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# Vakum tüplü kollektör kullanan güneş enerjisi destekli organik rankine çevriminin termodinamik analizi

# *Thermodynamic analysis of solar organic rankine cycle using evacuated tubular collector*

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# Thermodynamic Analysis of Solar Organic Rankine Cycle Using Evacuated Tubular Collector

## Highlights

- *Simple SORC thermal efficiency increases as the turbine inlet pressure increases.*
- *Simple SORC efficiency decreases with increasing temperature at turbine inlet for dry fluid R600.*
- *Turbine isentropic efficiency impacts the SORC efficiency significantly.*
- *Required collector area may change depending on the organic working fluid thermophysical properties.*

## Graphical Abstract

*A thermodynamic analysis of a solar organic Rankine cycle with evacuated tubular collector is performed. The required collector area for different months and different source temperatures are determined.*

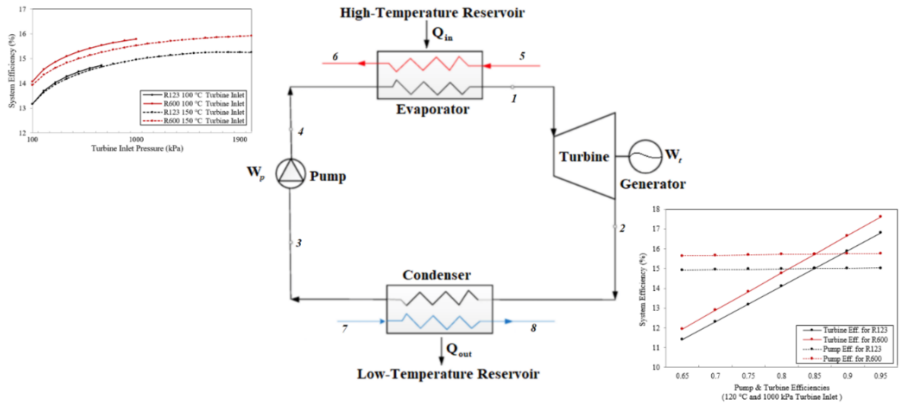


**Figure.** Graphical abstract

## Aim

*The study aims the first law analysis and investigation of the parameters that affect the performance of a solar organic Rankine cycle system.*

## Design & Methodology

*Engineering Equation Solver (EES) software is used to perform the thermodynamic analysis of the system. The solar radiation data on a tilted surface for Antalya is obtained by a computer software developed by the authors.*

## Originality

*The use of evacuated tubular collector in a solar organic Rankine cycle is very limited. The determination of the required collector area for a fixed solar fraction for different months and different organic fluids depending on the solar radiation data is the other novelty of the study.*

## Findings

*The SORC thermal efficiency increases as the turbine inlet pressure increases for both R123 and R600 working fluids. The SORC thermal efficiency decreases with the increase in the turbine inlet temperature for a non-recovery system with dry fluid R600. The turbine isentropic efficiency impacts the SORC efficiency significantly. The SORC with R600 is required more collector area than that with R123 due to the difference in their thermodynamic properties.*

## Conclusion

*Organic Rankine cycle driven by renewable energy sources can be applied in regions that have high solar energy potential such as Antalya.*

## Declaration of Ethical Standards

*The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.*

# Thermodynamic Analysis of Solar Organic Rankine Cycle Using Evacuated Tubular Collector

***Research Article / Araştırma Makalesi***

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## ABSTRACT

This study investigates the affecting parameters for the thermal performance of a Solar Organic Rankine Cycle. The thermodynamic analysis covers the research on the effects of the following parameters: the pressure and temperature of the working fluid at the turbine entrance, and the turbine and pump isentropic efficiencies. The solar organic Rankine cycle is analyzed for an evacuated tubular solar collector. The required collector area for both a fixed value (0.8) of solar fraction and several source (solar collector output) temperatures is also determined for different months of the year in the study. The computer software of Engineering Equation Solver (EES) is used to construct the mathematical model of the cycle and to perform the thermodynamic analysis of the system. In the analysis, R123 and R600 organic fluids are used, and a comparison is made between the two fluids in terms of their effects on the system performance. The results show that R600 has better performance characteristics than R123. The results also show that the system efficiency decreases with increasing temperature at turbine entrance, but with decreasing pressure at turbine entrance. The turbine efficiency influences the system thermal efficiency significantly while the pump efficiency does not have a significant effect on the system thermal efficiency.

