Thermodynamic Analysis and Performance Optimization of Organic Rankine Cycles for the Conversion of Low-to-Moderate Grade Geothermal Heat

Yekoladio, P.J., Bello-Ochende, T. and Meyer J.P.
Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria
Private Bag X20, Hatfield 0028, South Africa.

Abstract
The present study considers a thermodynamic analysis and performance optimization of small binary-cycle geothermal power plants operating with moderately low-temperature and liquid-dominated geothermal resources in the range of 110°C to 160°C. The paper consists of an analytical and numerical thermodynamic optimization of selected Organic Rankine Cycles (ORC) to maximize the cycle power output. The optimization process and Entropy Generation Minimization (EGM) analysis were performed to minimize the exergy loss of the power plant. Optimal operating conditions were determined for maximum cycle power output per unit mass flow rate of the geothermal fluid. The maximum cycle power output was observed to increase exponentially with the geothermal resource temperature, whereas the optimal turbine inlet temperature increased almost linearly with the increase in the geothermal heat source. In addition, a performance analysis of selected organic working fluids, namely refrigerants R123, R152a, isobutane and n-pentane, was conducted under saturation temperature and subcritical pressure operating conditions of the turbine. Organic fluids with higher boiling point temperature, such as n-pentane, were recommended for the basic type of ORCs, whereas those with lower vapour specific heat capacity, such as butane, were more suitable for the regenerative ORCs.

Keywords: Geothermal energy, Organic Rankine Cycles, Optimization, Exergy analysis, binary cycle.

Nomenclature

Alphabetic symbols

Cp	Specific heat capacity, J/kg.K
$\dot{E}x$	Exergy rate, W
h	Enthalpy, kJ/kg
$\dot{I}$	Exergy destruction, W
$\dot{m}$	Mass flow rate, kg/s
P	Pressure, Pa
$\dot{Q}$	Heat transfer rate, W
s	Specific entropy, J/kg.K
T	Temperature, °C
$\dot{W}$	Power output, W

Abbreviations

HC	Hydrocarbons
$HCFC$	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons

Greek symbols

η_I	First Law efficiency, %
η_{II}	Second Law efficiency, %
ε	Effectiveness, %
ν	Vapour
ψ	Specific exergy, W/kg

Subscripts

0	Reference state
$1-15$	Thermodynamic states
c	Condenser
cr	Critical value
CS	Cooling system
$dest$	Destruction
E	Evaporator
geo	Geothermal fluid
HE	Heat exchanger
in	Inlet
max	Maximum
min	Minimum
opt	Optimum
out	Outlet
p	Circulation pump
pp	Pinch-point
rej	Reinjection
s	Isentropic
t	Turbine
th	Thermal

1. Introduction

For decades, diverse studies have been conducted to develop renewable and sustainable energies while reducing the environment defects of global warming, greenhouse effect, air pollution and waste of natural resources. Among a diversity of energy-efficient and environmental friendly technologies identified for power generation, the geothermal energy has proved to be an alternative energy source for electric power generation due to its economic competitiveness, the operational reliability of its power plants, and its environmentally friendly nature [1]. Current research activities undertaken worldwide have aimed at reducing the cost of geothermal electricity production either in resource exploration or extraction, reservoir stimulation, drilling techniques, or energy conversion systems.

The present study considers a thermodynamic analysis and performance optimization of four energy conversion systems utilized in small binary-cycle geothermal power plants operating with moderately low-temperature and liquid-dominated geothermal resources in the range of 110^{o}C to 160^{o}C. Various studies were conducted by diverse authors proposing innovative methods to improve the performance of the binary-cycle geothermal power plant operating with moderately low-temperature geothermal resources. Among others, we may acknowledge Gu and Sato [2] who studied the supercritical cycles. Kanoglu [3] discussed dual-level binary geothermal power plant, and DiPippo [4] proposed both a recovery heat exchanger (RHE) with a cascade of evaporators with both high- and low-pressure turbines operating in a Kalina cycle. Desai and Bandyopadhyay [5] recommended incorporating both regeneration and turbine bleeding to the basic organic Rankine cycles, whereas Gnutek and Bryszewska-Mazurek [6] suggested multicycle with different thermodynamic properties.

An investigation on the optimal design of the binary cycle power plants for maximum cycle power output, the sole objective of this study, was discussed by Borsukiewicz-Gozdur and Novak [7] who maximized the working fluid flow to increase the power output of the geothermal power plant by repeatedly returning a fraction of the geofluid downstream of the evaporator to completely vaporize the working fluid prior expanding in the turbine. Madhawa Hettiarachchi et al [8] presented a cost-effective optimum design criterion based on the ratio of total heat transfer area to the net cycle power output as the objective function, for the simple ORC employing low temperature geothermal resources.

In most of the studies mentioned above, the minimization of the geothermal fluid flow rate (or specific brine consumption) for a given cycle power output was addressed as the objective function for the optimum design of the ORCs. The present study, however, focuses on maximizing the cycle power output for a given geothermal fluid flow rate while minimizing the geothermal plant exergy destruction (or irreversibility) with careful design of the heat exchangers utilized in the geothermal power systems.

The paper consists of an analytical and numerical thermodynamic optimization of the selected ORCs to maximize the cycle power output. The optimization process and Entropy Generation Minimization (EGM) analysis were performed to minimize the exergy loss of the power plant. Optimal operating conditions were determined for maximum cycle power output per unit mass flow rate of the geothermal fluid. In addition, a performance analysis of the selected organic working fluids, namely refrigerants R123, R152a, isobutane and n-pentane, was conducted to demonstrate the extent at which they do affect the design and operation of the binary geothermal power plants under saturation temperature and subcritical pressure operating conditions of the turbine.

2. Proposed model

Small binary cycle geothermal power plants operating with moderate low-grade and liquid-dominated geothermal resources in the range of 110^{o}C to 160^{o}C are considered. The low-grade geothermal heat can suitably be recovered by an ORC or Kalina cycle. For the purpose of this study, the ORC was preferred considering its widely use in geothermal power generation, the simplicity of its power cycle, and the ease of maintenance [9].

In the literature, more than 50 pure and mixtures of organic compounds for ORC have been considered, and classified as “wet”, “dry” or “isentropic” organic fluids according to the slope of its saturated-vapour line [9]. This study considers refrigerants R123, R152a, isobutane and n-pentane as binary working fluids for the conversion of the low-to-moderate grade geothermal heat. Refrigerant R123 is an isentropic organic fluid with a near-vertical saturated vapour-phase line, thus a nearly infinitely large slope of the saturated-vapour line. Refrigerant R152a belongs to the wet type, thus having a negative slope of the saturated-vapour line. Isobutane and n-pentane represent dry organic compounds characterized by a positive slope of the saturated-vapour line. The thermodynamic phases of the selected working fluids are illustrated on a Temperature vs. Entropy diagram in Fig. 1. In Table 1, the main thermo-physical properties of the selected binary working fluids are listed, as obtained from EES (Engineering Equation Solver) software [10].

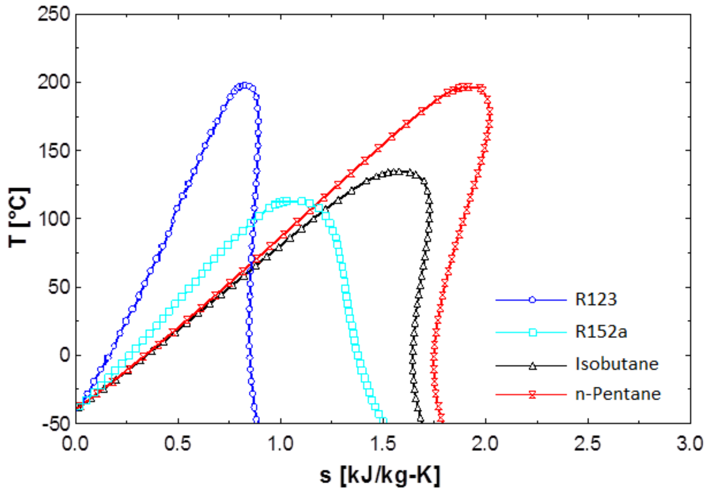

Figure 1: T-s diagram of selected binary fluids for ORC

Working fluid	**R123**	**R152a**	**R600a**	**R601**
Name	2,2-Dichloro-1,1,1-trifluoroethane	1,1-Difluoroethane	Isobutane	n-Pentane
Chemical formula	$CHCl_2C-F_3$	CH_3CH-F_2	C_4H_{10}	C_5H_{12}
Type	HCFC	HFC	HC	HC
Organic type	Isentropic	Wet	Dry	Dry
		Thermo-physical properties		
Molecular weight	152.93	66.05	58.12	72.15
$\boldsymbol{T_{bp}}$ **@ 1atm** $[^{o}C]$	27.82	-24.02	-11.67	36.0
$\boldsymbol{T_{cr}}$ $[^{o}C]$	183.68	113.26	134.67	196.55
$\boldsymbol{P_{cr}}$ **[MPa]**	3.662	4.517	3.62	3.37
$\boldsymbol{Cp_v}$ $[\mathrm{J}/kg.\mathrm{K}]$	738.51	1456.02	181.42	1824.12
Latent heat L $[\mathrm{kJ}/kg]$	161.82	249.67	303.44	349.00

Table 1: Thermodynamic properties of selected binary fluids for [8,11]

Four ORCs were analysed analytically and numerically, and their performance optimized to maximum the cycle power output. The selected ORCs are illustrated in Fig. 2. In Fig. 2a, a simple ORC type is shown. The primary heat transfer medium is pumped at high pressure and continuously circulated through the earth in a closed pipe system [12-13]. The fluid is thus heated by the linearly increasing underground temperature with depth, as it flows down the well. A secondary or binary fluid with a lower boiling point and higher vapour pressure is therefore completely vaporized and usually superheated by the primary fluid through a closed pipe system heat exchanger, to expand in the turbine and then condense either in an air-cooled or water-cooled condenser prior returning to the vaporizer and thus completing the Rankine cycle [14]. If the expansion process in the turbine terminates in the superheated region, a heat recuperator (or Internal Heat Exchanger, IHE) can be advantageous to preheat the binary working fluid prior evaporating in the heat exchanger to reduce the evaporator load, and hence improve the thermal efficiency of the cycle (Fig. 2b) [15-16].

