Dynamic simulation and power output of small scale solar based organic Rankine cycle with thermal storage system

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Abstract

In this present study, the thermal energy storage system of small scale solar powered organic Rankine cycle system is modelled from governing equations of thermodynamical theories. This model can accurately simulate and predict the charging and discharging processes of thermal energy storage system for the small scale ORC system. The dynamic characteristics of the thermal energy storage system were analyzed by Matlab Simulink which helps for the design, operating, and control strategy of small scale solar ORC system. Furthermore, in this study the solar organic Rankine cycle power output based on solar collector was also analyzed by means of a mathematical model for system components which can evaluate system performances on a monthly basis.

Keywords — Dynamic Simulation, Organic Rankine Cycle, Thermal Storage System, Solar Energy

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I. INTRODUCTION

The major challenge faced in todays's solar power plant is the energy production when the sun sets or is blocked by clouds. So the concept of thermal energy storage system provides a good solution for addressing the challenge. The operating principle of solar organic Rankine cycle (ORC) is described as below [1]: the sun's rays are reflected by solar collector into the receiver which heats the water. The heated water is used for the evaporation of the organic fluids used in ORC system. The evaporated organic vapor is then passed into the turbine from the heat exchanger which creates mechanical power. The mechanical power helps in generating electricity when coupled with generator. The organic fluid is then passed into the condenser for phase change from vapor to its liquid state. The liquid organic working fluid is then feed into receiver for completing of the cycle in the system. Therefore, the thermal storage system is needed in order to operate the system for prolong time even after sunshine. There are several types of solar thermal energy storage technologies that have been tested and adopted for CSP technologies such as the two-tank direct system, two-tank indirect system, and single-tank thermocline system [2].

The solar ORC technology can be economically feasible if the power generation is high. Since the plant stops to generate energy when there is no sunshine, therefore the dynamic simulation of solar thermal storage is necessary to the know the pattern of the power output for the given climatic conditions of the particular solar ORC plant. The one way to study the solar ORC systems improvement in the performances is to pass through the dynamic modeling and simulations for the components in the system. The components are solar thermal storage system, solar collectors, ORC units and the power block. In addition, the power out of the system from the single collector can also be obtained with the thermodynamic modeling.

In this study, the solar ORC heat source temperature ranges from 90 °C -120°C for power out less than 2kW. The dynamic simulation is carried out within these boundary conditions. Furthermore, for the vacuum type of solar collector, the maximum power out from the single tube will be calculated when there is the provision of thermal storage system.

II. MODELING OF THE SYSTEM

Various parameters should be address in order to model the system for analyzing the performance of the solar ORC system. The main models that should be taken into account are discussed below:

A. Solar radiation modeling

The solar radiation data accounts for beam, diffuse and reflected components of the solar irradiation. The model consists of computation of clear-sky global irradiation on a horizontal surface, calculation of clear sky index, diffuse and beam components on inclined surfaces.

B. Solar collector model

Solar collector can be modeled for two different types of collector. They are non-concentrating and concentrating collector. In these models development, the evacuated tube and parabolic trough technology collectors will be taken for non-tracking and tracking cased global and direct beam irradiance data. The governing equation for solar collector is as follows [3]:

$$\eta = C_o - C_1\left(\frac{T_c - T_a}{I_{sol}}\right) - C_2\frac{(T_c - T_a)^2}{I_{sol}}$$

Here C_o, C_1 and C_2 are collector constants and T_c and T_a are mean collector temperature and ambient temperature respectively.

C. ORC components models

The ORC components models descriptions and described as follows:

Pump: $$W_p = \frac{\bar{v}_p (P_o - P_i) \times \dot{m}_f}{\eta_p}$$

where P_o and P_i denotes pressure at inlet and outlet of pump. Mass flow rate of working fluid (m_f) and efficiency of pump (η_p) and specific volume of fluid (v_f).

Evaporator: $$Q_{eva} = m_f (h_i^{\cdot} - h_o)$$

Nusselt Number (N_u) $= \dfrac{hD_h}{K}$

Renold's Number (R_e) $= \dfrac{\rho v D_h}{\mu}$

Here, h convection heat transfer coefficient , ρ density of material, v of velocity, μ viscosity of material and D_h hydraulic diameter of the heat exchanger.

