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Research Article

Energy Efficiency Assessment and Optimization of Solar Organic Rankine Cycle for Combined Heat and Power Generation for a Residential Building: Case Study of Baghdad City, Iraq

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ABSTRACT

Solar Organic Rankine Cycle (SORC) is a successful approach to sustainable development and exploiting clean energy sources. The research aims to improve and evaluate the energy efficiency of the SORC for combined heat and power generation for a residential home under the climatic conditions of Baghdad, Iraq. Thermoeconomic analysis was carried out for the proposed energy supply system. Refrigerant HFC-245fa was used as a working fluid in a solar organic Rankine cycle, and oil poly alkyl benzene (TLV-330) was suggested as a heat transfer fluid in the solar collector field. Parametric studies for some key parameters were conducted to examine the impact of various operating conditions on energy efficiency. The results showed a significant improvement in energy efficiency. The maximum efficiency of SORC CHPG reached 79.14 % when solar heat source temperatures were in the range of 100 to 150 °C and the solar radiation was at a maximum value of 870 W/m^2 at noon on the 15^{th} day of July in Baghdad. The maximum energy produced by SORC CHPG was 472.5 kW when the optimal average value of global solar radiation was 7.5 kWh/m^2/day in June. The economic investigations revealed that the payback period of the new energy supply system was 10 years with the positive net present cost when the solar power plant was working 18 h/day.

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1. INTRODUCTION

Currently, fossil fuels are used to meet 70 % of the world's energy demands, 40 % of which are spent in building sectors for various purposes, including air conditioning, ventilation, cooling, and heating (Razmi et al., 2019). Today, oil and gas are the main and dominant sources of energy supply in Iraq. The combustion products of conventional fuels lead to serious environmental problems (Saeed et al., 2016; Martins et al., 2019; Solarin, 2020a). The emergence of recent technology and an increase in population have led to an increase in energy consumption worldwide and in the Republic of Iraq particularly. The use of non-conventional solar energy sources for energy supply addresses these issues (Solarin, 2020b; Bigerna et al., 2021). Renewable solar energy is characterized by stability and purity. Iraq is a country located near the Sun Belt and characterized by high solar radiation intensity and brightness throughout the year. Therefore, solar energy can be used as an alternative source of energy to meet energy needs and address the acute shortage of energy supply in Iraq (Al-Hamdani, 2017; Chaichan and Kazem, 2018; Al-Kayiem and Mohammad, 2019; Kazem and Chaichan, 2012). An organic Rankine cycle (ORC) has become a reliable technology to convert heat into electricity using various heat sources such as biomass, geothermal, heat recovery, solar, and heat from industrial processes (Malwe et al., 2022; Oyekale and Emagbetere, 2022). The heat sources divide into high, medium, and low depending on the temperature range between 50 °C and 350 °C. Moreover, the advantages of ORC technology include extremely high turbine efficiency (up to 90 %), high system efficiency, low peripheral speed, low turbine mechanical stress, low turbine rotation speed, dry expansion process, low environmental impact, and simplicity of expander design, thus making it desirable (Oyekale and Emagbetere, 2022; Malwe et al., 2021). Organic fluids with a lower boiling point and higher vapor pressure are utilized as heat carriers in the ORC cycle. Over the past years, the small-scale Solar Organic Rankine Cycle (SORC) has become a mature technology and a topic of extensive research by researchers (Gupta et al., 2022). Organic working fluids are selected according to the specified criteria involving environmentally-friendly, non-flammable, and appropriate physical properties that meet the system requirements for optimum efficiency. The working fluids can be

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hydrofluorocarbons, hydrocarbons, siloxanes, and mixtures of these components (Herath et al., 2020). In this regard, many studies have been conducted to examine the performance of ORC using various organic fluids, taking into account solar energy as a heat source under different conditions (Tchanche et al., 2009; Rayegan and Tao, 2011). In recent years, many studies have investigated the SORC for poly-generating applications. Yang et al., (2019) constructed a new SORC for generating 1 MW. Different working fluids were used in the performance evaluation for the new mode. Outcomes revealed that the efficiency was elevated by 4.2 % higher than an unstable operating. Freeman et al., (2017) tested an SORC for Combined Heat and Power Generation (CHPG) integrated with a thermal energy storage unit with phase change materials. They investigated the efficiency of the system under UK and Cyprus conditions. The results pointed out that hydrated-salt PCMs provided high performance and power output. Bouvier, (2016) performed experimental investigation for micro SORC CHPG. The obtained energies were 1.3 kW of electricity and 19 kW of heat energy. The efficiency of converting solar energy into electricity and heat energy reached 3 % and 38 %, respectively. Garcia-Saez et al., (2019) conducted thermal and economic research on the implementation of SORC CHPG in residential sectors for various scenarios. They used on-grid and off-grid operating modes. The results showed the feasibility of applying the system in locations characterized by specific climatic conditions. The main indicators of an economic analysis estimated 13 % IRR, 3.1 years PP, and positive NPV. Habka and Ajib, (2016) considered the utilization of zeotropic mixtures in SORC for CHPG. Numerical simulations were carried out for predicting energy efficiency and feasibility. The outcomes confirmed that the use of R409A in ORC was ideal and the cost of energy production was reduced by 16.20 %. Yüksel, (2018) applied SORC for power, cooling, and hydrogen generation. Hydrogen is produced using produced electricity. The findings showed that the energy efficiency of the system increased from 58 % to 64 % when solar radiation increased from 400 W/m^2 to 1000 W/m^2, and the rate of hydrogen generation rose from 0.1016 kg/h to 0.1028 kg/h. Singh and Mishra, (2018) carried out exergy and energy analysis of both supercritical CO_2 (SCO_2) cycle and organic Rankine cycle (ORC) driven by solar energy to produce power. It was found that the exergetic and thermal efficiency of all the combined cycles increased when the direct normal irradiance rose from 0.5 kW/m^2 to 0.95 kW/m^2. The maximum thermal and exergetic efficiency was around 78.07 % and 43.49 %, respectively. Despite the reported attractive results of the SORC technology, it has not been simulated in the climatic conditions of Baghdad, Iraq. In this study, by contributing to the enhancement of the energy efficiency of the current system, this paper analyzes a new model of SORC CHPG to meet the needs of electric power, Domestic Hot Water (DHW), and heating for a typical residential building in the conditions of Baghdad city. The suggested technique is not dependent on the grid or fossil fuels. It appears that the suggested solution is extremely realistic due to the presence of both low- and high-temperature water for usage at home. A calculation method for the main performance indicators associated with the proposed solar energy system is developed, taking into account the peculiarities of the new design and the potential of solar radiation in Baghdad.