Further improvement of the heat exchange performance and the Rankine cycle overall efficiency can be achieved with the addition of a two-phase regenerative cycle [5,13], utilizing an open feed-heater to preheat the binary working fluid prior evaporating in the heat exchanger, with the extracted fluid from the turbine expanded vapour (Fig. 2c). A combination of regenerator and recuperator can also be employed to improve the performance of heat exchanger process (Fig. 2d) [13].

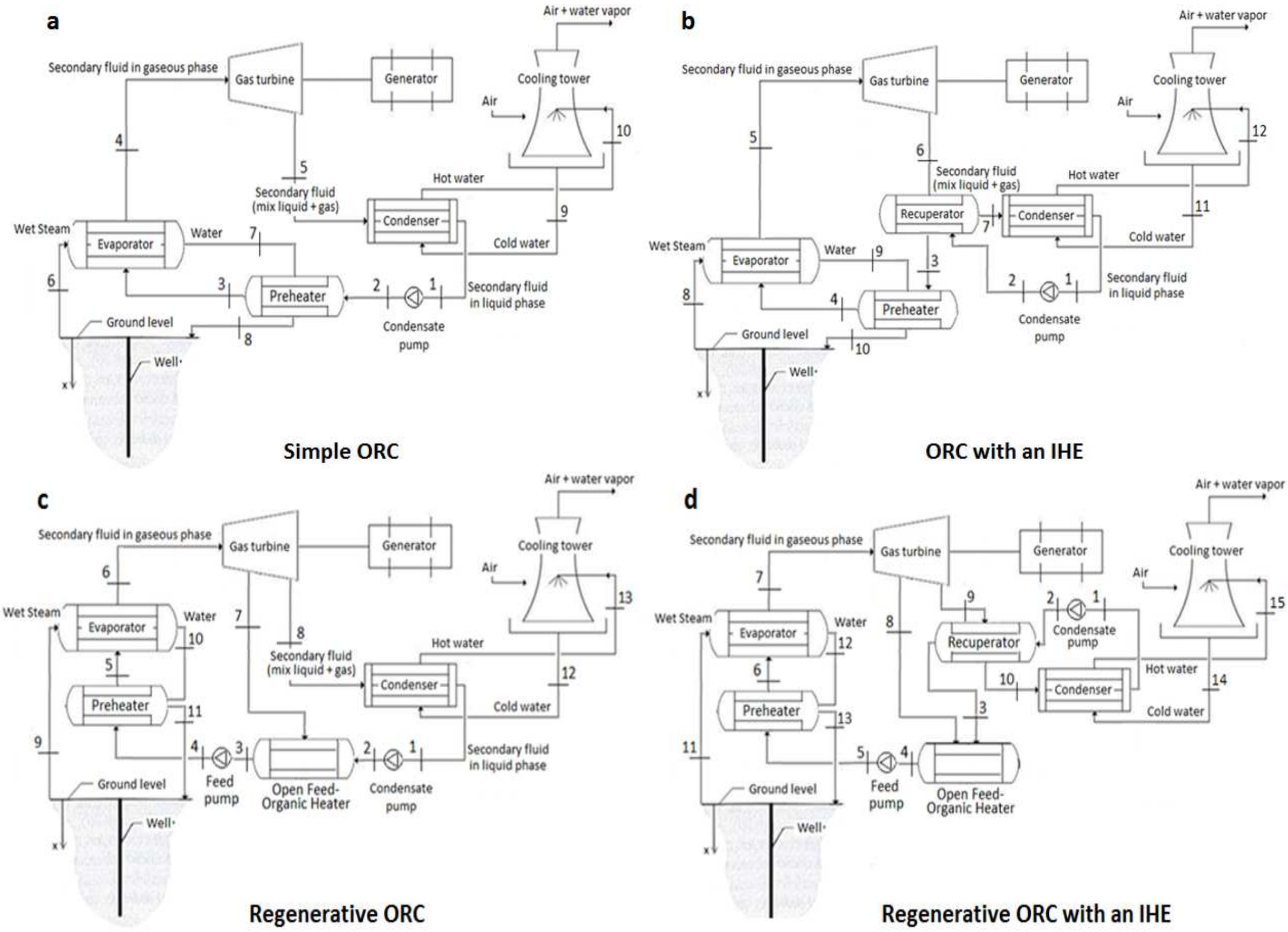

Figure 2: Schematic diagrams of the binary-cycle geothermal power plants

The cycles Temperature vs. Entropy diagrams are illustrated in Fig. 3. For the simple ORC (Fig. 3a), processes 1-2 and 4-5 refers to reversible adiabatic pumping and expansion processes, respectively; whereas process 2-3 and 5-1 represent constant-pressure heat addition and rejection, respectively. The addition of an IHE to the simple ORC is represented by states 3 and 7 on the cycle T-s diagram shown in Fig. 3b.

In contrast to the basic ORC's, the regenerative cycles consist of three constant-pressure heat transfer processes (Fig. 3c). Ideally, the mixture of the turbine bleeding and the condensate at the exit of the open feed-organic heater is assumed at saturated liquid condition and at the evaporator pressure [17]. The addition of an IHE to the regenerative ORC is illustrated by states 3 and 10 on the cycle T-s diagram shown in Fig. 3d.

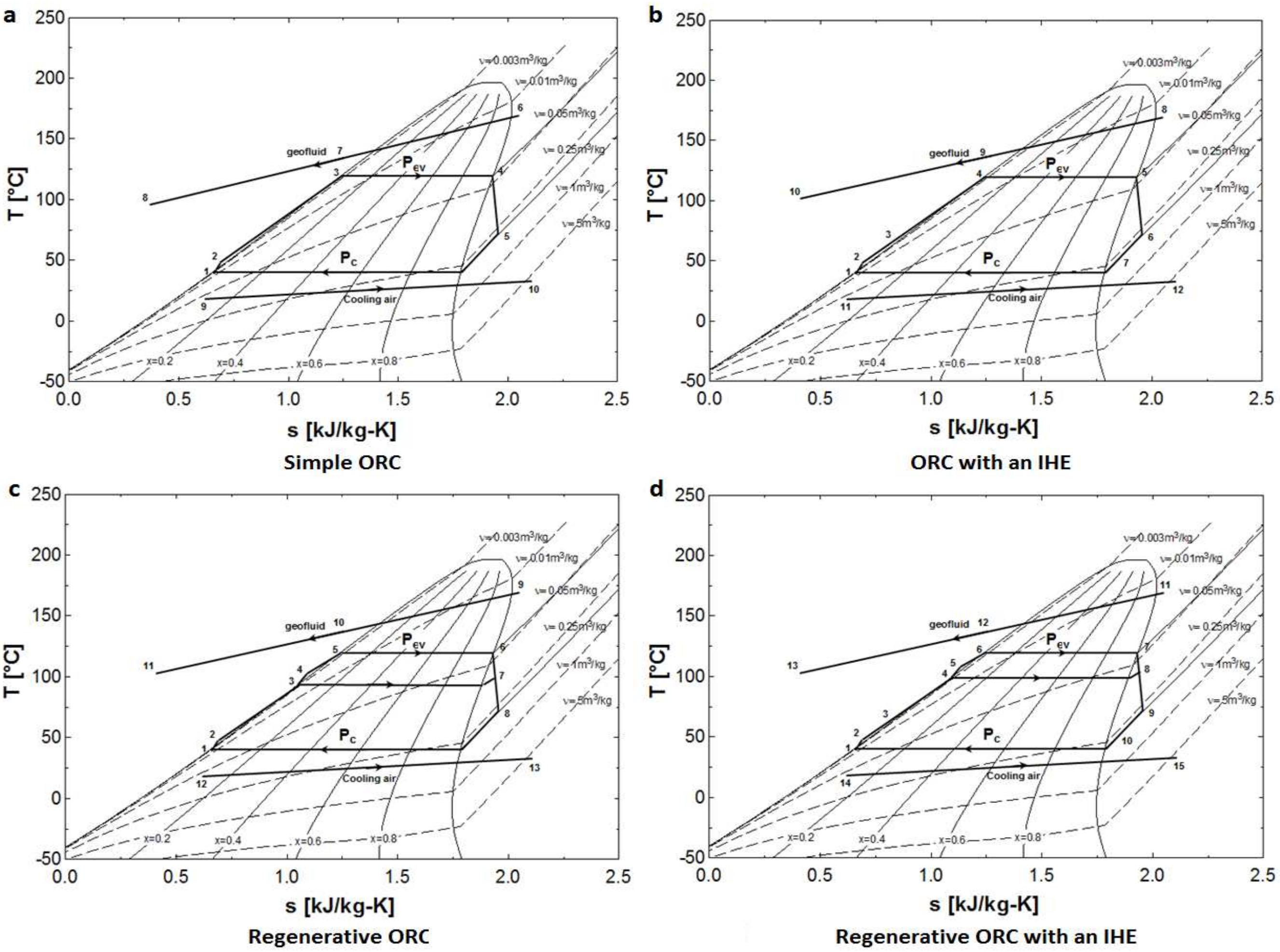

Figure 3: T-s diagrams of the binary-cycle geothermal power plants

Many other power cycle designs have been proposed and studied in the literature for the conversion of low-to-moderate grade heat resources, and aiming at improving the performance of the binary-cycle power plant. For instance, a heat recovery exchanger with a cascade of evaporators employed in a Kalina cycle [18], a heat recovery cycle with a high and low-pressure turbine [3] or multiple pressure levels [3], the Goswami cycle [11], a supercritical Rankine cycle [2], a trilateral flash cycle [11], etc.

