosen day of the year

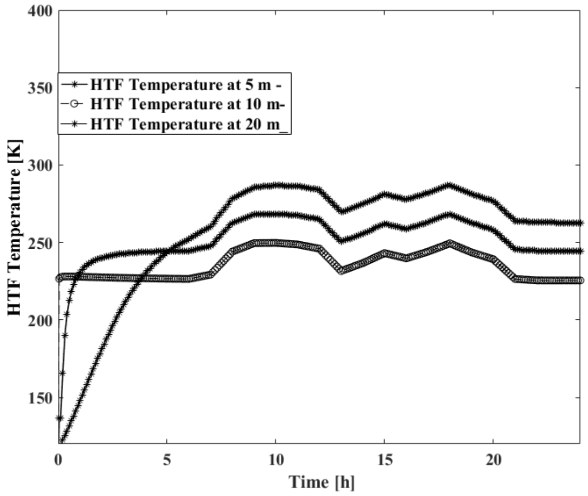

Fig. 8: Plot of fluid exit temperature for 24 hours at different lengths of the collector

3.2 Solar-thermal Storage Model output

Fig. 9 shows the comparisons of the temperature before and after storage tank entrance and exit at a different point in the system over 24 hours. It was observed that the storage tank helps to stabilise and accumulate the heat of the system.

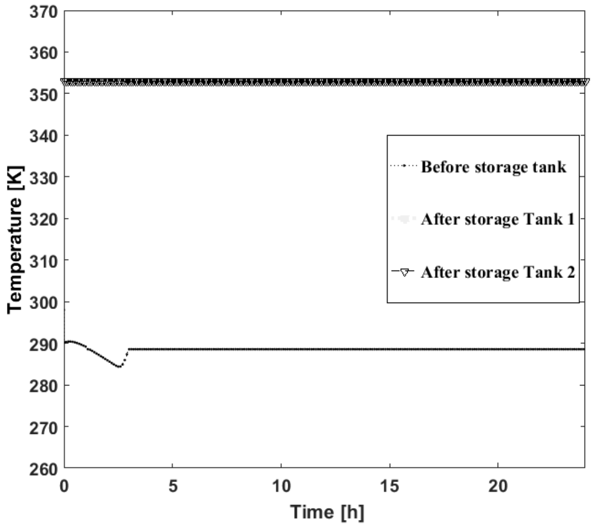

Fig. 9: Comparisons of the temperatures (K) before and after storage tank boundary in the system

3.3 Organic Rankine Cycle Model output

Fig. 10 and 11 shows the power output over a day and with a different variable that affects the output. Fig. 11 presents the variation of power output with WF and HTF. It was seen that the power output is higher for steam as HTF combined with refrigerant R410 as working fluid in the ORC. The plot shows different gradients for the power output indicating the effect of fluid on the output of the system. The length of the collector has also affected the power output as seen in Fig. 12. The gradient of the power output curve is steeper more for the lower length than the higher length, indicating the rapid increase with a shorter or smaller system. Fig. 13 shows the cycle efficiency plotted over 24-hours' time (scaled of 1:2). The curve shows a constant efficiency after the system attained a steady state.