2. MATERIAL AND METHODS

The research methodology relies on theoretical and experimental studies of previous research on the topic of SORC CHPG. To calculate the main parameters and energy efficiency of the proposed system, the basic concepts of thermodynamics were applied (Çengel, 2004; Rajput, 2007). Commercial software "Engineering Equation Solution (EES)" was used for simulating and obtaining the results of the study (F-Chart Software, 2022). The indispensable operating parameters were added to the EES to obtain the full outcomes of the proposed solar system. An optimized model of SORC CHPG was employed to obtain initial results from the available parameters. Modeling of the obtained results was conducted by considering various operating parameters to help determine the optimal operating conditions of the system to provide maximum performance. The findings were compared with reported investigations for the model verification and validation of results, taking into account the small deviations and loads of case studies. Iraq is characterized by the abundance of incoming solar radiation during the year thanks to its location. Solar radiation of 1000 W/m^2 for one hour is equal to one kWh/m^2 (Akram Al-Khazzar, 2018). The maximum measured value of solar radiation at noon is about 950 W/m^2 (Al-Obaidi et al., 2020). The received average daily solar radiation ranges between 4.4-5.45 kWh/m^2/day, as shown in Figure 1. The incident average value of solar radiation in Baghdad is about 5 kWh/m^2/day (Chaichan and Kazem, 2018).

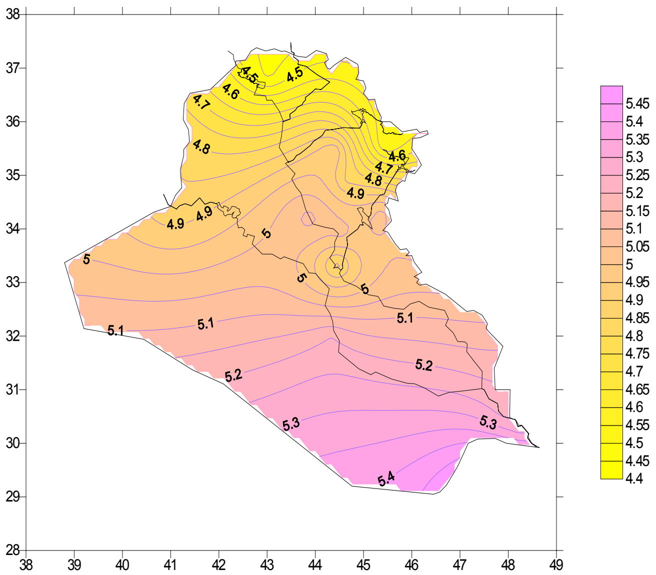


Figure 1. Average daily solar radiation for different locations in Iraq (Chaichan and Kazem, 2018)

The recorded average values of global solar radiation (AGSR) and high/low ambient temperature for Baghdad city are tabulated in Table 1.

Baghdad city is the capital of Iraq and located in the central region (latitude 33°.33′, longitude 44°.39′), which was selected as the location of a residential home. The thermal loads for heating, DHW, and electrical loads of the residential home were calculated, as shown in Table 2.

In this work, in response to the climatic conditions of Baghdad and the requirements of the energy system, it is proposed that oil poly alkyl benzene (TLV-330) be used as a new Heat Transfer Fluid (HTF). The characteristics and thermophysical properties of HTF are presented in Table 3.

Table 1. AGSR data and ambient temperatures by month for Baghdad (Hassan et al., 2021)

Month	GSR (MJ/m²/day)	GSR (kWh/m²/day)	Average high temperature (°C)	Average low temperature (°C)
January	10.6	2.9	16	4
February	13.33	3.7	19	6
March	17.7	4.9	24	10
April	21.6	6	30	15
May	23.4	6.5	37	20
June	27.0	7.5	42	24
July	26.0	7.2	44	26
August	24.6	6.8	44	25
September	20.8	5.7	40	22
October	15.8	4.3	33	16
November	11.9	3.3	24	9
December	9.8	2.7	17	5
Total average yearly	18.6	5.2	30.8	15

Table 2. Calculated loads of the case study (Mohammed Ali, 2020)

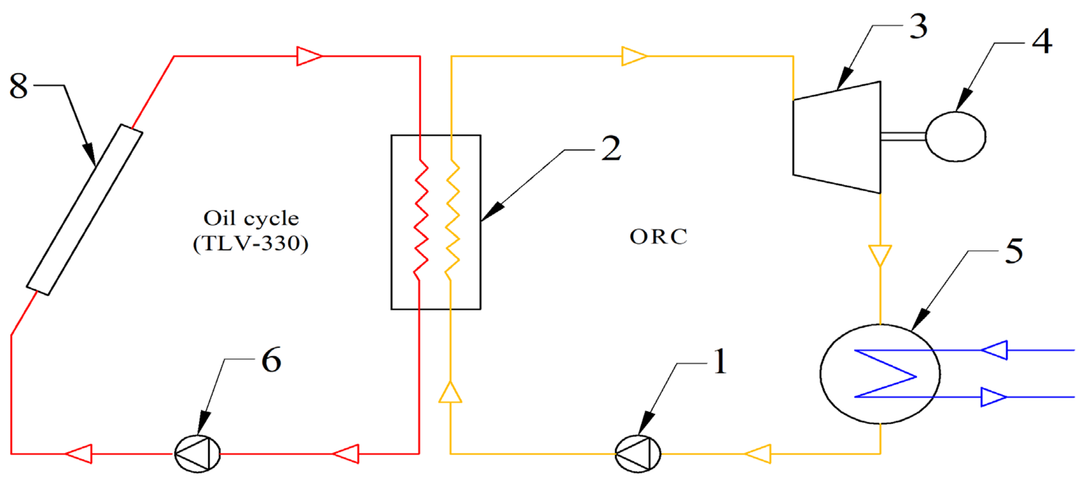
Type of load	Value (kW)
Electrical loads (P_{ele})	15
Thermal load for heating (Q_h)	29
Domestic hot water demand (Q_{DHW})	19

Table 3. Characteristics of TLV-330 (https://termolan.ru/tlv-330m/)

