# Parametric Analysis of the Solar-assisted Intercooled Gas Turbine and Organic Rankine Cycle for Waste Heat Recovery and Power Production

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## Abstract

The energy consumption has gradually increased in the current context. Fossil fuels are the primary source of energy for the world's population. Furthermore, energy derived from fossil fuels has significant disadvantages, including increased pollution and global warming. Solar energy is the fastest-growing alternative to fossil fuels among the various energy options. As a result, the focus of the present work is on the thermo-economic analysis of a hybrid solar-assisted intercooled gas turbine (GT) and organic Rankine cycle (ORC) for waste heat recovery and power production at near-zero-emissions. The work outcome and maximum efficiency of the hybrid arrangement are 1342.12 kW and 71.12% respectively at the cycle pressure ratio of 8, and 443 K entry point turbine temperature. The economic model of the integrated

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system depicts that the unit power production cost for the combined system has been evaluated as 1932 € per kW.

**Keywords:** Solar-powered, intercooler, heat utilization, gas turbine, waste heat recovery, molten salt.

## Nomenclature

| Nomenclature | | Subscripts | |
|---|---|---|---|
| 1,2,3… | States | He | Heliostats |
| T | Temperature, K | R | Receiver |
| P | Pressure, bar | Inlet | Inlet |
| C | Compressor | exit | Exit |
| A | Area, $m^2$ | c | Compressor |
| HX | Heat Exchanger | S | Solar |
| GT | Gas turbine | tot | Total |
| G | Generator | orc | Organic Rankine cycle |
| I | Solar irradiation, $W/m^2$ | p | pump |
| $\eta$ | Efficiency | net | Overall |
| $\varepsilon$ | Effectiveness | HX | Heat Exchanger |
| m | Mass flow rate, kg/s | | |
| ORC | Organic Rankine Cycle | | |
| $\Upsilon$ | Specific heat ratio | | |
| W | Work, kW | | |
| UPC | Unit power Cost | | |

## 1 Introduction

In the present scenario, the energy demand has gradually increased. Fossil fuels are the major source to accomplish the need for energy in the world. Moreover, the energy produced from fossil fuels has several drawbacks, such as it generates more pollution and increasing global warming. Therefore, scientists are more attractively looking for different techniques to utilize available energy sources efficiently. Among the several energy options, renewable energy is growing fastest as an alternative to fossil fuels. Several different technologies such as photovoltaic (PV) panels or thermal power will be used to convert solar energy into electrical energy. Solar collectors transfer heat into these cycles, which generate electricity. There are two types of collectors: non-concentrating and concentrating collectors [1]. Concentrating collectors have a lesser aperture area than a receiver compared to the aperture area of the concentrator [2]. They are usually utilized in applications where the medium or high temperature requires and maintains the sun's track position to attain proper sunlight concentration. In contrast to concentrating collectors, Non-concentrating collectors [3] can be utilized in applications where a low temperature requires but without tracking.

Generally, the power cycles are categorized into Brayton cycles with gas/single-phase and Rankine cycles with vapor/two-phase [4]. The simplest form of the Rankine cycle has different components like a pump, an evaporator, a turbine, and a condenser [5]. A pump is used for circulating the organic working fluid in the Rankine cycle. The working fluid absorbs heat at constant pressure in the evaporator; the turbine generates power by expanding the working fluid in it, and the working fluid rejects heat at constant pressure in the condenser. Several different working fluids, majorly water; organic fluids, can be utilized for running the ORC. The ORC is running on an organic working fluid. The characteristics of organic fluids show that the critical temperature of the fluid has a low value compared to the water, which makes them more eligible for low and medium-temperature heat applications, for example, solar systems [6]. Besides having several advantages, a major advantage of ORC is that the system can be applied at a small scale compared to the water/steam RC systems [7]. Different energy sources like biomass, geothermal, and industrial waste heat other than solar energy can also be integrated with the ORC system for power generation [8–15]. For future sustainable energy systems, utilization of the organic fluid for the energy extraction from the exhaust heat from different energy sources is a viable option for the waste heat recovery system.