Expander: $$W_{\exp} = m_f (h_i^{\cdot} - h_o)$$

where h_i and h_o enthalpy at specific pressure and temperature at inlet and outlet of expander.

Condenser: $$Q_{con} = m_f (h_i^{\cdot} - h_o)$$

where h_i and h_o enthalpy at specific pressure and temperature at inlet and outlet of condenser.

The above mentioned governing equations are based on basic laws of thermodynamics as presented by the author [4].

The useful collected energy rate from the vacuum tubular single collector is defined as :

$$\dot{Q}_u = \dot{m}_c (C_{po} T_o - C_{pi} T_i)$$

where, C_p is the specific heat capacity, $\dot{m}_c$ mass flow rate in the collector and T_o and T_i outlet and inlet temperature of solar collector respectively.

The area of the solar collector is calculated using collector energy balance equation which is as follows:

$$\dot{m}_c .(h_o - h_i) = G_b .\eta_c .A_c$$

where, η_c, A_c and (G_b) are collector efficiency, area of collector and global radiation on the surface respectively.

The net solar ORC efficiency of the system is given by the following equation [5-6]:

$$\eta_{SORC} = \eta_c \times \eta_{ORC}$$

where, η_{ORC} is a thermal efficiency of the ORC system .

D. Flat plate collector

Flat type solar collectors are used to collect the solar radiation. When the solar radiation falls on the glass cover, it is absorbed by absorber plate and carried away by water in the tubes attached to the collector plate. The hourly radiation falling on a tilted surface is given by the following expression [7]:

$$I_T = I_b R_b + I_d R_d + (I_b + I_{d)}) R_r$$

Where, I_b and I_d are the hourly beam and diffuse radiation that the collector receives, and R_b , R_d , R_r are defined as tilt factors for different kinds of radiation, whose values are given by :

$$R_b = \frac{\cos(\theta)}{\cos(\theta_z)} = \frac{\sin\delta \sin(\phi - \beta) + \cos\ \delta \cos\omega(\phi - \beta)}{\sin\phi \sin\delta + \cos\phi \cos\ \delta \cos\omega}$$

for beam radiation, where δ is the declination angle .

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$$

$$R_d = \frac{1 + \cos\beta}{2}$$

for diffuse radiation, and

$$R_r = \rho\left(\frac{1 - \cos\beta}{2}\right)$$

for reflected radiation falling on the surface of the plate.

The incident solar flux absorbed in the absorber plate is given by

$$S = I_b R_b (\tau\alpha)_b + [I_d R_d + (I_b + I_d) R_r](\tau\alpha)_d$$

Where $(\tau\alpha)_b$ and $(\tau\alpha)_d$ represent the transmissivity-absorptivity product for beam and diffuse radiation falling on the collector respectively.

The useful heat gain rate for the collector is given by the following expression:

$$Q_u = F_R . A_c . [S - U_L . (T_i - T_a)]$$

where, F_R , U_L, A_c, T_i and T_a are collector heat – removal factor, total loss coefficient, thermal-absorption area of the collector, water inlet temperature and ambient temperature respectively.

E. Vacuum type collector

The solar collector efficiency can be calculated as function of solar incident, mean temperature of collector and ambient air temperature and can be given by following expression [8]:

$$\eta_c = C_o - \frac{C_1 (T_i - T_a)}{I_{sol}} - \frac{C_2 (T_i - T_a)^2}{I_{sol}}$$

where, S is the solar flux absorbed in the absorber plate , C_o, C_1, C_2 are coefficient constants for collector. If it is assumed that solar collector cover is glass plate with very small order of thickness and that solar heat flux variations have a 24 hours period, the solar collector can be assumed in a state of steady. So, in this case, the useful thermal energy absorbed by the solar-collector fluid is given by following expression:

$$\dot{Q}_u = \eta_c . S . A_c$$

where, A_c is the area of solar collector.