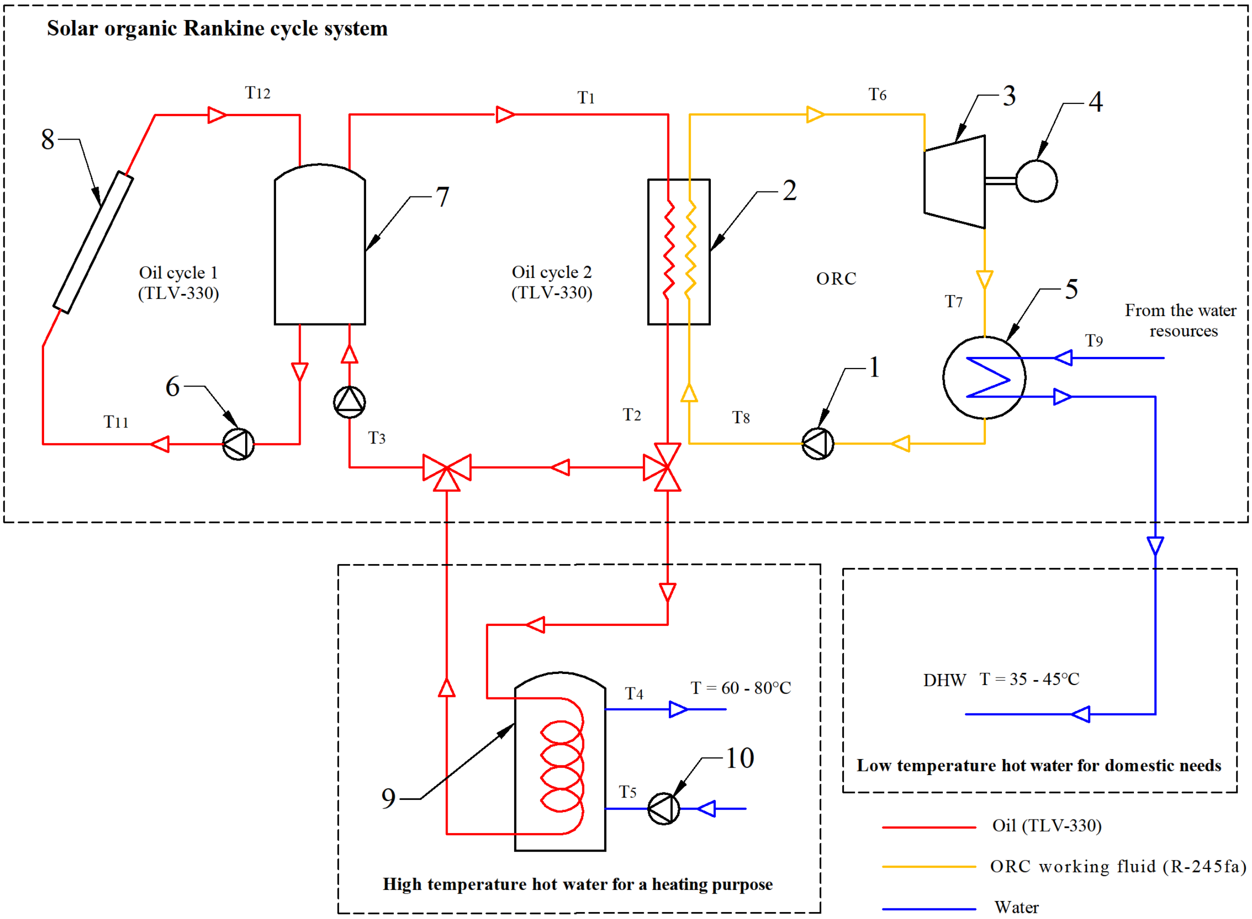
Name of an indicator	Norm
Appearance	Light yellow oily, homogeneous liquid
Minimum operating temperature	40 °C
Maximum operating temperature of the liquid phase	330 °C
Maximum operating temperature of the vapor phase	330 °C
Density 20 °C	850-870 kg/m³
Average specific heat	2.2 kJ/kg.°C
Freezing temperature	− 30 °C
Boiling temperature	330 °C
Manufacturer country	Russia

2.1. System description

The basic SORC standalone (SORC SA) for the generation of electricity is illustrated in Figure 2a. The proposed new SORC system for providing electricity, DHW, and hot water for a heating purpose depending on solar energy as a heat source is shown in Figure 2b. The novel design of SORC CHPG works as follows. The liquid working fluid (R-245fa) flows by the pump (1) to the ORC evaporator (2). It absorbs the heat in the evaporator and then, converts it into steam. The vapor working fluid enters the expander (3) under given thermodynamic conditions to drive it and generate electricity via an electric generator (4). Then, vapor enters the condenser (5) to be condensed. The hot water at the outlet of the condenser at an accepted temperature is used as DHW. The liquid working fluid enters the pump and the cycle repeats. The thermal energy storage unit (9) is integrated to ensure that the system operates stably throughout the day, avoids the influence of climate changes, and fills the collector with non-freezing liquid. The HTF enters the SORC evaporator (2) and the outlet HTF flows via the heat exchanger (9) where hot water is released for heating purposes in the winter season. In the end, the working fluid returns to the heat storage unit (9) and is reheated thanks to the solar energy, and the next cycle begins. A three-way valve is utilized to control the flow direction of the liquid and shut off the heating system in the summer season. These two proposed variants of heating consider a successful solution under Baghdad conditions. In this system, there is no demand for fuel to heat the water.



(a)



(b)

Figure 2. Schematic diagram of (a) basic SORC SA for generation of electricity and (b) proposed developed design of SORC CHPG: 1. organic fluid circulation pump, 2. evaporator, 3. expander/ turbine, 4. electric generator, 5. condenser, 6. oil circulation pumps, 7. heat storage tank, 8. solar thermal collector, 9. heat exchanger for heating purposes, 10. hot water circulating pump

2.2. Thermodynamic analysis and mathematical modeling

The analysis and calculations were built on the following assumptions:

1. The efficiency rates of the ORC generator, expander, and pump are constant and non-dependent in the operating mode.
2. Hydraulic resistance of heat exchangers and pipelines is not considered.
3. No heat is exchanged with the environment.
4. Changes in kinetic and potential energy are not considered.
5. Refrigerant HFC-245fa is used as working fluid in the SORC cycle due to its thermophysical characteristics and for economic grounds.

Table 4 presents the required operating parameters for modeling the proposed SORC CHPG under Baghdad conditions.

Table 4. Design parameters of the proposed SORC CHPG (Aghaziarati and Aghdam, 2021)

Parameter	Value
Power output (P_{ele})	15 kW
Cooling water temperature at the inlet of the condenser (T_9)	15 °C
Hot water temperature at the outlet of the condenser (T_{10})	40 °C
SORC condensation temperature (T_8)	50 °C
Maximum operating temperature of ORC (T_6)	140 °C
Maximum working pressure of ORC (P_{evap})	2828.7 kPa
Ambient temperature (T_{am})	25 °C
The temperature at the evaporator inlet (T_1)	150 °C
The temperature at the evaporator outlet (T_2)	110 °C
The temperature at the heat exchanger (9) inlet (T_2)	110 °C
The temperature at the heat exchanger (9) outlet (T_3)	80 °C
Water temperature at the inlet of the heat exchanger (T_5)	60 °C

water temperature at the outlet of the heat exchanger (T_4)	75 °C
The temperature of HTF at the inlet of the heat storage tank (T_{12})	150 °C
The temperature of HTF at the outlet of the heat storage tank (T_{11})	130 °C
Isentropic efficiency of the ORC expander (η_e)	80 %
Efficiency of the ORC pump (η_p)	80 %
Efficiency of the ORC generator (η_g)	96 %
Solar collector efficiency (η_{sc})	70 %
Solar radiation (G)	1000 kWh/m^2

The equations of mass and energy balance for control volume in SORC CHPG are as follows (Rajput, 2007):

$$\left.\begin{aligned} \sum m_{in} - \sum m_{out} = 0 \\ \sum Q_{in} - \sum Q_{out} = 0 \\ Q_{in} - W_{in} + \sum_{in} m.h - \sum_{out} m.h = 0 \end{aligned}\right] \tag{1}$$

2.2.1. Modeling of solar field

The energy collected by the solar collector and transmitted to the HTF is determined via the application of the thermo-balance as follows (Bellos and Tzivanidis, 2017):

$$Q_{sc} = G(\tau).\, A_{sc}.\eta_{sc}(\tau) = m_{HTF}.C_{HTF}.(T_{out} - T_{in})_{HTF} \tag{2}$$

