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"Combining Ground Source Heat Pump and Organic Rankine Cycle for Power and Heat"

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Abstract— This study is conducted to analyze the working of borehole thermal energy storage (BTES) with ground source heat pump (GSHP) and organic Rankine cycle (ORC). Drake Landing Solar Community (DLSC) situated in Okotoks, Alberta, Canada with 144 boreholes generating 236 kW of the heating load is taken as a case study to investigate its functionality when coupling with GSHP and ORC. Nine different refrigerants falling in the desired temperature range when BTES temperature drops to 60°C or 50°C during the winter season. This work is an effort to make the existing heating system into a combined heat and power (CHP) system, which is able to generate power to run the BTES and district loop pumps and also provides the heating at the same time. Results revealed that, at a source temperature of 50°C from the BTES, the combination of refrigerant R1234YF-R1234YF was considered to be the best at 75°C evaporation temperature; it raised the fluid temperature at the condenser to 83°C by having maximum coefficient of performance of 3.5 of GSHP and overall combined heat and power efficiency of 77%.

Keywords: borehole thermal energy storage; ground source heat pump; organic Rankine cycle.

I. INTRODUCTION

Canada has been ranked sixth worldwide in 2015 based on primary energy production with a 3% production rate which is almost 17% more compared to 2005 [1]. However, the world on average energy production rate has increased by 19% in the same tenure. In the year 2015, Canada's ranking in the global scenario in the energy production of electricity and natural gas was 6% and 4%, respectively. These statistics were published by Natural Resources Canada in 2018 in the report "Energy Fact Book 2018-2019". According to this report, residential usage of energy in 2015 is recorded at 1,544 petajoules (PJ), out of which 62% is dedicated for the space heating purpose i.e. 964 PJ, 19% (289 PJ) is for the domestic water heating (DWH) and the remaining consumption is due to other appliances. The two major consumptions of space heating and domestic water heating (DWH) are functioning on the utilization of natural gas and ultimately providing an opportunity to the rise of greenhouse gases (GHG). This environmental issue is compelling the research community to build new ways of heating the spaces with minimal usage of natural gas.

Research is continuously being focused to make urban areas more sustainable and harvest the energy from the resources whose potential were previously unnoticeably lost in the environment. Ground thermal energy storage (GTES) is a potential technology that make use of a renewable energy like solar thermal energy to be stored in ground and later could be utilized for heating domestic spaces. GTES differs from a geothermal energy system because latter extracts energy from earth's radiative decay. Drake Landing Solar Community (DLSC) in Okotoks, Alberta, Canada is a one-of-a-kind project which saves solar energy in the summer to a GTES system to be utilized in the winter for the space heating [2]. This heat may be regarded as low grade (up to 90°C) but can be utilized to generate electrical power [3]. There are many challenges to map down such a system which can be of dual purposes, i.e. combined heat and power (CHP) generation through utilizing thermal energy from the ground. Borehole thermal energy storage (BTES) is a type of GTES that is installed to vertically penetrate the storage medium, i.e. deep-down earth, with the aid of pipes having working fluid flowing inside to absorb heat from the earth and bring it up to the ground surface for utilization [4]. The entire bore filed at DLSC has a depth of 37 m and a diameter of 35 m. It operates from 40 to 80°C as solar energy is pumped into it, i.e. from the beginning to the end of the summer, respectively, as mentioned in the 10-years operational report of DLSC [5]. This heat can be transferred to an organic Rankine cycle (ORC) for power generation. ORC is a promising power cycle functioning on an organic fluid to produce shaft work from a turbine. Low-temperature ORC which functions below 150°C is a suitable match to the BTES technology [6]. Taking an example of a geothermal low-temperature ORC which nearly operates in the same temperature range, such as 80-100°C, the thermal efficiency with an organic fluid of R123 is 11.1% and exergy efficiency of 54.1%, as cited in the research article by Zhang et al. [7]. Leong and Mudasar [8] did a study on power generation from BTES with the aid of a simple ORC taking the DLSC system as a base model for the analysis. Firstly, they found the possibility of integrating the ORC with BTES, and secondly, when source temperature was above 67°C, the CHP system provided enough power to operate all the pumps of BTES and district loops. Apart from this, the heat which is being discharged at the condenser of the ORC is utilized for cogeneration purposes, i.e. district heating with 40°C of hot-water supply temperature [9]. This concluded that DLSC could become a self-sustainable system with no external power usage.