F. Solar ORC system efficiency

The net electrical output power: $\dot{W}_{net} = \dot{W}_{exp} - \dot{W}_p$

The Solar ORC cycle efficiency: $\eta_{ORC} = \dfrac{\dot{W}_{net}}{\dot{Q}_u}$

III. DETAILED MODELS FOR THE SMALL-SCALE SOLAR ORC SYSTEM

The large fluctuation in solar radiation greatly impact the solar ORC system, so it necessary to have automatic control to operate the system. The solar collector thermal storage system's temperature is controlled by a PID control scheme. This control scheme uses measurements of direct normal irradiance to anticipate changes in outlet temperature. For a system with storage, the power output is controlled using PID controller, which is activated after hot water storage tank begins charging. In order to keep equipment well-maintained and running properly and for safety reasons, a minimum temperature of storage tank is applied. The temperature of 120 °C is the requirement for this small-scale solar ORC system. The control system is designed to control the outlet temperature of storage tank. The system is assumed to operate at 10 bar pressure. Matlab Simulink block model aims to capture the important dynamics of the ORC system. The thermal storage tank is modeled by dynamic mass and energy balances. The mass balance for a tank is given by following expression:

$$\rho_f \frac{dV}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

where V is the total volume of the HTF in the tank and the subscripts in and out refer to flow in and out of the tank, respectively.

The energy balance for tank is given by the following expression [9-10]:

$$\rho_f C_F \frac{dV}{dt} = C_F (T_{in} - T_{out}) - UA_t (T - T_{air})$$

where U is the overall heat transfer coefficient for the tank walls and A_t is the surface area of the tank subject to the heat transfer. It is assumed that no heat transfer occurs from top or bottom of the tank.

The model that captures the dynamics of the storage tank and ORC system is given below:

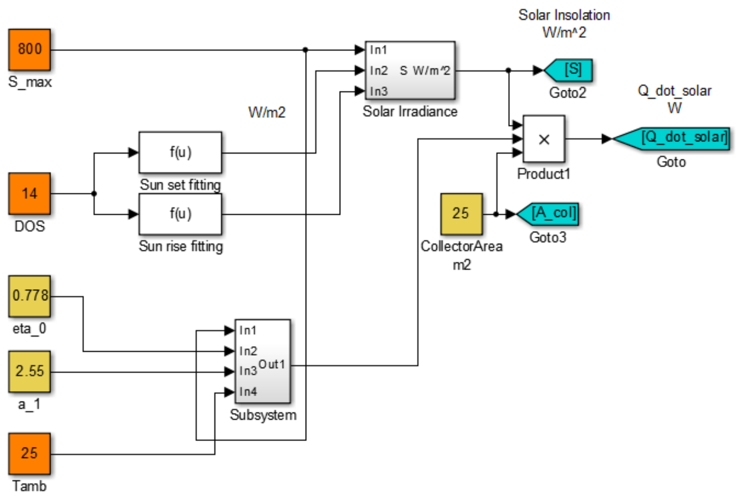


Figure 1: Flow sheet for the model block for solar thermal storage for ORC

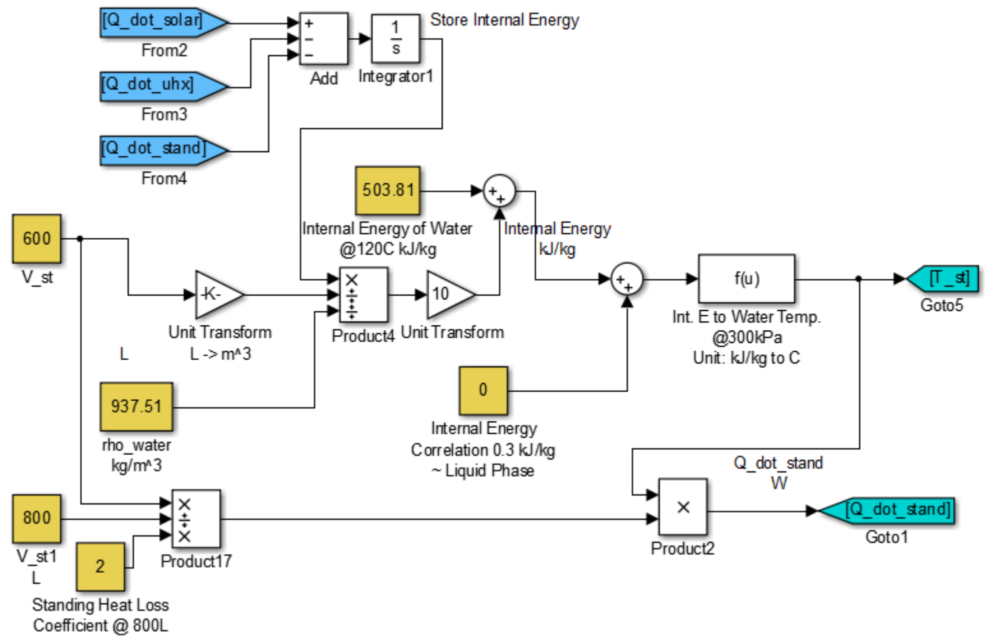


Figure 2 Dynamic simulation model block for solar thermal storage for ORC

IV. RESULTS AND DISCUSSION

A. Startup/Shut down

To simulate the daily cycle, the control must have the ability to shut down the system at the end of the day or at any time when there is insufficient irradiance to warrant running the pumps. In the similar manner, it will need to simulate startup. During normal operation, the real irradiance signal is input to the operating model. A controller inputs to model to maintain the storage tank temperature at the shutdown trigger temperature, where the only heat loss from the model is that lost to the environment through the storage tank. At the beginning of the day, the storage tank is initialized to 90 °C, if the temperature goes below it, the system is shut down. The system must not also exceed above 120°C. From the model, the figure 3 shows the effects of the thermal storage temperature variation during the day. There occurs two shut down when the solar irradiation changes and the temperature of the storage system changes below the design set point temperature. The variation in the temperature in the thermal storage tank changes from 8 am to 8 pm during the day. Likewise, from the dynamic simulation, the expander power output has been simulated through the day.

The maximum power output is 1102 W. Figure 4 shows that variation of power output when the solar radiation changes. After the 8 pm of day, the ORC is shut down because the tank is below the shutdown trigger temperature, but there are still some large oscillations in the collector temperature. This behavior can be simulated at 800 W/m^2 of solar irradiance. The ORC system can work smoothly from 12 pm to 4 pm. There is no lot of fluctuation during this period.

The necessary heat input to obtain the power from the solar ORC is the temperature from the solar thermal tank. The maximum amount of the heat that can be able to produce the power output of 1102 W is 18 kW.