The following empirical equation can be utilized to estimate the mass flow rate of oil (Bellos and Tzivanidis, 2017; Baral and Kim, 2014):

$$m_{HTF} = 0.02.A_{sc} \tag{3}$$

The solar collector area is used to calculate the volume of the thermal storage tank (Bellos and Tzivanidis, 2017):

$$V_{HST} = \frac{A_{sc}}{80} \tag{4}$$

The system is examined in the stable mode; therefore, the results are not significantly affected by the volume and shape assumptions made for the storage tank (Aghaziarati and Aghdam, 2021). The required area of the collector for a solar plant is calculated as follows:

$$A_{sc} = \frac{Q_h + Q_{DHW} + P_{ele}}{G(\tau).\eta_{sc}(\tau)} \tag{5}$$

The collector efficiency is expressed in the following formula (Gupta et al., 2022):

$$\eta_{sc} = \eta_o + a_1.\frac{(T_{av} + T_{am}(\tau))}{G(\tau)} - a_2.\frac{(T_{av} + T_{am}(\tau))^2}{G(\tau)} \tag{6}$$

where η_o represents optical efficiency. a_1 W/(m^2.°C) and a_2 W/(m^2.°C) are coefficients of heat loss. The values of these parameters were taken 0.825, 0.91, 0.0006, respectively (Hossin and Mahkamov, 2015). The average collector temperature is calculated as:

$$T_{av} = \frac{T_{sc,in} + T_{sc,out}}{2} \tag{7}$$

2.2.2. Devices modeling of ORC unit

The power required to operate the ORC pump is calculated as (Wang et al., 2012):

$$W_p = \frac{m_{wf}.\, v_1.\, (P_{evap} - P_{cond})}{\eta_p} = m_{wf}.\, (h_2 - h_1) \tag{8}$$

The mass flow rate m_{wf} kg/s flowing in the ORC cycle is calculated using the following formula:

$$m_{wf} = \frac{P_{ele}}{(h_3 - h_4).\eta_g} \tag{9}$$

The rate of heat transmitted in the ORC evaporator is determined as (Hossin and Mahkamov, 2015):

$$Q_{evap} = m_{wf}.(h_3 - h_2) = m_{HTF}.C_{HTF}.(T_{in} - T_{out})_{HTF} \tag{10}$$

An ORC turbine power output is determined as (Hossin and Mahkamov, 2015):

$$P_{ele} = m_{wf}.\, (h_3 - h_4).\, \eta_e.\, \eta_g = m_{wf}.\, (h_3 - h_4).\, \eta_g \tag{11}$$

The heat removal in the condenser can be expressed as (Hossin and Mahkamov, 2015):

$$Q_{cond} = m_{wf}.(h_4 - h_1) = m_w.C_w.(T_{out} - T_{in})_w \tag{12}$$

The volumetric flow rate is calculated using the following formula:

$$V = m_{wf}.\, v_{wf} \tag{13}$$

The application of a heat balance determines the mass flow rate of cooling water in a condenser as follows:

$$m_w = \frac{m_{wf}.(h_4 - h_1)}{C_w.(T_{out} - T_{in})} \tag{14}$$

The work performed by the SORC cycle is calculated as follows (Bellos and Tzivanidis, 2017):

$$P_{net} = P_{ele} - W_p \tag{15}$$

The thermal efficiency of the ORC is expressed as follows:

$$\eta_{ORC} = \frac{P_{net}}{Q_{evap}}.100 \tag{16}$$

2.2.3. Energy efficiency

The energy efficiency of the proposed SORC in various energy generation scenarios is defined as follows (Bellos and Tzivanidis, 2017):

- For electrical generation standalone:

$$\eta_{SORC\,SA} = \frac{P_{net}}{G(\tau)\,.A_{sc}(\tau)}.100 \quad (17)$$

- For multi-generation of energy:

$$\eta_{SORC\,CHPG} = \frac{P_{net} + Q_{DHW} + Q_h}{G(\tau).\,A_{sc}(\tau)}.\,100 \quad (18)$$

2.2.4. Heat exchanger modeling

The size of heat exchangers plays a vital role in the system cost of SORC CHPG. To predict the area of heat exchangers of the SORC CHPG, an average logarithmic temperature difference (LMTD) method was used. It is expressed in the following formula (Rajput, 2012):

$$Q_i = U_i\,.\,A_i\,.LMTD_i \quad (19)$$

where U is the overall heat transfer coefficient (OHTC), W/(m^2.°C). A is the heat exchanger area m^2. LMTD$_i$ is the average logarithmic temperature difference °C. For counter flow, the LMTD is determined as follows (Çengel, 2004):

$$\left.\begin{aligned} LMTD_i &= \frac{T_{h,in} - T_{c,out} - T_{h,out} - T_{c,in}}{\ln\left(\dfrac{T_{h,in} - T_{c,out1}}{T_{h,out} - T_{c,in}}\right)} \\ \Delta T_1 &= T_{h,in} - T_{c,out} \\ \Delta T_2 &= T_{h,out} - T_{c,in} \end{aligned}\right] \quad (20)$$

where ΔT_1 and ΔT_2 represent the temperature difference between two fluids at the two ends (inlet and outlet) of the heat exchanger. The values of OHTC for the evaporator, condenser, and heat exchanger for heating were taken as average depending on representative values in (Çengel, 2004). They are tabulated in Table 5.

Table 5. Average representative values of OHTC

Heat exchanger type for SORC CHPG	U, W/(m^2.°C)
Evaporator	300
Condenser	650
Heat exchanger for heating	225

3. RESULTS AND DISCUSSION

The main findings of the study regarding the desired working conditions are presented in Table 6.

Table 6. Results of the study

Parameter	Value
Heat rate in the evaporator (Q_{evap})	93.45 kW
Heat rejection in the condenser (Q_{cond})	78.62 kW
Work turbine (P_{ele})	15 kW
Work pump (W_P)	1.035 kW
Mass flow rate of the working fluid (m_{wf})	0.4223 kg/s
Mass flow rate of cooling water (m_w)	0.6241 kg/s
Mass flow rate of HTF (m_{HTF})	1.8 kg/s
Volumetric flow rate of the working fluid at the input of the expander (V_3)	0.002031 m^3/s
Volumetric flow rate of the working fluid at the outlet expander (V_4)	0.0003332 m^3/s
Net power output (P_{net})	13.97 kW
Thermal efficiency of the ORC (η_{ORC})	14.94 %
Energy efficiency of the SORC SA ($\eta_{SORC\,SA}$)	17.84 %
Total Energy efficiency of the SORC CHPG ($\eta_{SORC\,CHPG}$)	79.14 %
Area of ORC evaporator (A_{evap})	11.6 m^2
Condenser area (A_{cond})	2.6 m^2
Heat exchanger area for heating (A_{HEH})	4.81 m^2
Solar collector area of the SORC SA (A_{sc})	21.4 m^2
Solar collector area of the SORC CHPG (A_{sc})	90 m^2
Heat storage tanks volume (V_{HST})	1.125 m^3

3.1. Influence of vapor temperature

The temperature of the heat source plays an important role in the performance of the solar plant. The high temperature of HTF in the solar collector under conditions of Baghdad city leads to a higher vapor temperature at the turbine inlet of the SORC and, consequently, high energy efficiency. The efficiency is enhanced as the working fluid temperature increases at the turbine inlet. The thermal efficiency of SORC SA varies from 7.25 % to 14.94 % depending on the temperature, as shown in Figure 3.