However, when supply temperature from BTES to ORC is below 67°C and to keep the DLSC to be a self-sustainable system, ground source heat pump (GSHP) may be required. In such cases, the low-grade heat from the BTES can be upgraded to higher-grade heat using a heat pump, matching the required temperature for ORC operation [10]. The net useful work coming out of the ORC will then be utilized to compensate for the pumps and compressor power in this case. The input heat can be augmented by a heat pump to increase the work output from the ORC and optimization can be reached to obtain a system that has significant power generation and considerable cogeneration heat for a community. This is part of the proposed research to investigate any possible match of working fluids in the heat pump cycle and the ORC to achieve the goal.

II. System Depiction

A. Drake Landing Solar Community system

DLSC is a community where space heating in winter is provided through the BTES, receiving heat during summer through the solar collectors and the entire system has achieved 96% solar fraction for space heating after 10 years of operation. Figure 1 explains the process description of the existing DLSC system. There are four streets with 52 houses each with a detached garage located behind the house [5]. The solar collector is mounted on the roof of the garage and joined together with other collectors in one lane to form an array, and four arrays are making a total solar collecting area of 2,293 m^2. Hot water which is heated through the solar collector is temporarily stored in two short-term thermal storage (STTS) tanks. STTS functions as a medium to control the demand and supply levels of thermal energy between the collector loop and BTES loop. Since BTES cannot accept heat as quick compared to the heat received by the solar collectors, it is being stored temporarily in STTS before dispensing to 144 boreholes network. This also helps to provide the heat to the district loop at times of high demand, when BTES does not extract heat as quickly as possible. Each borehole is 35m deep having a distance of 2.25m with the adjacent boreholes. It consists of a PEX U-tube pipe with 25 mm of diameter. The total volumetric flow rate of 3.8 liters per second is circulated through a variable speed pump and extracts heat from all the boreholes. At the district loop, a 63mm PEX pipe is installed to distribute the heat among 4 lanes of the community and further to the individual house. Variable speed pumps are running to distribute a total of 6.6 liters per second of the volumetric flow rate in the district loop.

B. Intergration of BTES with GSHP–ORC combined heat and power system

When source temperature of BTES drops to 60°C and 50°C, the ORC alone cannot generate enough power to compensate for the BTES loop and district loop pumps, so ground source heat pump must be introduced to increase its temperature so that ORC can be run and generate enough power. Figure 2 explains the schematic diagram of BTES with GSHP and ORC to make it a combined heat and power system. The thermodynamic processes of the same system can be seen on the temperature-entropy diagram in Figure 3.

For the thermodynamic analysis, all components of the system are considered as steady-state flow devices with negligible pressure drops and heat losses. The working fluid entering pump 1 is assumed to be a saturated liquid.

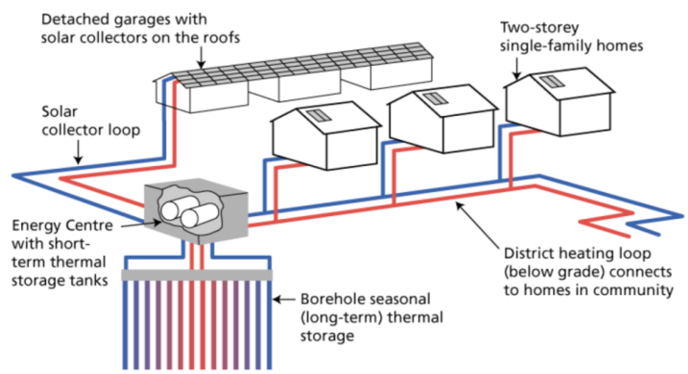

Figure 1 : Solar and borehole thermal storage system at Drake Landing Solar Community [5]