**Keywords: Solar air collector, conical spring, fuzzy logic, modeling, outlet temperature, thermal efficiency.**

# Vakum Tüplü Kollektör Kullanan Güneş Enerjisi Destekli Organik Rankine Çevriminin Termodinamik Analizi

## ÖZ

Bu çalışma, güneş enerjisi destekli bir Organik Rankine Çevriminin ısıl performansını etkileyen parametreleri araştırmaktadır. Termodinamik analiz, sırasıyla aşağıdaki parametrelerin etkileri üzerine araştırmayı kapsamaktadır: türbin giriş sıcaklığı ve basıncı ile türbin ve pompa izentropik verimleri. Güneş destekli organik Rankine çevrimi, vakum tüplü güneş kollektörü için analiz edilmiştir. Çalışmada, gerekli kollektör alanı hem sabit bir güneşten yararlanma oranı (0.8) hem de çeşitli kaynak (kollektör çıkış) sıcaklıkları için aylık olarak belirlenmiştir. Çevrimin matematiksel modelini oluşturmak ve sistemin termodinamik analizini yapmak için Engineering Equation Solver (EES) yazılımı kullanılmıştır. Analizde R123 ve R600 organik akışkanları kullanılmış ve iki akışkan arasında sistem performansı açısından bir karşılaştırma yapılmıştır. Sonuçlar, R600'ün R123'ten daha iyi performans özelliklerine sahip olduğunu göstermektedir. Sonuçlar ayrıca türbin giriş sıcaklığının artmasıyla ve türbin giriş basıncının azalmasıyla sistem veriminin düştüğünü göstermektedir. Türbin verimi sistemin ısıl verimini önemli ölçüde etkilerken pompa veriminin ısıl verim üzerinde önemli bir etkisi olmadığı görülmüştür.

**Anahtar Kelimeler: Organik Rankine çevrimi, güneş enerjisi, vakum tüplü kollektör, termodinamik analiz.**

## 1. INTRODUCTION

Alternative energy generating systems become more important to meet the energy demand increasing day by day [1]. Nowadays, instead of developing new technologies, existing technologies that are modified or integrated with alternative energy sources [2] are more preferred to meet the unstoppable energy demand rise [3]. Organic Rankine Cycle (ORC) is a modified version of Rankine Cycle, which is generally known as steam power cycle. The ORC uses organic fluids that have lower evaporation temperatures in comparison to water used in the conventional Rankine Cycle. The low- and medium-temperature sources (65-400 $^{o}$C) such as solar energy, geothermal energy, biomass energy or waste heat [4] can therefore be used in the ORC systems [5].

Electricity generation by ORC systems has attracted much attention from scientific and industrial fields in recent years. The compatibility and utility of renewable energy sources with the ORC have significantly increased the theoretical and experimental studies on the ORC systems. The recent researches on the ORC generally focus on the application of different types of heat source, different types of the organic working fluid, and constructional modifications for system performance improvement. A lot of studies have been performed for

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working fluid selection [6,7]. The performance of several organic working fluids was investigated by Herath et al. [8] and they concluded that Benzene gives significantly higher efficiencies than the others at the evaporator temperatures of 100 °C to 200 °C. The performance of various organic fluids in an ORC system was investigated in another study [9] and toluene showed the best performance with 31.5% system efficiency. Different configurations of the ORC and several system parameters were optimized using the multi-criteria approach by Toffolo et al. [10]. The results showed that the optimal cycle configuration was simple subcritical for isobutane and regenerative supercritical for R134a. The ORC was evaluated for three configurations: basic ORC, reheating ORC, and regenerative ORC system from thermoeconomic standpoints in [11]. The regenerative one had better efficiency while the other two had similarly 13% less efficiency. The basic, recuperative, regenerative, and recuperative-regenerative types of ORC were analyzed from the exergoeconomic point of view [12]. Different sources were examined with the ORC, geothermal energy [13,14], biomass energy [15], waste heat energy [16] and solar energy [17,18] have been integrated with the ORC system in low- and medium-temperature applications.

