Thermodynamic and Techno-economic Analysis of a Triple-pressure Organic Rankine Cycle: Comparison with Dual-pressure and Single-pressure ORCs

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Abstract: Investigation of a triple-pressure organic Rankine cycle (TPORC) using geothermal energy for power generation with the net power output of the TPORC analyzed by varying the evaporation pressures, pinch temperature differences (\(t_{pp}\)) and degrees of superheat (\(t_{sup}\)) aimed to find the optimum operation conditions of the system. The thermodynamic performance of the TPORC was compared with a dual-pressure organic Rankine cycle (DPORC) and a single-pressure ORC (SPORC) for geofluid temperatures ranging from 100°C to 200°C, with particular reference to the utilization of a hot dry rock (HDR) geothermal resource. Thermodynamic performances of the TPORC system using eight different organic working fluids have also been investigated in terms of the net power outputs. Results show that a higher geofluid mass flow rate can make a considerable contribution to shortening the payback period (PBP) as well as to decreasing the levelized electricity cost (LEC), especially when the geofluid temperature is low. For the temperature range investigated, the order from high to low based on thermodynamic and techno-economic performances is found to be TPORC > DPORC > SPORC. In terms of using geothermal resources within the given temperatures range (100°C–200°C), the TPORC system can be a better choice for geothermal power generation so long as the wellhead geofluid temperature is between 140°C and 180°C.

Key words: geothermal energy, techno-economics, power generation systems, triple-pressure organic Rankine Cycle (TPORC), thermodynamic performance

I Introduction

Global geothermal resources can be roughly divided into five categories: hydrothermal geothermal; dry steam geothermal; abnormal stratum pressure geothermal; magmatic hot dry rock and hot dry rock (Xu et al., 2015). Hot dry rock (HDR) usually refers to formations consisting primarily of granites that have high temperature but very low permeability and which lack stored fluid and are located within subsurface of 3–10 km depths (Dipippo, 2012). The concept of an Enhanced Geothermal System (EGS), which includes the earlier concept of HDR, originated from the Los Alamos National Laboratory in the USA (Olasolo et al., 2016). An EGS has an engineered geothermal reservoir usually created from HDR resources. A major concern in the development of an EGS is achieving and maintaining adequate injection, while avoiding the development of preferential short-circuiting flow paths (Na et al., 2013). The permeability of the reservoir is increased by hydraulic fracturing, and this factor has been widely used in the unconventional oil or gas development. The regional effective moisture and terrestrial heat flow rate are other two problems that need to be considered during geothermal exploration (Feng et al., 2019; Liu et al., 2020). Heat transmission fluids, such as water or \(\text{CO}_2\), can be used to circulate in the reservoir to extract heat from the HDR resources (Sun et al., 2017). EGS could become a promising energy technology for power generation and considerably reduce the consumption of fossil fuels (Olasolo et al., 2016; Hussain et al., 2017).

In terms of utilizing geothermal energy efficiently from the EGS, reducing the temperature difference between the heat resource (geofluid) and working fluid is a commonly used method, including the introduction of a zeotropic mixture into the organic Rankine cycle (ORC) system (Liu et al., 2015; Collings et al., 2016). Kang et al. (2015) analyzed the influences of 10 groups of mixtures on the performance of ORC. Karimi et al. (2018) established thermodynamic models of three different ORCs to compare their performances of power generation using geothermal energy. Hu et al. (2016) put forward a selection method for power generation plants used for EGS; the comparative analysis results show that each upgraded system (double-flash (DF), flash-ORC (FORC), and double-flash-ORC (DFORC)) can produce more power output compared with the single-flash (SF) system and that the FORC system can produce more power than...
using other power cycles when the heat source temperature is below 170°C. Wang et al. (2015, 2016) established mathematical models of two new combined systems that use ammonia-water as the working fluid to obtain the optimum performance using the maximum exergy efficiency as an objective function. A transcritical ORC is also an important approach to increase the heat-power conversion ability. In these transcritical ORCs, the evaporation pressure is higher than the critical pressure and hence can decrease the exergy loss caused by the temperature difference between the geofluid and the working fluid, because the transcritical ORC provides a better temperature match between the working fluid and the heat source than a subcritical ORC (Zhang et al., 2011; Lecompte et al., 2014; Landelle et al., 2017; Li et al., 2017). By selecting R600a/R601a as working fluids, Ge et al. (2018) analyzed mole fraction effects of mixtures on net power output, exergy efficiency, exergy destruction rate and heat utilization ratio of waste heat. The results showed that the use of mixtures for the two loops can reduce the exergy destruction rate of the high-temperature loop (HTL) evaporator and low-temperature loop (LTL) condenser compared to when pure working fluids are used.