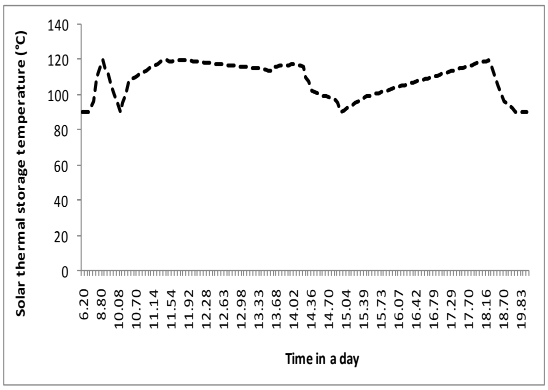


Figure 3Variation of temperature during a day in the thermal storage system

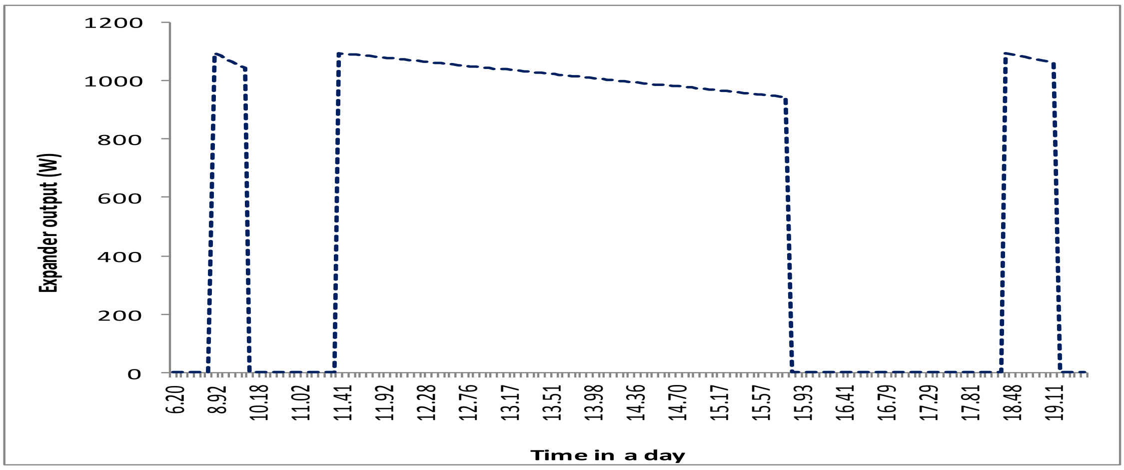


Figure 4 Dynamic simulation of power output through the day

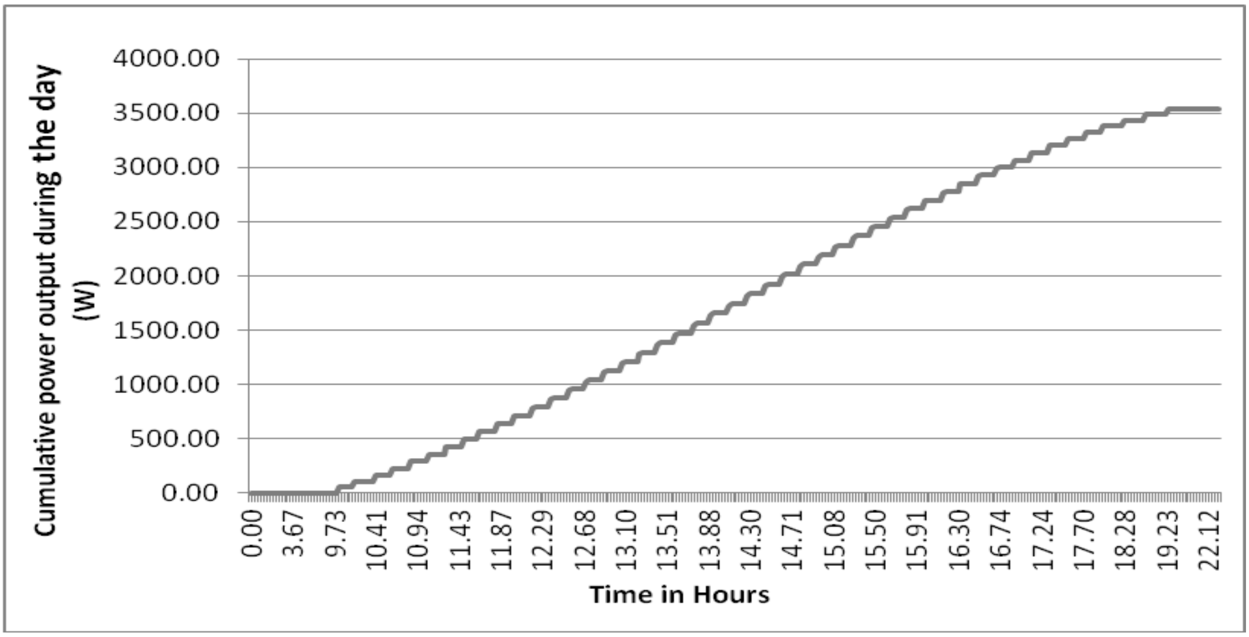


Figure 5 Dynamic simulation of cumulative power output during a day

Finally, from the dynamic model, the cumulative power output from the solar ORC has been simulated and can be shown by figure 5. This indicates that the total power of 3.5 kW per day is developed when the solar thermal storage tank is installed. The variation or fluctuation due to solar irradiance can be control by the PID control for smooth operation of the ORC system. The dynamic simulation was carried out with the solar irradiance of 800 W/m^2 and 200 L heat transfer fluid. According to the meteorological conditions of the location, the simulation for the solar ORC has been carried out. During the analysis of solar ORC, the maximum output is found in the month of April and May which are 69 W and 65 W respectively.

The estimation was done by using the single panel and it was simulated through the year. The monthly profile of solar power output by using single panel is shown by figure 6a-6c.

The maximum solar ORC power is in the month of May whereas the lowest is in December. The simulation was carried out with System Advisor Model (SAM) developed by NREL, USA [11]. The solar irradiance estimated values were obtained from the SAM website.

The solar ORC prototype for such system has been built by various authors in order to see the performance characteristics of the system [12-14].