Rovense et al. [16] have performed a thermodynamic and economic investigation of the solar-powered power plant capacity of 150 MWe for maximum energy generation. A novel combined cycle power plant capable of the solar air entry heating facility system has been proposed and analyzed for the several types of solar collectors by Wang et al. [17]. They have also done the first law analysis of the thermal energy storage system on an hourly basis. The maximum first law efficiency of the proposed method has been evaluated by 68%, and the thermal energy storage has provided the space heating facility of 5.89 MWe. Habibzadeh et al. [18] presented a detailed investigation to carry out the study of the hybrid energy and cooling from the ejector-refrigeration cycle by utilizing the different working organic fluids, mainly R245fa, R141b, R123, R600a, and R601a, and remarked that the R601a has the maximum thermal efficiency and minimum total exergy loss. Nafey and Sharaf [19] presented thermodynamic modeling of parabolic trough collectors powered ORC and reverse osmosis (RO) hybrid system to produce energy and water. They have concluded from the study that toluene and water show a significant improvement in terms of cost; however, butane and hexane have a negative impact on the system. Shukla et al. [20] have proposed and performed the first law analysis of the triple summed power cycle for power production.

The combined cycle's efficiency and work output have been found equal to 21.89% and 218.98 kJ/kg of air having the R245fa organic working fluid in the ORC. Binamer [21] reviewed solar-driven power plants and presented his investigation on his research article. They found that the combined system's work output was equal to 290 MWe when the solar heat input is 75 GJ/s without any $CO_2$ emissions. Liu and Karimi [22] studied a combined gas turbine power plant for the variable load conditions. They have also optimized the system based on the multi optimization methods to find out the best operating state when the load conditions have fluctuated.

By utilizing solar power, Hosseini [23] presented an arrangement for power generation and hydrogen generation. To propose a novel system, they have integrated different subsystems like a solar, gas turbine, and solid oxide steam electrolyzer. They have investigated the novel system based on the thermodynamic analysis to analyze the impact of the different non-dependent parameters. The authors reported that the fuel utilization in the plant significantly reduced from 7 to 2.7 kg/s by increasing the solar contribution in the power plant. Colakoglu and Durmayaz [24] presented a solar power plant for power production and cooling effect generation. The authors integrated the solar system, GT, VARS, and ORC system and studied the overall system's energy, exergy, and cost analysis. The first law, second law efficiency, and unit exergy cost of the system are 39.81%, 34.44%, and 0.0798 $/kWh, respectively. Yilmaz et al. [25] proposed a solar-powered combined system for power production, heat, and cooling effect generation. The investigation of the combined system is done based on energy and exergy analysis. The obtained results from the study showed that the maximum energy and exergy efficiency of the integrated system is determined as 58.43% and 54.18%, respectively.

A parametric analysis of the solar governed new arrangement with intercooled compressor to lower the work requirement has not been provided till now, according to a thorough literature review. The heliostat field concentrates the sun's solar radiation onto the solar tower. The heat from the receiver is transferred to compressed air via a heat exchanger, preparing it for expansion in the gas turbine. The cycle configuration includes a gas turbine topping cycle and an organic Rankine bottoming cycle, both of which run on exhaust and intercooler heat. The originality of this study is that it reduces the amount of effort required for the process while increasing its efficiency. This can be accomplished by introducing an intercooling stage into the system and using the heat generated to supplement further heat input into the ORC. This heat might be used for a variety of purposes, but in this instance, it would be used to supplement the ORC's additional work output. As a result, the current unique solar-assisted power generation cycle is investigated from a thermodynamic standpoint to determine the impact of various parameters on the suggested arrangement. As a result, the study gave a parametric analysis of the layouts as well as thermodynamic modelling of the unique solar-assisted power generation cycle. The proposed cycle setup is based on a closed process. Therefore, there will be no pollutant generating difficulties in this proposed system.

## 2 Systematic Description of the Arrangement

Figure 1 depicts the proposed hybrid cycle arrangement. The solar-assisted gas turbine for power generation is shown in this illustration. To lessen work needs, the compressor is separated into two parts: a low compressor and a high compressor. The exhaust stream from the turbine heats the compressed air. The compressed air is heated by molten salt after obtaining heat from the turbine exhaust stream. This molten salt used a solar tower to absorb energy from the sun and then exchanged heat with compressed air to raise the air temperature. Compressed air enters the turbine after getting heat from the molten salt to generate work. The compressed air temperature is reduced after power generation, yet it is adequate to heat the compressed air to 3 to 4 states. The heat from the exhaust is then transferred to the heat exchanger 4. This provides heat to the organic fluid, which is used to power the ORC. Heat exchanger 4 has two different heat sources, the first being turbine exhaust heat and the second is compressor intercooling heat. It will increase the work output of both the organic and hybrid Rankine cycles. The pump, condenser, turbine, and power supply make up the ORC. The heat that is rejected into the compressor's intercooling is used to boost the ORC's work output. The molten salt serves as a solar energy receiver and heat exchanger for the gas turbine's operating fluid in this setup.