In the literature, many studies have been conducted on solar-assisted ORC (SORC) systems. The energy, exergy, and thermo-economic analyzes of a SORC system were performed by Jing et al. [19]. The thermodynamic analysis of a regenerative SORC system with flat-plate solar collectors was performed by Man et al. [20]. They obtained better system performances for higher turbine inlet temperatures and lower turbine back pressures. It was also concluded that R123 and R245fa were the best working fluids since they showed higher performances at lower operational pressures. Different types of solar collectors were used in the SORC to find out the best design in another study [21]. Softwares such as Engineering Equation Solver (EES) [22] or MATLAB [23] are usually used to save time and facilitate the calculations performed in the thermodynamic analysis of the ORC system.

In SORCs, different types of solar collectors can be used depending on the desired temperature level. Evacuated tubular collectors have the advantages of high efficiency, less heat loss, attaining 200 ºC temperature [24], not having freezing and overheating problems, and less corrosion. The current studies in the literature on the SORC with evacuated tubular solar collector are limited and insufficient to make a comprehensive evaluation and comparison of it with the other configurations from technical and economical perspectives. In the current study, a thermodynamic analysis of a SORC system with an evacuated tubular solar collector is carried out. The study covers the first law analysis and parametric investigation of significant factors affecting the system performance. EES software is used for solving the mathematical model and performing the parametric investigation. Two different organic working fluids, R123 and R600 are examined for a basic type SORC system. The effects of the pressure and temperature at the turbine entrance, and the isentropic efficiencies of the pump and turbine on the first law efficiency of a basic SORC are investigated in the parametric study. Additionally, the required area of the evacuated tubular solar collector is determined for the months of the year for a fixed value (0.8) of the solar fraction (*SF*). The variation of the required collector area is also explored on a monthly basis for different solar heat source temperatures.

## 2. MATERIAL and METHOD

A basic ORC system contains a pump, an evaporator, a turbine/expander, and a condenser. The pump circulates the organic working fluid throughout the cycle. The evaporator acts as a low-temperature heat reservoir and transfers heat to the working fluid to vaporize it. The turbine/expander generates power output using the thermal energy of the working fluid. The condenser acts as a high-temperature reservoir and rejects heat from the working fluid to the outside of the system so as to return the working fluid to its initial state. The schematic of the ORC is represented in Figure 1. Firstly, the working fluid at low pressure is sent to the evaporator by using the pump. Then the thermal energy of the alternative energy source is transferred to the organic working fluid during the evaporation. In this process, the temperature of the working fluid increases in the evaporator while the temperature of the hot fluid decreases. Thus, the state of the working fluid changes from the liquid phase to the gas phase, and the working fluid in the gas state is sent to the turbine at high temperature and high pressure. The turbine blades start rotating when the superheated working fluid strikes on them, and the generator converts the rotational mechanical energy into electrical energy. In this process, the working fluid expands in the turbine, and its pressure decreases. After the expansion process, the working fluid at low pressure goes to the condenser which acts as a heat exchanger, and its temperature decreases by the secondary cooling fluid in the condenser due to heat interaction. With the temperature decrease, the working fluid is condensed and turns into the saturated liquid phase. In this way, the properties of the working fluid return to the properties at the pump inlet by completing the cycle.

While installing a solar power generation system, the solar energy potential should be taken into consideration for the region of interest where the system is to be installed. Therefore, before the installation of the system, it is essential to measure the solar radiation values in that region or to calculate with theoretical methods. Thus, a feasibility study could be carried out to reveal how reasonable it is to invest in the system. In this study, a computer software, which is developed in another study [25], was used to determine the incident solar radiation on the tilted surface for Antalya. For brevity, the radiation calculations are not presented in this study, and the values of solar radiation were taken directly via the software developed before and are shown in Table 1. In this study, Antalya province is chosen as the region where the system would be installed. The obtained radiation values have significant importance in the determination of the effect of solar heating with evacuated tubular collectors. The solar fraction for the evaporation heat load can be calculated by this way.