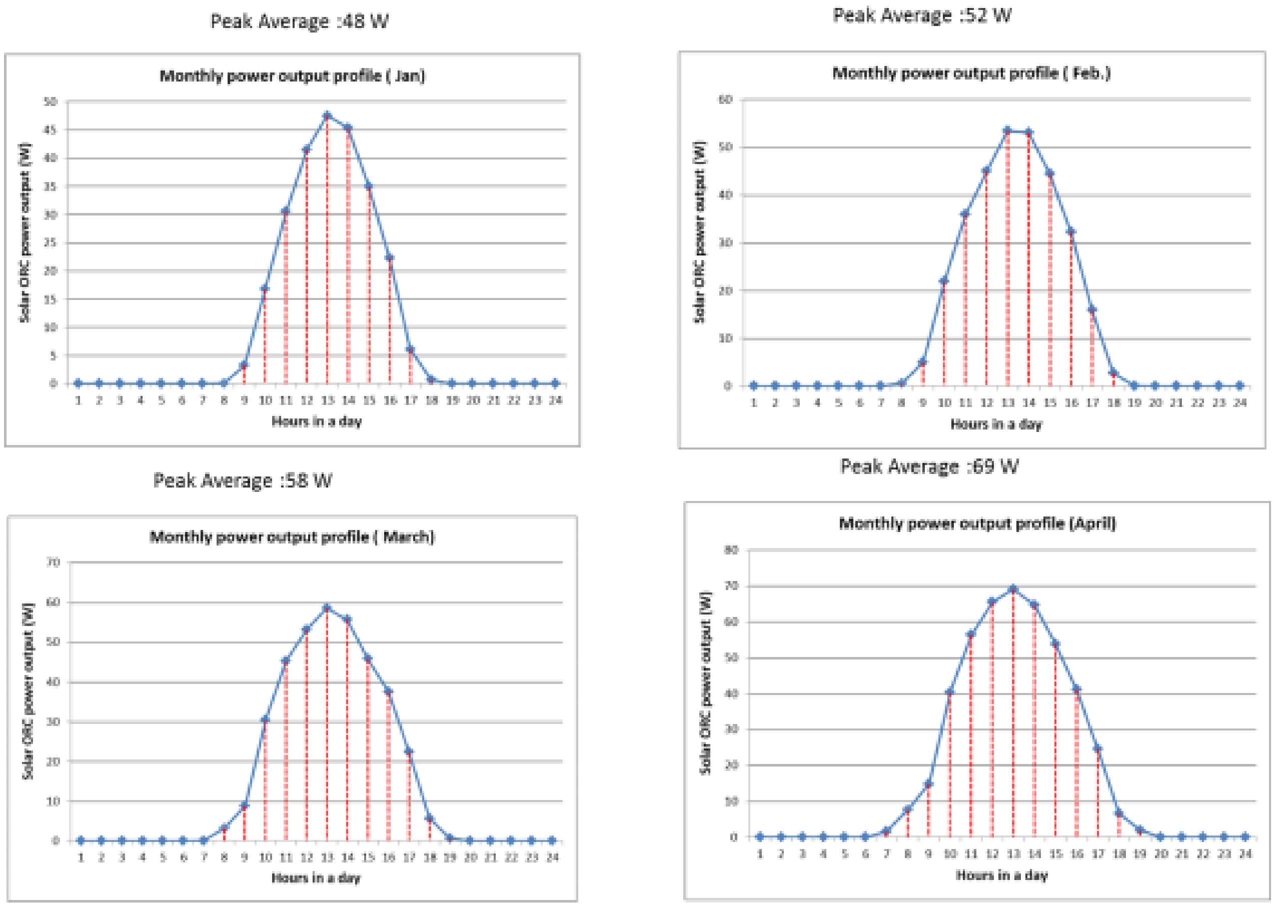
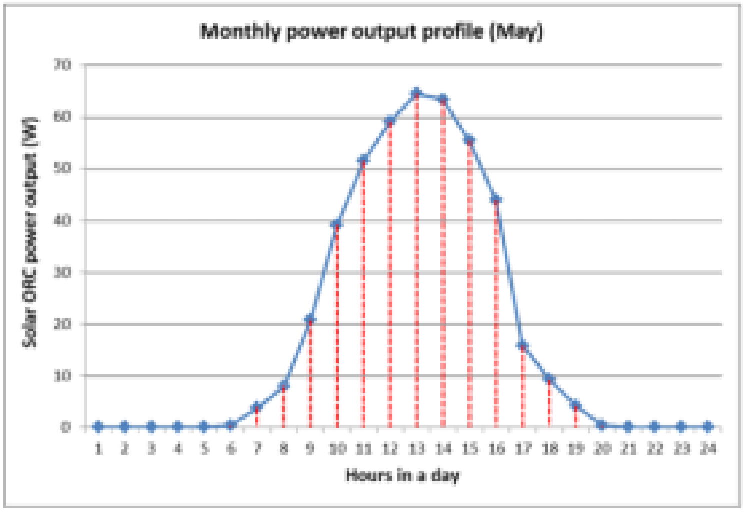
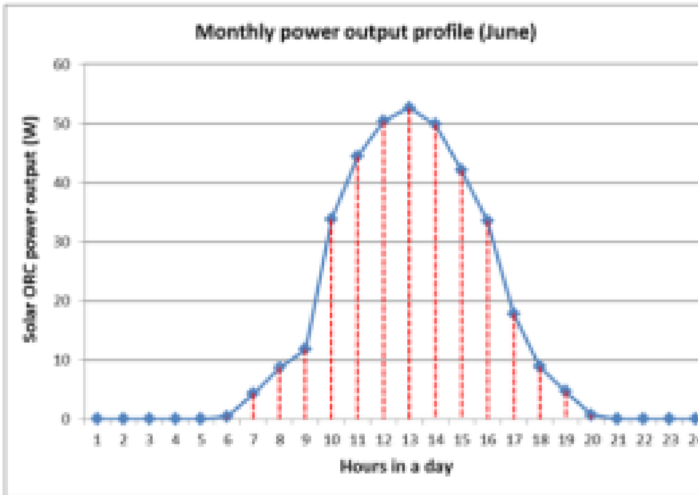