3. Research methodology

3.1. Energy and exergy analysis

Mass, energy, and exergy balances for any control volume at steady state with negligible potential and kinetic energy changes can be expressed, respectively, by [13-14,16]

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

$$\dot{E}x_{heat} - \dot{W} + \sum \dot{m}_{in} \psi_{in} - \sum \dot{m}_{out} \psi_{out} = \dot{I} \tag{3}$$

The heat exergy at temperature T_j is given by [13,16]

$$\dot{E}x_{heat} = \sum \left(1 - \frac{T_o}{T_j} \right) \dot{Q}_j \tag{4}$$

And the flow (specific) exergy is

$$\psi = (h - h_o) - T_o (s - s_o) \tag{5}$$

The cycle power output is determined by, [16]

$$\dot{W}_{net} = \dot{W}_t + \dot{W}_p \tag{6}$$

And the total exergy lost in the cycle and plant are given respectively by [14,16]

$$\dot{I}_{cycle} = \sum_{all\ components} \dot{I}_i = \dot{I}_p + \dot{I}_{HEs} + \dot{I}_t + \dot{I}_c \tag{7}$$

$$\dot{I}_{plant} = \dot{I}_{cycle} + \dot{I}_{rej} + \dot{I}_{CS} = \dot{E}x_{in} - \dot{W}_{net} \tag{8}$$

Where the total exergy inputs to the ORC is determined by [3, 9,14,18]

$$\dot{E}x_{in} = \dot{m}_{geo}\left[\left(h_{geo} - h_o\right) - T_o\left(s_{geo} - s_o\right)\right] \tag{9}$$

3.2. Performance analysis

The First- and Second-law efficiencies, based on the geothermal fluid state at the inlet of the primary heat exchanger and with respect to the reference temperature T_o, are defined respectively as [3,14,18]

$$\eta_I = \frac{net\ work\ output}{total\ energy\ inputs} = \frac{\dot{W}_{net}}{\dot{m}_{geo}\left(h_{geo} - h_o\right)} \tag{10}$$

$$\eta_{II} = \frac{net\ work\ output}{total\ exergy\ inputs} = \frac{\dot{W}_{net}}{\dot{m}_{geo}\left[\left(h_{geo} - h_o\right) - T_o\left(s_{geo} - s_o\right)\right]} \tag{11}$$

Based on the heat transfer or energy input to the cycle, the First- and Second-law efficiency are given by [3,14,18]

$$\eta_{I,2} == \frac{\dot{W}_{net}}{\dot{m}_{geo}\left(h_{geo} - h_{rej}\right)} = \frac{\dot{W}_{net}}{\dot{m}_{wf}\left(h_{wf,out} - h_{wf,in}\right)} \tag{12}$$

$$\eta_{II,2} = \frac{\dot{W}_{net}}{\dot{m}_{geo}\left[\left(h_{geo} - h_{rej}\right) - T_o\left(s_{geo} - s_{rej}\right)\right]} \tag{13}$$

The performance of a binary-cycle geothermal power plant can also be evaluated using the cycle effectiveness, which represents the effectiveness of heat transfer to the cycle from the geothermal fluid, as [3,9,14,18]

$$\varepsilon = \frac{\dot{W}_{net}}{\dot{m}_{wf}\left[\left(h_{wf,out} - h_{wf,in}\right) - T_o\left(s_{wf,out} - s_{wf,in}\right)\right]} \tag{14}$$

As discussed by Subbiah and Natarajan [9], the First-law efficiency is a quantitative measure of the effectiveness of the conversion of the available geothermal energy into useful work. The cycle effectiveness measures both quantitatively and qualitatively the amount of available energy to be transferred, and the Second-law efficiency accounts for the overall exergy inputs to the cycle between the geothermal fluid temperature at the outlet of the resource well and the reference temperature T_o.

The performance analysis of individual component of the cycle was evaluated using the fuel depletion ratio, which is defined by [13,19]:

$$\delta_i = \frac{\dot{I}_i}{\dot{E}x_{in}} \tag{15}$$

3.3. Irreversibility analysis

In Fig. 4a, the loss of exergy (irreversibility) generated during the heat transfer process occurring in the Evaporator-Preheater unit is represented by the marked area of the temperature vs. heat transfer diagram, assuming linearity of the geofluid cooling curve. This significance loss of exergy is a consequence of the large difference in enthalpy or temperature between the geothermal and the binary fluids [20]. The addition of an IHE to the simple ORC is demonstrated to reduce the irreversibility of the heat transfer process as the working fluid was preheated prior entering the preheater (Fig. 4b). A decrease in irreversibility can also be achieved while utilizing a regenerative Rankine cycle to improve the heat exchange performance (Fig. 4c). Further reduction in irreversibility is possible with a combination of a regenerator and recuperator (Fig. 4d).

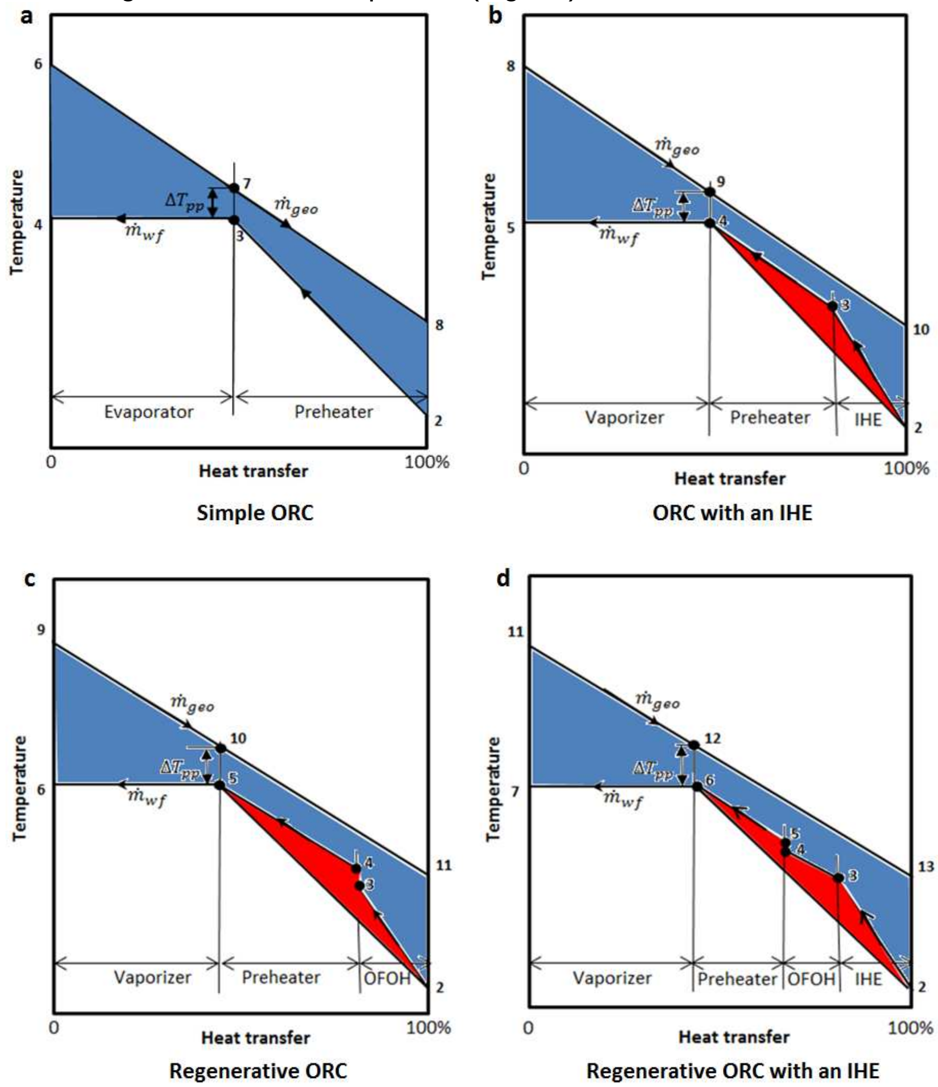

Figure 4: T-Q diagrams of the heat exchange process in the Evaporator-Preheater unit

3.4. Model validation

To validate the simulation, the thermodynamic performance of the selected ORCs was analysed using EES software [10]. The numerical data were validated with the work of Yari [13] for refrigerant R123, at the operating conditions listed in Table 2.

Parameters	P_o [kPa]	P_{ext} [kPa]	T_o [^{o}C]	T_c [^{o}C]	T_E [^{o}C]	T_{geo} [^{o}C]	ΔT_{pp} [^{o}C]	□$_p$ [%]	□$_t$ [%]	ε_{IHE} [%]
Value	101.3	494* 581**	25	40	120	180	10	90	80	80

Table 2: Operating parameters used in the validation of results

* For the regenerative ORC

** For the regenerative ORC with an IHE

The comparison shown in Table 3 illustrates a very good agreement between the present work and the results of Yari [13].