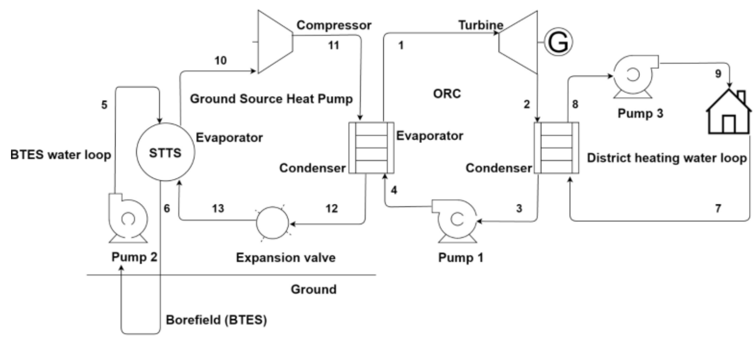

Figure 2 : Schematic diagram of BTES with GSHP and ORC

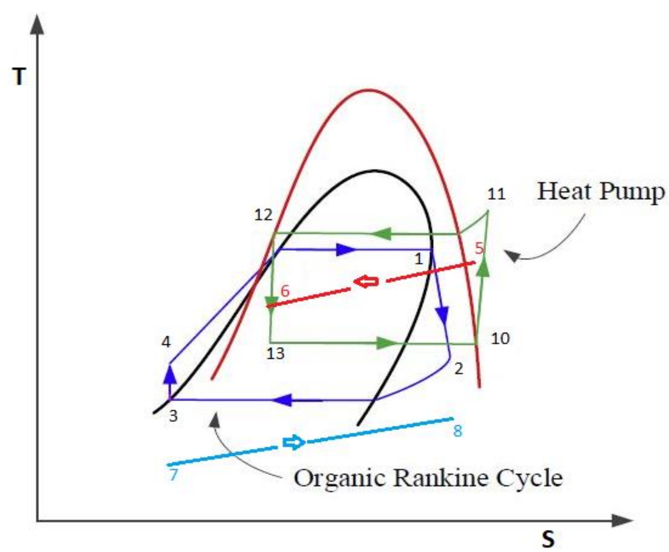

Figure 3: Temperature-entropy diagram of BTES with GSHP and ORC

Heat pump cycle operates on four components, where a refrigerant accepts heat via an evaporator in the STTS from state 13 to state 10; it is then compressed to high temperature and pressure by a compressor from state 10 to state 11; following that it rejects waste heat to an ORC via a condenser from state 11 to state 12; and finally it expands through an expansion valve from state 12 to state 13 reducing its temperature and pressure. During the process through the expansion valve, enthalpy of the fluid remains the same. Energy analysis of the heat pump cycle produces the following relations:

Heat absorbed by the refrigerant in the evaporator of the heat pump from BTES is given as:

$$\dot{Q}_{in,HPC} = \dot{m}_h \left(h_{10} - h_{13}\right) / \eta_e = \dot{m}_s \left(h_5 - h_6\right) = \dot{m}_s c_{ps} \left(T_5 - T_6\right) \quad (1)$$

Compressor work can be given as:

$$\dot{W}_c = \dot{m}_h \left(h_{11} - h_{10}\right) = \frac{\dot{m}_h \left(h_{11s} - h_{10}\right)}{\eta_{cp}} \quad (2)$$

Heat rejected via the condenser of the heat pump can be calculated as:

$$\dot{Q}_{out,HPC} = \dot{m}_h \left(h_{11} - h_{12}\right) \eta_c = \dot{m}_{wf} \left(h_1 - h_4\right) \quad (3)$$

Coefficient of performance (COP) of heat pump cycle is given as:

$$COP_{HPC} = Q_{out,HPC} / W_c \quad (4)$$

In the organic Rankine cycle, another working fluid undergoes four processes to produce work output from this power cycle. The expansion process from state 1 to state 2 occurs with the aid of a turbine to produce shaft work for running an electric generator. Condensation process from state 2 to state 3 is achieved by rejecting heat to district loop water entering the condenser at state 7. The compression process happens from state 3 to state 4 through a pump. Finally, the evaporation process happens from state 4 to state 1 considering superheating as well, and the same processes repeat all over again in the cycle. Similarly, energy analysis of the organic Rankine cycle produces the following relations:

The heat absorbed by the working fluid in the evaporator is the same heat rejected by the condenser of the heat pump cycle and is given as:

$$\dot{Q}_{in,ORC} = \dot{m}_{wf} \left(h_1 - h_4\right) = \dot{m}_h \left(h_{11} - h_{12}\right) \eta_c \quad (5)$$

The power generated by the turbine can be given as:

$$\dot{W}_t = \dot{m}_{wf} \left(h_1 - h_2\right) = \dot{m}_{wf} \left(h_1 - h_{2s}\right) \eta_t \quad (6)$$

The heat rejected by the condenser of the ORC is given as:

$$\dot{Q}_{out,ORC} = \dot{m}_{wf} \left(h_2 - h_3\right) \eta_c = \dot{m}_w \left(h_8 - h_7\right) = \dot{m}_w c_{pw} \left(T_8 - T_7\right) \quad (7)$$

The shaft power consumed by the pump to compress and raise the pressure of the working fluid is expressed as:

$$\dot{W}_{p1} = \dot{m}_{wf} \left(h_4 - h_3\right) = \frac{\dot{m}_{wf} \left(h_{4s} - h_3\right)}{\eta_p} \quad (8)$$

The heat provided by the district heating loop to the houses for space heating is given as:

$$\dot{Q}_h = \dot{m}_w \left(h_9 - h_7\right) \eta_h = \dot{m}_w c_{pw} \left(T_9 - T_7\right) \eta_h \quad (9)$$

The net power output of the ORC is given as:

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_{p1} \quad (10)$$

The thermal efficiency of the ORC is defined as:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in,ORC}} \quad (11)$$

The thermal efficiency of the ORC as a CHP system is defined as:

$$\eta_{CHP} = \frac{\dot{W}_{net} + \dot{Q}_{out,ORC}}{\dot{Q}_{in,ORC}} \quad (12)$$

The overall thermal efficiency of the BTES-GSHP-ORC-district system is defined as:

$$\eta_{CHP,o} = \frac{\dot{W}_{net} - \dot{W}_{p2} - \dot{W}_{p3} - \dot{W}_c + \dot{Q}_h}{\dot{Q}_{in,HPC}} \quad (13)$$

where the shaft powers consumed by pumps 2 and 3, respectively, are as follows:

$$\dot{W}_{p2} = \dot{m}_s g H_{Bloop} / \eta_p \quad (14)$$

$$\dot{W}_{p3} = \dot{m}_w g H_{dloop} / \eta_p \quad (15)$$

III. Design considerations

To formulate the energy analysis for the ground source heat pump, the first step is to set the temperature range for which refrigerants are selected. Since in this case temperature range varies from 60 to 50°C and the analysis are to be done for sub-critical temperature, as shown in Figure 3. The selection of an efficient, safe and environmentally friendly refrigerant is an important factor to achieve an energy-efficient heat pump and organic Rankine cycle system. Refrigerants are categorized into three types depending on the slope of the saturated vapor curve i.e. dT/ds [11]. The wet fluids having a negative slope which requires the refrigerant to be superheated before entering the turbine. If the fluid enters the turbine as a saturated vapor, it falls in the two-phase region after expansion which can damage turbine blades due to corrosion. However, in the case of isentropic and dry fluids which have a non-negative slope, superheating is not required as the fluid is in the superheated vapor state at the turbine outlet. Therefore, dry and isentropic fluids are recommended for an ORC so that superheating equipment is not needed to be installed and the possibility of turbine blade damage due to corrosion may be avoided. Table 1 provides information, including ozone depletion potential (ODP) and global warming potential (GWP), of nine organic fluids (pure and mixtures) that are selected for the heat pump cycle. R1234YF has been fixed for the bottoming cycle of ORC because of its better performance when source temperature is above 67°C as cited by Leong and Mudasar [8].