A dual-pressure ORC (DPORC) consists of two evaporators at different pressures. The power outputs obtained from the dual pressure configuration are particularly high (up to 29%) at lower geothermal fluid temperatures (100–125°C) (Manente et al., 2017). Li et al. (2018a, b) studied the optimal cycle parameters for various heat source temperatures by selecting nine pure organic fluids as working fluids and performed a comparative analysis of two turbine layouts. In addition, the thermodynamic performances of the basic, DP and DF ORCs and Kalina cycles using geothermal energy for power generation have been analyzed by energy, exergy and exergoeconomic viewpoints, respectively (Guzović et al., 2014; Shokati et al., 2015; Du et al., 2018). When choosing R1233zd as the working fluid, an average increasing rate of 20.87% in net power output (\(W_{\text{net}}\)) brings no economic benefits to a DP system because the electricity production cost (EPC) also increases on average 12.98% compared to a single-pressure system (SPORC) (Mosaffa et al., 2017; Wang M et al., 2018; Wang S et al., 2018). Sadeghi et al. (2016) considered the net power output and turbine size parameter (TSP) as two objective functions with the aim of maximizing the first function and minimizing the second one, the results showing that STORC (series two-stage ORC) has the highest net power output. R407A can be selected as the most appropriate working fluid. Li et al. (2018) analyzed the performance improvement of two-stage serial organic Rankine cycle (TSORC) driven by dual-level heat sources (DHS) of geothermal energy coupled with solar energy, the results showing that the TSORC driven by DHS can supply more net power, but the thermal efficiency is lower than that of a TSORC driven by a single heat source (SHS) with temperature below 140°C.

Previous studies have shown that the DPORC can increase the power output by reducing the exergy loss in evaporation (Li et al., 2018; Wang M et al., 2018). Our study was triggered by a qualitative comparison between the SPORC and triple-pressure ORC (TPORC), shown on the pressure-enthalpy diagram (Fig. 1). It can be seen that, under the same geofluid inlet temperature \(T_{\text{in}}\) and pinch temperature difference \(\Delta T_{\text{pinch}}\), the geofluid outlet temperature \(T_{\text{out}}\) of the TPORC is lower than that of the SPORC \(T_{\text{out}}\), implying that the energy utilization efficiency of the TPORC is higher than that of the SPORC and hence more net electricity power can be produced.

In this study, a TPORC has been investigated to find out whether more evaporation stages will lead to more net power output by comparison with the DPORC and SPORC for heat source temperatures between 100°C and 200°C, with particular reference to the utilization of an HDR geothermal resource. The Rankine cycle has been retained in this study but a range of working fluids has been examined.

2 Description of Geothermal Power Generation Systems

Schematics of the SPORC, DPORC and TPORC using geothermal energy for power generation are shown in Fig. 2. Each system can be categorized into three parts based on the type of fluids: dashed lines represent the geothermal water flow path; heavy lines represent the flow path of the ORC working fluid; fine lines represent the flow path of cooling water.

The SPORC schematic diagram (Fig. 2a) and its temperature-entropy diagram (Fig. 3a) represents a basic ORC, which refers to a single-stage evaporation-pressure organic Rankine cycle. SPORC is widely used in conventional ORC power stations, which usually consists of four basic components: evaporator, turbine, condenser, and feed pump. The geofluid from the production well goes into the evaporator and preheater where the organic working fluid absorbs heat from the geofluid and eventually evaporates (process 4–5). The vapor (state 1) flows through the turbine to generate shaft work that drives the generator for electricity (process 1–2). The turbine exhaust (state 2) flows into the condenser where it
is condensed into a liquid state (process 2r-3), and then pressurized through the pump to its evaporation pressure (process 3-4); then another cycle starts (Fig. 3a).