The volumetric flow rate of R-245fa at the turbine outlet is crucial and affects the system cost and size. It decreases as the temperature increases, as shown in Figure 4.

Figure 5 shows the change in the mass flow rate of the working fluid depending on the temperature at the turbine inlet. The mentioned rate decreases following a rise in the temperature at the turbine inlet due to an increase in enthalpy difference. The temperature of the condensation affects the efficiency adversely, as presented in Figure 6.

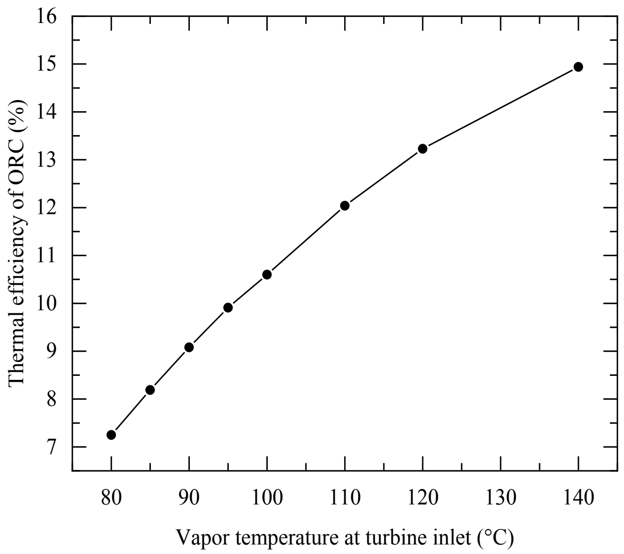


Figure 3. Influence of vapor temperature at the turbine inlet on the thermal efficiency of the ORC

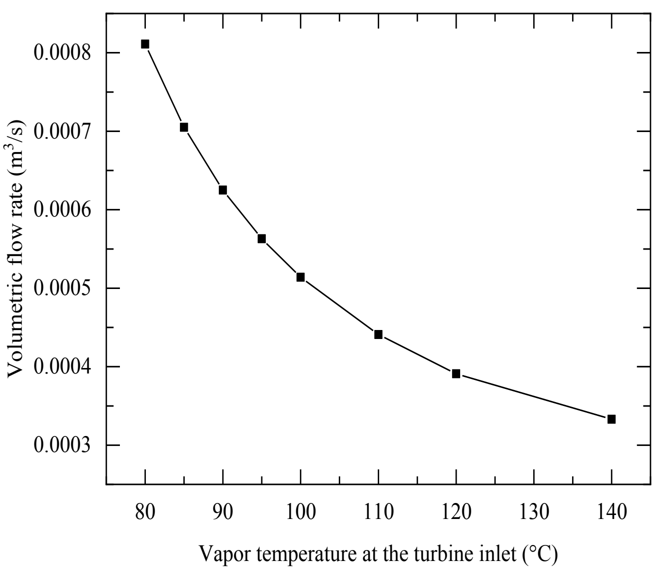


Figure 4. Influence of vapor temperature at the turbine inlet on the volumetric flow rate

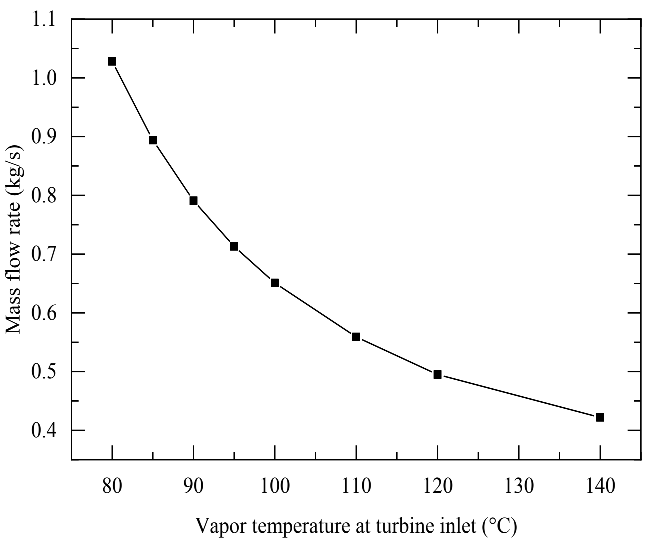


Figure 5. Influence of vapor temperature at the turbine inlet on the mass flow rate

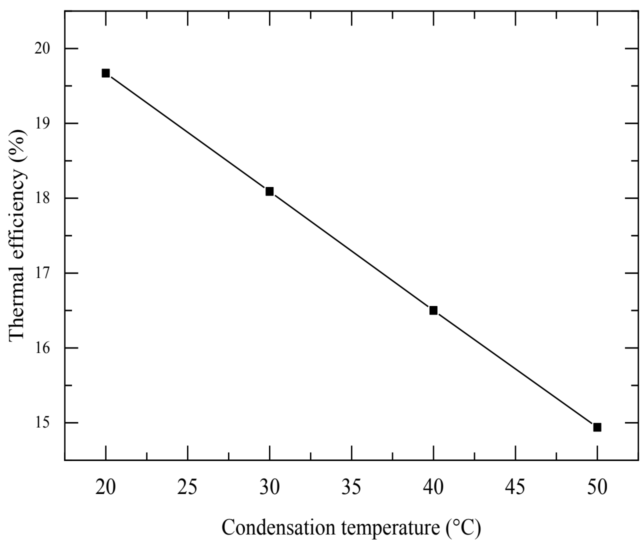


Figure 6. Influence of condenser temperature on the thermal efficiency of the ORC

3.2. Effect of pressures

To ensure the optimum system performance, the working pressure range of the working fluid must be determined along with its thermophysical properties when exposed to a certain temperature. High working pressure requires reliability and strength for the evaporator. The performance of SORC SA increases with an elevation of evaporation pressure, as illustrated in Figure 7.

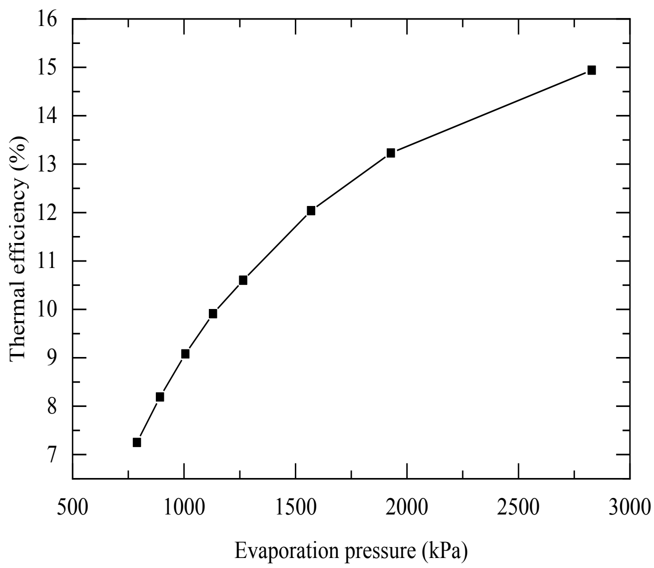


Figure 7. Influence of evaporation pressure on the performance of the ORC

3.3. Effect of solar radiation on Baghdad city

The area of the solar collector strongly depends on the intensity of solar radiation in the place of construction of the solar power plant. The high incident solar radiation, long periods of brightness, and high temperature in Baghdad reduce the solar collector area and subsequently, the cost of the system minimizes. The maximum and minimum values of the collector area for SORC SA and SORC CHPG range from 7.937 to 2.857 m^2 and 33.33 to 12 m^2, respectively, as shown in Figure 8.

