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Research Article

Comparison Of The Electricity Generation Potentials Of Solar ORC Designed With Different Fluids Depending On Instantaneous Solar Radiation In Four Districts Of Türkiye

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Abstract

In this study, the solar Organic Rankine Cycle (ORC) system was analyzed to meet some of the electrical energy needed in large and medium-sized buildings and large enterprises such as hotels from solar energy. A simulation study was conducted for different districts in Türkiye that are rich in solar energy potential. These counties and the provinces they are affiliated with; Silifke-İçel, Alanya-Antalya, Bodrum-Muğla, Çeşme-İzmir. The power value transferred to the ORC was determined by considering the instantaneous radiation values and sunshine durations for the districts. The performance of solar ORC was determined by comparing fluids from three different organic fluid types. Organic fluids and types used in design; benzene-aromatic hydrocarbon, cyclohexane-alkane, octamethylcyclotetrasiloxane (D4)-siloxane. Considering the maximum electrical energy values obtained from Solar ORC in the summer months, it was seen that 205 MWh electricity generated was obtained for Silifke with benzene at a heat source temperature of 223 ºC in July. Maximum solar parabolic trough collector (PTC) specific electric power value was determined as 59.52 W/m^2 in Alanya district with benzene in June. When the four districts are evaluated together, it has been determined that benzene performs better than cyclohexane by 3.8% on average and 23% better than D4. When the annual electrical energy values are examined, the highest production was determined as 1625 MWh with benzene fluid in Alanya district.

Keywords: *Annual-monthly produced electricity; organic fluid; solar-organic rankine cycle (ORC); solar energy potential; different district in Turkey.*

1. Aims and Scope

Photovoltaic (PV) panels, which are the most common and practical method of generating power from solar energy, may not be economically advantageous due to their low efficiency and problems such as storage. For this reason, it has been sought to find different methods and new technologies to benefit from solar energy. One of these technologies is the solar-powered Organic Rankine Cycle (ORC) systems, which is a method of producing heat and power efficiently from solar energy. It has been shown in some studies that generating power with the solar ORC system is more economical than PV systems alone, and hybrid power plants created by integrating these two systems will be more efficient [1-3].

In this study, the electricity generation potential of ORC was investigated by conducting a thermodynamic simulation study to meet the electrical energy needed in large enterprises such as hotels with solar ORC. In the calculations, in order to benefit more from solar energy, settlements with intense summer tourism were preferred. Because businesses such as hotels used in summer tourism are actively used in periods when the solar radiation value is high and the demand for electrical energy is higher in these months. For this reason, it is hoped that this research will be an encouraging study in order to increase the energy demand from renewable energy in settlements where the amount of sunshine is high. Studies on the subject in the literature are summarized below.

Jahangir et al. [1] conducted a study on the solar-powered ORC hybrid power plant with a capacity of 80 kW, which will meet the energy needs of 20 families in a city of Iran. The feasibility of this solar-powered ORC system has been made using the exergy and exergoeconomic method. They found that the hybrid ORC-PV system is more economical than the ORC system alone. Kutlu et al. [2], the power generation of an innovative solar energy system combined with a vacuum planar solar collector and amorphous PV cells with ORC was investigated and compared with power systems in different situations. The necessary analyzes for these systems were made in Istanbul according to the hourly solar radiation values in two different days. For July 26, the daily power generation of the innovative power generation system integrated with ORC, which has a solar collector area of 550 m^2 in Istanbul, was calculated as 452.35 kWh.

Patil et al. [3] compared the technical and economic performances of a 50-kW solar-powered ORC power plant and a PV power plant. When compared with energy storage systems for the same region, it has been determined that the solar-powered ORC power plant is more advantageous than the PV power plant. The reduced energy cost of the solar-powered ORC system with 1029 m^2 parabolic trough collector (PTC) area and the working fluid of isobutane is calculated as \$0.19/kWh, and the 1742 m^2 PV system is calculated as \$0.26/kWh.

Cakici et al. [4] conducted a study on integrating a geothermal energy sourced supercritical regenerative ORC power plant with PTC. The solar radiation value was accepted as 800 W/m^2 as the design parameter and the effect of the solar collector area variation between 822 m^2 and 24675 m^2 on the system performance was investigated by considering 5 different organic fluids. R134a showed the best performance among organic fluids. It has been concluded that hybrid ORC power systems with geothermal and solar energy are more advantageous than the ORC power system based on geothermal energy alone.

Yang et al. [5] developed an innovative operating mode for the solar-powered ORC power plant producing 1 MWe of power to be stable and regular in one day. According to the data obtained, it was observed that ORC operating in stable mode within one day had a system efficiency of 4.2% higher than ORC operating in irregular condition due to variable solar radiation values. Ustaoglu et al. [6] stated that R141-b fluid showed preferable performance when evaluated in terms of collector and total system efficiency in solar regenerative ORC studies. With a collector area of 6318 m^2 and an instantaneous radiation value of 1000 W/m^2, a power output of 616.47 kW was obtained from the turbine.

Elakhdar et al. [[7] investigated the effect of solar radiation intensity on cooling and power generation by conducting a study on ORC and ejector cooling system from a low temperature solar energy source for cooling and power generation. Approximately 20% higher cooling performance (COP) was obtained from R601a fluid compared to other fluids. It was concluded that the turbine expansion ratio increased the ejector cooling system efficiency at a high rate. Arteconi et al. [8] used a linear Fresnel collector (LFR) in a micro-scale and solar-powered ORC power plant. In their study, the surface area of the collector, which gives a heat output of 80 kW at a nominal radiation value of 900 W/m^2, was determined as 146 m^2. With this micro-scale ORC system, it has been determined that 4 to 6 houses of 100 m^2 can meet the heating, cooling and hot water needs.

Dragomir-Stanciu et al. [9] investigated the effect of condenser temperature on cycle efficiency in ORC based solar power systems. It was determined that the thermal efficiency increased by 24.76% for the R600 fluid and by 29.78% for the R134a fluid, as the temperature decreased from 25 °C to 10 °C. Petrollese et al. [10] analyzed the Ottana solar power plant located in Italy. The facility consists of 630 kW solar powered ORC and 400 kW concentrator photovoltaic (CPV) systems. Power was produced with ORC from the energy provided by 8592 m^2 linear Fresnel solar collector (LFR). MM fluid from the siloxanes group was preferred as the ORC working fluid. Although the ORC unit operates with a net efficiency of 20.3% under nominal conditions, it has been determined that the cycle is generally far from this efficiency at partial loads since the actual operating conditions are dynamic. Therefore, a new control strategy has been developed to accurately predict the next day's ORC power output of the system, which is affected by the change in ambient temperature and solar radiation values, and to maximize production efficiency.

Roumpedakis et al. [11] conducted a study on evaluating many different scenarios including different fluid types and collector types related to solar-powered ORC for four different regions (Athens, Thessaloniki, Istanbul, and Cyprus) and finding the best scenario for each region. In order to minimize the payback period and maximize the exergy efficiency, multi-purpose genetic algorithm method and optimization technique were applied. The highest exergy efficiency of the system was obtained in Istanbul when the vacuum tube solar collector and R245fa fluid were used.