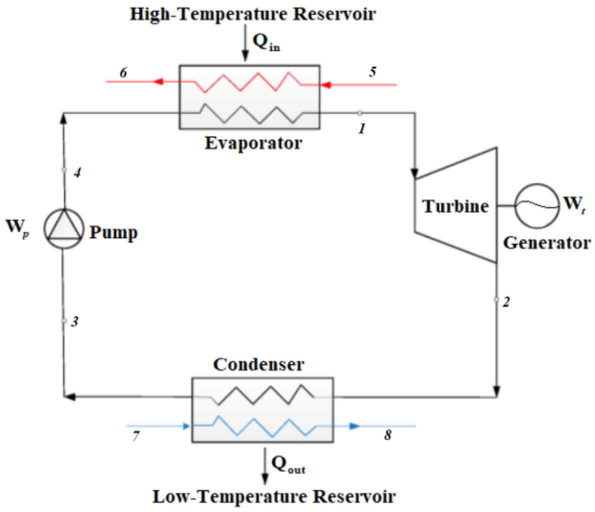



**Figure 1.** Schematic diagram of ORC

In this part, the mathematical model of the SORC system is introduced. The parameters to be calculated at each point in the system, the input parameters, the initial conditions of the system, and the assumptions to be made are first defined. The mathematical model is then introduced to EES software to perform the necessary calculations. The EES software saves time in the parametric study of the system providing ease of calculation. Figure 2 shows T-s diagram of the SORC. The assumptions for the thermodynamic analysis of the SORC system are listed in the following:

- Steady working conditions
- Constant $T_1$ and $P_1$
- Neglected pressure drops in the condenser and evaporator ($P_1=P_4$ and $P_2=P_3$)
- 10 °C higher collector exit temperature ($T_5$) than the turbine inlet temperature ($T_1$)
- Saturated liquid phase at Point 3
- Adiabatic evaporation and condensation
- Neglected heat and head losses along the pipeline
- $F_R(\tau\alpha)$=0.7055 and $U_L(\tau\alpha)$=3.315 for solar calculations (They assumed to be constant for the corresponding temperature range. For different ranges, values may change)
- Superheated region at Point 1
- 2 kg/s mass flowrate of organic working fluid
- Constant pressure ratio in ORC

The enthalpy ($h_1$) and entropy ($s_1$) values at the turbine inlet are determined from thermodynamic property tables for the working fluid. The pressure at the condenser inlet ($P_2$) is calculated by the constant pressure ratio ($r_p=P_1/P_2$).

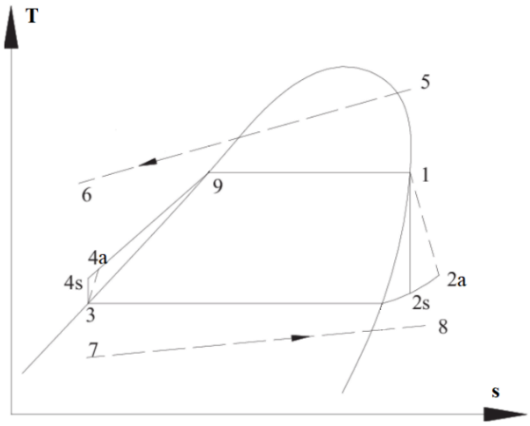



**Figure 2.** T-s diagram of SORC

For the condenser inlet pressure and isentropic expansion process ($s_1=s_{2s}$), the isentropic temperature ($T_{2s}$) and isentropic enthalpy ($h_{2s}$) values of the working fluid at Point 2s can be calculated. The actual enthalpy ($h_{2a}$) and actual temperature ($T_{2a}$) values of Point 2 can be determined by means of thermodynamic relations considering that the turbine efficiency is 0.85. Thus, the turbine work ($w_t$) and turbine power ($\dot{W}_t$) can be determined by using well-known thermodynamics relations. Neglecting the pressure drops in the condenser and evaporator, the pressure values at the inlet and outlet of the condenser and evaporator are considered to be the same ($P_1=P_4$, $P_2=P_3$). Similarly, the pump work ($w_p$) and pump power ($\dot{W}_p$) can be calculated for saturated liquid properties of the working fluid at Point 3.