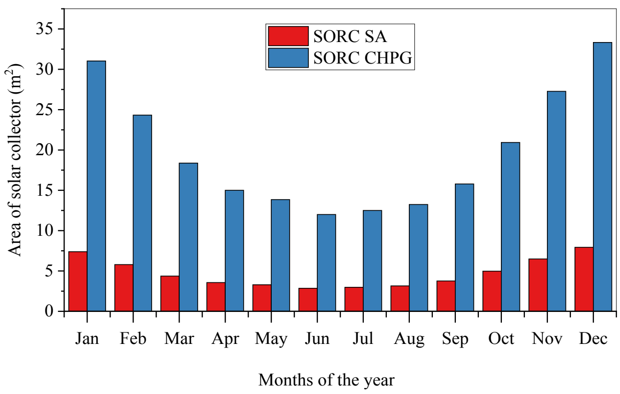


Figure 8. Variation of solar collector area with AGSR

The collector efficiency of the proposed SORC CHPG changes with the intensity of the Hourly Solar Radiation (HSR) and ambient temperature. The highest collector efficiency was 74.38 % when the recorded maximum value of HSR was 870 W/m^2 on the 15th day of July for Baghdad, as illustrated in Figure 9.

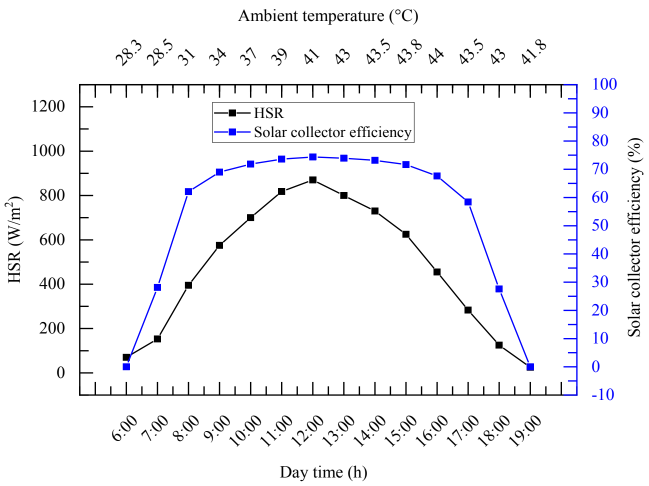


Figure 9. Variation of solar collector efficiency with the HSR and ambient temperature

Figure 10 shows the variation of the energy produced by both SORC SA and the novel SORC CHPG with HSR on the 15th day of July for Baghdad city. The maximum electric energy generated by SORC SA and the total energy (electric and heat demand) obtained by SORC CHPG reached 13.77 kW and 54.81 kW, respectively, when the HSR value was at its highest value of 870 W/m^2, as illustrated in Figure 10.

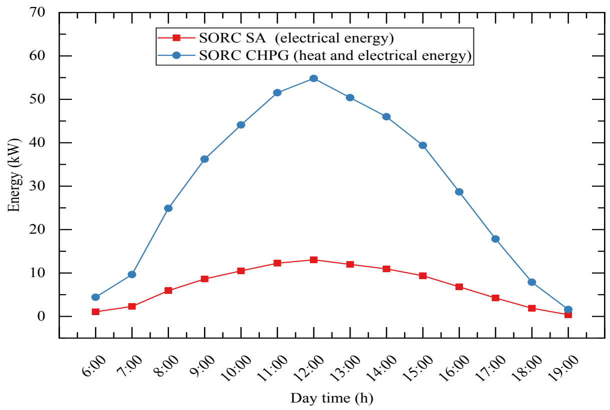


Figure 10. Daily energy generation by the hour

The maximum energy generated by both SORC SA and SORC CHPG was 118.1 and 472.5 kW, respectively, when the recorded AGSR of Baghdad was 7.5 kWh/m2/day in June, as presented in Figure 11.

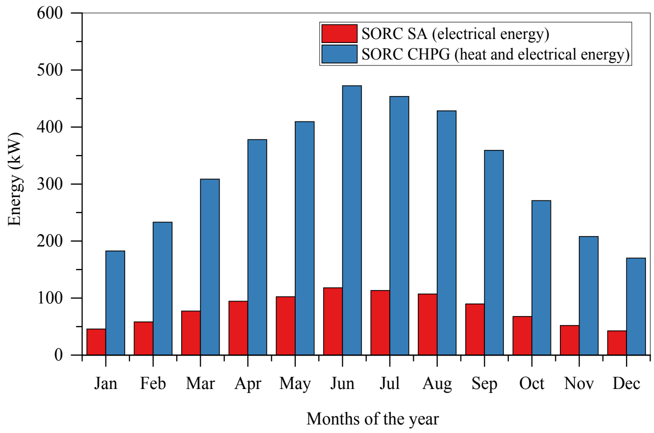


Figure 11. Variation of energy generated in different months of the year

3.4. Energetic efficiency enhancement

In the proposed developed design of SORC CHPG, many scenarios of energy generation can be achieved. The energy efficiency and its improvement for multi-generation are shown in Figure 12. The optimal efficiency and enhancement reached 79.1 % and 68.1 %, respectively, when the HSR was at the highest value of 870 W/m^2 in July. In the new model, the rate of heat transferred for DHW and heating purposes was taken into account; as a result, the total energy efficiency increased significantly.

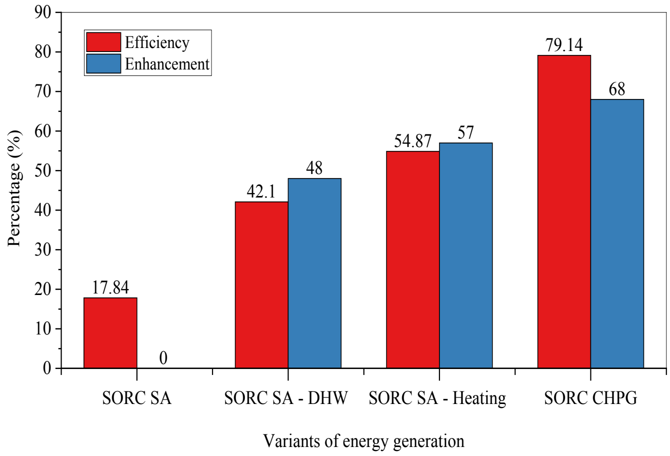


Figure 12. Comparison of the energy efficiency and improvements for different variants of energy generation

4. ECONOMIC ASPECTS AND COST ESTIMATION

It is important to investigate the economic aspects of the proposed energy supply system. The feasibility study of SORC CHPG was carried out for electric power of 15 kW, DHW demand of 19 kW, and heating load of 29 kW. The method of Payback Period (PP) and way of Net Present Cost (NPC) were employed to examine the feasibility of applying the SORC CHPG under the current state of energy in Iraq (Garcia-Saez et al., 2019; Gomaa et al., 2020). The cost of the solar collector was taken as 150–200 \$/m^2 (Gomaa et al., 2020). The cost of fittings, oil, and pipes was neglected in the current work given their minor contribution to the total cost of the system (Aghaziarati and Aghdam, 2021). Table 7 presents the economic assumptions used in the feasibility study. The Investment Capital Cost (ICC) and Operation and Maintenance (O & M) costs are calculated, as presented in Table 8.