Atiz and Karakilcik [12] analyzed the system that generates power with ORC by utilizing solar energy throughout the year for Adana climate conditions. In this study, 10 m^2 planar and vacuum tube solar collectors were compared and isobutane was used as the fluid. According to the results obtained, it was noted that when vacuum tube solar collector was used, 350.8 MJ/month was produced with approximately 70% collector efficiency and 6.25% cycle efficiency in July, and the highest turbine inlet temperature was reached with 83.24 °C in this month. Yilmaz et al. [13] designed and analyzed a hybrid power plant using solar and wind energy. To obtain power from solar energy, ORC with a capacity of 195.9 kW, working with a vacuum tube solar collector and R744 working fluid, was preferred.

Cao et al. [14] analyzed a combined solar ORC plant producing cooling, heating, and power. The system has been studied in three different modes: low irradiation state (solar mode), high irradiation state (solar and storage mode) and no solar radiation (thermal storage depletion mode).

Atiz et al. [15] evaluated the performance of an integrated geothermal solar ORC system for hydrogen and power generation relative to n-pentane, n-hexane, n-butane and cyclohexane fluids. The ORC power system has been tested according to the hourly solar irradiance values on a clear and sunny day in July for the province of Manisa. According to the results obtained, the best performance was obtained with n-butane fluid with a flow rate of 0.4 kg/s.

Aghaziarati and Aghdam [16] proposed a solar ORC system integrated with a cascade cooling system to meet the heating, cooling and electricity needs of a four-storey hospital. The effects of different ORC fluids, solar radiation variation, different type of collector and ambient temperature variation were investigated. PTC as solar collector and cyclohexane as organic fluid gave the best results for this system. Mahmood and Al-Ansari [17] studied greenhouse production with renewable energy, which is an innovative and sustainable project. They determined that 1.03 MW electricity, 4.36 MW cooling load and 17.5-27.3 m^3/day water production required by the greenhouse to grow plants throughout the year can be provided by the combined power system.

Desai et al. [18] proposed a solar-powered ORC system as a cheap and feasible project, which could be a solution to the energy and water problem. Among the five different fluids (cyclopentane, n-pentane, MM, isopentane and MDM) compared, cyclopentane was found to be the most suitable circulating fluid. The reduced electricity and freshwater generation cost of the 1 MWe power plant is £0.116/kWh and £1.13/m^3 for a region in Chile, and £0.163/kWh and £1.62/m^3 for a region in South Africa, respectively.

Ancona et al. [19] investigated the performance of low-GWP fluids (R1234yf, R1234ze(E), R1243zf, R513A, R515A) as an alternative to R134a in their micro-solar-ORC study. The performance of these fluids was found to be lower than R134a due to the small isentropic enthalpy drop in the turbine and high pump consumption. They found that while R134a met 39% of the family's electricity needs, it met 17.5% of R513A (best low-GWP fluid). However, they suggested examining the methods of increasing their performance due to their superior environmental properties.

Aryanfar et al. [20] performed the energy, exergy, and economic analysis of the PTC-ORC- vapor compression cycle combined system. They compared the performance of R245fa, R114, R600 and R142b. They found that the minimum exergy destruction occurred in R245fa, and the minimum cost in R114 (for 137 ºC turbine inlet temperature) and R142b (for 2500 kPa turbine inlet pressure).

Mirjavadi et al. [21] compared the performance of Steam Rankine Cycle (SRC)-ORC and SRC-Kalina Cycle (KC) combinations under PTC heat source. Although the two systems have different sensitivities to turbine inlet and outlet pressure changes, they stated that the two systems are equal from an economic point of view. They determined that the levelized costs of energy for both systems were 0.011 $/kWh. Rostami et al. [22] examined the production system with PTC, PEM fuel cell, ORC, alkaline electrolysis, and TEG unit. They found that 140.8 kW of thermal power was provided from PTC, resulting in 22.5 kW of electricity and 97.3 kg of hydrogen per hour.

Kara [23] studied recuperated ORC using toluene, cyclohexane, and isopentane with PTC using Therminol 66. It was determined that the efficiency increase with the decrease of the condenser temperature. With the hourly analysis carried out on January 15 and June 15, the thermal efficiency was determined as 29.97% and 28.08%, respectively. Pourmoghadam and Kasaeian [24] studied the solar multi-generation system with PTC heat source. They determined that the solar unit consisting of PTC collector and Phase Change Material (PCM) storage tank constitutes 60.5% of the total initial cost. They achieved the best performance with toluene fluid in ORC unit. The payback period of the system was determined as 6 years.

Khalid and Kumar [25] investigated the production of electricity, cooling, water and hydrogen by ORC and vapor compression refrigeration cycles with PTC as the heat source. They have reached 17.5% energy efficiency under 2000 m^2 PTC and 700 W/m^2 radiation. Alshammari et al. [26] investigated the radial turbine model in solar ORC with PTC. They found that an increase in evaporator pressure by 100 kPa resulted in a 17.5% decrease in turbine size. Kara [27] studied PTC solar and ground cooling performance in three different ORC configurations (basic, single-stage regenerative and double-stage regenerative). He compared the annual electricity production values in different regions of Turkey. They determined 4151, 3965, 3286 and 2847 kWh/years values for Antalya, Izmir, Istanbul and Trabzon, respectively.

In this study, the prominent fluids from three different fluid groups as a result of the literature research were compared. For aromatic hydrocarbons, Yagli et al. [28], Vaja and Gambarotta [29], Carcasci et al. [30], Herath et al. [31] suggested benzene; for alkanes, Tzivanidis et al. [32], Song and Gu [33], Xu et al.[34] cyclohexane; for siloxanes, Uusitalo et al. [35], Delgado-Torres and García-Rodríguez [36], Liang et al. [37] D4 fluid in their study. Therefore, in this study, it is aimed to determine the performance of these three fluids in the solar-ORC configuration.

When the literature studies are examined, no study has been found that determines the annual electricity energy that can be produced for Turkey, which has a significant solar energy potential, by considering the instantaneous radiation value and sunshine duration of the region with the solar ORC system designed with different fluids. Since this electrical energy to be produced changes depending on the organic fluid, it has been seen that both the solar capacity of the region and the thermophysical state of the organic fluid should be examined together.