For isentropic pump ($s_3=s_{4s}$), $T_{4a}$ and $h_{4a}$ are determined and the thermodynamic properties of the organic fluid at each point throughout the cycle are hereby obtained. The evaporation rate of the organic fluid in the evaporator ($\dot{Q}_e$) can be calculated as follows:

$$\dot{Q}_e = \dot{m}_f(h_1 - h_{4a}) \tag{1}$$

where $\dot{m}_f$ is the mass flow rate of the organic fluid. In this power generation system, solar energy is utilized as an alternative energy source by using evacuated tubular solar collector. The equation, which is used to calculate the useful gain from the solar collector ($\dot{Q}_u$), is as follows:

$$\dot{Q}_u = \frac{A_c I_T}{1000}\left[F_R\ \tau\alpha - F_R\ U_L\left(\frac{T_6 - T_0}{I_T}\right)\right] \tag{2}$$

where $T_6$ represents the temperature of the fluid at the inlet collector, $A_c$ is total solar collector area, $I_T$ is solar radiation on the tilted surface, $\tau\alpha$ transmittance-absorptance coefficient, $U_L$ is collector overall heat loss coefficient, $T_0$ is outdoor temperature and $F_R$ is collector heat removal factor. The amount of energy per unit time required for the evaporation of the organic fluid in the evaporator ($\dot{Q}_e$) is provided by both the useful solar energy obtained from the collector and the auxiliary heater. Considering that particular part of the energy required for evaporation is obtained from the solar collector, the solar energy utilization factor (Solar Fraction, *SF*), that is used to express this part, is calculated as follows:

$$SF = \frac{\dot{Q}_u}{\dot{Q}_e} \tag{3}$$

The system thermal efficiency is lastly calculated by:

$$\eta_{th} = \frac{q_e - q_c}{q_e} = \frac{w_t - w_p}{q_e} = \frac{w_{net}}{q_e} \tag{4}$$

800 m$^2$ solar collector area ($A_c$) is taken as the base parameter for the parametric investigations except for the required collector area. The useful energy per unit collector area ($\dot{Q}_u$) has been calculated at different months of the year for Antalya province. The monthly average incident solar radiation on the tilted surface, which is calculated by assuming the monthly average ambient temperature, is given in Table 1.

**Table 1.** Values of parameters used in the radiation calculations

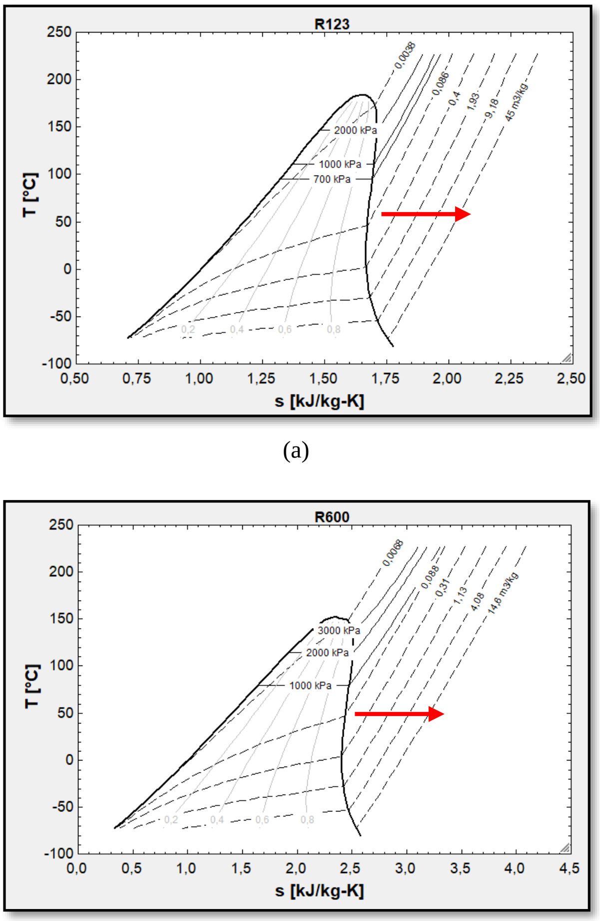
| Months | $T_0$ (ºC) | $I_T$ (W/m$^2$) | $\dot{Q}_u$ (W/m$^2$) |
|---|---|---|---|
| January | 10.0 | 477.67 | 270.70 |
| February | 10.7 | 543.82 | 319.68 |
| March | 12.9 | 621.43 | 381.73 |
| April | 16.4 | 681.82 | 435.94 |
| May | 20.6 | 734.56 | 487.07 |
| June | 25.3 | 764.75 | 523.95 |
| July | 28.4 | 789.12 | 551.42 |
| August | 28.4 | 818.38 | 572.06 |
| September | 25.2 | 786.10 | 538.68 |
| October | 20.5 | 684.80 | 451.63 |
| November | 15.4 | 597.61 | 373.21 |
| December | 11.6 | 470.70 | 271.08 |