Figure 6a Power output during the months in a year (Jan-April)

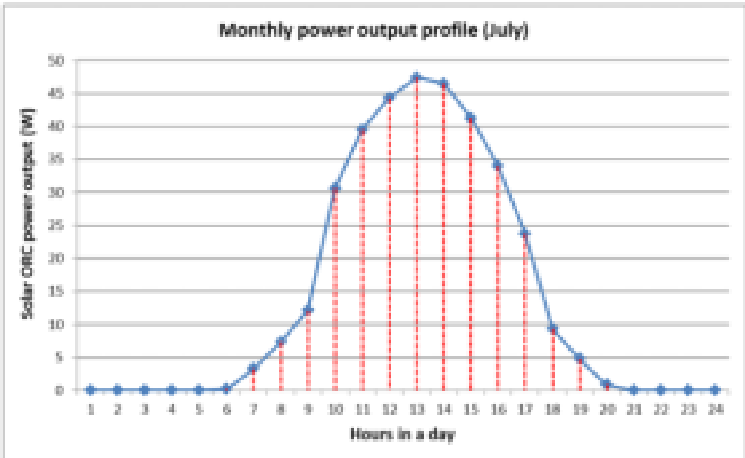
Peak Average :65 W



Peak Average :52 W



Peak Average :47 W



Peak Average :51 W

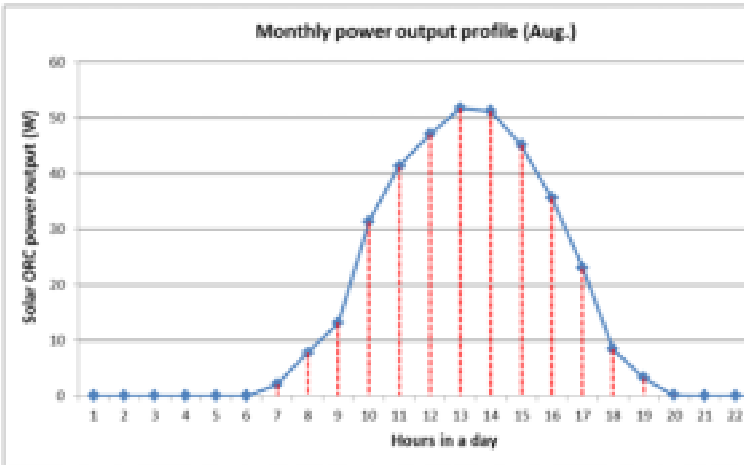


Figure 6b Power output during the months in a year(May-Aug)