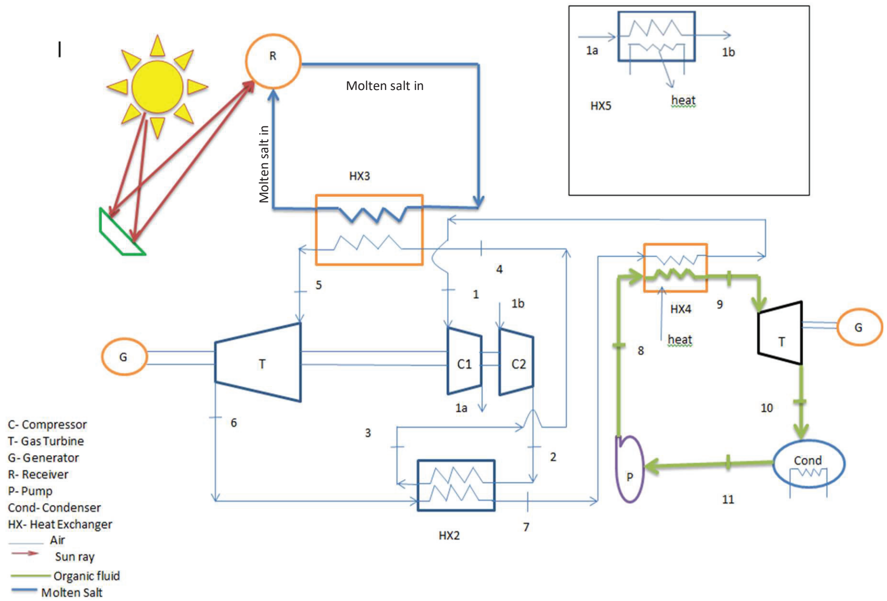


**Figure 1** Schematic arrangement of the solar-assisted intercooled GT-ORC hybrid power cycle.

## 3 Thermodynamic Modeling of the Arrangement

A C-language program is written to perform the computer simulation to evaluate the independent parameter's impact on the hybrid cycle arrangement and carry out a more parametric study of the proposed arrangement. The different organic working fluids like R1233zd(E), R245fa, and R123 are utilized in ORC [26]. But, in this study, R1233zd(E) is being used as the organic working fluid on the organic Rankine cycle because of its less toxicity, non-flammable, and very low GWP [27].

The assumptions considered for the mathematical modeling of the proposed solar-assisted cycle are given below:

(a) The adiabatic conditions are considered in the pumps and turbines.
(b) The kinetic energy change and potential energy change are considered negligible.
(c) Negligible pressure losses.
(d) Adiabatic throttling process.
(e) The study presented under steady-state conditions.

Air is assumed as the mixture of 21% $O_2$ & 79% $N_2$ (molar form) as a component. The fluid running in the GT cycle will be used as the air. The change in the enthalpy can be evaluated as,

$$\text{Enthalpy's change} = \int C_p dt \tag{1}$$

The principle of the conservation of mass for the selected control volume can be used to express evaluating the rate of mass flow at each component of the cycle:

$$\sum m_i - \sum m_e = \frac{dm_{cv}}{dt} \tag{2}$$

## 3.1 Compressor

The exit temperature of each compressor is calculated by:

$$\left(\frac{T_{exit}}{T_{inlet}}\right) = \left(\frac{P_{exit}}{P_{inlet}}\right)^{\left(\frac{(\gamma-1)}{\gamma \cdot \eta_c}\right)} \tag{3}$$

where

$\gamma$ is the specific heat ratio,
$\eta_c$ is the compressor's polytropic efficiency.