Table 7. Economic input parameters

Parameters	Value
Price of kWh by the Iraqi government, (C_{ele})	0.024 $/kWh (https://www.globalpetrolprices.com/)
Price of kWh from the SORC system, (C_{SORC})	8 cent/kWh (0.08 $/kWh) (Muslim et al., 2018)
The lifetime of the SORC system, (LT)	20 years (Baral et al., 2015)
Interest rate, (r)	5 % (Garcia-Saez et al., 2019)
Operating time of solar plant per day, OT_{sp}	10-22 h

Table 8. Estimated cost of major components of SORC CHPG (Garcia-Saez et al., 2019; Gomaa et al., 2020; Baral et al., 2015)

No.	Parameter	ICC, $	O & M costs ($ for 20 years)	TICC ($)
1	Solar collector	175 $/m^2	(15 %.ICC_{sc}).LT	ICC_{sc} + O & M_{sc}
2	Expander/turbine	$4750.(P_{ele})^{0.75}$	(2 %.ICC_{ele}).LT	ICC_{ele} + O & M_{ele}
3	Evaporator	$150.(A_{evap})^{0.8}$	(4 %.ICC_{evap}).LT	ICC_{evap} + O & M_{evap}
4	Condenser	$150.(A_{cond})^{0.8}$	(4 %.ICC_{cond}).LT	ICC_{cond} + O & M_{cond}
5	Heat exchanger for heating	$150.(A_{HEH})^{0.8}$	(4 %.ICC_{HEH}).LT	ICC_{HEH} + O & M_{HEH}
6	Working fluid pump	$3500.(W_p)^{0.47}$	(2 %.ICC_p).LT	ICC_p + O & M_p
7	Heat storage tank	$1380.(V_{HST})^{0/4}$	(1 %.ICC_{HST}).LT	ICC_{HST} + O & M_{HST}
Total investment capital cost				$\sum TICC$ ($)

The associated revenues from the new installation include electricity bill, savings for heating, and DHW. The number of years required to recover the TICC can be calculated using the following formula (Gomaa et al., 2020):

$$PP = \frac{TICC}{S_y} \tag{21}$$

where TICC is the total cost of the SORC CHPG, including O & M costs (Table 8). S_y is the annual saving per year, $, and is calculated as the sum of the following:

$$S_y = C_{DHW} + C_h + C_{sp} \tag{22}$$

where C_{DHW} is the cost of DHW supply from an electric water heater, which runs on electricity supplied by the Iraqi government, and given as follows:

$$C_{DHW} = P_{ewh} \times OT \times C_{ele} \tag{23}$$

where P_{ewh} is the power consumed by the electric water heater, kWh. OT is the operating time, h. C_{ele} is the cost of kWh in Iraq established by the government, $/kWh. C_h is the cost of electricity consumption for heating devices run on the local grid in winter and can be determined using the following formula:

$$C_h = P_{hd} \times OT \times C_{ele} \tag{24}$$

where P_{hd} is the electric power of heating devices, kWh. In the case of using the proposed SORC system to supply DHW and home heating, the costs that are spent on heating and hot water supply from the local network are considered savings for the consumer/investor; therefore, they are used in the payback period equation as benefits. C_{sp} represents the cost of electric power generated by the SORC system and is determined using the following formula (Muslim et al., 2018):

$$C_{sp} = P_g \times C_{SORC} \tag{25}$$

where C_{SORC} is the price of electricity unit generated by the SORC system, $/kWh. P_g is the actual generation of electricity by the SORC system, kWh, and is determined via Eq. (26):

$$P_g = OT_{sp} \times 340 \times P_{ele} \tag{26}$$

where OT_{sp} is the daily actual operating time, 340 days is the real number of days that the system operates, and 25 days for rest and maintenance purposes. NPC reflects investment performance better. For regular savings per year, it can be calculated as follows:

$$NPC = \left[S_y . \frac{1-(1+r)^{-LT}}{r} \right] - TICC \tag{27}$$

NPC is calculated depending on the lifetime of SORC CHPG. The benefits of applying the SORC CHPG for a 20-year LT can be calculated by the following formula:

$$S_{LT} = (S_y \ . \ 20) - TICC \tag{28}$$

The payback period for the total costs of the solar plant decreases upon increasing the operating time. It is 10 years when the operating time is 18 h, as shown in Figure 13. In addition, a positive net present value was obtained at an operating time of 18h, as presented in Figure 14. Table 9 illustrates the findings of the economic investigation for the proposed SORC CHPG.

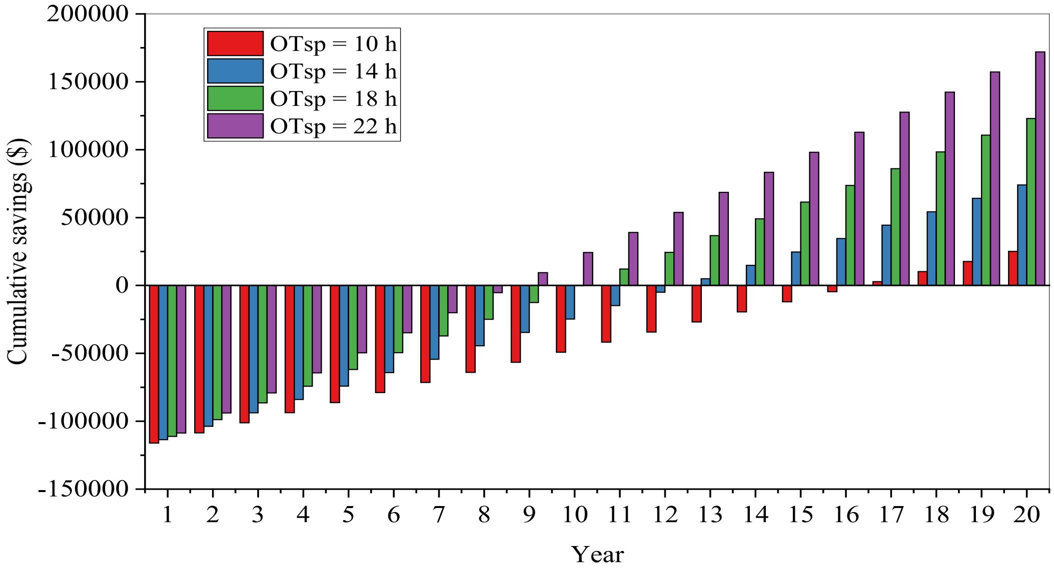


Figure 13. Variation in the payback period with operating time of SORC CHPG system