Performance parameters	Simple ORC		ORC with IHE		Regenerative ORC		Regenerative ORC with IHE	
	Present work	[13]	Present work	[13]	Present work	[13]	Present work	[13]
$\dot{W}_{net}$ [kJ/kg]	50.29	50.38	50.29	50.38	44.13	43.61	43.88	44.02
$\dot{E}x_{dest}$ [kJ/kg]	79.67	80.25	79.67	80.25	85.84	85.98	86.09	86.59
η_I [%]	7.37	7.65	7.37	7.65	6.466	6.623	6.43	6.686
$\eta_{I,1}$ [%]	13.06	13.28	13.97	14.2	14.49	14.52	15.08	15.35
η_{II} [%]	37.84	38.76	37.84	38.76	33.2	33.56	33.01	33.87
$\eta_{II,2}$ [%]	48.56	49.06	50.92	51.4	50.64	50.39	52.20	52.73
ε [%]	63.28	64.33	64.75	65.82	62.5	62.67	64.25	65.41

Table 3: Validation of the numerical model with a previously published data [13]

3.5. Optimization model

The paper consists of an analytical and numerical thermodynamic optimization to maximize the cycle power output. The optimization process and Entropy Generation Minimization (EGM) analysis were performed to minimize the exergy loss of the power plant. For a given combination of the thermodynamic cycle and working fluid, the optimal operating conditions, i.e. evaporative and condensing temperatures, were determined for maximum cycle power output per unit mass flow rate of the geothermal fluid, as illustrated by the simulation flow chart shown in Fig. 5.

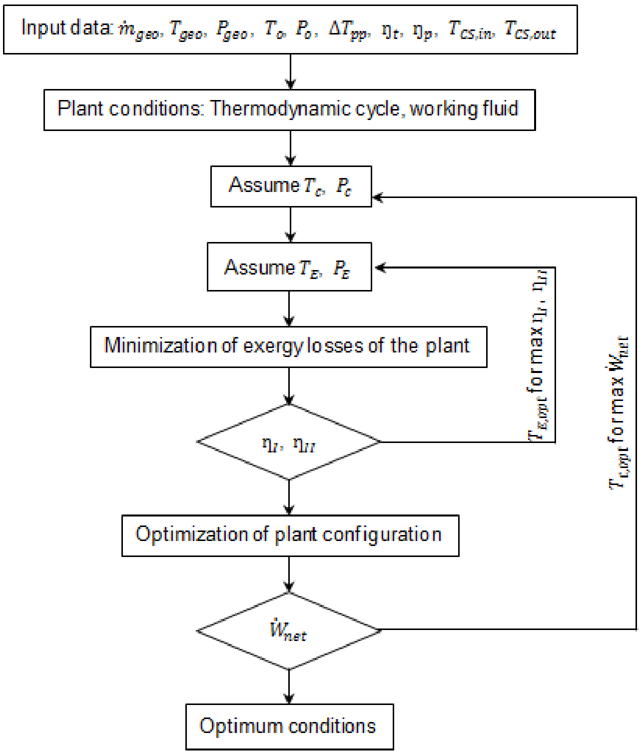

Figure 5: Flow chart of the simulation procedure

4. Results

4.1. Thermodynamic performance of the selected organic binary fluids

A thermodynamic performance of the selected organic binary fluids is considered for the simple and regenerative ORCs. The pinch-point and condensing temperatures were fixed at

5°C and 40°C respectively, while the turbine inlet temperature was varied from the limiting temperature of condensation to the geofluid input temperature.

In Fig. 6, the variation of the cycle power output per unit mass flow rate of the geofluid is plotted for both ORCs at subcritical pressure operating conditions. For the simple ORC, a nearly identical maximum cycle power output per unit mass flow of the geothermal fluid was obtained at about similar optimal turbine inlet temperature, irrespective of the type of organic binary fluids (Fig. 6a). For the regenerative ORC, however, the optimal turbine inlet temperature and maximum cycle power output per unit mass flow of the geothermal fluid differed significantly for all the working fluids (Fig. 6b). A brief comparison of Figs. 6a and 6b has shown nearly identical thermodynamic performance for isobutane, whereas the addition of an OFOH to the binary cycle utilizing R152a, R123 or n-pentane as working fluid resulted to a substantial reduction in the cycle power output by as much as 15%, 26% and 42%, respectively.

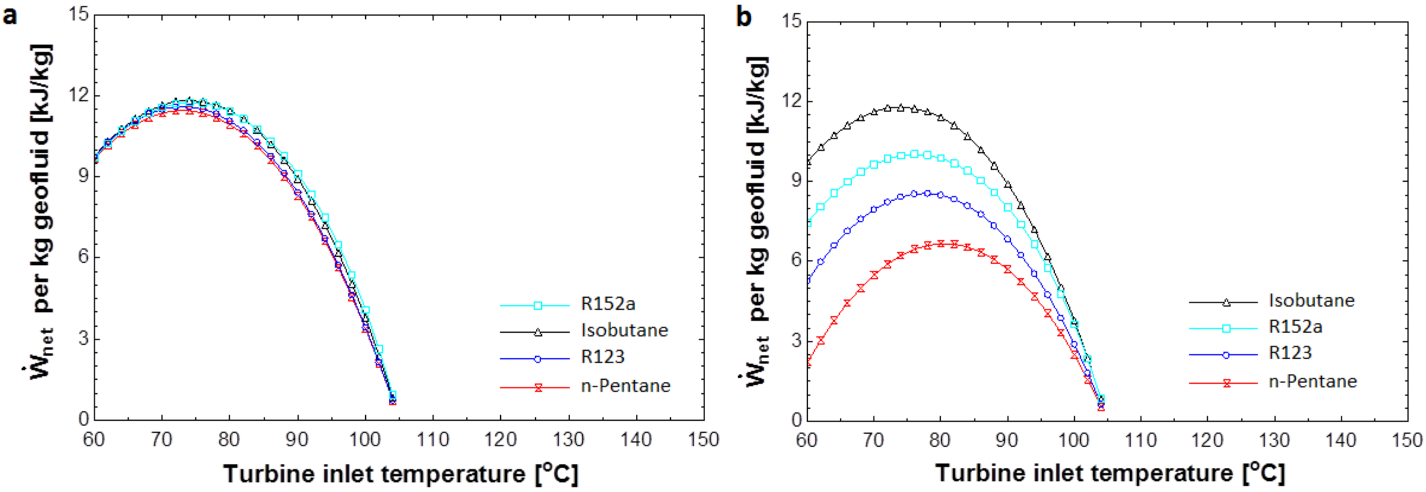

Figure 6: Cycle power output per kg geofluid as a function of the turbine inlet temperature for geothermal resource temperature of 110°C (a) Simple ORC and (b) Regenerative ORC

In the studied range of heat source temperature, the lower the boiling point temperature of the organic fluid, the higher the evaporating temperature for its simple ORC (Fig. 7a). On the other hand, the supremacy of organic fluids with low vapour specicific heat capacity, such as isobutane, to convert low-to-moderate geothermal resource temperature at relatively low evaporating temperature is remarkably demonstrated for the regenerative ORC (Fig. 7b). Hence, for the conversion of low-to-moderate grade geothermal heat, organic fluids with higher boiling point temperature, such as n-pentane, would be recommended for the simple ORC as discussed by Mago et al. [17], whereas organic fluids with lower vapour specific heat capacity, such as butane, would be more suitable for the regenerative ORC.

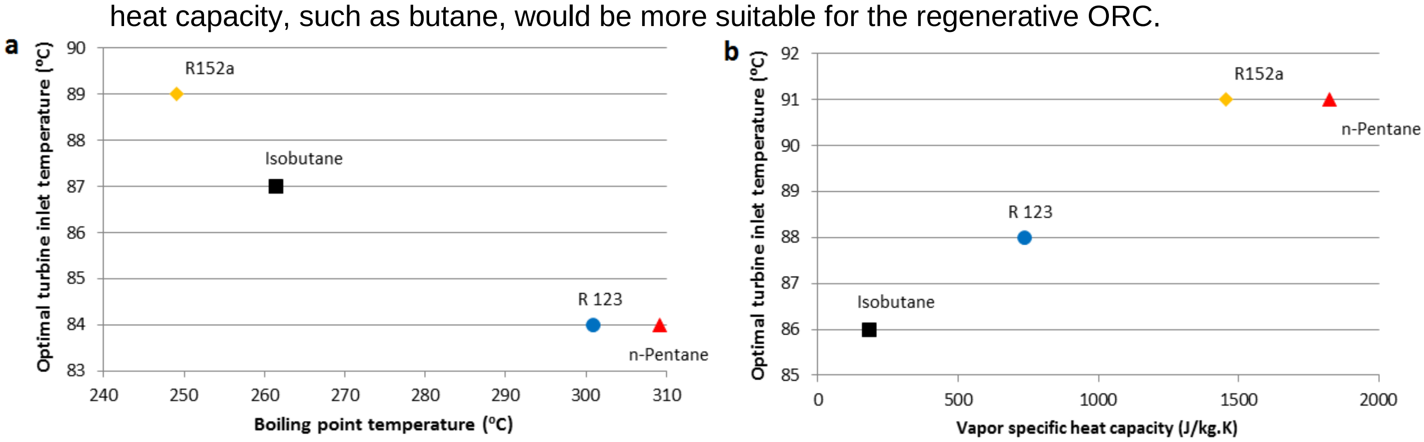

Figure 7: Effect of fluid's (a) boiling point temperature, and (b) vapour specific heat capacity, on the optimal turbine inlet temperature for geothermal resource temperature of 130°C

4.2. Performance analysis of the Organic Rankine Cycles

A performance analysis of the selected binary-cycles was conducted using n-pentane as the organic binary fluid. The cycle power output per unit mass flow rate of the geothermal fluid is plotted against the turbine inlet temperature for the geothermal resource temperatures of 110°C and 160°C (Fig. 8). As discussed by Lakew and Bolland [21], the increase in the turbine inlet temperature resulted in an increase of the enthalpy of the inlet fluid to the turbine and decrease in the flow rate of the working fluid. Consequently, for each type of ORC, a maximum cycle power output per unit mass flow rate of the geofluid was obtained for an optimal turbine inlet temperature. Moreover, for the given operating conditions of the ORCs, one can conclude that the addition of an IHE did not really impact on the thermodynamic performance of the cycle, whereas the regenerative system reduced significantly the cycle performance.