The work requirement in the low-pressure compressor can be evaluated as (in kW),

$$W_{C1} = m_a \cdot (h_{1a} - h_1) \tag{4}$$

The work requirement in the high-pressure compressor can be determined as (in kW),

$$W_{C2} = m_a \cdot (h_{1b} - h_{1a}) \tag{5}$$

Total work required for the compressor is the addition of the low pressure and high-pressure compressor. Therefore, it is evaluated as:

$$W_C = W_{C1} + W_{C2} \tag{6}$$

The heat rejected during intercooling can be evaluated with the presented formula below. This heat in this study is utilized in the heat exchanger of ORC.

$$Q_{heat} = m_a \cdot (h_{1b} - h_{1a}) \tag{7}$$

## 3.2 Modeling of Central Receiver

Normally, the heliostat field consists of a large number (for example thousands) of heliostats for concentrating the solar energy at a particular section.

The central receiver system collects all the energy from the heliostat of the solar field [28]. For achieving the high temperature at the entry point of the turbine, a large number of heliostats are required to focus the solar energy into the receiver. This receiver is mounted on the top of the tower which absorbed and transferred the solar energy to the downstream system via molten salt as fluid for the heat exchanger.

The calculation of the heat received by the Heliostat field can be determined in Watts as:

$$Q_S = I \cdot A \tag{8}$$

Total effective heat carried by the Heliostat field can be determined by;

$$Q_{he} = Q_S \cdot \eta_{he} \tag{9}$$

Total heat received by the receiver can be calculated in terms of Watts as,

$$Q_R = Q_{he} \cdot \eta_R \tag{10}$$

Total heat absorbed by the compressed air can be evaluated as,

$$Q_{HX} = Q_R \cdot \epsilon_{HX} \tag{11}$$

## 3.3 Modeling of Gas Turbine

Turbine exhaust temperature can be calculated by,

$$\left(\frac{T_6}{T_5}\right) = \left(\frac{P_6}{P_5}\right)^{\left(\frac{(\gamma-1)\cdot\eta_{gt}}{\gamma}\right)} \tag{12}$$

Here

$\eta_{gt}$ is polytropic efficiency of gas turbine.

Gas turbine's work can be determined in unit of kW,

$$W_{gt} = m_a \cdot (h_6 - h_5) \tag{13}$$

Gas turbine cycle's overall work outcome is determined in unit of kW;

$$W_{tot} = W_{gt} - W_C \tag{14}$$

## 3.4 Modeling of Organic Rankine Cycle

### 3.4.1 Turbine

The work generated by the turbine of the ORC can be determined in kW by;

$$W_{orc} = m_{orc} \cdot (h_9 - h_8) \tag{15}$$

### 3.4.2 Condenser

The amount of heat required to be dissipated from the condenser can be evaluated as;

$$Q_{cond} = m_{orc} \cdot (h_{11} - h_{10}) \tag{16}$$

### 3.4.3 Pump

The requirement of work for running the ORC pump is;

$$W_p = m_{orc} \cdot (h_{10} - h_8) \tag{17}$$

The combined cycle's work output is calculated as:

$$W_{net} = W_{tot} + W_{orc} - W_p \tag{18}$$

The efficiency of the combined solar-assisted cycle,

$$\mathit{Eff\_net} = \frac{W_{net}}{Q_s} \tag{19}$$

**Table 1** Input data [9, 10]

| Parameter with Unit | Numeric Value |
|---|---|
| Temperature of ambient, K | 300 |
| Pressure of ambient, bar | 1 |
| $\eta_{\mathrm{c}}$, % | 92 |
| $\eta_{\mathrm{gt}}$, % | 86 |
| GT cycle pressure ratio, bar | 8 to 16 |
| Net area of heliostats, $m^2$ | 10000 |
| $\eta_{\mathrm{He}}$, % | 75 |
| I, $W/m^2$ | 1000 |
| $\eta_{\mathrm{R}}$, % | 80 |
| $\varepsilon_{\mathrm{HX}}$, % | 95 |
| ORC pressure ratio, bar | 4 to 12 |
| Temperature at the inlet of ORC turbine, K | 443 |
| Temperature at the condenser of ORC, K | 313 |
| Outlet pressure of GT, bar | 1 |
| R1233zd(E)'s critical temperature, K | 438.75 |
| R1233zd(E)'s boiling point temperature, K | 291.12 |
| R1233zd(E)'s Critical pressure, MPa | 3.2 |
| Chemical formula of the R1233zd(E) | CF3CH=CHCl |