The thermodynamic properties have been taken from the NIST REFPROP 9.1 database [12], which is used in MATLAB R2018b (9.5) simulation code [13] to solve the thermodynamic processes of the ORC system. MATLAB provides many built-in mathematical and thermophysical property functions that can efficiently evaluate any thermodynamic property of a fluid from a built-in function call from the REFPROP database in terms of any two other state properties.

Table 1: Refrigerants for ORC and GSHP

Refrigerants	ODP	GWP	Critical temperature, T_c [ºC]	Critical pressure, P_c [bar]
R134A (pure)	0	1300	101.06	40.59
Propane (pure)	<0	3.3	96.70	42.48
R22 (pure)	0.05	1760	96.15	49.90
R1234YF (pure)	0	4	94.70	33.80
R407C (mixture)	0	1774	86.14	46.39
R424A (mixture)	0	2440	84.64	39.00
R404A (mixture)	0	3922	72.12	37.35
R410A (mixture)	0	2088	71.34	49.00
R507A (mixture)	0	3985	70.62	37.05

The design conditions for the current work are summarized in Table 2. Specifically, the thermal energy input from the BTES through circulating water is 236 kW coming out of 144 boreholes and the mass flow rate of the water in the BTES loop is 3.68 kg/s [5]. The turbine and pump isentropic efficiencies of 85% and 65% respectively have been selected according to the literature [14]. Isentropic efficiency of the compressor is taken as 70% for the application of low-temperature organic Rankine cycle coupled with heat pump [15]. The thermal efficiencies of all heat exchangers are assumed to be 96% [16]. Superheating of 2°C is selected for the analysis since, in real industrial processes, the superheating of zero is difficult to ensure [17]. Condenser temperature of the ORC is kept constant at 45°C in order to provide about 40°C of the district loop water to the air handling units in the houses, while returning water temperature is taken as 30°C. The hydrodynamic head losses of the BTES and district loops are estimated to be 21.3m each, based on the design flow rates, pipe sizes and layouts [18] of the loops. There is a single varying-parameter used to investigate the impact on the output of the cycle, i.e. evaporation temperature of the organic Rankine cycle.

IV. RESULTS AND DISCUSSION

Figures 4 and 5 show the ORC work output for the source temperature (T_5) of 60°C and 50°C, respectively, and would be best understood if studied simultaneously for the comparison. All the nine fluids in the legends of the graphs are arranged in the decreasing order of the critical temperatures of the fluids, so that their performance can also be assessed w.r.t. their critical temperatures apart from the graph trend. When the BTES temperature drops below 67°C, the ORC will not produce enough power to run BTES and district loop pumps [8]. The introduction of GSHP is incorporated here to raise the temperature of fluid so that ORC can be operated to produce power to run the pumps.

Table 2 : Major design considerations for ORC and GSHP

Parameter	Units	Values
BTES capacity, Q_{BTES}	kW	236
BTES inlet temperature, T_5	°C	60 and 50
Mass flowrate of BTES loop, m_s	kg/s	3.68
ORC condenser temperature, T_3	°C	45
District loop water inlet temperature, T_7	°C	30
ORC degree of superheating	°C	2
Pinch point difference	°C	5
Evaporator efficiency, η_e	%	96
Turbine isentropic efficiency, η_t	%	85
Condenser efficiency, η_c	%	96
Pump isentropic efficiency, η_p	%	65
Compressor isentropic efficiency, η_{cp}	%	70
District loop efficiency (including air handling units in the houses), η_h	%	96
Head loss in BTES and district loops, H	m	21.3

