Parametric Study of Combined Cooling and Power (CCP) Plant Integrated with Parabolic Trough Solar Collectors (PTSCs)

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Abstract. This study presents a detailed energy analysis of a Combined Cooling and Power (CCP) plant operated by Parabolic Trough Solar Collectors (PTSCs). The integrated cycles; Vapor Absorption Refrigeration Cycle (VARC) and Organic Rankine Cycle (ORC) are used to produce cooling and power, respectively. Six organic working fluids, namely, R113, R141b, R123, R245fa, R142b, and isobutane were selected for ORC, while LiBr-H2O solution used in VARC. Four key energetic parameters, useful heat gain, work output, cooling rate, and energy utilization factor (EUF) were examined during varying direct normal irradiance (DNI). A parametric study was carried out in three modes of operation, power only, combined power and cooling and cooling only under the limits of DNI from 0.6 kW/m² to 0.88 kW/m² recorded on the yearly-average basis in two cities of Pakistan, Lahore, and Quetta respectively. Results enunciated that R113 given the highest thermal efficiency of 17.12%, while isobutane gave the least thermal efficiency of 7.88%, hence R113 was chosen as organic working fluid for further study. The maximum EUF was found in the cooling mode of operation which increased from 63.95% to 66.79% at 0.6 kW/m² and 0.88 kW/m² respectively. During the combined cooling and power mode, maximum cooling rate, power output, and EUF were 3456 kW, 822.5 kW, and 41.34% respectively at 0.88 kW/m².

1. Introduction

Due to gradual depletion in fossil fuels and increasing greenhouse gases (GHG), the world is exploring alternate energy resources, in which solar energy has shown promising results. Solar photovoltaic cells convert solar energy directly into electrical energy, whereas in solar-thermal technologies, thermal energy absorbed from sun is used to generate the electrical energy. Pakistan is a developing country, striving to commensurate its supply-demand gap in electricity production. Pakistan is located in high-insolation region, and averagely 95% of area experience 5 – 7 kWh/m²/day of insolation throughout 85% days of the year [1]. Solar-thermal collectors, specifically parabolic trough solar collector is medium-temperature range technology, which can greatly help us in harvesting the enormous solar potential of Pakistan. Solar-thermal technology can directly be used as a primary source for trigeneration (cooling, heating, and power) systems, resulting in lower environmental impact and greater efficiency.

Various researchers have presented performance analysis of solar based systems. Energetic and exergetic analysis of a solar-operated tri-generation (power, heating, and cooling) system with thermal energy storage (TES) option was carried out for building applications. The Parabolic Trough Solar...
Collectors (PTSCs) integrated with ORC, VARC and a Thermal Energy Storage (TES) were analysed and found that ORC with working fluid R123 showed slightly better energy and exergy efficiencies as compared to R245fa with overall energy and exergy efficiencies of 61.21% and 37.6-18.7% respectively [2]. Energetic analysis and size estimation of solar field of PTSCs integrated with Steam Rankine Cycle (SRC) and binary vapour cycle was performed and concluded that that binary cycle with R134a as working fluid has the best performance and for the same power output requires smallest solar field size as compared to the other fluids considered, whereas R600a showed the lowest performance [3]. In another study, SRC and TES system integrated with PTSCs was thermodynamically analysed and optimized using nano-fluids in PTSC, namely CuO, SiO$_2$, TiO$_2$ and Al$_2$O$_3$ [4]. It is found that HTF embedded with CuOnano-particles resulted in higher energy efficiency among other nano-fluids. Moreover, the rise in solar intensity increased the collector outlet temperature of HTF and net power output. Also, the rise in dead state temperature from 280 K to 325 K increased the energy and exergy efficiency of the system from 12.6 to 12.8% and 17.4 to 17.8% respectively. It was also reported that by increasing percentage of nanoparticles in a nano-fluid, the exergy and energy efficiencies can be increased. The 3E (energetic-exergetic-environmental) analysis of solar-thermal power plant using different fluids in PTSC has been performed using four different HTFs namely Al$_2$O$_3$/oil, Fe$_3$O$_4$/oil, Glycerol, and Therminol-66 and found that by increasing the solar irradiation intensity from 400 to 1100 W/m$^2$, overall exergetic efficiency of the plant using four HTFs increased from 22.83 to 24.56%, 22.63 to 24.38%, 22.79 to 27.18% and 29.11 to 31.23% respectively [5].

Keeping in view the importance of harnessing solar energy for power and cooling and very small work performed in Pakistan climate, this study attempts to examine the behaviour of a combined cooling and power plant integrated with PTSCs for different locations in Pakistan. The effects of direct normal irradiation are studied on net power output, cooling rate, and EUF. The parameters of the system are studied in three modes of operation namely, power only mode, cooling and power mode, and cooling only mode.