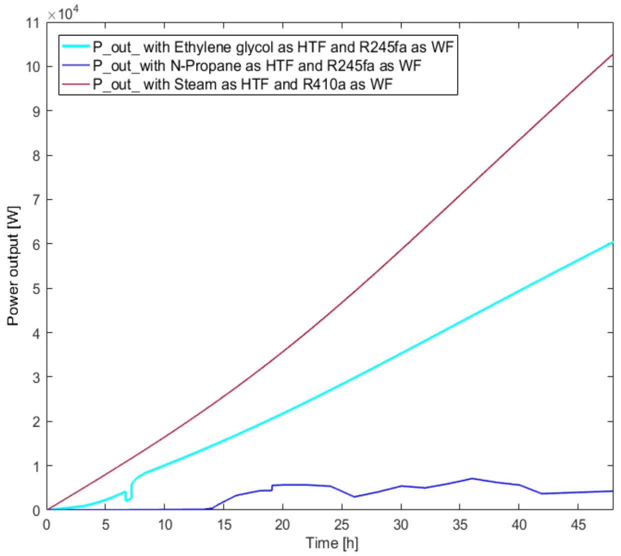

Fig. 11: Power output for different HTF and WF in the system

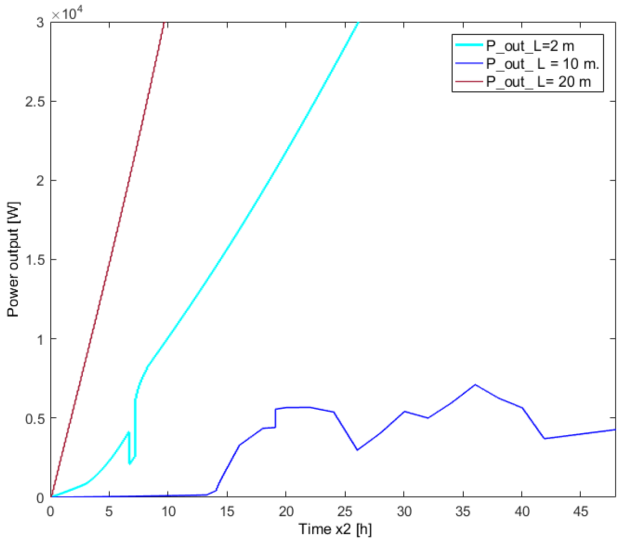

Fig. 12: Power output with different lengths of the collector

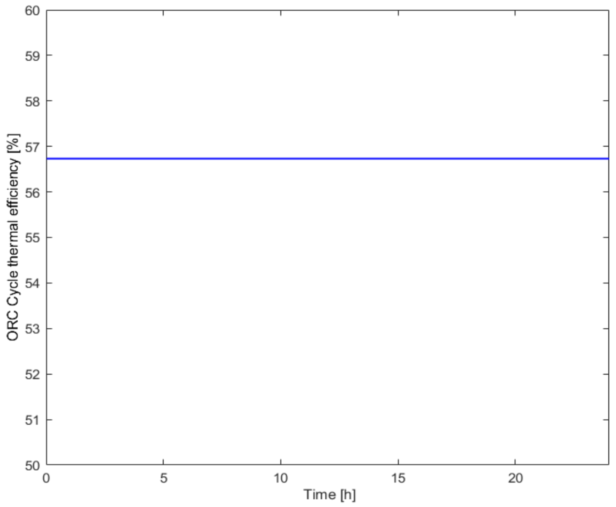

Fig. 13: Thermal efficiency of the system for the chosen day

3.4 Organic Rankine Cycle Model output

It is essential to estimate the output and the input requirement of a power plant before investing in the technology. From the model developed above the outputs of the components of the plant as well as that of the integrated unit were investigated. Knowledge of the optimum heat gain and temperature output of the collector, the capacity of the thermal storage and the power output of the ORC with regard to size of the plant and the HTF used in the systems, provided a reasonable basis for design of the power plant.

The validity of the model was also determined by using parameters from different plants and comparing the results with the current model. For instance, the input parameter from the AZTRAK test was used on the present model, and the results were plotted for the different cases. From the graph in Fig. 14, the maximum discrepancy was 15 %. The outcomes from the validations of the outputs indicate the extent of model acceptability.

Furthermore, collector optimisation could be achieved by using the best HTF, building with the correct dimension of the aperture, suitable length and diameter of pipes, and choosing a location that will generate the required power. For instance, Bloemfontein and its vicinity tend to provide more heat gain than the other two sites considered.

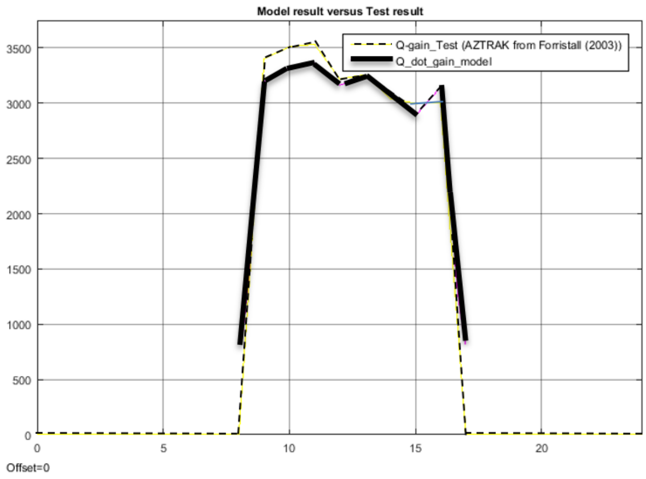

Fig. 14: Heat gain (in Watt on Vertical axis) of the test model compared to heat gain of the present model over a day (in hours on horizontal axis)

4 CONCLUSIONS

From the study results and validations, the verified solar irradiance values sourced from the database could be used for correct input parameters for the collector model. The values from SAURAN were compared to other values from different weather databases and provided reasonable acceptance after statistical analysis. The solar-thermal collector of the model determines the useful energy gain, HTF outlet temperatures and collector thermal efficiencies and other useful parameters for analysis. It was observed that the larger the aperture and the longer the length of the collector, the higher the heat gain. Concerning storage, the correct storage capacity must be chosen to achieve the required performance. From the ORC engine model, the power output shows a realistic output could be generated from the plant. It was also found from a recent investigation that the PTCs technology is now in operation by Abengoa’s in KaXu Solar One, located near the town of Pofadder in the Northern Cape Province of South Africa. Other plants are under construction and are also located the in the Northern Cape Province. The plants are the Khi Solar One, which is expected to generate around 50 MW and Xina, which has a total installed capacity of 100 MW. The study created awareness useful utilisation and optimisation of the related plants that involves cleaner energy.

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