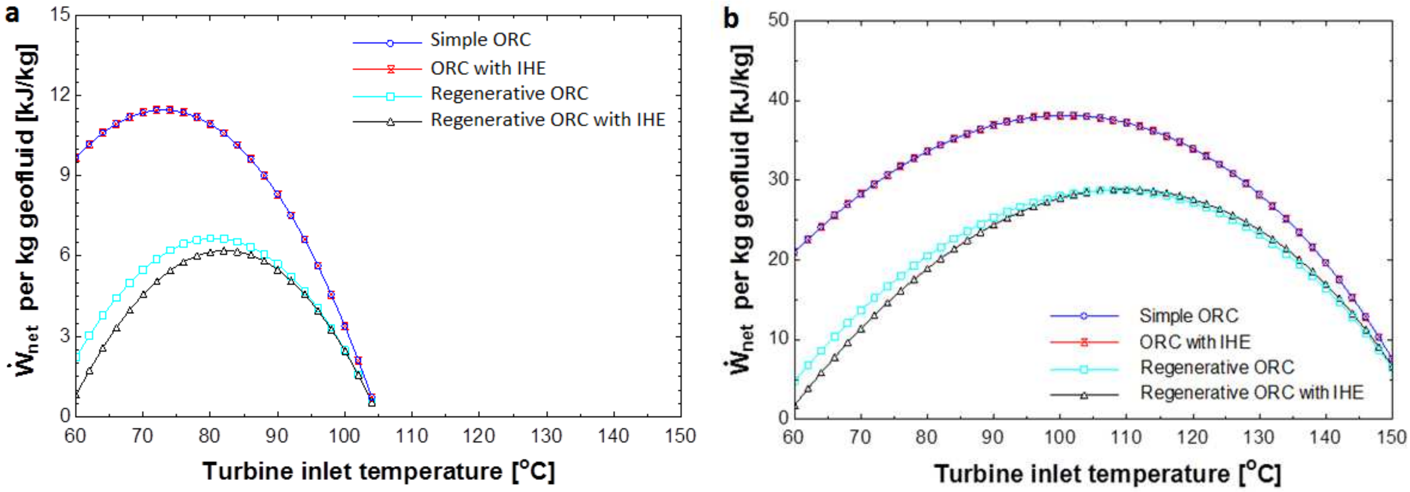

Figure 8: Cycle power output per kg geofluid as a function of the turbine inlet temperature for geothermal resource temperature of (a) 110°C and (b) 160°C

The First- and Second-law efficiencies, based on the geothermal fluid state at the inlet of the primary heat exchanger, and with respect to the reference temperature T_o, are illustrated by Figs. 9 and 10 respectively, for the geothermal resource temperatures of 110°C and 160°C. Both efficiencies are observed to increase with the turbine inlet temperature up to the same optimal turbine inlet temperature, which also produced maximum cycle power output. Clearly, based on the effectiveness of the conversion of the available geothermal energy and exergy into useful work, the regenerative cycles have been less efficient and less performing compared to the basic ORCs.

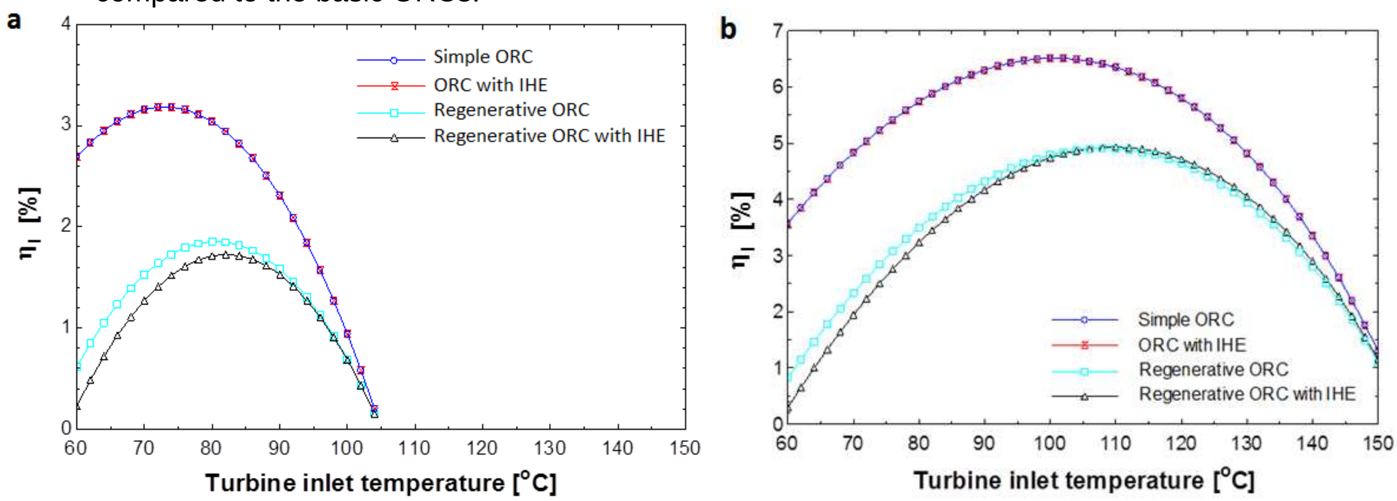

Figure 9: First-law efficiency at the primary heat exchanger inlet as a function of the turbine inlet temperature for geothermal resource temperature of (a) 110°C and (b) 160°C

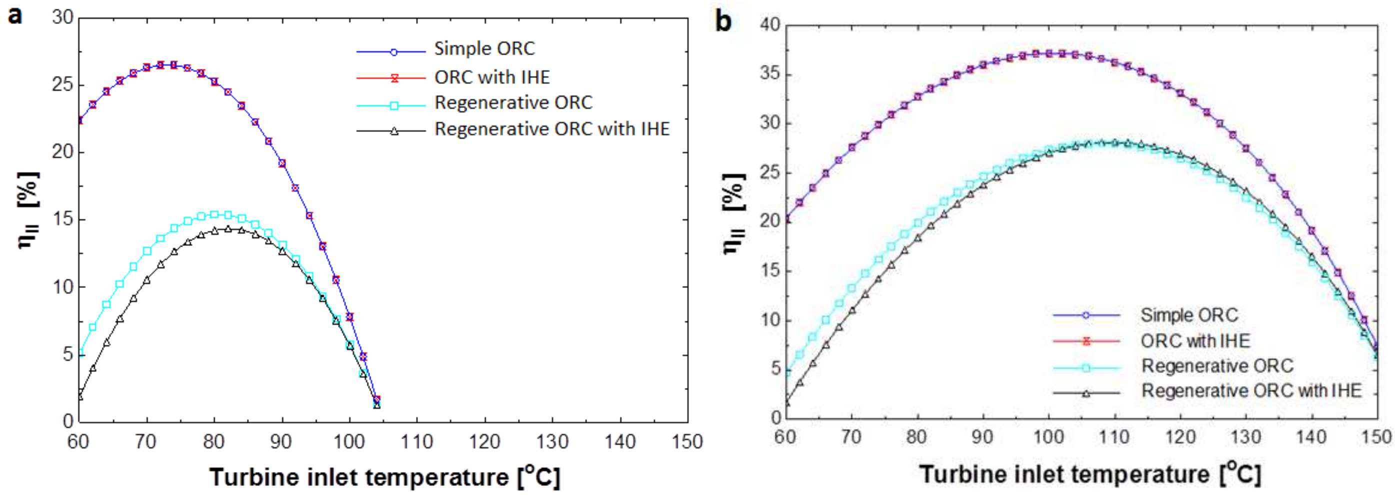

Figure 10: Second-law efficiency at the primary heat exchanger inlet as a function of the turbine inlet temperature for geothermal resource temperature of (a) 110^{o}C and (b) 160^{o}C

Based on the energy input to the cycle, the First- and Second-law efficiencies are represented in Fig. 11. At low turbine inlet temperatures, the basic ORCs have been more efficient than the regenerative ORCs. As the turbine inlet temperature increased, the regenerative ORC with an IHE became the most efficient whereas the simple ORC showed a poor performance. This could be attributed to the ability of the regenerative cycles to minimize the exergy loss (irreversibility) during the heat transfer process. The choice of the appropriate ORC for the conversion of low-to-moderate grade geothermal heat in the given range of temperatures and based on the energy input to the ORC, is highly reliant on the turbine inlet conditions required.