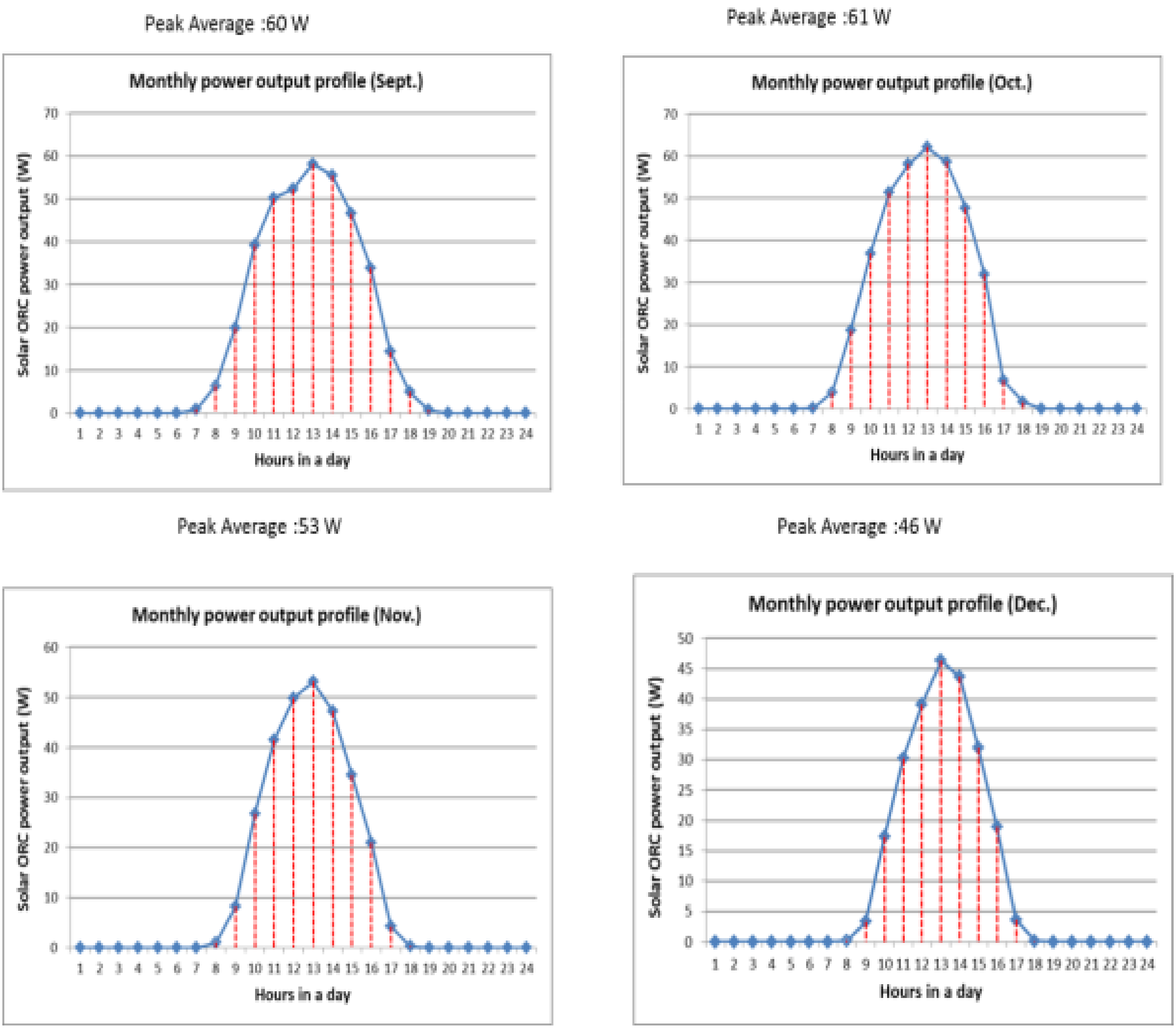


Figure 6c Power output during the months in a year(Sept-Dec)

V. CONCLUSIONS

The dynamic simulation of the solar thermal storage system has the capacity for controlling the system when there is no enough sunshine or high irradiance for running of the ORC system. When the solar source temperature is less than the minimum temperature required for operating working fluid feed pump then the system will be shut down. The system operates again when there is threshold irradiance for running of solar ORC. Similarly, the power output of the solar ORC system from the single collector can be estimated monthly. The power output is maximum in month of April whereas minimum in month of December.

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