**Table 2** Economic analysis co-relations [11, 12]

| Parameter | Cost, Unit (€) |
|---|---|
| Heat exchangers | $190 + 310.A$ |
| Pump's working fluid | $900 \cdot \left(\frac{W_p}{300}\right)^{0.25}$ |
| Miscellaneous Working fluid | $20.M$ |
| Miscellaneous hardware | 300 |
| Control system | 500 |
| Labor | $0.3.TCC$ |
| Cost of Low compressor; per kW (cost 1) | $(39.5m_a/(0.9 - \eta_C))(P_{1a}/P_1)\ln\frac{P_{1a}}{P_1}$ |
| Cost of High compressor; per kW (cost 2) | $(39.5m_a/(0.9 - \eta_C))\,(P_2/P_{1b})\ln\frac{P_2}{P_{1b}}$ |
| Organic Rankine cycle cost | $2345000 \cdot W_{net,orc}/1115$ |
| Cost of turbine | $1318.5W_{gt} - 98.328\ln W_{gt}$ |

### 3.5 Economic Modeling

The solar-driven combination arrangement was assessed using basic prices to determine the plant's unit electricity price. The plant's total cost is determined by numerous characteristics listed in Table 2. After running an economic simulation of the combined system, the economic model of the combined arrangements shows that the integrated system's unit power production price is 1932 € per kW, which is cheaper than the solar-powered GT-ORC combination system provided by Khan and Mishra [11]. The sum of the represented values in Table 2 is the total cost. The unit power cost (UPC) of the arrangement can be defined as:

$$UPC = \frac{Total\ Cost}{W_{net}} \tag{20}$$

## 4 Results and Discussion

For investigating the impact of several parameters like compressor pressure ratio and organic Rankine cycle turbine entry temperature on the integrated system, a computer code has been written to look out the effect of the parameter while considering the input parameter provided in Table 1. ORC runs on the R1233zd(E) organic fluid in the integrated system.

Figure 2 depicts the pressure ratio's fluctuation on the efficiency of the solar-assisted power cycle overall, gas turbine, and ORC. The total efficiency

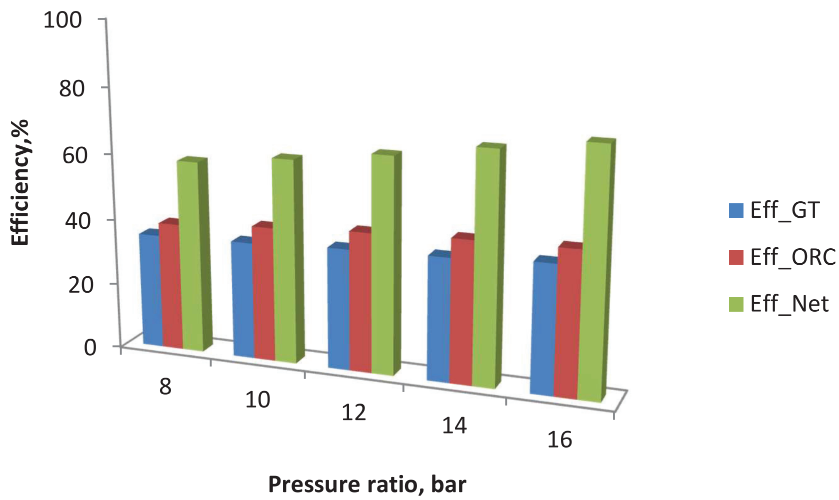


**Figure 2** Impact of the different pressure ratio on the solar assisted intercooled GT-ORC hybrid power cycle.

of the integrated system increases with the increment in the integrated arrangement's pressure ratio due to the work output of the combined cycle increases on the exact heat utilization from the sun. The obtained value of the efficiency of the overall cycle is determined with the change of 58.46% to 71.12%. Similarly, the obtained efficiency of the gas turbine and ORC has been determined in the range of 34.92% to 38.81%, 38.92% to 43.57% respectively. Here, the ORC's efficiency increases because of the heat available from two heat exchangers.