In the TPORC system (Fig. 2c), there are three different pressure (high-, medium-, low-pressures) evaporation processes. The working fluid is divided into two streams in Separator 1: one is heated to low-pressure superheated vapor (state 1l); the other is pumped into the medium-pressure (process 5l-7) and is heated to saturated liquid (state 5m) in the MP-preheater. It then flows into Separator 2 where it is again divided into two parts: one stream passes the MP-evaporator and becomes superheated vapor (state 1m) that goes to the MP-turbine; the other is pumped to a higher pressure condition (state 8) and passes through the HP-preheater and the HP-evaporator, attaining a superheated state (state 1h) before it enters the HP-turbine. The TPORC temperature-entropy diagram is shown in Fig. 3c.

3 Methodology

3.1 Power cycle modeling and optimization

Thermodynamic models of the power cycles can be
found in Appendix A. Some assumptions used in the models are listed here, as follows:

1. heat and pressure loss in the systems were neglected;
2. \( t_F \) varied from 5°C to 15°C;
3. degree of superheat \( (\Delta t_{sp}) \) varied from 2°C to 12°C;
4. ambient temperature and pressure: \( t_0 = 20°C, p_0 = 1 \) bar;
5. HP-evaporator pressure \( (p_{ev}) \), MP-evaporator pressure \( (p_{me}) \), LP-evaporator pressure \( (p_{le}) \) range: \( p_{min} < p_{ev} < p_{me} < p_{le} \), where \( p_{min} \) and \( p_{max} \) are dependent on the condensation pressure and critical pressure, respectively;
6. the basic ORC working fluid used for both the thermodynamic and techno-economic analyses is R245fa.

Thermodynamic performance analyses of seven other organic working fluids (R600, R601a, R134a, R1234yf, R152a, R600a, and R143a) have also been investigated for comparison.

The system parameters used in this study are shown in Table 1. The thermo-physical properties of the organic working fluids used are shown in Table 2. The optimum evaporation pressure is subject to an upper limit of the evaporation temperature, which is set at 12°C below the critical temperature of the working fluid in order to maintain thermal stability. Here, the optimum evaporation pressure refers to the evaporation-pressure corresponding to the best thermodynamic performance (maximum net power output) of the system.

The Engineering Equation Solver (EES) has been used for the numerical simulation. The governing equations were formulated based on mass and energy balances. The maximum net power output was chosen as an objective function, which is a function of decisive variables (in this study, evaporation-pressures). The power consumptions of geothermal water, cooling water, as well as fan power consumption of the cooling tower, have been taken into account for the net power output calculation. Thermodynamic modeling for TPORC, DPORC, and SPORC are presented in Appendix A.

3.2 Techno-economic analysis

The Levelized Electricity Cost (LEC) and Payback Period (PBP) were chosen as the assessment criteria of techno-economic analysis. In this section, both ground and underground investments were considered, as shown in Appendix B.

3.2.1 Levelized electricity cost analysis

The LEC represents the net present value of the unit cost of electricity over the lifetime of a plant. The LEC method has been used by previous researchers for evaluating engineering economic performance of enhanced geothermal systems (Lu et al., 2018), the formula is given by:

\[
LEC = \frac{COST \cdot CRF + COM}{r_w^{n_i} \cdot i^{n_i} - 1}
\]

where \( COST \) is the capital cost of the power station (shown in Table 3), \( COM \) is the operating cost (shown in Table 4), \( r \) is the operation time per year of the power station (7000 h/year), \( W_{net} \) is net power output, and \( CRF \) is the investment recovery factor calculated by:

\[
CRF = \frac{(i + 1)^{n_i} - i}{(i + 1)^{n_i} - 1}
\]

where \( i \) is the interest rate (5% in this study), \( n \) is the power station lifetime (25 years in this study). The calculated LEC of TPORC is optimized and compared with that of DPORC and SPORC under different geo-fluid temperature conditions, respectively. The LEC is calculated in CNY (Chinese Yuan) converted into US Dollars (USD $) according to the exchange rate on August 27, 2021 (1 USD = 6.4836 CNY).