From the previous study [8], it was concluded that R1234YF is providing better results in the ORC energy analysis; therefore, it has been fixed for the bottom cycle of ORC. The top cycle of GSHP is then operated with all nine refrigerants to make a combination to get maximum work output. Plots of both Figures 4 and 5 are showing an increasing trend producing a considerable amount of power for the pumps, reaching 16.5 kW for source temperature 60°C and 18 kW for source temperature 50°C. Evaporation temperature is varied from 60 to 75°C which is high compared to source temperature and is achieved after passing through GSHP. It can be noticed that R404A-R1234YF, R410A-R1234YF, and 507A-R1234YF are performing till 65°C or lower, due to their low critical temperatures. If the heat pump cycle is to operate at lower temperatures, these three combinations will be the suitable refrigerants as they are giving the highest power output from the ORC at that temperature range. However, other combinations are performing well for even higher temperatures with R424A-R1234YF showing the highest work output, followed by R1234YF-R1234YF and R407C-R1234YF. The remaining three refrigerants i.e. R134A-R1234YF, R22-R1234YF, and Propane-R1234YF are showing relatively less power but due to their environmental issues, they can be ignored.

Since T_5=60°C shows similar cycle results to T_5=50°C, therefore, further analysis has been done for T_5=50°C only. As GSHP is introduced to raise the temperature (T_{11}-T_{12}) to run the ORC, Figure 6 shows the same temperature curves. At this point, three refrigerants (R134A, R22, and Propane) with environmentally dangerous prospects are not taken into consideration, the remaining six are shown here.