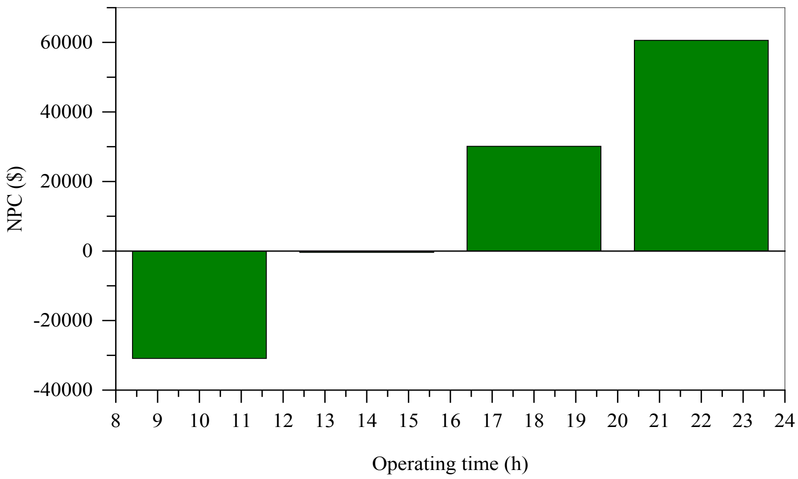


Figure 14. Variation in net present cost with the operating time of SORC CHPG system

Table 9. Outcomes of the economic investigation

Indicators	Value
Cost of the proposed SORC CHPG, (TICC)	123477 $
Net present cost, (NPC)	30112.7 $
Payback period, (PP)	10 years
Annual benefits, (S_y)	12324.4 $
Benefits for a 20-year lifetime from SORC CHPG, (S_{LT})	123011.7 $

5. CONCLUSIONS

In the present work, a thermo-economic assessment of improved solar ORC was carried out for supplying electrical energy and thermal energy in the form of hot water for domestic needs and heating purposes for a residential home under conditions of Baghdad city. A comparative study between the new design of SORC CHPG and conventional SORC SA was conducted concerning the thermal efficiency and energy generated. Parametric research and debating were conducted on key parameters of the proposed solar plant to determine optimal performance. The thermal energy storage unit was integrated for continuous and stable operation during climatic changes. The following conclusions can be derived from the study results:

1. The energetic efficiency of SORC CHPG was calculated as 79.14 %, compared to 17.84 % of SORC SA, which was 61.3 % higher than the thermal efficiency of SORC SA when the temperature of the solar heat source was in the range of 100 to 150 °C and solar radiation of 870 W/m^2 on the 15th day of July for Bagdad city.

2. The results of mathematical modeling showed that the optimal heat and electric energy produced by SORC CHPG was 54.81 kW when the HSR was approximately 870 W/m^2 at noon on the 15th day of July.

3. The total maximum energy (power and heat) obtained was 472.5 kW when the AGSR was at a higher value of 7.5 kWh/m^2/day in June under the climatic conditions of Baghdad.

4. The study of the influence of solar radiation proved that upon increasing solar radiation, the area of the solar collector decreased and, consequently, the energy efficiency of the system improved.

5. To obtain the high temperature of hot water, it could be provided directly from the solar collector.

6. From an economic point of view, the costs related to the solar field are reduced with increase in the potential of solar energy in Baghdad.

7. The economic investigation provided in this research showed that the payback period, net present cost, and annual benefits were 10 years, 30112.7 $, and 12324.4 $/year, respectively, at an operating time of 18 h. They significantly depended on the operating time of the solar power plant. Following the increased reliance on the proposed system, the economic indicators rose in value.

8. Compared to the power cost of an ordinary standard grid, the price of producing electricity with ORC was higher, which was about 3-8 cents per kWh. The proposed new design of SORC CHPG could be improved based on distributed off-grid applications, and the results might significantly enhance performance and lower costs. Despite the higher cost of SORC CHPG, it can be appealing for a variety of off-grid and waste heat recovery applications. To improve ORC system and reduce the costs, the trend of thermal performance and turbine size had meaningful relations with the temperature of vapor and mass flow rates of the working fluid. SORC CHPG or multi generation are variants that enhanced the total energy efficiency and reduce the costs. Solar ORC with tri generation seems to be implemented more cost-effectively than photovoltaic power generation system.

According to the results obtained from the study, the use of the SORC system in the cogeneration of electricity and hot water for a residential building illustrated the attractiveness of applying it for energy conservation, reduction of CO_2 emission, and solving of the acute shortage of energy supply in Baghdad, Iraq. The further research opportunities are theoretical and experimental studies of the SORC system for combined cooling, heating, and power generation under Iraqi climatic conditions with thermal energy storage units based on phase change materials.

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NOMENCLATURE

P_{ele}	Electrical power (kW)
P_{net}	Net output power, (kW)
T	Temperature (°C)
m	Mass flow rate (kg/s)
h	Enthalpy (kJ/kg)
Q	Heat flow rate (kW)
G	Solar radiation (W/m^2)
A	Area (m^2)
C	Specific heat (kJ/kg.°C)
a_1, a_2	Coefficient of heat loss (W/(m^2.°C))
v	Specific volume (m^3/kg)
V	Volumetric flow rate (m^3/s)
U	Overall heat transfer coefficient (W/(m^2.°C))
LMTD	Logarithmic mean temperature difference (°C)
P	Pressure (kPa)
ICC	Investment capital cost ($)
TICC	Total investment capital cost ($)
S_y	Benefits/Savings per year ($)
S_{LT}	Benefits/savings during the lifetime of a system ($)
r	Interest rate (%)
C_{DHW}	Cost of domestic hot water supply ($)
C_h	Cost of heating ($)
P_{ewh}	Power of the electric water heater (kW)
OT	Operating time (h)
OT_{sp}	Daily actual operating time (h)
C_{ele}	Cost of kWh in Iraq ($)
C_{sp}	Cost of electric power generated by the SORC ($)
C_{SORC}	Cost of kWh by the SORC ($)
P_{hd}	Electric power of heating devices (kWh)
P_g	Actual generation of electricity by the SORC (kWh)
NPC	Net present cost ($)
O & M	Operation and maintenance ($)
Greek letters	
η	Efficiency (%)
τ	Time interval (h)
Subscripts	
ele	Electric
sc	Solar collector
HTF	Heat transfer fluid
out	Outlet
in	Inlet
HST	Heat storage tank
h	Heating
o	Optical
av	Average
am	Ambient
DHW	Domestic hot water
p	Pump
g	Generator, generation
e	Expander
evap	Evaporator
cond	Condenser
wf	Working fluid
w	water
sp	Solar plant
y	Year Lifetime
LT	Lifetime
Acronyms	
ORC	Organic Rankine cycle
SORC	Solar organic Rankine cycle
SORC SA	Solar organic Rankine cycle standalone
SORC CHPG	Solar organic Rankine cycle for combined heat and power generation
DHW	Domestic hot water
HFC	Hydrofluorocarbon
sc	Solar collector
spp	Solar power plant
NPC	Net present cost
EES	Engineering Equation Solver
PP	Payback period
ICC	Investment capital cost
LT	Lifetime

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