As the result is expressed in the graphical form as presented in Figure 3, the variation is shown in the pressure ratio & the work outcome of the different components of the hybrid cycle and overall system. The maximum work outcome from the integrated system is achieved as 4325.9 kW for the environment temperature of 303 K. The minimum work outcome from the system is equal to 3332.62 kW. It shows that as the pressure ratio increases then the outcome of the solar governed combined cycle has been improved continuously. As shown in the graph, some portion of the work outcome of the gas turbine is utilized for the compressor. Similarly, the recovered work outcome by the ORC has been determined as 1342.12 kW to 2113.27 kW as the pressure ratio of the combined system increases. This shows that the pressure ratio increment has a positive impact on the work outcome of the ORC for the same environmental condition. The work output of the combined

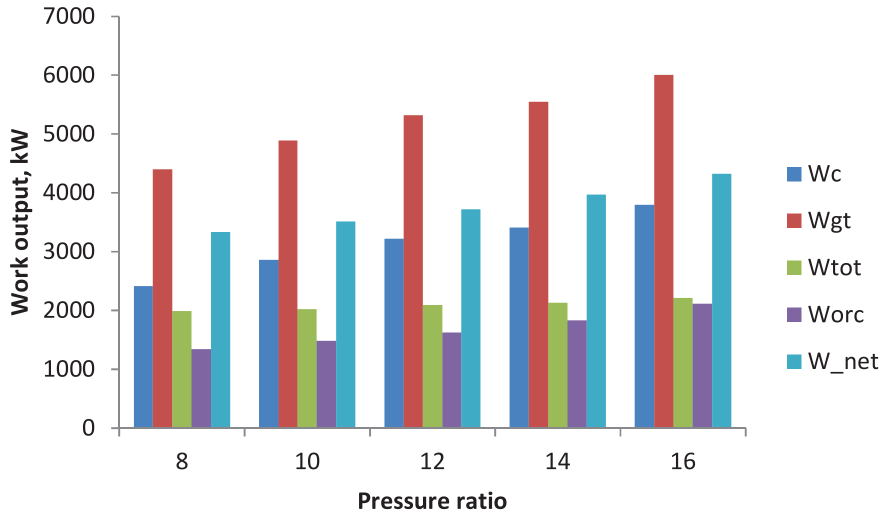


**Figure 3** Variation of the pressure ratio and work outcome of the solar assisted intercooled GT-ORC hybrid power cycle.

system increased to 2113.27 kW while considering the key input data of the 4 bar pressure ratio in the ORC turbine & 443K entry turbine temperature in ORC.

Figure 4 depicts the impact of the variation of the temperature at the turbine entry on the work outcome and the efficiency of the solar-assisted system. The work outcome of the ORC improves with the increment of the ORC turbine inlet temperature which has a major impact on the hybrid arrangement work outcome and efficiency of the combined system and the organic Rankine cycle's efficiency. Because of improvement in the ORC's work outcome from 1329.54 kW to 1685.98 kW, then the work outcome of the solar governed arrangement would be enhanced from 2810.03 kW to 3166.48 kW at GT arrangement's pressure ratio 8 bar, ORC pressure ratio 4 bar. The work outcome & efficiency reports are presented in Figure 4. The efficiency of the solar-assisted combined cycle is found maximum of 64.55% at a pressure ratio of 4 bar of ORC, ORC's entry turbine temperature of 473 K, and gas turbine arrangement pressure ratio of 8. Likewise, the ORC can achieve the maximum efficiency of 45.20 % at the pressure ratio of 4 bar, ORC's entry turbine temperature of 463 K, and gas turbine arrangement pressure ratio of 8 bar.

Figures 5(a) and 5(b) depict the consequences of the organic Rankine cycle pressure ratio on the work outcome and efficiency of the combined