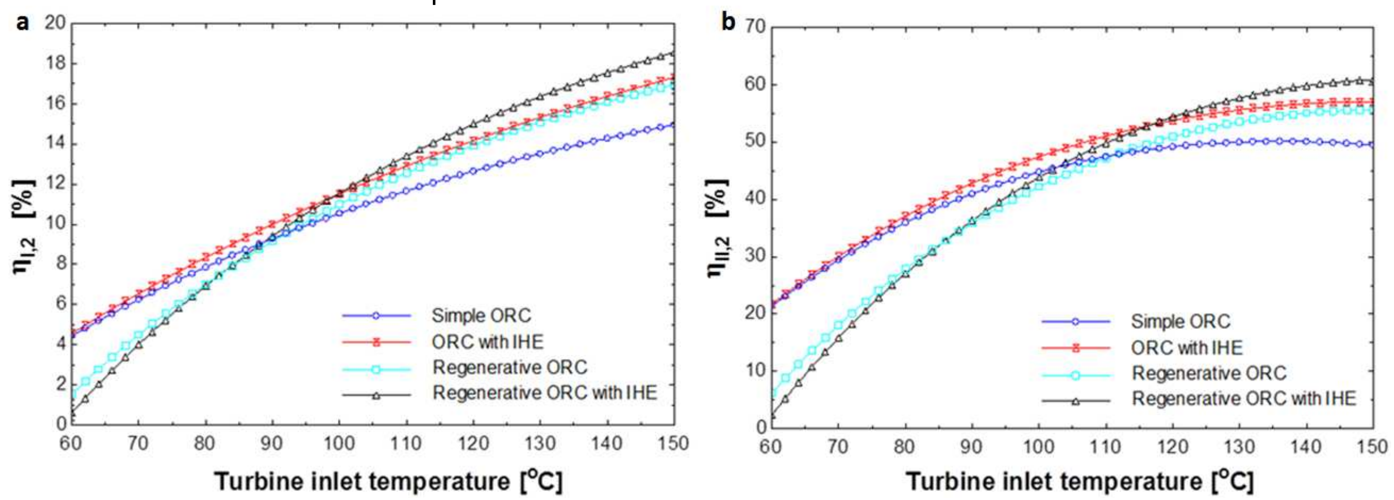

Figure 11: (a) First- and (b) Second-law efficiency on heat transfer input to the ORC as a function of the turbine inlet temperature

The cycle effectiveness, which measures both quantitatively and qualitatively the amount of available energy to be transferred from the geothermal resource to the organic working fluid is plotted in Fig. 12, as a function of the turbine inlet temperature. At high turbine inlet temperatures, the curves of the cycle effectiveness for the different ORC types are observed to flatten. Nevertheless, one could conclude that the ORC with IHE enabled maximum conversion of the available energy from the geothermal resource to the organic working fluid.

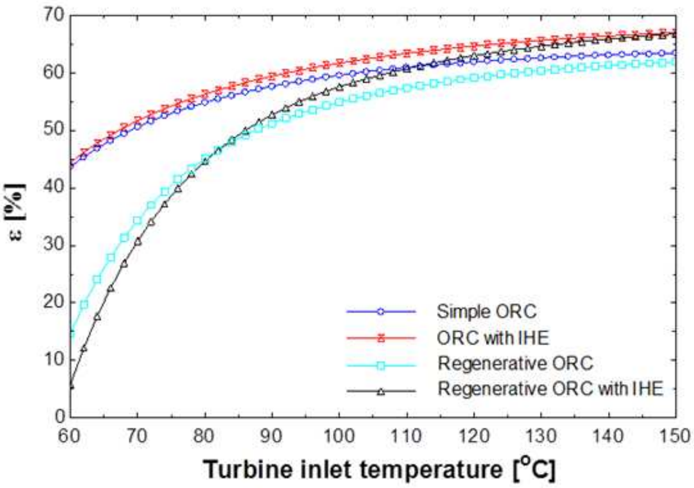

Figure 12: Cycle effectiveness as a function of the turbine inlet temperature

4.3. Irreversibility analysis

As illustrated by Fig. 13, the addition of an IHE to the binary cycle has substantially reduced the exergy destruction in the Evaporator-preheater, condenser and cooling system, by about 40-70%, 20-30% and 5-15% respectively. The cycle power output increased only marginally with the regenerative ORC by less than 5% for a given combination of the geothermal fluid, evaporator and condenser temperatures. Adding an OFOH to the binary cycle, on the other hand, resulted in a remarkable reduction of the exergy destruction in all individual components of the binary cycle, typically 80-90% for the Evaporator-preheater unit, 25-35% for both the condenser and cooling system, 20-30% for the turbine, and 10-20% for the pumping system. A significant reduction of 15-25% in cycle power output was, however, observed.

The major drawback with the addition of an IHE or/and OFOH lies in the increase in rejection exergy destruction, 0-20% with the addition of an IHE alone, 20-35% while employing an OFOH and up to 40% for both IHE and OFOH added to the binary-cycle.

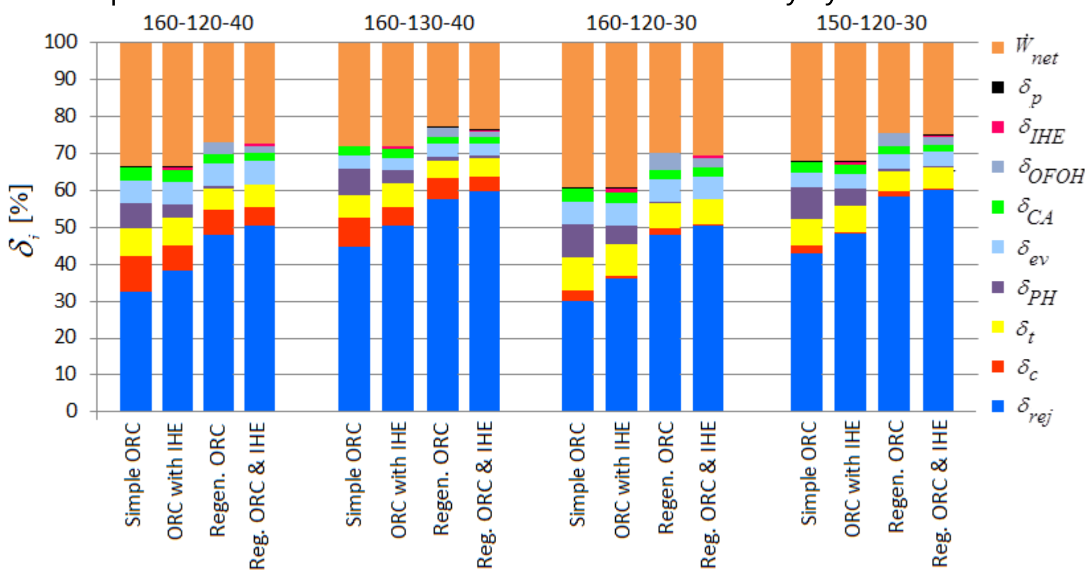

Figure 13: Variation of Fuel depletion ratio with T_{geo}, T_E and T_c respectively (given in °C)

From Fig. 13, a sensitivity analysis is discussed for a change in operating evaporation temperature, decrease in condensing temperature and variation in the temperature of the geofluid resource:

- For a given geothermal fluid and condensing temperatures, an increment of 10°C in the evaporating temperature resulted to a substantial increase in the rejection exergy destruction, back to the exploitation reservoir, at approximately 16-27%, whereas the exergy destruction of both the evaporative and condensation processes decreased by 20-40% and 20-25% respectively. In addition, the ability to convert the total exergy input to useful work output also dropped by approximately 15%.
- For a given geothermal fluid and evaporating temperatures, a decrease in condensing temperature of 10°C yielded a decrease of roughly 71% in exergy destruction of the condenser itself for cycles not using an IHE and nearly 92% for those with an IHE. Moreover, the cycle power output was increased by 10-15%. Hence, the advantage of using an IHE is demonstrated to reduce significantly the condensing load; and the optimal condensing temperature to maximize the cycle power output.
- As the temperature of the geofluid resource is reduced by 10°C, the cycle power output is reduced by approximately 18%. In short, a substantial decrease in work output can result from a small decrease in the geothermal resource temperature.

In Fig. 14, the overall plant irreversibility is plotted against the turbine inlet temperature for the geothermal resource temperatures of 110°C and 160°C. An optimal turbine inlet temperature is observed to yield minimum overall plant irreversibility, which also produced maximum cycle power output. Consequently, minimizing the loss of exergy in each components of the cycle, thus the overall plant irreversibility, would also maximize the cycle power output.