3.2.2 Payback period analysis

The PBP is usually used for techno-economic evaluation of a plant. The calculation formula is shown below:

\[
PBP = \frac{COST}{NE}
\]

\[
NE = Rev \times COM
\]

\[
Rev = \frac{W_{net} \times Rate}{n}
\]

where \( NE \) is the annual net earnings, \( Rev \) is the annual revenue of the power station, \( Rate \) is the electricity price. The calculated PBP of the TPORC is also compared those of the DPORC and SPORC (see next section).

4 Optimization Results

4.1 Parametric study of TPORC

The optimization results of the TPORC system are presented in the subsequent sections.
4.1 Thermodynamic performance analysis

The net power output was calculated for different thermodynamic parameters. The calculation results of SPORC and DPORC are not presented in full, only used as reference systems.

The net power output variations of the TPORC are given with respect to \( t_{gw} \) and the degree of superheat \( \Delta t_{in} \) under the condition that \( p_h = 25 \) bar, \( p_m = 16 \) bar, and \( p_l = 8 \) bar (Fig. 4). When \( t_{sup} \) is constant, the increase of \( t_{pp} \) will result in a decrease of the net power output; when \( t_{pp} \) is constant, the higher the \( t_{sup} \), the less the net power output. Lowering \( t_{pp} \) and the \( t_{sup} \) will lead to more power generation. It is also seen from Fig. 4 that the decrease of net power output along A-C is greater than that along A-B, indicating that the \( t_{pp} \) has greater influence than the \( t_{sup} \) on the net power output.

Here, the maximum net power output was chosen as an objective function, and the three pressures \( (p_h, p_m, p_l) \) were optimized simultaneously. The net power output contours vary with respect to \( p_h \) and \( p_m \) when the geofluid temperatures \( (t_{gw}, t_{in}) \) are 125°C, 150°C, 175°C, and 200°C, respectively (Figs. 5a–d).

The optimum values (in bars) of the three pressures \( (p_h, p_m, p_l) \) are (11.43, 6.92, 3.84), (17.74, 9.82, 4.73), (29.08, 14.42, 5.92) and (29.08, 5.78, 3.40), corresponding to the maximum net power outputs of 231.2 kW, 388.0 kW, 589.5 kW, and 834.0 kW, respectively (Fig. 5). When the geofluid temperatures are 125°C, 150°C, and 175°C, the optimum values of the \( p_h \) are within the domain (see Figs. 5a, b, c). It is worth mentioning that, in this optimization, the upper limit of the \( p_h \) was set as 29.08 bar in order to have the high-pressure evaporation temperature as 12°C below the critical point temperature (154°C) of the working fluid R245fa. For the same reason, the optimum value of \( p_m \) is on the upper boundary (see Fig. 5d) when the geofluid temperature is 200°C. Also, the change of \( p_m \) under this condition has very little influence on the net power output because the contours are almost horizontal (Fig. 5d).

The net power output contours (corresponding to optimized results in Fig. 5) are demonstrated as well, but with respect to \( p_m \) and \( p_l \) (Fig. 6). It can be seen that the gradient along constant \( p_m \) is greater than that along the constant \( p_l \), indicating that the change of \( p_l \) has more influence than that of \( p_m \) on the net power output.

Comparison of net power output among eight different organic working fluids with respect to different heat source (geofluid) temperatures over a wide range from 100°C to 200°C shows that R601a, R245fa, R600a, and R600 have about the same performance with advantages over R143a, R1234yf, R134a and R152a (Fig. 7). When the geofluid temperature is higher than 185°C, working fluid R600a (isobutene) shows the best performance.

There are changes in optimum values (in bars) of the three evaporation pressures \( (p_h, p_m, p_l) \) with respect to the \( t_{gw} \) for various working fluids (Fig. 8). Fig. 8a shows the three optimum evaporation pressures when the working fluid R600 is used. First the high evaporation pressure \( p_h \) increases and then remains constant (upper pressure limit) with an increase of \( t_{gw} \). The values of \( p_m \) and \( p_l \) first increase and then decrease, but the amplitude of variation of \( p_m \) is greater than that of \( p_l \).