2. Methodology

2.1. System Description
The flow diagram of the ORC and VARC integrated with PTSC system is shown in figure 1. The PTSC subsystem is a series-parallel combination of solar collectors, and receiver pipeline passes through the focal point of the parabolic trough where all solar radiations converge to heat the heat transfer fluid passing through the receiver. A fraction of HTF is directed towards the ORC which transfers heat to organic fluid and vaporizes it to run the turbine for electric power generation. Another fraction of the HTF is directed towards generator of VARC to run the refrigeration cycle for providing cooling to the residential and commercial buildings.

2.2. Site selection
The parametric analysis of the system was carried out using two regions selected from the Pakistan, the region having the lowest average-yearly DNI value and the region having the highest value of average-yearly DNI. The solar irradiation data for the selected sites were collected from a meteorological database known as Meteonorm [6]. The selected two regions are Lahore, because of a major portion of Punjab province and Quetta which covers a major portion of Balochistan province. The clear sky radiation model was used for the calculation which gave the average yearly value of 600 W/m$^2$, whereas using the same radiation model average yearly value of DNI for this site found to be 880 W/m$^2$.

2.3. Thermodynamic Modelling
In this section thermodynamic models are presented which are used in Engineering Equation Solver (EES) to evaluate the performance of the system, followed by the parametric study of the system for
which constant parameters used are exhibited in table 1 [3,7,8]. Following assumptions are made for the analysis:

- Steady-state conditions are accounted for the overall system.
- Pressure drops in piping are negligible.
- Changes in kinetic and potential energies are negligible.
- System components work adiabatically.

Latest collector design used in SEGD plant, LS-3 collector is selected for the plant. HTF temperature at the outlet of the PTSC is 663K (390°C) and mass flow rate of the HTF per single row of PTSCs is 0.35-0.8 kg/s [3,9]. The energy balance equation used for each component of the system is given as

\[ Q + W + \sum_{\text{in}} (\text{r}h) - \sum_{\text{out}} (\text{r}h) = 0 \]  

(1)

### Table 1. Constant Parameters Used in Analysis

| Constant Parameters (Value)            | Constant Parameters (Value)                                      |
|----------------------------------------|------------------------------------------------------------------|
| Reflectance of mirror, \( \rho \) (0.94) | Number of collectors in one row, Col \( i \) (7)                 |
| Intercept factor, \( \gamma \) (0.93)   | Mass flow rate of HTF in one row, \( \dot{m}_\text{HTF} \) (0.35-0.8 kg/s) |
| Transmittance of glass cover, \( \tau \) (0.96) | Ambient temperature, \( T_0 \) (298 K)                             |
| Absorbance of receiver, \( \alpha \) (0.96) | Ambient pressure, \( P_0 \) (101.325 kPa)                           |
| Incidence angle modifier, \( K \) (1)   | Isentropic efficiency of turbine, \( \eta_T \) (0.85)             |
| Emittance of the cover, \( \varepsilon_{\text{cv}} \) (0.86) | Isentropic efficiency of pump, \( \eta_P \) (0.80)                |
| Emittance of the receiver, \( \varepsilon_r \) (0.15) | Turbine inlet pressure (1 MPa)                                    |
| Thermal conductivity of receiver tube, \( k_r \) (0.017 W/m.K) | Quality at the turbine inlet (100%)                              |
| Thermal conductivity of HTF, \( k_f \) (0.11 W/m.K) | Condenser temperature (303 K)                                    |
| Receiver inner diameter, \( D_{r,i} \) (0.066 m) | Evaporator temperature (283 K)                                   |
| Receiver outer diameter, \( D_{r,o} \) (0.07 m) | Absorber temperature (298 K)                                     |
| Generator temperature (363 K)          | Condenser temperature (308 K)                                    |
| Solution temperature at the outlet of SHX (337 K) |                                                      |

### Figure 1. Flow diagram of the cogeneration plant coupled with PTSCs

2.3.1 Parabolic Trough Solar Collectors (PTSCs). The energy analysis of PTSCs is based on the equations presented in ref [3]. Useful energy gained by single collector is determined by using Equation (1) as

\[ \dot{Q}_u = \dot{m}_\text{HTF} \cdot C_p \cdot [T_3 - T_2] \]  