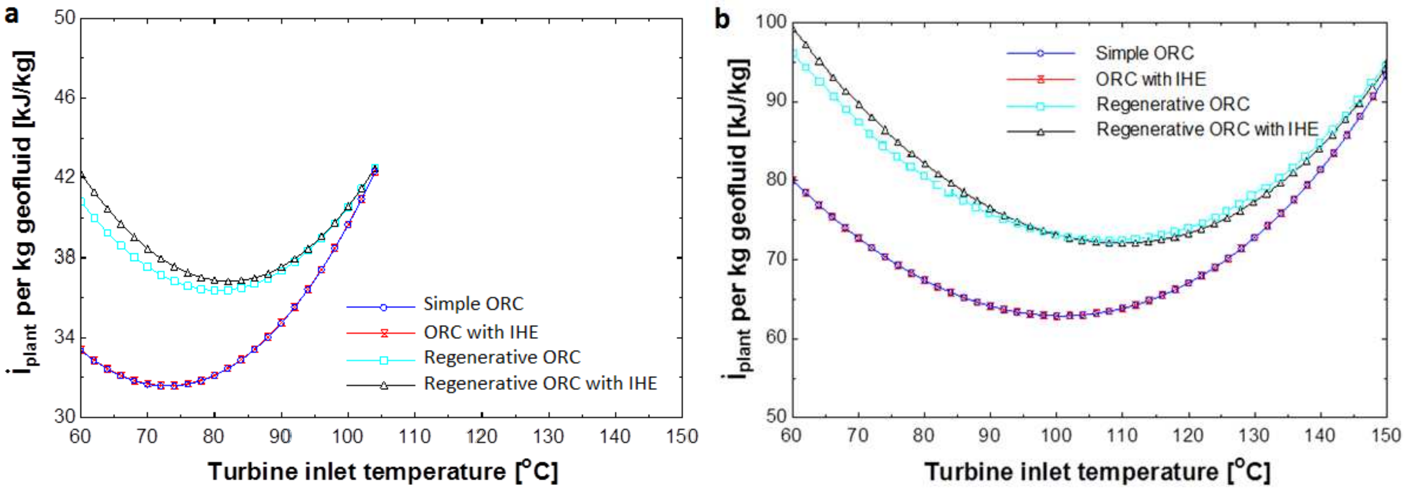

Figure 14: Overall plant irreversibility as a function of the turbine inlet temperature for geothermal resource temperature of (a) 110°C and (b) 160°C

4.4. Optimized solution

A parametric optimization with n-pentane as working fluid for the selected cycles was conducted for a geothermal resource temperature in the range of 110°C and 160°C. The optimal operating conditions were determined for maximum cycle power output per unit mass flow rate of the geothermal fluid, as well as minimum overall plant irreversibility.

As illustrated by Fig. 15a, the optimal turbine inlet temperature is seen to increase almost linearly with the increase in the geothermal resource temperature. The addition of an IHE to the binary cycle has merely impacted on the optimum operating conditions of the ORCs, whereas adding an OFOH has required high optimal turbine inlet temperatures, approximately 10°C as compare to the basic Rankine ORCs, for a given geothermal resource temperature.

In Fig. 15b, the maximum cycle power output to be produced per unit mass flow rate of the geothermal fluid is plotted. At low geothermal resource temperatures, below 120^{o}C, the basic ORCs generate nearly twice as much power output than the regenerative ORCs. Clearly, the maximum cycle power output per unit mass flow rate of the geothermal fluid increases exponentially with the geothermal resource temperature. Hence, a substantial increase in cycle power output is expected with a slight increase in the geothermal resource temperature [9].

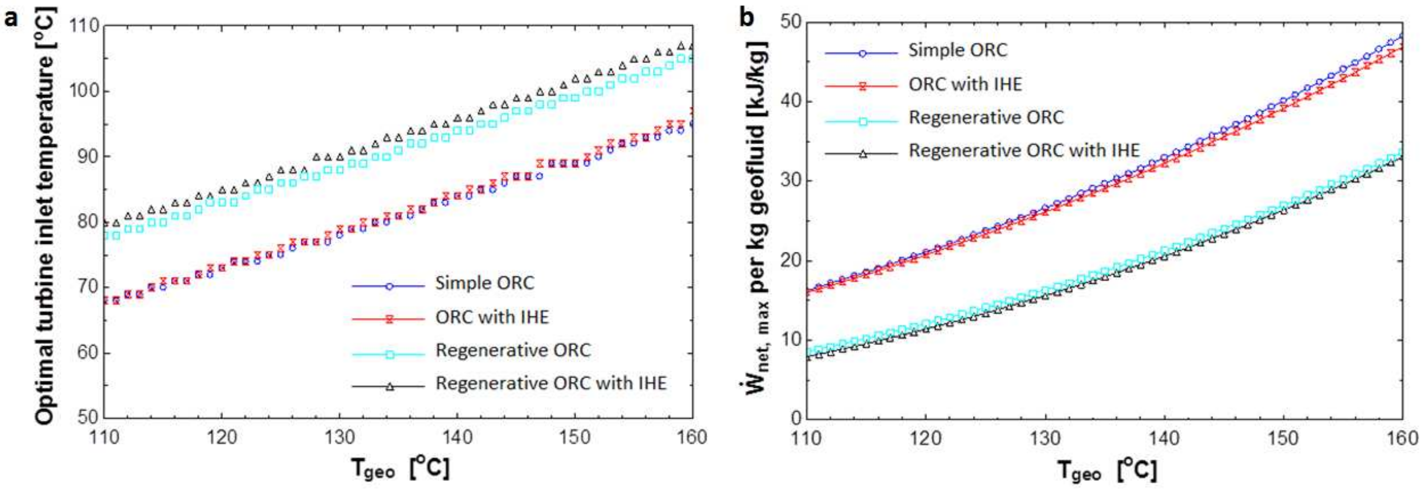

Figure 15: (a) Optimal turbine inlet temperature, and (b) Maximum cycle power output per kg geofluid

An optimal First- and Second-law efficiency, at the primary heat exchanger inlet, is illustrated in Fig. 16. Based on the geothermal fluid state at the primary heat exchanger inlet, the First and Second Law efficiencies are in the range of 4-9% and 37-47% respectively for the basic ORCs; 2-6% and 19-33% respectively for the regenerative ORCs.

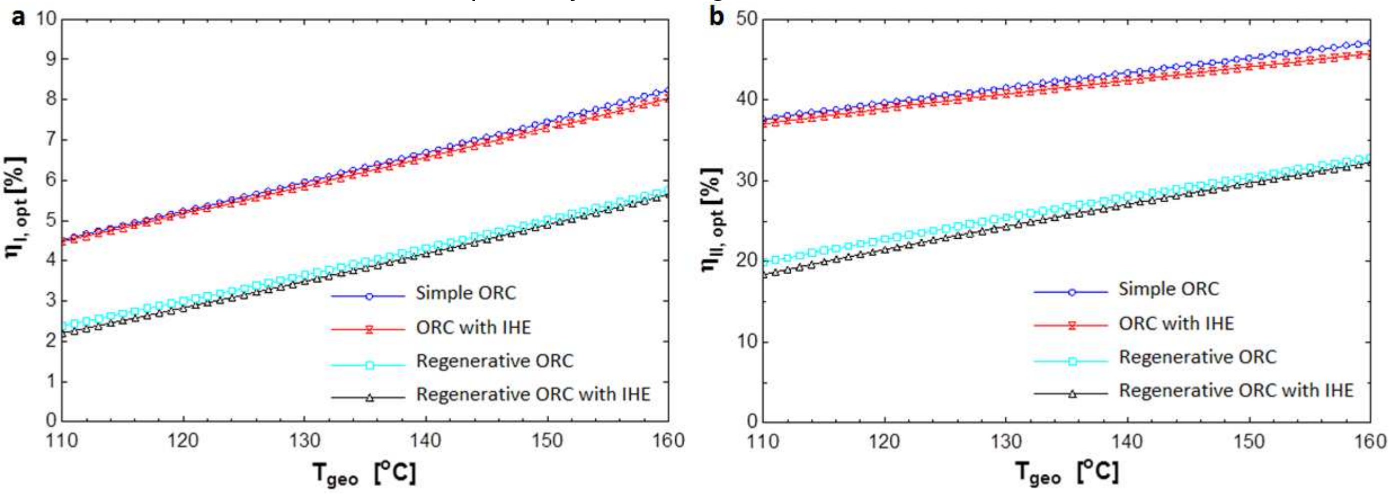

Figure 16: Optimal (a) First- and (b) Second-law efficiency at primary heat exchanger inlet

Based on the energy input to the cycle, the First- and Second-law efficiencies as well as the cycle effectiveness are illustrated by Figs. 17-18. From Fig. 17a, the First-law efficiency for the optimum operating conditions is in the range of 8-15% for all ORCs considered in this study. The noticeable lower First-law efficiency is attributed to the moderately low-temperature of the geothermal resources [14]. In Fig. 17b, the advantage of adding an IHE to the binary cycle to improve the cycle Second-law efficiency is evident, and particularly at geothermal resource temperatures above 130^{o}C. For the optimum operating conditions, a maximum of 56% in Second Law efficiency is reached for the ORCs with an IHE. This is approximately 2-3% higher as compared to the ORCs without an IHE for the studied range of the geothermal resource temperature. A look at the cycle effectiveness (Fig. 18), on the other hand, showed better capability of transfer of the available energy to the working fluid for the basic ORCs at 70-74%, as compared to 56-69% for the regenerative ORCs. Here, the high sensitivity of the regenerative ORCs to variations in the geothermal resource temperatures is demonstrated, as discussed by Franco and Villani [22].