The three optimum evaporation pressure curves of working fluid R245fa are shown in Fig. 8b, which is similar to those for R600. However, the geofluid temperature corresponding to the turning points of the pressure curves for R245fa is 180°C (Fig. 8b), higher than that (170°C) in for R600 (Fig. 8a). Unlike those already noted (Fig. 8a, b), the three optimum pressures using working fluid R601a exhibit differences that increase monotonously with the increase of \( t_{gw} \) (Fig. 8c). Using R601a as the working fluid for a TPORC does not show a peak pressure value for the whole temperature range investigated (100–200°C) because the operating range is

![Fig. 4. The net power output variations of the TPORC with respect to the pinch temperature difference (\( \Delta t_{in} \)) and the degree of superheat (\( \Delta t_{in} \)) (\( p_h = 25 \) bar, \( p_m = 16 \) bar, \( p_l = 8 \) bar, working fluid: R245fa).](image)

<table>
<thead>
<tr>
<th>Items</th>
<th>Computational formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water fees (WF)</td>
<td>( WF = 4 \times 10 \times 7000 \ (4 \text{CN¥}/\text{t}, 100\text{h}/\text{a}) ).</td>
</tr>
<tr>
<td>Wages for workmen (WW)</td>
<td>5000CN¥/month ( \text{person} \cdot \text{person} ) (2 \text{workers}).</td>
</tr>
<tr>
<td>Maintenance cost (MC)</td>
<td>( MC = COST \times 0.02 ).</td>
</tr>
<tr>
<td>Management cost (MC1)</td>
<td>( MC1 = (WF + WW + MC) \times 0.025 ).</td>
</tr>
<tr>
<td>Depreciation cost (DC1)</td>
<td>( DC1 = EC \times (1-0.05)/25 ).</td>
</tr>
<tr>
<td>Costs of operating (COM)</td>
<td>( COM = WF + WW + MC + MC1 + DC1 ).</td>
</tr>
</tbody>
</table>

Table 4 Budget statement of operating costs (COM) \( (\text{Lu et al., 2018}) \)

<table>
<thead>
<tr>
<th>Items</th>
<th>Computational formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill cost (DC)</td>
<td>( DC = ((t_{gw} \times 20)+25) \times 4000=2 ).</td>
</tr>
<tr>
<td>Exploration cost (EC1)</td>
<td>( EC1 = DC \times 0.05 ).</td>
</tr>
<tr>
<td>Fracturing cost (FC)</td>
<td>( FC = DC \times 0.4 ).</td>
</tr>
<tr>
<td>Log experiment cost (LEC1)</td>
<td>( LEC1 = DC \times 0.1 ).</td>
</tr>
<tr>
<td>Equipment cost (EC)</td>
<td>( EC = C \times 20 ).</td>
</tr>
<tr>
<td>Installation cost (IC)</td>
<td>( IC = EC \times 0.25 ).</td>
</tr>
<tr>
<td>Direct engineering cost</td>
<td>( DEC = DC + EC1 + FC + LEC1 + EC ).</td>
</tr>
<tr>
<td>Labor cost (LC)</td>
<td>( DEC \times 0.2 ).</td>
</tr>
<tr>
<td>Capital cost (COST)</td>
<td>( COST = DEC + LC ).</td>
</tr>
</tbody>
</table>

Table 3 Budget statement of capital costs (COST; including ground and underground investments; \( \text{Lu et al., 2018} \))

<table>
<thead>
<tr>
<th>Items</th>
<th>Computational formula</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Capital cost (COST)</td>
<td>( COST = DEC + LC ).</td>
</tr>
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</table>

Fig. 4. The net power output variations of the TPORC with respect to the pinch temperature difference (\( \Delta t_{in} \)) and the degree of superheat (\( \Delta t_{in} \)) (\( p_h = 25 \) bar, \( p_m = 16 \) bar, \( p_l = 8 \) bar, working fluid: R245fa).
well below the critical pressure and temperature of that working fluid. When R600a is used, the pressure curve turning point is 160°C, after which the gap between $p_m$ and $p_l$ decreases gradually (Fig. 8d). When the $t_{g,in}$ is higher than 190°C, the $p_m$ and $p_l$ are identical and close to the condensation pressure, implying that only when the geofluid temperature $t_{g,in}$ is lower than 190°C can R600a be used as the working fluid for a TPORC system.