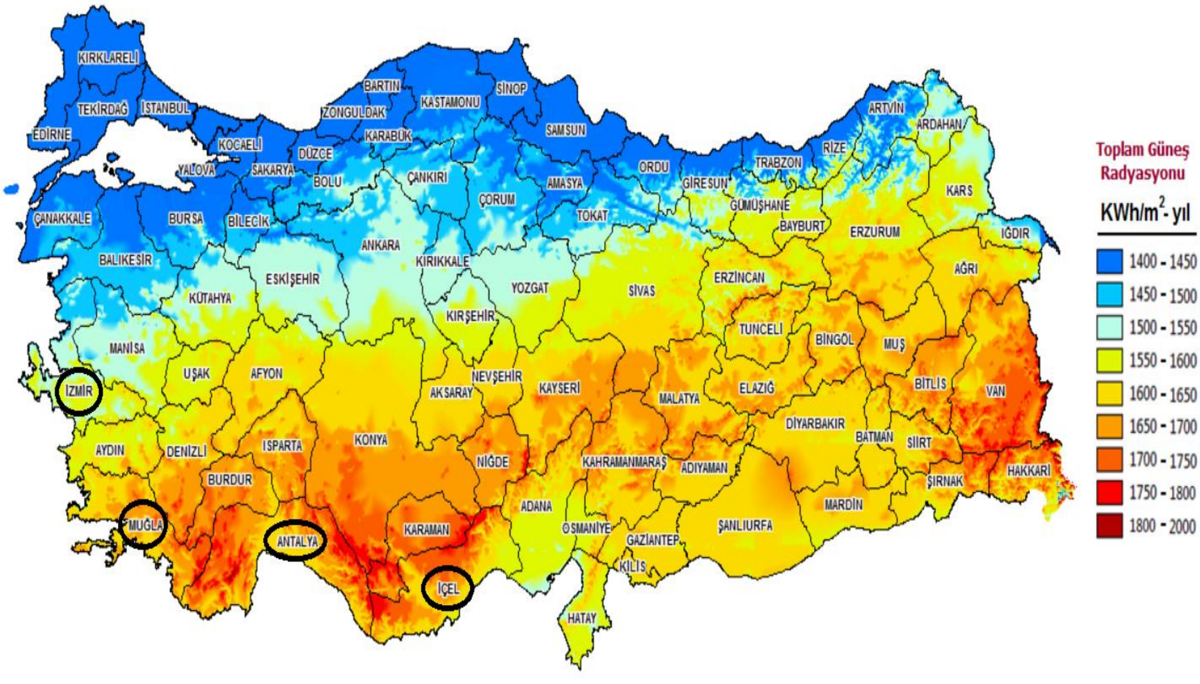

Figure 1. Turkey's Solar Energy Potential Atlas (The provinces of the examined districts are shown on the map)[38].

In this study, it is discussed that some of the electrical energy needed in large and medium-sized buildings and large enterprises such as hotels is met from solar energy. By using 3 different organic fluids in the ORC power system, 4 different districts rich in solar energy potential were simulated and the electricity generation potential of ORC was examined.

These counties and the provinces they are affiliated with; Silifke-İçel, Alanya-Antalya, Bodrum-Muğla, Çeşme-İzmir. Turkey's solar energy potential atlas and the provinces of the examined districts are given in Figure 1.

The performance of different types of organic fluids was determined in the Solar ORC system. Organic fluids and types used in design; benzene-aromatic hydrocarbon, cyclohexane-alkane, D4-siloxane.

Solar ORC was simulated with Engineering Equation Solver (EES). A solar-ORC system has been simulated that can generate 175-200 MWh of electrical energy per month and 1250-1650 MWh of electrical energy annually during the summer months.

2. Materials and Methods

In Figure 2, the working principle of the solar ORC system is given. A fluid from three different organic fluid groups was used in the design. T-s diagrams of organic fluids are given in Figure 3. The thermophysical and environmental properties of the fluids are given in Table 1. It is seen that benzene and cyclohexane are close to each other at critical temperature values, while D4 has a higher critical temperature. All three fluids are in the dry fluid category and D4 has more molecular weight and boiling point temperature. It is seen that benzene and cyclohexane show closer properties in terms of thermophysical properties. When the safety values are examined according to the National Fire Protection Association (NFPA) classification, it is seen that cyclohexane is better for health hazard.

Solar ORC simulation was done with EES. ORC thermodynamic analysis and solar collector calculations are given below Eqs. (1)-(17) . Characteristics of the IST PTC system are given in Table 2.

Mass and Energy Balance [43];

$$\sum_i \dot{m}_{in} = \sum_i \dot{m}_{out} \quad (1)$$

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = 0 \quad (2)$$

Turbine and Pump;

$$\eta_t = \frac{(h_3 - h_4)}{(h_3 - h_{4s})} \quad (3)$$

$$\eta_p = \frac{(h_{2s} - h_1)}{(h_2 - h_1)} \quad (4)$$

$$W_t = \dot{m}_{ORC} x (h_3 - h_{4s}) * \eta_t \quad (5)$$

$$W_p = \dot{m}_{ORC} x (h_{2s} - h_1) / \eta_p \quad (6)$$

Evaporator and Condenser-Pinch Point Analysis;

$$\Delta T_{pp,e} = T_{p,e} - T_{3,f} \quad (7)$$

$$\Delta T_{pp,c} = T_{1,g} - T_{p,c} \quad (8)$$

$$Q_c = \dot{m}_{ORC} x (h_4 - h_1) \quad (9)$$

$$Q_e = \dot{m}_{ORC} x (h_3 - h_2) = \dot{m}_{solar} x (h_{h,i} - h_{h,o}) \quad (10)$$

Solar Collector Analysis [32];

$$\eta_c = \alpha_0 - \alpha_1 * \frac{T_{h,i} - T_0}{G} - \alpha_2 * \frac{(T_{h,i} - T_0)2}{G} \quad (11)$$

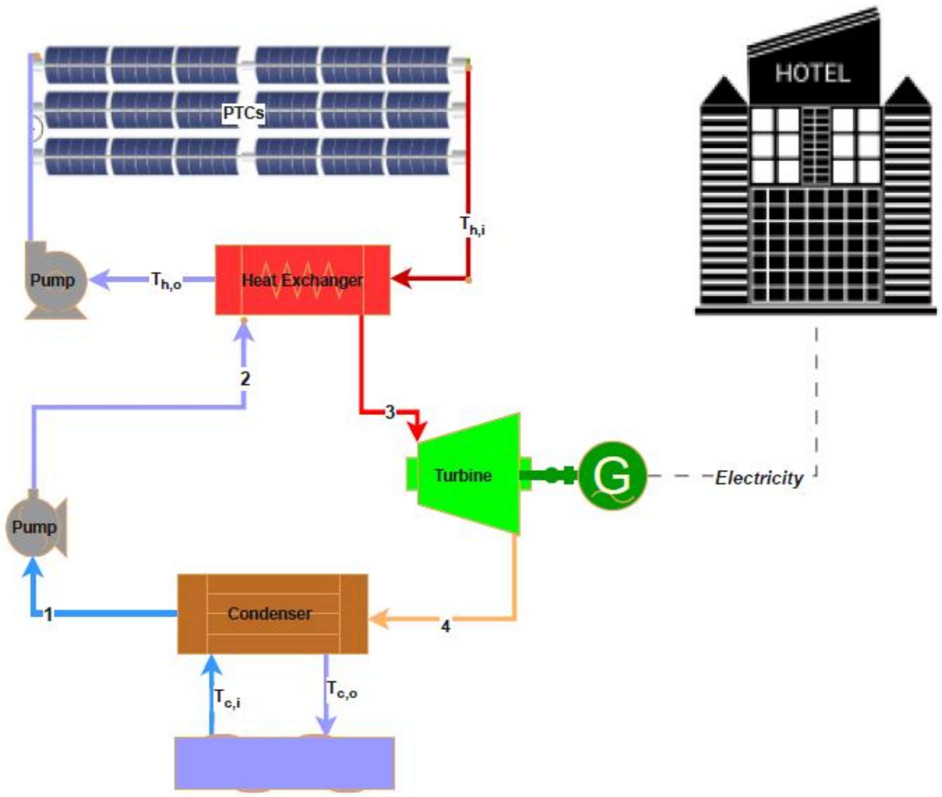

Figure 2. Solar ORC Working Principle.