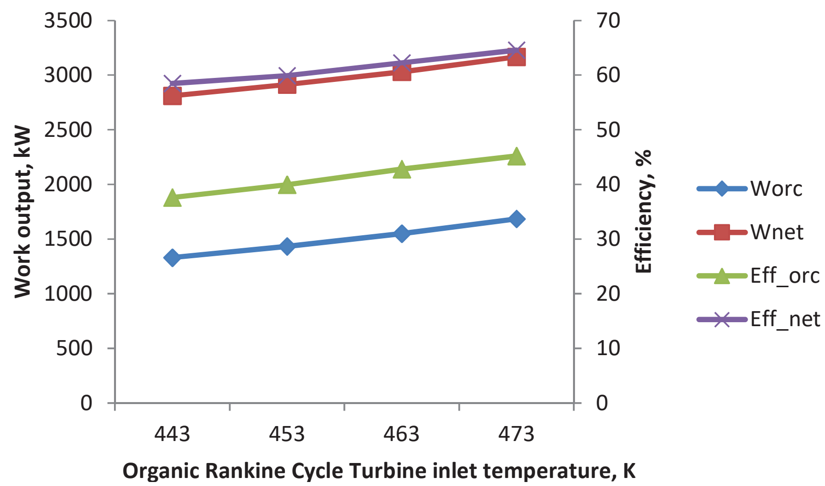


**Figure 4** Effect of the ORC Turbine inlet temperature on work outcome and efficiency of the solar-assisted intercooled GT-ORC hybrid power cycle.

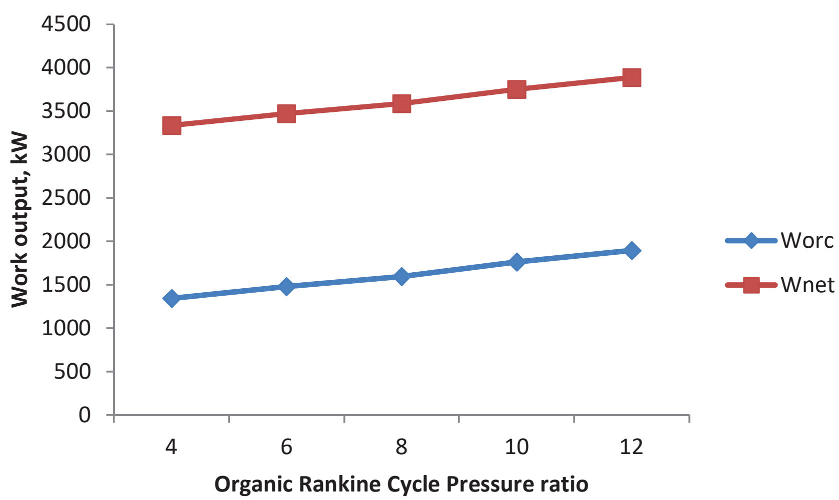


**Figure 5(a)** The effect of the organic Rankine cycle pressure ratio on the work outcome of the solar-assisted intercooled GT-ORC hybrid power cycle.

system. As the ORC's pressure ratio improves then the efficiency of the combined cycle and the work outcome of the combined arrangement as well increases. The calculated value of the work outcome of the ORC increases from 1342.12 kW to 1894.0 kW as the organic Rankine cycle pressure ratio increases from 4 pressure ratio to 12 bar ORC pressure ratio with fixed

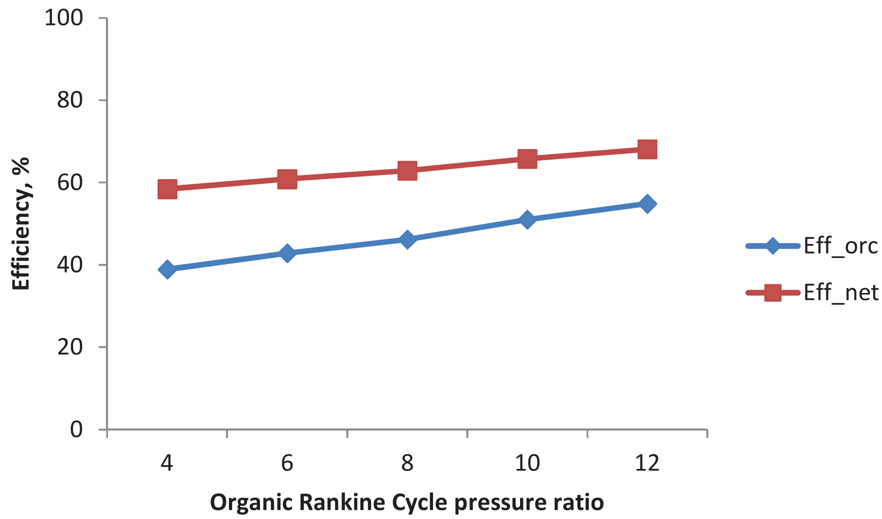


**Figure 5(b)** The effect of the organic Rankine cycle pressure ratio on the efficiency of the solar-assisted intercooled GT-ORC hybrid power cycle.