The optimized evaporation pressures for the other four working fluids are shown in Fig. 9. The critical temperatures of R152a, R134a, R1234yf and R143a are 113°C, 101°C, 94.7°C and 72.7°C, respectively, and the turning points of their high pressure ($p_h$) curves decrease in turn (Figs. 9a, b, c). The $p_h$ curve of R143a has no turning point (Fig. 9d) because the critical temperature of this working fluid is too low.

It can also be seen that the $p_m$ and $p_l$ become identical when the $t_{g,in}$ is greater than 180°C, 160°C, and 150°C, respectively (Figs. 9a, b, c). As explained in Fig. 8d, R152a, R134a, and R1234yf cannot be used for a TPORC system if the $t_{g,in}$ is above a certain temperature for each case. Only when the $t_{g,in}$ is lower than 180°C, can R152a be used for a TPORC system (Fig. 9a), whereas in the cases of R134a and R1234yf, the upper limits of the $t_{g,in}$ are 160°C (Fig. 9b) and 150°C (Fig. 9c), respectively.

The optimized three pressure curves using R143a as working fluid are different again (Fig. 9d). When the $t_{g,in}$ is 130°C or higher, the $p_m$ and $p_l$ are identical with a value equal to the condensation pressure, implying that, in this temperature range, R143a can only be used for a SPORC system; when the $t_{g,in}$ is 120°C, the values of $p_m$ and $p_l$ are equal but greater than the condensation pressure. Therefore, R143a can be a choice for a DPORC system. Only when the $t_{g,in}$ is less than 120°C, can R143a be used as the working fluid for a TPORC system.

4.1.2 Techno-economic analysis

There are influences both of the $t_{g,in}$ and geofluid mass flow rates ($m_g$) on the techno-economy (Fig. 10), with variation of the LEC over $t_{g,in}$ and $m_g$. Fig. 10a. When $t_{g,in}$ is constant, the increase of $m_g$ will result in a decrease of the LEC; when $m_g$ is constant, the higher the $t_{g,in}$ the lower the LEC. The gaps among the curves become narrow as the $t_{g,in}$ increases (Fig.10a). When $t_{g,in}$ is 100°C,
the difference between the maximum and minimum values of LEC is 0.0613 USD/kWh, whereas it is only 0.0171 USD/kWh when the temperature is 200°C.

The Payback Period (PBP) varies with respect to $t_{g,in}$, $m_g$, and $t_g$. When the $t_{g,in}$ is constant, the increase of $m_g$ will lead to a decrease of the PBP. If the $m_g$ is constant, the higher the $t_{g,in}$, the lower the PBP. Given a power station’s lifetime is 25 years, when the $m_g$ is 50 kg/s, the $t_{g,in}$ cannot be lower than 120°C, otherwise the payback period is too long. When the $m_g$ is 80 kg/s, the minimum temperature required becomes 100°C.

It is found out that a higher $m_g$ can make a considerable contribution to shorten the PBP as well as to decrease the LEC, especially when the geofluid temperature is low.

The optimization results of the TPORC system contain the LEC as the objective function (Fig. 11). The minimization of LEC has been carried out by optimizing the three pressures ($p_h$, $p_m$, and $p_l$) simultaneously. The LEC contours differ with respect to $p_h$ and $p_m$ when the $t_{g,in}$ are 125°C, 150°C, 175°C, and 200°C, respectively (Figs. 11a–d).

The optimum values (in bars) of the three pressures ($p_h$, $p_m$, and $p_l$) are (11.61, 7.28, 4.21), (18.01, 10.44, 5.31), (29.00, 14.51, 6.90) and (29.00, 4.83, 3.89) (Fig. 11), corresponding to the minimum LEC of 0.0845 USD/kWh.
Fig. 8. Optimization results of the three evaporation pressures for the TPORC with respect to $t_{g,in}$ ($t_{pp} = 10^\circ C$, $t_{sup} = 5^\circ C$): working fluids (a) R600; (b) R245fa; (c) R601a; (d) R600a.