Table 1. Thermophysical properties of fluids [36,39-41].

Properties/Fluid	Benzene	Cyclohexane	D4
Fluid Group	Aromatic Hydrocarbon	Alkane	Siloxane
Fluid Type	Dry	Dry	Dry
Molecular structure	C_6H_6	C_6H_{12}	$C_8H_{24}O_4Si_4$
CAS Number	71-43-2	110-82-7	556-67-2
Critical Temperature (ºC)	288.9	280.5	313.3
Critical Pressure (kPa)	4.89	4.081	1.332
Molecular Weight (kg/kmol)	78.11	84.16	296.6
Boiling Point (ºC)	80.2	80.9	175.35
Melting Point (ºC)	6.8	6.5	17
Flash Point (ºC)	-11	-18	51
Autoignition Temperature (ºC)	498	260	400
Specific Gravity	0.95	0.77	0.956
*Health	3	1	2
*Flammability	3	3	2
*Instability	0	0	0
GWP	3-4	4-6	n.a

** Safety information according to NFPA classification*
For health hazard; 0: Normal Material; 1: Slightly Hazardous; 2: Hazardous; 3: Extreme Danger; 4 Danger.
For fire hazard; 0: Will not burn; 1: Above 93.33 °C; 2: Below 93.33 °C; 3: Below 37.78 °C; 4 Below 22.77 °C.
For instability hazard; 0: Stable; 1: Unstable if heated; 2: Violent chemical change; 3: Shock and heat may detonate; 4 May detonate.

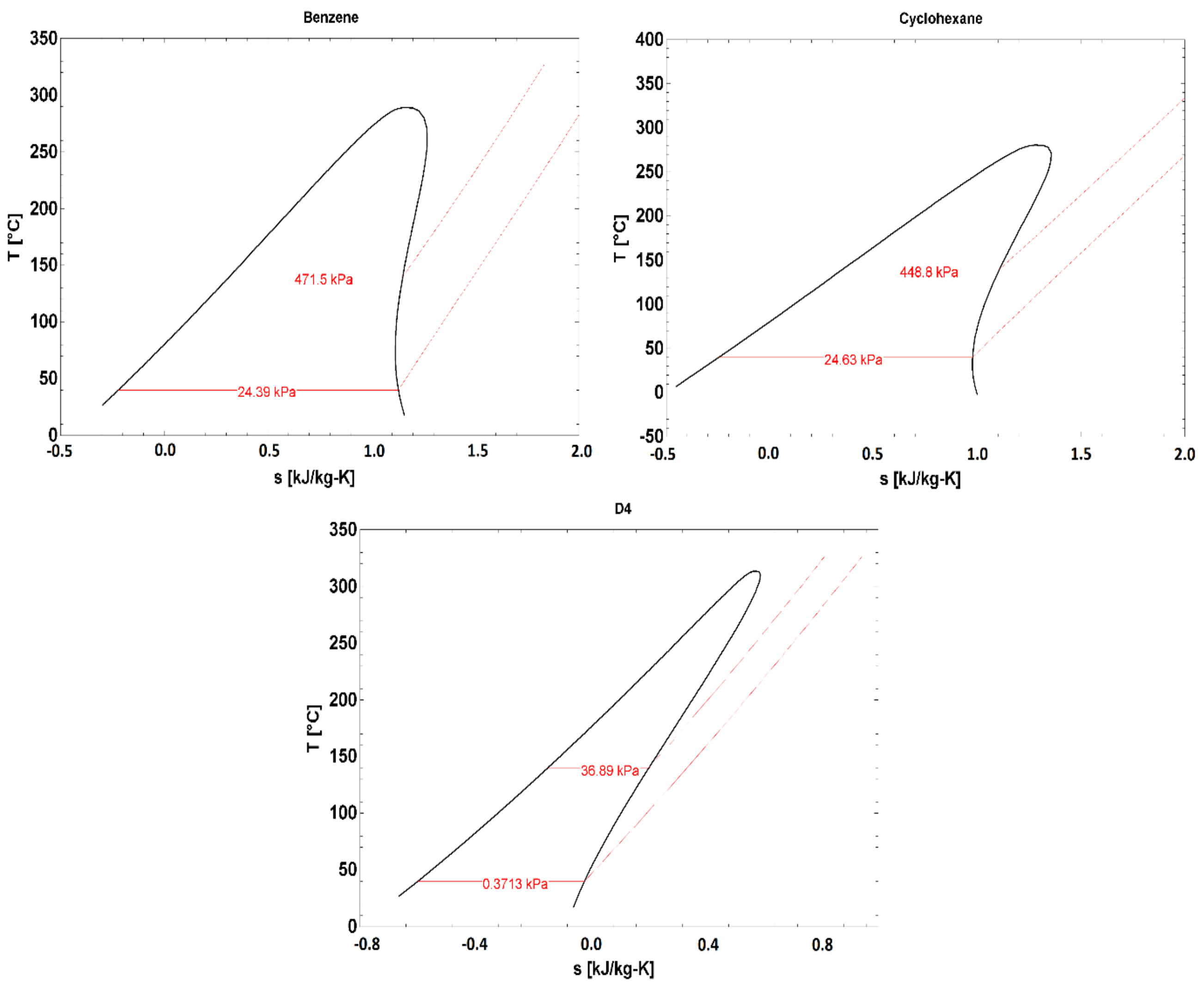

Figure 3. T-s diagrams of organic fluids used in design with evaporating and condensing pressure (Benzene, cyclohexane and D4)[42].

Table 2. Characteristics of the IST PTC system [32,44].

Efficiency Coefficient α_0	0.762
First Heat Loss Coefficient α_1 (W/m^{2}K)	0.2125
Second Heat Loss Coefficient α_2 (W/m^{2}K)	0.001672

$$Q_e = \mathrm{G} \times A_c \, x \, \eta_c = \dot{m}_{solar} x\left(h_{\mathrm{h,i}} - h_{\mathrm{h,o}}\right) \quad (12)$$

To calculate the year-round power generation of this ORC system locally under variable solar irradiance values, daily global irradiance intensity values, averaged over months, were used. Accordingly, the average instantaneous radiation values for each month were obtained as in Equation 13.

$$G = \ (E_g/t_g) \, x1000 \quad (13)$$

Here, E_g shows the average daily solar irradiation intensity (kWh/m^2-day) in a month, tg shows the daily sunshine duration (hours/day) in the same month. In the calculations, the average G value of each month was used as W/m^2.

The average daily solar radiation intensity values (a) and sunshine durations (b) for four districts in Turkey are given in Figure 4-7. Calculations of instantaneous radiation values for four districts are also shown in Table 3-6.