solar governed gas turbine arrangement pressure ratio 8 bar. Likewise, the total work outcomes of the integrated arrangements have been also improved because of the increase in the work output of the ORC. The solar-driven integrated arrangement work outcome is determined as 3884.5 kW for 12 pressure ratio of ORC. As the continuation of the explanation of Figure 5(b), the effect of the variation of the pressure ratio of ORC on the ORC efficiency & integrated arrangement is determined in the graph which shows the positive consequences of the pressure ratio on the system. Maximum efficiency of the solar-driven combined cycle can be gotten at the 12 bar ORC pressure ratio and 443 K ORC entry turbine temperature, 8 bar pressure ratio at integrated subsystem GT.

The impact of the fluctuation of the solar irradiation on the solar-assisted cycle is shown in Figure 6. The graph shows that the work outcome and efficiency of the solar-driven hybrid arrangement increases as the intensity of solar radiation changes from the lower side to the higher side. As the obtained result shows the minimum work outcome is found to be 3067.6 kW for the 8 cycle pressure ratio, 500 W/m$^2$ solar radiations. The maximum work outcome and efficiency have been evaluated as 3332.62 kW and 59.82% for the 8 cycle pressure ratio and 1100 W/m$^2$ solar irradiation. As the intensity of solar irradiation has been improved then the work outcome of the gas turbine arrangement also improves. The increment in the work outcome of the gas

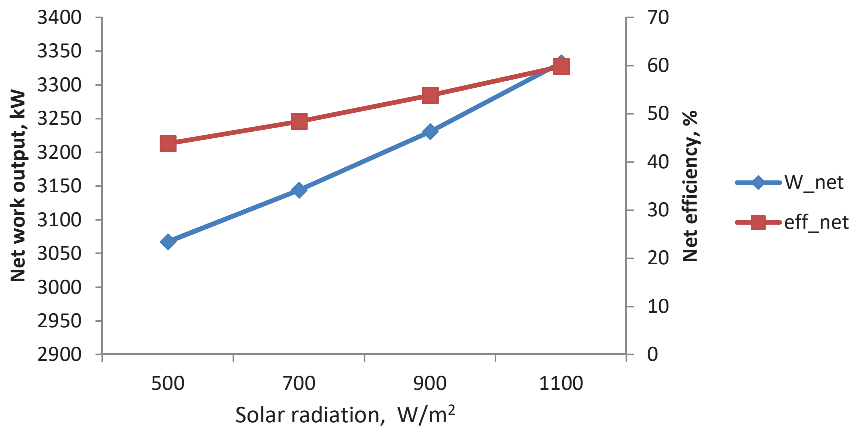


**Figure 6** The effect of the variation of the solar radiation on the net-work output and the net efficiency of the solar-assisted intercooled GT-ORC hybrid power cycle.

**Table 3** Comparison of the present modeling with the published data

| Cycle Pressure Ratio | 8 | 9 | 10 | 11 |
|---|---|---|---|---|
| Work output from the present study in kW | 333.2 | 342.3 | 351.4 | 361.6 |
| Work output from Khan and Mishra study [31] in kW | 275 | 273 | 271 | 269 |

turbine makes a great impact on the system as the net-work outcome increases along with the efficiency of the system.

The exact model of the arrangement of the solar-assisted cycle has not been studied. Therefore, the validation of the arrangement is not possible. The authors have considered the GT-ORC system in reference [31] for the validation purpose of the present system in Table 3.

## 5 Conclusions

The authors have investigated a novel solar powered GT integration system with organic system utilizing the waste heat releasing during different steps from the combined system. After studying this novel type of solar-driven arrangement, the authors have summarized the main point here. They are as follows –

1. The combined arrangement is meant for generating zero pollution in the environment. The integration of the organic Rankine cycle with the solar-assisted gas turbine improves the efficiency and the work output of the combined system.

2. The work outcome of the combined arrangement is 1342.12 kW at the cycle pressure ratio of 8 bar, 4 bar pressure ratio at the ORCT, and 443 K its entry point turbine temperature.
3. The maximum efficiency of the solar-powered combined system has 71.12% at the cycle pressure ratio of 8, 4 bar pressure ratio at the ORCT, and 443 K its entry point turbine temperature.
4. The economic model of the integrated system depicts that the unit power production cost for the combined system has been evaluated as 1932 € per kW.

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