Fig. 9. Optimization results of the three evaporation pressures for the TPORC with respect to $t_{g,in}$ ($t_{pp} = 10^\circ C$, $t_{sup} = 5^\circ C$): working fluids (a) R125a; (b) R134a; (c) R1234yf; (d) R143a.
0.0617 USD/kWh, 0.0481 USD/kWh, and 0.0388 USD/kWh, respectively. When the \(t_{g,in}\) are 125°C, 150°C, and 175°C, the optimum values of the \(p_h\) are within the domain, as can be seen in Figs. 11a, b and c.

Similarly, in the optimization of net power output, \(p_h\) is again on the upper boundary (Fig. 11d) when \(t_{g,in}\) is 200°C. The change of \(p_m\) under this condition has a very small influence on the LEC because the contours are almost horizontal.

The LEC contours, corresponding to optimized results (Fig. 11) are also demonstrated in Fig. 12, but with respect to \(p_m\) and \(p_l\). There the gradient along constant \(p_m\) is
greater than that along the constant $p_l$, indicating that the change of $p_l$ has more influence than that of $p_m$ on the LEC.

### 4.2 Comparison of SPORC, DPORC and TPORC

Comparison of the net power output between the SPORC, DPORC and TPORC systems relates to different heat source (geofluid) temperatures (Fig. 13). All three systems have attained their optimum operation conditions. The net power output differences between the SPORC and the multiple-pressure systems (DPORC and TPORC) increase firstly and then decrease with the temperature increase. The net power output of the TPORC is 40.3% and 11.3% higher than that of the SPORC and DPORC, respectively, when the $t_{g,in}$ is 100°C; It is 31.4% and 9.05% when the temperature is 140°C. The differences become almost negligible (3.8% and 2.4%, respectively) when the $t_{g,in}$ is 200°C, indicating that the advantage of using a multiple-pressure system diminishes as the $t_{g,in}$ is around 200°C. For the temperature range investigated, the order from high to low based on the thermodynamic performance (net power output) is: TPORC > DPORC > SPORC. In terms of using geothermal resources with temperature ranging from 100°C–200°C, the TPORC could be a choice but a techno-economic analysis should be carried out to validate this.

![Fig. 12. Optimization results of the TPORC showing the LEC contours with respect to $p_m$ and $p_l$ ($t_{pp} = 10\degree C, t_{sup} = 5\degree C, R245fa$).](image1)

![Fig. 13. Net power output comparisons among SPORC, DPORC and TPORC with respect to different geofluid temperatures (working fluid: R245fa).](image2)

Techno-economic comparison of SPORC, DPORC and TPORC systems was made when the $t_{g,in}$ equals 120°C, 140°C, 160°C, 180°C, and 200°C, respectively, resulting in LECs (Fig. 14). The LEC of these systems decrease with the $t_{g,in}$ increase. As can be seen in Fig. 14a, $LEC_{SPORC} > LEC_{DPORC} > LEC_{TPORC}$, but the difference between $LEC_{DPORC}$ and $LEC_{TPORC}$ is a decrease with the
When the $t_{\text{g, in}}$ is 200°C, the difference between LEC$_{\text{DPORC}}$ and LEC$_{\text{TPORC}}$ becomes negligible. Considering the payback period (PBP) of SPORC, DPORC and TPORC systems (Fig. 14b), the PBP$_{\text{SPORC}}$ is higher than the PBP$_{\text{DPORC}}$ and PBP$_{\text{TPORC}}$ under any temperature condition, especially when the $t_{\text{g, in}}$ is 120°C when the PBP$_{\text{SPORC}}$ is 1.54 times and 1.77 times higher than PBP$_{\text{DPORC}}$ and PBP$_{\text{TPORC}}$, respectively. Assuming a power plant lifetime of 25 years, the PBP of a TPORC is too long if the $t_{\text{g, in}}$ is lower than 140°C. When $t_{\text{g, in}}$ is 200°C, the difference between PBP$_{\text{TPORC}}$, PBP$_{\text{DPORC}}$ or PBP$_{\text{SPORC}}$ becomes negligible.