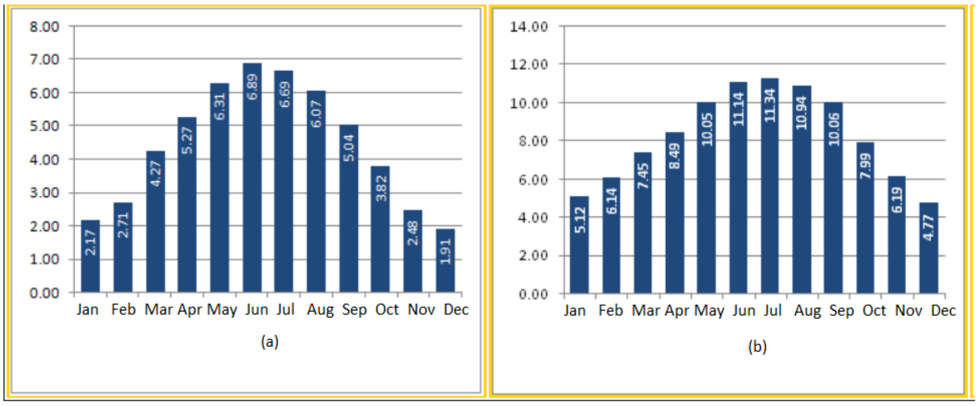

Figure 4. Average daily solar radiation intensity values for Silifke-kWh/m^2-day (a) and sunshine duration-hour (b) [38].

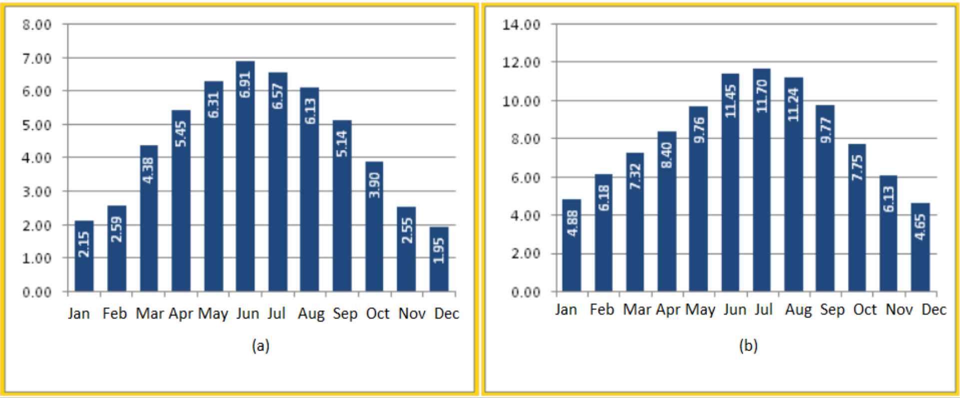

Figure 5. Average daily solar radiation intensity values for Alanya-kWh/m^2-day (a) and sunshine duration-hour (b) [38].

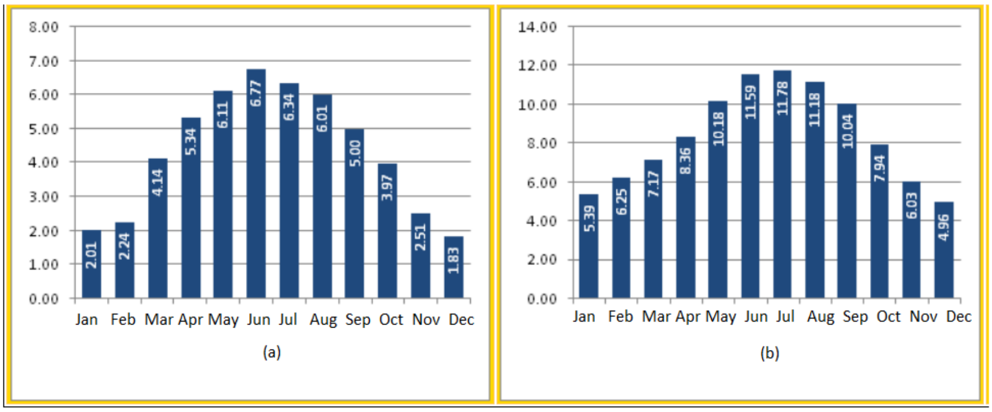

Figure 6. Average daily solar radiation intensity values for Bodrum-kWh/m^2-day (a) and sunshine duration-hour (b) [38].

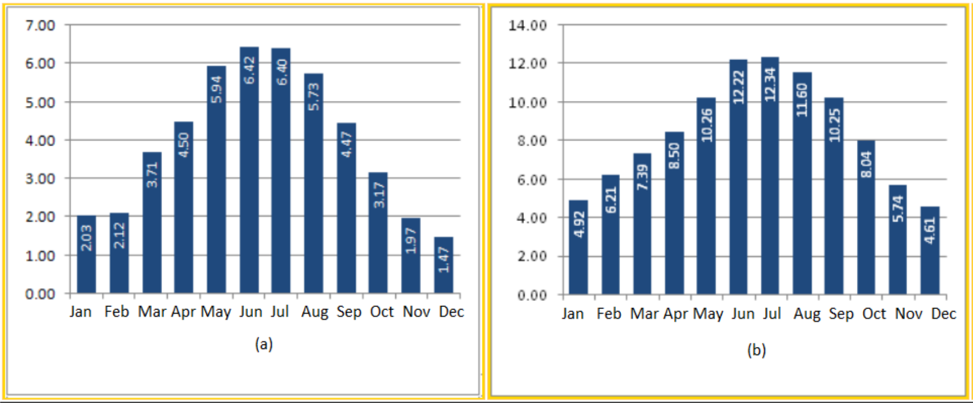

Figure 7. Average daily solar radiation intensity values for Çeşme-kWh/m²-day (a) and sunshine duration-hour (b) [38].

Table 3. Average instantaneous radiation values for Silifke.

SİLİFKE	Jun	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Sunbathing Time t_g [hour/day]	5.12	6.14	7.45	8.49	10.05	11.14	11.34	10.94	10.06	7.99	6.19	4.77
Monthly Average Irradiation values E_g (kWh/m^2-day)	2.17	2.71	4.27	5.27	6.31	6.89	6.69	6.07	5.04	3.82	2.48	1.91
Instant average radiation value $G = (E_g/t_g)*1000$ [W/m^2]	424	441	573	621	628	618	590	555	501	478	401	400

Table 4. Average instantaneous radiation values for Alanya.

ALANYA	Jun	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Sunbathing Time t_g [hour/day]	4.9	6.2	7.3	8.4	9.8	11.5	11.7	11.2	9.8	7.8	6.1	4.7
Monthly Average Irradiation values E_g (kWh/m^2-day)	2.2	2.6	4.4	5.5	6.3	6.9	6.6	6.1	5.1	3.9	2.6	2.0
Instant average radiation value $G = (E_g/t_g)*1000$ [W/m^2]	441	419	598	649	647	603	562	545	526	503	416	419

Table 5. Average instantaneous radiation values for Bodrum.

BODRUM	Jun	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Sunbathing Time t_g [hour/day]	5.39	6.25	7.17	8.36	10.18	11.59	11.78	11.18	10.04	7.94	6.03	4.96
Monthly Average Irradiation values E_g (kWh/m^2-day)	2.01	2.24	4.14	5.34	6.11	6.77	6.34	6.01	5	3.97	2.51	1.83
Instant average radiation value $G = (E_g/t_g)*1000$ [W/m^2]	373	358	577	639	600	584	538	538	498	500	416	369

Table 6. Average instantaneous radiation values for Çeşme.