(2)
where \( \dot{m}_{HTF}, C_{pHTF}, T_3 \) and \( T_2 \) mass flow rate in receiver, specific heat of HTF, outlet and inlet temperatures at the exit of receiver respectively. Useful energy gained can also be calculated as follows,

\[
\dot{Q}_u = A_{ap}.F_R.[G_b.\eta_r - \frac{A_r}{A_{ap}}.U_L.(T_2-T_0)]
\]

(3)

where \( F_R, G_b, \eta_r, A_{ap}, A_r \) and \( U_L \) are heat removal factor, direct radiation heat, receiver efficiency, aperture area, the surface area of receiver and heat loss coefficient respectively. Solar energy received on the collector surface is determined as:

\[
\dot{Q}_{solar} = A_{ap}.G_b.\eta_{r,Col_f}.Col_s
\]

(4)

where \( Col_f \) and \( Col_s \) is the total number of collectors connected parallel and series.

2.3.2 Organic Rankine and Vapor Absorption Cycles (ORC and VARC). The application of equation (1) to all components of ORC and VARC lead to the cycles’ fundamental model equations as shown in table 2, which also includes respective performance parameters.

| Model equations of ORC components | Model equations of VARC components |
|----------------------------------|-----------------------------------|
| Feed Pump: \( W_{FP} = \dot{m}_{evap}(h_f-h_r) \) | Evaporator: \( \dot{Q}_{evp} = \dot{m}_e(h_{11}-h_{10}) \) |
| Evaporator: \( \dot{Q}_{evp} = \dot{m}_{ORC}(h_f-h_h) = (1-\lambda)\dot{Q}_u \) | Absorber: \( \dot{Q}_{abs} = \dot{m}_{16}h_{18} + \dot{m}_{12}h_{12} + \dot{m}_{13}h_{13} \) |
| Turbine: \( \dot{W}_{turb,out} = \dot{m}_{ORC}(h_f-h_h) \) | SHX: \( \dot{m}_{15}(h_{15}-h_{14}) = \dot{m}_{16}(h_{16}-h_{17}) \) |
| Condenser: \( \dot{Q}_{cnd} = \dot{m}_{ORC}(h_f-h_f) \) | Generator: \( \dot{Q}_{gen} = \dot{m}_g(h_9-h_9) + \dot{m}_g(h_9-h_7) + \dot{m}_g(h_7-h_9) = \lambda\dot{Q}_u \) |
| Net power output: \( \dot{W}_{ORC,net} = \dot{W}_{turb,out} - \dot{W}_{FP} - \dot{W}_{Solar Pump} - \dot{W}_{SP} \) | Condenser: \( \dot{Q}_{CND2} = \dot{m}_g(h_9-h_9) \) |
| Thermal efficiency: \( \eta_{th,ORC} = \frac{\dot{W}_{ORC,net}}{\dot{Q}_{EVp}} \) | Coefficient of Performance: \( \text{COP}_{VARC} = \frac{\dot{Q}_{evp}}{\dot{Q}_{gen}} \) |

Energy Utilization Factor (Overall performance) \( \text{EUF} = \frac{\dot{W}_{net} + \dot{Q}_{EVp}}{\dot{Q}_{solar}} \)

2.4. Validation of results

The mathematical model and results presented in this study are validated by comparing them with other studies in [7] and [8]. The results of VARC are compared with similar analysis in [7] and that of ORC present in [8]. From the validation of this study, it is observed that the models of ORC and VARC performed well with percentage error for ORC efficiency for five working fluids, namely R113, R141b, R123, R245fa, R142b, and isobutane are 0.351%, 0.882%, 1.99%, 2.35%, 0.187% and 0.711% respectively on comparison, while the same is 2.11% on comparing COP of VARC.

3. Results and discussions

In this research, detailed energetic analysis of ORC and VARC integrated with PTSC has been carried out in three modes of operation, power only, combined cooling and power and cooling only. According to the variation in the fraction (\( \lambda \)) of mass flow rate of HTF, the modes of operation are defined as power only (\( \lambda = 0 \)), combined cooling and power (\( \lambda = 0.50 \)), and cooling only (\( \lambda = 1.00 \)). The parametric study is performed using EES software to examine the energetic performance of the system against the variations in direct normal irradiance. Currently, the two limits of direct normal irradiance
on average-yearly basis, i.e. 0.6 kW/m$^2$ and 0.88 kW/m$^2$ according to climate conditions in Lahore and Quetta respectively has been chosen for parametric study to examine the effect on useful thermal energy, net power output, cooling rate and EUF, while keeping mass flow rate of HTF at 0.35 kg/s.