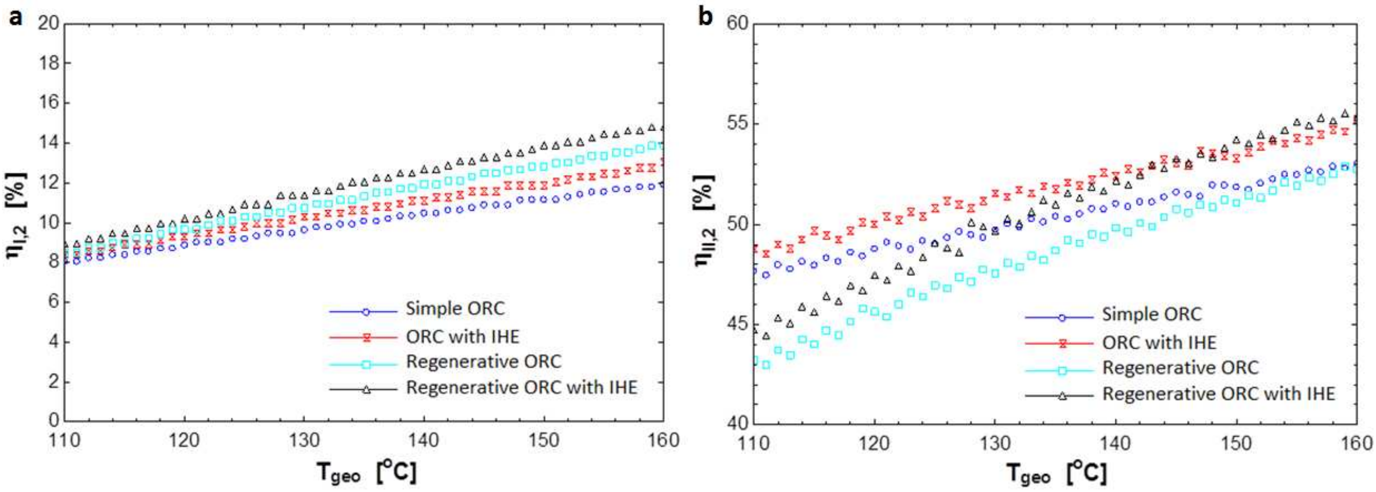

Figure 17: (a) First- and (b) Second-law efficiency on heat transfer input to the ORC at the optimum operating conditions

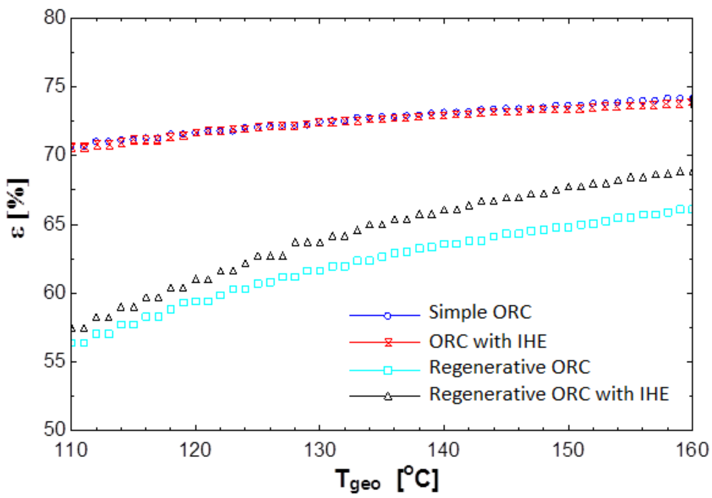

Figure 18: Cycle effectiveness at the optimum operating conditions

5. Conclusions and recommendations

A thermodynamic analysis and performance optimization of small binary cycle geothermal power plants operating with moderately low-temperature and liquid-dominated geothermal resources in the range of 110°C to 160°C, was considered. Optimal operating conditions were determined for maximum cycle power output per unit mass flow rate of the geothermal fluid. The maximum cycle power output was observed to increase exponentially with the geothermal resource temperature, whereas the optimal turbine inlet temperature increased almost linearly with the increase in the geothermal heat source. The addition of an IHE and/or an OFOH has been very prolific in improving the effectiveness of the conversion of the available geothermal energy into useful work. However, to avoid a susceptible thermal pollution of the environment caused by the geofluid being discarded as waste heat at relatively high temperature [23], a combined power generation and direct use in process or district heating applications as a cogeneration system, can be an additional option to improve the energy utilization [14,23]. In addition, a performance analysis of selected organic working fluids, namely refrigerants R123, R152a, isobutane and n-pentane, was conducted under saturation temperature and subcritical pressure operating conditions of the turbine. Organic fluids with higher boiling point temperature, such as n-pentane, were recommended for the basic type of ORCs, whereas those with lower vapour specific heat capacity, such as butane, were more suitable for the regenerative ORCs. Although the present study limited itself to the thermodynamic performance of the selected organic fluids based on their thermodynamic properties, the selection of the optimal organic fluid is also subject to the chemical stability and compatibility with materials, the environmental impacts, the safety concerns, and the economical operation of the working fluids [24-27].

References

[1] DiPippo, R 1998, 'Geothermal Power Systems', in Elliott, TC, Chen, K & Swanekamp, RC, *Standard handbook of power plant engineering*, 2nd edn, MacGraw-Hill, New York, pp. 8.27 - 8.60.
[2] Gu, Z & Sato, H 2001, 'Optimization of cyclic parameters of a supercritical cycle for geothermal power generation', *Energy Conversion and Management*, vol. 42, no. 1, pp. 1409-1416.
[3] Kanoglu, M 2002, 'Exergy analysis of a dual-level binary geothermal power plant', *Geothermics*, vol. 31, no. 1, pp. 709-724.
[4] DiPippo, R 2008, *Geothermal power plants principles, applications, case studies and environmental impact*, Butterworth-Heinemann, London.
[5] Desai, N & Bandyopadhyay, S 2009, 'Process integration of organic Rankine cycle', *Energy*, vol. 34, no. 1, pp. 1674-86.
[6] Gnutek, Z & Bryszewska-Mazurek, A 2001, 'The thermodynamic analysis of multicycle ORC engine', *Energy*, vol. 26, no. 1, pp. 1075-1082.
[7] Borsukiewicz-Gozdur, A & Nowak, W 2007, 'Maximising the working fluid flow as a way of increasing power output of geothermal power plant', *Applied Thermal Engineering*, vol. 27, pp. 2074–8.
[8] Calm, JM & Hourahan, GC, 2001, 'Refrigerant Data Summary', *Engineered Systems*, vol. 18, no. 11, pp. 74-88.
[9] Subbiah, S & Natarajan, R 1988, 'Thermodynamic analysis of binary-fluid rankine cycles for geothermal power plants', *Energy Conversion and Management*, vol. 28, no. 1, pp. 47-52.
[10] Klein, SA 2012, 'Engineering Equation Solver EES Academic Commercial V7.933', McGraw Hill. See also https://www.fchart.com.
[11] Chen, H, Goswami, DY & Stefanakos, EK 2010, 'A review of thermodynamic cycles and working fluids for the conversion of low-grade heat', *Renewable and sustainable energy reviews*, vol. 14, no. 1, pp. 3059-3067.
[12] Bejan, A 1993, *Heat transfer*, Wiley, New York.
[13] Yari, M 2010, 'Exergetic analysis of various types of geothermal power plants', *Renewable Energy*, vol. 35, no. 1, pp. 112-121.
[14] Kanoglu, M & Bolatturk, A 2008, 'Performance and parametric investigation of a binary geothermal power plant by exergy', *Renewable Energy*, vol. 33, no. 1, pp. 2366–74.
[15] Demuth, OJ & Kochan, RJ 1981, *Analyses of mixed hydrocarbon binary thermodynamic cycles for moderate temperature geothermal resources using regeneration techniques*, INEL Rep. EGG-GTH-05710, Idaho Falls, ID.
[16] Aljundi, IH 2011, 'Effect of dry hydrocarbons and critical point temperature on the efficiencies of organic Rankine cycle', *Renewable Energy*, vol. 36, no.1, pp 1196-1202.
[17] Mago, PJ, Chamra, LM, Srinivasan, K & Somayaji, C, 2008, 'An examination of regenerative organic Rankine cycles using dry fluids', *Applied Thermal Engineering*, vol. 28, no. 1, pp. 998-1007.
[18] DiPippo, R 2004, 'Second Law assessment of binary plants generating power from low-temperature geothermal fluids, *Geothermics*, vol. 33, no.1, pp. 565–86.
[19] Hepbasli, A 2008, 'A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future', *Renewable and Sustainable Energy Reviews*, vol. 12, pp. 593-661.
[20] Kaplan, U 2007, *Advanced organic Rankine cycles in binary geothermal power plants*, World Energy Council, Ormat Technologies, inc.

[21] Lakew, AA & Bolland, O 2010, 'Working fluids for low-temperature heat source', *Applied Thermal Engineering*, vol. 30, no. 1, pp. 1262-1268.
[22] Franco, A & Villani, M 2009, 'Optimum design of binary cycle power plants for water-dominated, medium-temperature geothermal fields', *Geothermics*, vol. 38, no.1, pp. 379-391.
[23] Guo, T, Wang, HX & Zhang, SJ 2011, 'Fluids and parameters optimization for a novel cogeneration system driven by low-temperature geothermal sources', *Energy*, vol. 36, no. 1, pp. 2639-2649.
[24] Maizza, V & Maizza, A 1996, 'Working fluids in non-steady flows for waste energy recovery systems', *Applied Thermal Engineering,* vol. 16, no. 1, pp. 579–90.
[25] Tchanche, BF, Lambrinos, Gr, Frangoudakis, A & Papadakis G 2011, 'Low-grade heat conversion into power using organic Rankine cycles- A review of various applications', *Renewable and Sustainable Energy Review*, vol. 15, no.1, pp. 3963-3979.
[26] Saleh, B, Koglbauer, G, Wendland M & Fischer, J 2007, 'Working fluids for low-temperature organic Rankine cycles', *Energy*, vol. 32, no. 7, pp. 1210-1221.
[27] DiPippo, R 1999, 'Small geothermal power plants: Design, performance and economics', *Geothermal Resources Council BULLETIN*, pp. 1-8.