ÇEŞME	Jun	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Sunbathing Time t_g [hour/day]	4.92	6.21	7.39	8.5	10.26	12.22	12.34	11.6	10.25	8.04	5.74	4.61
Monthly Average Irradiation values E_g (kWh/m^2-day)	2.03	2.12	3.71	4.5	5.94	6.42	6.4	5.73	4.47	3.17	1.97	1.47
Instant average radiation value $G = (E_g/t_g)*1000$ [W/m^2]	413	341	502	529	579	525	519	494	436	394	343	319

Net Power and Efficiency;

$$W_{net} = W_t - W_p \tag{14}$$

$$\eta_{ORC} = W_{net}/\dot{Q}_e \tag{15}$$

Solar System Efficiency;

$$\eta_{solar} = \eta_{ORC}\ x\ \eta_c \quad (16)$$

Power supplied from solar energy and produced per square meter of solar collector area- Specific Power-Collector (SPc);

$$SP_c = \eta_{solar}\ x\ G\ [W/m^2] \quad (17)$$

Design values are given in Table 7. The assumptions made in thermodynamic analysis; steady state process, heat exchangers, turbine, and pump adiabatic, kinetic, and potential energy changes are neglected. Solar collector efficiency is assumed to be unaffected by ambient temperature. Turbine, pump, generator, and solar collector efficiencies are assumed constant over all operating ranges. Pressure losses and friction in heat exchangers and pipes has been neglecting.

Table 7. Design values for Solar-ORC.

Parameter	Value	Unit
Expander efficiency [45]	0.7	-
Pump efficiency [45]	0.7	-
Evaporating temperature [45]	140	ºC
Evaporator pinch point temperature difference [46]	20	ºC
Condenser pinch point temperature difference [47]	5	ºC
Cooling water temperature difference [47]	5	ºC
Ambient temperature	25	ºC
Ambient pressure	101	kPa
Solar mass flow rate	10	kg/s
Collector Area [48-49]	10000	m^2

3. Result and Discussion

In this section, simulation results of monthly electricity production values of solar ORC designed using three different organic fluids are presented.

Considering the thermophysical properties of organic fluids, it is seen that the heat input per unit mass (enthalpy difference) is less in D4 fluid than in the others. Therefore, the required flow rate for D4 is higher at the same evaporator capacity.

Under the same evaporator capacity, the highest power was obtained in the benzene fluid, although the heat input per unit mass was higher and the flow rate was lower than the others.

Despite the low flow rate in the benzene fluid, the turbine power was found to be higher due to the high enthalpy drop in the turbine. The fact that the pump work was more than D4 also did not affect the net power. Therefore, the net power order was determined as benzene>cyclohexane>D4.

In Figure 8, monthly electricity generated for Silifke district is given. Unlike Alanya district, the highest production value was realized in July, albeit with a small difference. In July, 205 MWh was obtained with benzene, 197 MWh with cyclohexane, and 165 MWh with D4. It was determined that a maximum power of 619 kW was obtained with benzene, while a power of 596 kW was obtained with cyclohexane. When ORC mass flow rates are examined, it is noteworthy that D4 has a mass flow rate of 75% more than other fluids. Maximum performance (205 MWh/month) for Silifke was reached in July under 589.9 W/m^2 radiation and 11.34 h sunbathing time. Under these conditions, the evaporator capacity was determined as 4130 kW (Table 8).

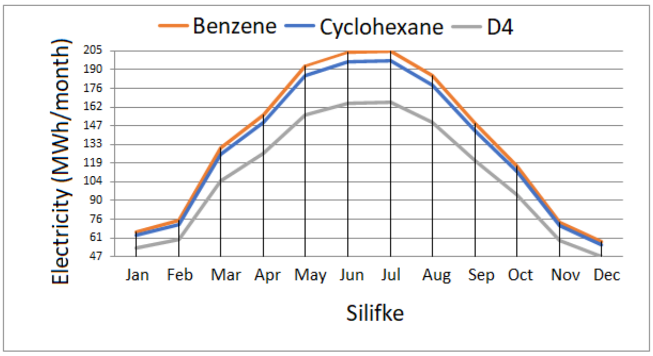

Figure 8. Distribution of electrical energy (MWh) produced by months when three different fluids are used for Silifke.

In Figure 9, monthly electricity generation for Alanya district is given. The highest production values were realized in June. In June, 204 MWh was obtained with benzene, 196 MWh with cyclohexane, and 165 MWh with D4. It was determined that maximum 638 kW power was obtained with benzene, while 614 kW power was obtained with cyclohexane. It was determined that while higher power was obtained with benzene, the mass flow rate required for ORC was also less than cyclohexane. While it is 7.83 kg/s for benzene, it is 8.01 kg/s for cyclohexane for July. Maximum performance (204 MWh/month) for Alanya was reached in June under 603.5 W/m2 radiation and 11.45 hour/day sunbathing time. Under these conditions, the evaporator capacity was determined as 4224 kW. (Table 9).

When Table 8 and Table 9 are examined for the benzene fluid with maximum performance;

In June, more net power was obtained in Silifke than in Alanya due to the higher radiation, consequently higher evaporator capacity, under same evaporation-condensing temperature. However, when the electricity produced by taking into account the sunshine durations is compared, it is seen that Alanya is more.

In July, although the radiation, accordingly evaporator capacity, for both districts decreased and the sunshine duration increased, the produced electricity in Silifke increased while it decreased in Alanya. Although the rate of increase in sunshine durations is close, the produced electricity in Silifke increased in July as the radiation decreased to a lesser extent.

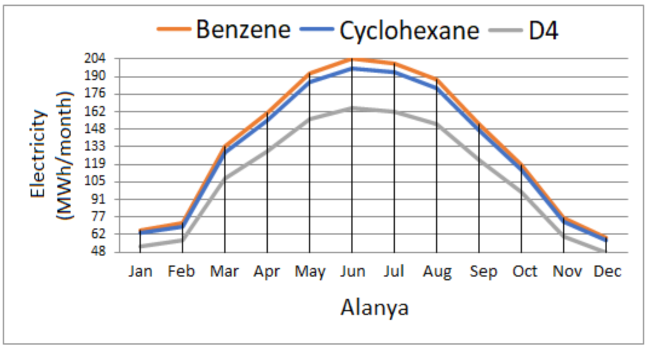

Figure 9. Distribution of electrical energy (MWh) produced by months when three different fluids are used for Alanya.

Table 8. Monthly average power (kW) and energy amounts (MWh) produced with ORC when different circulation fluids are used for Silifke in summer.