3.1. Power mode ($\lambda = 0$)
The effect of DNI on the net power output is shown in figure 2(a). The results have been evaluated for six organic working fluids to find the suitable organic working fluid for ORC. As it can be seen in the figure, R113 gives maximum power output and EUF, whereas isobutane gives minimum power output and EUF among all working fluids. The figure depicts that as the DNI increases from 0.6-0.88 kW/m$^2$ while keeping the mass flow rate of HTF at 0.35 kg/s, net power output of ORC increases from 1065 to 1645 kW, 977.9 to 1511 kW, 716.9 to 1400 kW, 495.6 to 765.8 kW and 490.5 to 757.8 kW for R113, R141b, R123, R245fa, R142b and isobutane respectively. The reason behind the increase in net power output is the increase in useful thermal energy available for the ORC, as it is already defined in the previous section that as the DNI increases, useful thermal energy from the PTSCs increase. From the results, it can be concluded that the system will give maximum performance in the region of maximum DNI (Quetta) by using R113 as working fluid for ORC.

Figure 2(b) shows the increase in EUF from 15.22% to 15.9%, 13.98% to 14.6%, 12.95% to 13.53%, 10.25% to 10.7%, 7.08% to 7.4%, 7.01% to 7.32% for R113, R141b, R123, R245fa, R142b and isobutane respectively due to increase in DNI from 0.6 kW/m$^2$ to 0.88 kW/m$^2$. The reason behind the increase in EUF is the increase in available useful thermal energy, which increases net power output and available solar energy due to the increase in DNI, therefore, EUF of the system increase. Due to the best performance of R113, this organic fluid is chosen for further performance analysis in combined cooling and power mode.

![Figure 2. Effect of variation in DNI on (a) net power output (b) EUF](image)

3.2. Combined Cooling & Power Mode (when $\lambda = 0.50$)
In figure 3(a) the effect on net power output of ORC and cooling rate of VARC due to variation in DNI are shown. It is illustrated in the figures that cooling rate of VARC increases from 2237 to 3456 kW net power output of ORC increases from 532.3 to 822.5 kW when DNI increases from 0.6-0.88 kW/m$^2$ at mass flow rate of 0.35 kg/s and $\lambda = 0.50$.  

![Figure 3a and 3b](image)
The reason behind the increase in net power output and cooling rate is increased in useful thermal energy which increases the output of integrated cycles by supplying more energy. It can also be seen in figure 3(b) that EUF increases from 39.58 to 41.34% when plant operates in combined cooling and power mode i.e. \( \lambda = 0.50 \). The increase in EUF is due to the same reason that more useful energy is utilized due to fractions of HTF directed in the circuits of ORC and VARC to operate the cycles. It was found that the EUF of the system was high in combined cooling and power mode when 75% of HTF was directed towards VARC.

### 3.3 Cooling mode (\( \lambda = 1.0 \))

The system operates in cooling mode when \( \lambda \) is set at 1.0, which represents that whole HTF is directed towards VARC. It can be seen in figure 4(a) that cooling rate increases from 4474 to 6912 kW due to the variation of DNI from 0.6 to 0.88 kW/m\(^2\). The increase in cooling rate is due to an increase in available useful thermal energy to drive the VARC. Figure 4(b) illustrates the variation of EUF w.r.t variation in DNI, the figure shows that EUF of the systems increases from 63.95 to 66.79% when DNI increases from 0.6 to 0.88 kW/m\(^2\). The increase in DNI increases the useful thermal energy which increases cooling rate, hence EUF increases. It can also be examined that system gives maximum EUF of 66.79% when operated in cooling mode, whereas minimum EUF is found when the system operated in power mode.
4. Conclusions
This research presents detailed energy analysis and performance assessment of a solar assisted cogeneration plant. The ORC and VARC were used as power and refrigeration cycle respectively. Two sites of Pakistan, Lahore, and Quetta were selected. Energy method was used for evaluating system performance and analysis was performed in EES and the model was validated and comparison showed good agreement among different quantities. Five working fluids, namely R113, R141b, R123, R245fa, R142b, and isobutane were compared on the basis of their thermal efficiency, and R113 given best performance among all working fluids. LiBr-H$_2$O pair was used in VARC in which H$_2$O worked as a refrigerant. Therminol VP-1 was used as HTF in the PTSCs. The system operated in three different modes, namely power mode, combined cooling and power mode and cooling mode. The parametric analysis of the system was performed based on the variation of DNI. The main conclusions from this study are summarized as follows:

- When the DNI was increased from 0.6 to 0.88 kW/m$^2$, net power output and cooling rate increased due to the increased supply of useful thermal energy which increased the overall EUF of the system.
- It was observed that the system gives maximum EUF in cooling mode, whereas the system operating in combined cooling and power mode where 50% of HTF directed in both systems gives feasible results for satisfactory operation.

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