In the present study, R123 and R600 organic working fluids are chosen for the SORC system. Using the dry (R600) and isentropic (R123) working fluids provides better system performance and they have already been used frequently in the literature recently. In Table 2, the technical features of these working fluids are given.

## 3. RESULTS AND DISCUSSION

In this investigation, the effects of pressure and temperature at the turbine entrance, turbine efficiency and pump efficiency on system efficiency are explored for R123 and R600 organic fluids, respectively. Moreover, the required solar collector area ($A_c$) was calculated monthly for both working fluid (R123, R600) when solar fraction is constant (*SF*=0.8). Lastly, all the results for each parametric study are compared from diagrams below.

Firstly, T-s diagrams of R123 and R600 given in Figure 3. The state of the working fluid was selected to be in the superheated vapor region at the turbine inlet by considering their T-s diagrams that were plotted by using EES software.




(a)

(b)

**Figure 3.** T-s diagram of a) R123, b) R600

**Table 2.** Properties of selected working fluid for this study [26]

| Working Fluid | Type | Critical Temp. (ºC) | Critical Pressure (MPa) | Normal Boiling Point (ºC) | Safety Group (ASHREA 34) | Atmospheric Lifetime (year) | ODP | GWP (100 year) |
|---|---|---|---|---|---|---|---|---|
| R123 | Isentropic | 183.7 | 3.668 | 27.8 | B1 | 1.3 | 0.02 | 77 |
| R600 | Dry | 152.0 | 3.796 | -0.5 | A3 | 0.018 | 0 | 20 |

### 3.1. Effect of Pressure and Temperature at the Turbine Entrance on the ORC Efficiency

The effect of pressure at turbine entrance on the system efficiency was investigated for 100-2000 kPa turbine inlet pressures and for 100 ºC and 150 ºC turbine inlet temperatures. The investigation was carried out for R123 and R600 organic working fluids. The change of the system efficiency depending on the pressure at the turbine entrance is given in Figure 4. For these turbine inlet temperatures, the range of pressure values were chosen in this interval in order to keep the working fluids in the superheated vapor region.