Organic Fluids	Month	Day Number	Sunbathing Time (hour/day)	G (W/m^2)	$\dot{m}_{ORC}$ (kg/s)	$T_{h,i}$ (°C)	$W_{net,ave}$ (kW)	Electricity (MWh/month)
Benzene	May	31	10.05	627.9	8.15	227	619.3	192.94
	June	30	11.14	618.5	8.03	226	610.0	203.86
	July	31	11.34	589.9	7.66	223	581.9	204.56
	August	31	10.94	554.8	7.20	220	547.3	185.61
Cyclohexane	May	31	10.05	627.9	8.33	221	596.3	185.78
	June	30	11.14	618.5	8.21	221	587.4	196.31
	July	31	11.34	589.9	7.83	218	560.3	196.97
	August	31	10.94	554.8	7.36	214	527.0	178.73
D4	May	31	10.05	627.9	14.24	209	500.3	155.87
	June	30	11.14	618.5	14.02	209	492.9	164.73
	July	31	11.34	589.9	13.38	206	470.1	165.26
	August	31	10.94	554.8	12.58	204	442.1	149.93

Table 9. Monthly average power (kW) and energy amounts (MWh) produced with ORC when different circulation fluids are used for Alanya in summer.

Organic Fluids	Month	Day Number	Sunbathing Time (hour/day)	G (W/m^2)	$\dot{m}_{ORC}$ (kg/s)	$T_{h,i}$ (°C)	$W_{net,ave}$ (kW)	Electricity (MWh/month)
Benzene	May	31	9.76	646.50	8.39	229.30	637.70	192.94
	June	30	11.45	603.50	7.83	224.70	595.20	204.45
	July	31	11.70	561.50	7.29	220.20	553.90	200.90
	August	31	11.24	545.40	7.08	218.40	537.90	187.43
Cyclohexane	May	31	9.76	646.50	8.58	223.30	614.00	185.77
	June	30	11.45	603.50	8.01	219.10	573.20	196.89
	July	31	11.70	561.50	7.45	214.90	533.30	193.43
	August	31	11.24	545.40	7.24	213.40	518.00	180.49
D4	May	31	9.76	646.50	14.66	210.80	515.20	155.88
	June	30	11.45	603.50	13.68	207.40	480.90	165.19
	July	31	11.70	561.50	12.73	204.10	447.50	162.31
	August	31	11.24	545.40	12.37	202.80	434.60	151.43

In Figure 10, monthly electricity generation for Bodrum district is given. The highest production values were realized in June. Unlike Alanya and Silifke, there is a difference of approximately 7 MWh between the electricity produced in June and July. In June, 200 MWh was obtained with benzene, 192 MWh with cyclohexane, and 161 MWh with D4. It was determined that a maximum power of 592 kW was obtained with benzene, while a power of 570 kW was obtained with cyclohexane. Although the mass flow rates of benzene and cyclohexane are close, the required flow rate for benzene is lower.

Maximum performance (200 MWh/month) for Bodrum was reached in June under 584.1 W/m^2 radiation and 11.59 sunbathing time. Under these conditions, the evaporator capacity was determined as 4089 kW. (Table 10).

In Figure 11, monthly electricity generated for Çeşme district is given. The highest production values were realized in July. While there was an overproduction of 7 MWh in Bodrum in June, it was observed that there was an excess of 6 MWh in July in Çeşme. In July, 195 MWh was obtained with benzene, 188 MWh with cyclohexane, and 158 MWh with D4. It was determined that a maximum power of 571 kW was obtained with benzene, while a power of 549 kW was obtained with cyclohexane. Maximum performance (196 MWh/month) for Çeşme was reached in July under 518.6 W/m^2 radiation and 12.34 sunbathing time. Under these conditions, the evaporator capacity was determined as 3630 kW (Table 11).

When all districts were examined, the best performance was obtained in benzene fluid under the same evaporator capacity.

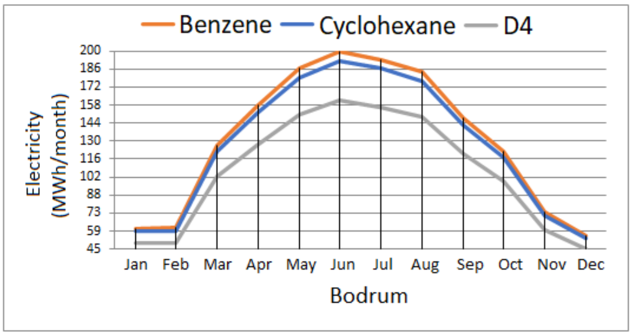

Figure 10. Distribution of electrical energy (MWh) produced by months when three different fluids are used for Bodrum.

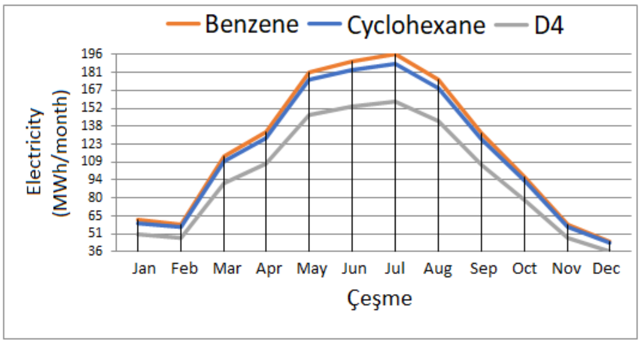

Figure 11. Distribution of electrical energy (MWh) produced by months when three different fluids are used for Çeşme.

It has been observed that the benzene fluid achieves the best performance in different districts. The purpose of comparison in different districts is to examine the effect of radiation and sunbathing time on net power and monthly electricity produced. It is seen that the energy transferred to the evaporator due to the high radiation is high for Silifke. In the same evaporation-condensation temperature conditions, the system mass flow rate was higher, so more net power generation was realized. On the other hand, the monthly electricity produced was determined by considering the sunbathing time. If we examine the districts of Bodrum and Çeşme; although the net power in Bodrum is higher than Çeşme, the monthly electricity produced is less. Although the radiation of Bodrum is 3.77% more than Çeşme, it is seen that the sunbathing time is 4.538% less. This also affected the amount of electricity produced. Solar data and analysis results of four districts are given in Table 12.

In Figure 12, annual electricity values for four districts are compared. Although more electricity is produced in Silifke than Alanya in July with benzene fluid, it is approximately 13 MWh electricity generated less in annual production. While the annual average radiation value is 519 W/m^2 in Silifke, it is 527 W/m^2 in Alanya. The average of sunbathing time is 8.30 and 8.26 hour/day for Silifke and Alanya, respectively. Despite the longer sunbathing time, the decrease in radiation value in Silifke resulted in less electricity production in annual production. The highest annual production was realized in Alanya with 1625 MWh electricity generated. It is seen that the performance order of the fluids is benzene>cyclohexane>D4. When the four districts are evaluated together, it has been determined that benzene performs better than cyclohexane by 3.8% on average and 23% better than D4.

Table 10. Monthly average power (kW) and energy amounts (MWh) produced with ORC when different circulation fluids are used for Bodrum in summer.