Using R600a as the working fluid also offers good thermodynamic performance under high temperature conditions, and so a techno-economic analysis of each system using R600a was also carried out. As can be seen in Fig. 15, the tendency of LEC or PBP to alter with temperature change is similar to that of the system using R245fa, as shown in Fig. 14.

In summary, for the temperature range investigated, the order from high to low based on the techno-economic performance is found to be: TPORC > DPORC > SPORC. In terms of using geothermal resources with temperatures ranging from 100°C to 200°C, the TPORC system can be a better choice for geothermal power generation if the wellhead geofluid temperature is between 140°C and 180°C.

5 Conclusions

A triple-pressure organic Rankine cycle (TPORC) using geothermal energy for power generation has been investigated. Both thermodynamic and techno-economic performances of the TPORC were compared with dual-pressure ORC (DPORC) and single-pressure ORC (SPORC), respectively, for the geofluid temperatures ($t_{\text{g, in}}$) ranging from 100°C to 200°C. The main conclusions can be summarized as follows:

(1) either a lower value of pinch temperature difference ($t_{\text{pp}}$) or a lower value of superheat degree ($t_{\text{sup}}$) results in a higher net power output. The $t_{\text{pp}}$ has more influence than the $t_{\text{sup}}$;

(2) for a given $p_{\text{h}}$, the change of $p_{\text{l}}$ has more influence than that of $p_{\text{m}}$ on the net power output and the levelized electricity cost (LEC);

(3) when the $t_{\text{g, in}}$ is below 145°C, a TPORC using R601a (isopentane) as the working fluid has better thermodynamic performance than using other working fluids. When the geofluid temperatures range from 145°C to 185°C, R245fa becomes the best working fluid. When the $t_{\text{g, in}}$ is between 185°C and 200°C, the working fluid R600a (isobutene) is the best choice in terms of the net power production;

(4) higher geofluid mass flow rate ($m_{\text{g}}$) can make a
considerable contribution to shorten the payback period (PBP) as well as decrease the LEC, especially when the $t_{in}$ is low.

(5) For the temperature range investigated, the order from high to low based on thermodynamic and techno-economic performances is found to be: TPORC > DPORC > SPORC. In terms of using geothermal resources with temperatures ranging from 100°C to 200°C, the TPORC system can be a better choice for geothermal power generation if the wellhead geofluid temperature is between 140°C and 180°C.

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Nomenclature

<table>
<thead>
<tr>
<th>Types</th>
<th>Terms</th>
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<tbody>
<tr>
<td>g</td>
<td>Gravity coefficient (m/s)</td>
<td>g</td>
</tr>
<tr>
<td>h</td>
<td>Specific enthalpy (kJ/kg)</td>
<td>h</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate (kg/s)</td>
<td>m</td>
</tr>
<tr>
<td>p</td>
<td>Pressure (bar)</td>
<td>p</td>
</tr>
<tr>
<td>n</td>
<td>Running years of power station</td>
<td>n</td>
</tr>
<tr>
<td>i</td>
<td>Bank rate</td>
<td>i</td>
</tr>
<tr>
<td>Q</td>
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<td>Q</td>
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<tr>
<td>W</td>
<td>Power (kW)</td>
<td>W</td>
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<tr>
<td>t</td>
<td>Temperature (°C)</td>
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</tr>
<tr>
<td>v</td>
<td>Volume flow rate (m³/h)</td>
<td>v</td>
</tr>
<tr>
<td>Cp</td>
<td>Heat capacity at constant pressure</td>
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</tr>
<tr>
<td>A</td>
<td>Heat exchanger surface area</td>
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Abbreviations

SPORC: Single-pressure organic Rankine cycle
DPORC: Dual-pressure organic Rankine cycle
TPORC: Triple-pressure organic Rankine cycle
LEC: Levelized electricity cost
PBP: Payback period
NE: Net earnings each year
ODP: Oxzone depletion potential
Rev: Revenue each year

Subscripts

out: Outlet
p,g: Geothermal water pump
p,w: Working fluid pump
p,c: Cooling water pump
pp: Pinch point
net: Net power
i: Isentropic
sup: Superheated
h: High-pressure stage
m: Medium-pressure stage
l: Low-pressure stage

Greek symbols

$\eta$: Efficiency
$\rho$: Density (kg/m³)

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