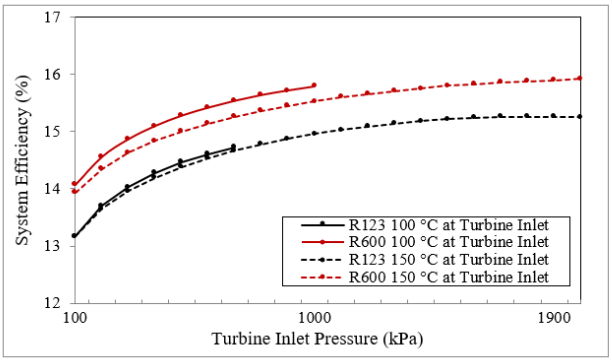



**Figure 4.** Effect of turbine inlet pressure on the system performance at 100 ºC and 150 ºC inlet temperatures

As illustrated in Figure 4, for a constant turbine inlet temperature, it is seen that the system efficiency increases as the turbine inlet pressure increases. As turbine inlet pressure increases at constant turbine inlet temperature, wt and, accordingly wnet decrease (because wp does not change much) while the heat transfer in the evaporator decreases. However, since the drop in the heat transfer in the evaporator is greater than the drop in the wnet, the system efficiency increases. Moreover, when compared to the working fluids each other, R600 rises the system efficiency more than R123 at the same conditions. The efficiency varies from 14.07% to 15.79% in the pressure range of 100-1000 kPa at 100 ºC turbine inlet temperature for R600 and varies from 13.17% to 14.73% in the pressure range of 100-700 kPa at 100 ºC turbine inlet temperature for R123. Besides, the efficiency varies from 13.93% to 15.92% in the pressure range of 100-2000 kPa at 150 ºC turbine inlet temperature for R600 and varies from 13.17% to 15.25% in the pressure range of 100-2000 kPa at 200 ºC turbine inlet temperature for R123. Maximum system efficiency was found as 15.26% and 15.92% for R123 at 150 ºC and 1800 kPa and R600 at 150 ºC and 2000 kPa, respectively. On the other hand, the larger turbine inlet temperature gives rise to the system efficiency to decrease a bit. The reason for that the study covers the simple type of ORC without heat recovery. When making heat recovery with recuperator or regenerator could give different results on the system efficiency [27].

### 3.2. Effect of Turbine and Pump Efficiency on the ORC System Efficiency

The effects of pump and turbine efficiencies on the system efficiency were investigated in the range of 0.65 to 0.95 isentropic efficiencies at 120 ºC and 1000 kPa turbine inlet conditions for R123 and R600 working fluids, separately. The results are represented in Figure 5. As can be seen in Figure 5, while the turbine and pump efficiencies increase, the system efficiency increase. But the pump efficiency has almost no effect on the system efficiency and its slope in the Figure 5 is almost horizontal because $w_p$ is very low compared to the $w_t$. When the change of $w_p$ with the pump efficiency is considered for a fixed turbine efficiency, it is clearly seen that the change can be neglected. However, when the change of $w_t$ with the turbine efficiency is considered for a fixed pump efficiency, there exists a significant change in $w_t$. The higher efficiencies of the pump and turbine cause decrease in the irreversibility in the system. The maximum system efficiency was found as 17.61% for R600 and 16.80% for R123 for 95% turbine efficiency, for a fixed value of %85 pump efficiency. Additionally, the maximum system efficiency was found as 15.75% for R600 and 15.03% for R123 for %95 pump efficiency, for a fixed value 85% turbine efficiency.

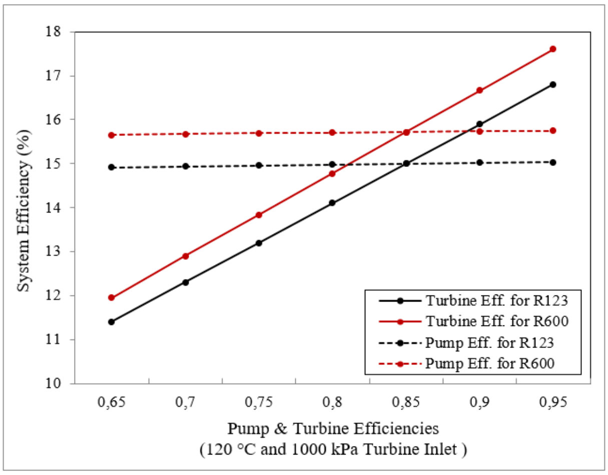



**Figure 5.** Effects of pump and turbine efficiencies on the system performance

### 3.3. Monthly Required Solar Collector Area

The required collector area at each month of the year is shown for R123 and R600 in Figure 6 for the turbine inlet conditions 150 ºC and 1000 kPa. The solar fraction was considered to be constant as *SF*=0.8. The maximum required collector areas with R123 and R600 are 1510.5 m$^2$ and 3889.2 m$^2$ for January, while the minimum required collector areas are 714.8 m$^2$ and 818.4 m$^2$ for August, respectively. As seen in Figure 6, if *SF* is maintained constant as 0.8, the months when the most collector area are demanded are December, January, and February, in the season of winter as expected. On the contrary, the months when the less collector are demanded are July, August, and October. Because when monthly average incident solar radiation increases on July, August, and October, the obtained solar radiation by the solar collector increases. Thus, the required solar collector area at the same conditions decreases by increasing the obtained solar radiation. Moreover, the required collector area with R123 is always less than with R600 at the same month all year round. Despite higher efficiencies with R123, the evaporation load for R123 is lower than that for R600. This may occur due to the difference in their thermodynamic properties.