Organic Fluids	Month	Day Number	Sunbathing Time (hour/day)	G (W/m^2)	$\dot{m}_{ORC}$ (kg/s)	$T_{h,i}$ (°C)	$W_{net,ave}$ (kW)	Electricity (MWh/month)
Benzene	May	31	10.18	600.2	7.79	224	592.0	186.82
	June	30	11.59	584.1	7.58	223	576.1	200.31
	July	31	11.78	538.2	6.99	218	530.8	193.84
	August	31	11.18	537.6	6.98	218	530.2	183.76
Cyclohexane	May	31	10.18	600.2	7.96	219	570.0	179.88
	June	30	11.59	584.1	7.75	217	554.8	192.90
	July	31	11.78	538.2	7.14	213	511.2	186.68
	August	31	11.18	537.6	7.13	213	510.6	176.96
D4	May	31	10.18	600.2	13.61	207	478.3	150.94
	June	30	11.59	584.1	13.24	206	465.5	161.85
	July	31	11.78	538.2	12.20	202	428.9	156.63
	August	31	11.18	537.6	12.19	202	428.4	148.47

Table 11. Monthly average power (kW) and energy amounts (MWh) produced with ORC when different circulation fluids are used for Çeşme in summer.

Organic Fluids	Month	Day Number	Sunbathing Time (hour/day)	G (W/m^2)	$\dot{m}_{ORC}$ (kg/s)	$T_{h,i}$ (°C)	$W_{net,ave}$ (kW)	Electricity (MWh/month)
Benzene	May	31	10.26	578.9	7.52	222	571.0	181.61
	June	30	12.22	525.4	6.82	216	518.2	189.97
	July	31	12.34	518.6	6.73	216	511.5	195.67
	August	31	11.60	494.0	6.41	213	487.2	175.20
Cyclohexane	May	31	10.26	578.9	7.68	217	549.9	174.90
	June	30	12.22	525.4	6.97	211	499.0	182.93
	July	31	12.34	518.6	6.88	211	492.6	188.44
	August	31	11.60	494.0	6.55	208	469.2	168.72
D4	May	31	10.26	578.9	13.13	206	461.4	146.75
	June	30	12.22	525.4	11.91	201	418.7	153.50
	July	31	12.34	518.6	11.76	201	413.3	158.10
	August	31	11.60	494.0	11.20	199	393.6	141.54

Table 12. Comparison of net power and amount of electricity produced in different districts of benzene fluid in July with evaporator capacity.

District	*G (W/m²)*	*Sunbathing Time (hour/day)*	$W_{net,ave}$ *(kW)*	*Electricity (MWh/month)*	Q_{evap} *(kW)*
Silifke	589.9	11.34	581.9	204.561	4130
Alanya	561.5	11.7	553.9	200.900	3931
Bodrum	538.2	11.78	530.8	193.838	3767
Çeşme	518.6	12.34	511.5	195.669	3630

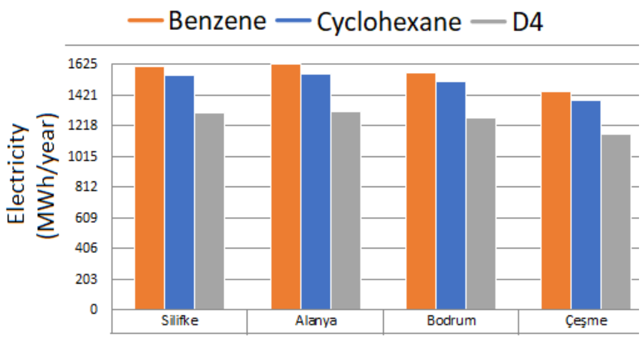

Figure 12. Annual total electricity energy production amounts (MWh) of the ORC system for four different districts with different fluids.

4. Conclusions

In this study, the potential of solar ORC designed using three different organic fluids (benzene, cyclohexane and D4) to meet some of the electricity needs of a building or hotel was analyzed. A simulation study was carried out considering the solar radiation value and sunshine duration of 4 different districts in Turkey (Silifke-İçel, Alanya-Antalya, Bodrum-Muğla, Çeşme-İzmir).

When the maximum electrical energy values obtained in the summer months are examined;

For Silifke, 205 MWh electricity generated was obtained with benzene at a heat source temperature of 223 °C in July. It has been determined that the mass flow rate for ORC should be 8.03 kg/s and the evaporator capacity is 4130 kW. The specific electric power value of the solar collector is 58.19 W/m^2.

For Alanya, 204 MWh electricity generated was obtained with benzene at a heat source temperature of 224 °C in June. It has been determined that the mass flow rate for ORC should be 7.83 kg/s and the evaporator capacity is 4224 kW. The specific electric power value of the solar collector is 59.52 W/m^2.

For Bodrum, 200 MWh electricity generated was obtained with benzene at a heat source temperature of 223 °C in June. It has been determined that the mass flow rate for ORC should be 7.58 kg/s and the evaporator capacity is 4089 kW. The specific electric power value of the solar collector is 57.61 W/m^2.

For Çeşme, 196 MWh electricity generated was obtained with benzene at 216 °C heat source temperature in July. It has been determined that the mass flow rate for ORC should be 6.73 kg/s and the evaporator capacity is 3630 kW. The specific electric power value of the solar collector is 51.15 W/m^2.

Similar results were obtained in Silifke and Alanya districts. Although Alanya is better than Silifke in the specific electrical power value of the solar collector, Silifke is in a better situation in terms of maximum electrical energy.

In each district, the best results were obtained with benzene fluid. Although the performance of benzene and cyclohexane is close to each other, there is a serious performance difference between benzene and D4.

When the annual electrical energy values are examined, the highest production was determined as 1625 MWh electricity generated with benzene fluid in Alanya district. Annual generated electrical energy values are listed below.

- Alanya;benzene-1625 MWh>cyclohexane-1564 MWh>D4-1313 MWh;
- Silifke;benzene-1612 MWh> cyclohexane-1553 MWh>D4-1303 MWh;
- Bodrum;benzene-1572 MWh> cyclohexane-1514 MWh>D4-1270 MWh;
- Çeşme;benzene-1442 MWh> cyclohexane-1389 MWh>D4-1165 MWh

As a continuation of the study, it is proposed to determine the payback period and the saved carbon dioxide emissions by performing thermo-economic and enviro-economic analysis.

Acknowledgement

This study includes a part of Serhat Yıldırım's master's thesis.

Nomenclature

Ac	: Collector Area (m^2)
E_g	: Daily solar irradiation intensity (kWh/m^2-day)
EES	: Engineering Equation Solver
G	: Instantaneous radiation (W/m^2)
GWP	: Global Warming Potential
IST	: Industrial Solar Technology
h	: Enthalpy (kJ/kg)
$\dot{m}$	: Mass Flow Rate (kg/s)
ORC	: Organic Rankine Cycle
PTC	: Parabolic Trough Collector
PV	: Photovoltaic
$\dot{Q}$	: Heat Flow (kW)

t_g	: Daily sunshine duration (hours/day)
T	: Temperature (°C)
T_0	: Ambient Temperature
$\dot{W}$	: Power (kW)

Greek letters

η_c	: collector efficiency (%)
η_{ORC}	: thermal efficiency (%)
η_p	: pump isentropic efficiency (%)
η_t	: turbine isentropic efficiency (%)
η_{solar}	: solar system efficiency (%)
Δ	: difference

Subscripts

0	: ambient condition
1,2,3,..	: state point
c	: condenser
e	: evaporator
in	: inlet of each component
p	: pump
out	: out of each component
t	: turbine

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