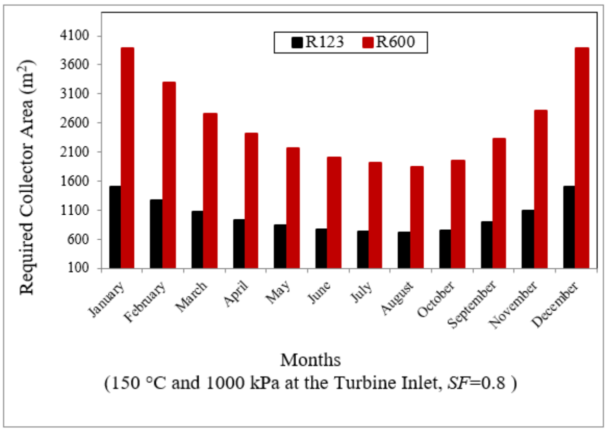



**Figure 6.** Monthly required collector area for R123 and R600

The variation of the solar collector area for different source temperatures for each month of the year with only R600 (for brevity) is shown in Figure 7. The required collector area increases when the source temperature increases as expected. This result is consistent with the other studies in the literature [28]. For higher temperatures of the source, more collector area is required naturally.

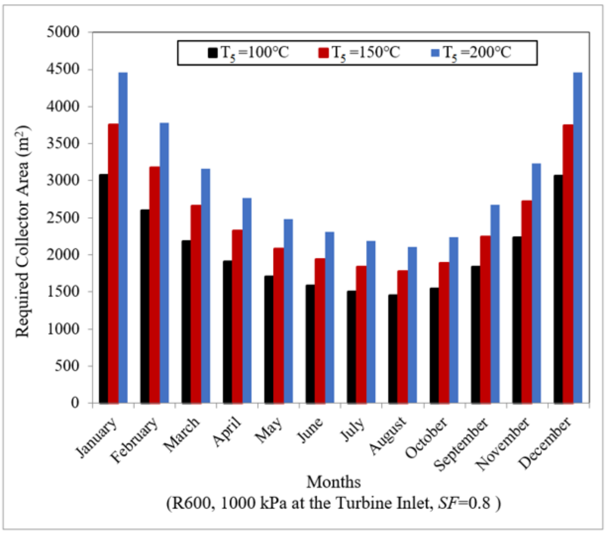



**Figure 7.** Monthly required collector area for R600 at the different source temperatures

## 4. CONCLUSION

A basic SORC system is analyzed for two working fluids and several system parameters using EES program. The effect of pressure and temperature at turbine entrance, and the turbine and pump isentropic efficiencies on the efficiency of the SORC with evacuated tubular solar collector is investigated for R123 and R600 organic fluids. The study also includes the determination of how much collector area is required for a certain value of *SF* and source temperature. The key findings of this study can be summarized as the following:

- The SORC thermal efficiency increases as the turbine inlet pressure increases for both R123 and R600 working fluids.
- The SORC thermal efficiency decreases with the increase in the turbine inlet temperature for a non-recovery system with dry fluid R600. On the other hand, the efficiency is not affected by the turbine inlet temperature for isentropic fluid R123.
- The turbine isentropic efficiency impacts the SORC efficiency significantly while the pump isentropic efficiency does not have a remarkable effect. The SORC efficiency rises from 0.12 to 0.178 when the turbine efficiency rises from 0.65 to 0.95.
- The SORC with R600 required more collector area than that with R123 due to the difference in their thermophysical properties. For a fixed value of solar fraction *SF*=0.8, the collector area requirement increases in the colder season of the year as expected since the radiation intensity is smaller at that period of the year. Additionally, as the temperature of the thermal energy source feeding the evaporator of the SORC increases, the collector area should be increased to reach the desired temperature level.

Consequently, SORC systems are promising alternative electricity production systems and can be solution for the energy supply deficit. Power generating systems driven by renewable and green energy sources can be applied in regions, such as Antalya, that have high solar energy potential.

## DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

## AUTHOR'S CONTRIBUTIONS

**Ahmet ÇAĞLAR:** Literature survey, writing, evaluation of results and revising.

**Mustafa Burak BAHADIR:** Thermodynamic analysis, data processing, artworks and writing.

## CONFLICT OF INTEREST

There is no conflict of interest in this study.

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