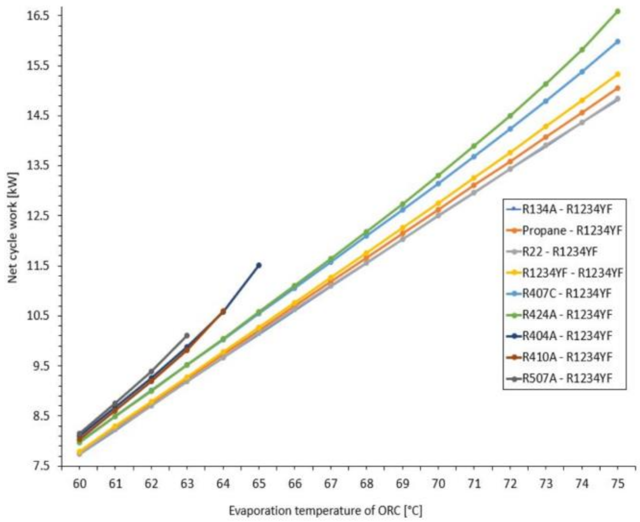

Figure 4: Net cycle work with source temperature 60°C

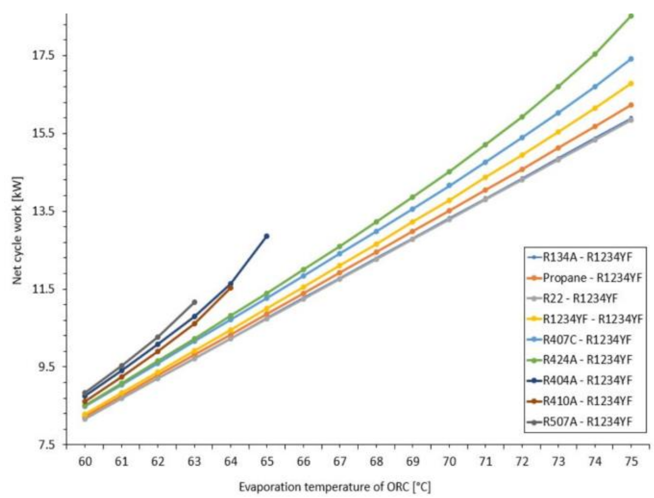

Figure 5: Net cycle work with source temperature 50°C

Refrigerants with low critical temperatures i.e. R404A, R410A, and R507A are producing lower temperatures (T_{11}) due to their sub-critical temperature limitation and are good to use below 65°C of evaporation temperature. Out of these three, R410A gave the maximum value of T_{11}=90°C to run ORC. While looking at all the combinations, the highest T_{11} is achieved for R407C-R1234YF i.e. 103°C. This highest temperature is obtained due to the extra work put into the heat pump cycle by the compressor below its sub-critical temperature range. Figure 7 describes the compressor work for the three refrigerants generating higher temperatures at T_{11}. Refrigerants with lower critical temperatures are ignored here to simplify the analysis. R424A-R1234YF is consuming the highest amount of compressor power and the lowest is for R1234YF-R1234YF. Studying Figures 6 and 7 in comparison, the refrigerant R1234YF-R1234YF is producing 83°C of T_{11} for ORC operation at evaporation temperature of 75°C with the lowest compressor work of 90 kW. Therefore, it can be concluded that R1234YF-R1234YF is a suitable combination in both cycles. The high value of compressor work is not desirable, though the higher value of T_{11} is best to run ORC to get more work out of the cycle.

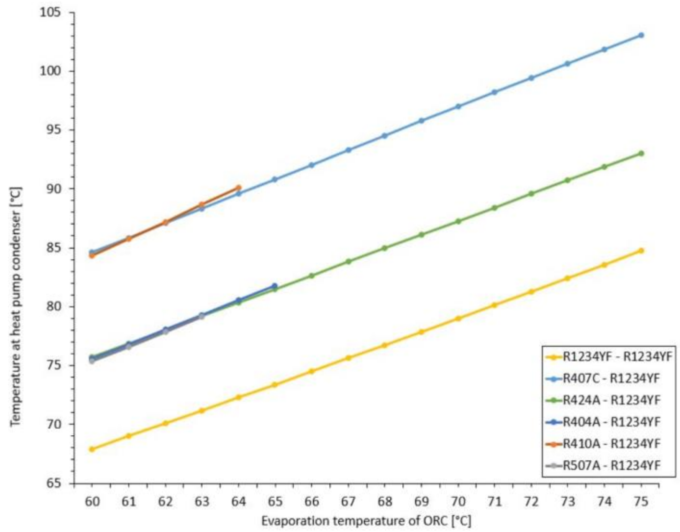

Figure 6: Temperature at GSHP condenser with source temperature 50°C

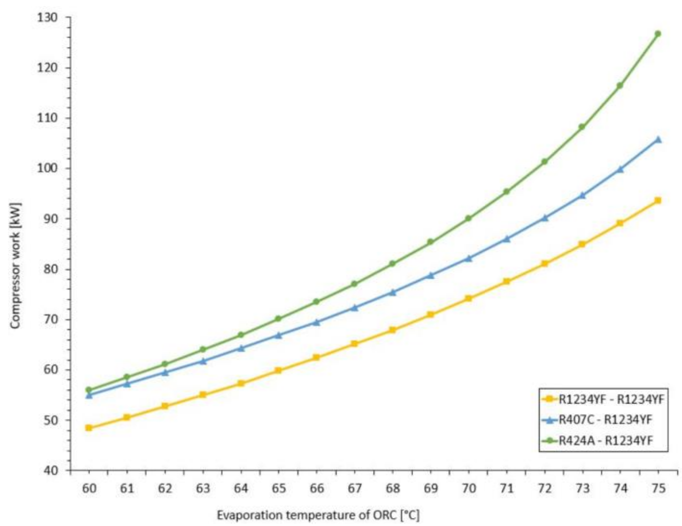

Figure 7: Compressor work with source temperature 50°C

Figure 8 provides the coefficient of performance (COP) of GSHP when the source temperature is 50°C. Combination of R1234YF-R1234YF is providing maximum COP value due to the less amount of compressor work as outlined above in Figure 7. And with higher evaporation temperature, compressor work increases and COP decreases. Therefore, there can be an optimum point where GSHP and ORC can be operated so that maximum ORC work is achieved to compensate for pump power meaning minimum compressor work and maximum COP value. Other combinations are producing a lesser value of above-mentioned parameters. This is mainly because when two different refrigerants are interacting inside the heat exchanger, their temperature-enthalpy match should be similar to maximize gains. In this case, R1234YF-R1234YF is giving the best results due to the same refrigerant being used in both the top and bottom cycle. Figure 9 explains the overall combined and heat power efficiency of the proposed system i.e., BTES + GSHP + ORC + District, which is maximum for the R1234YF-R1234YF.

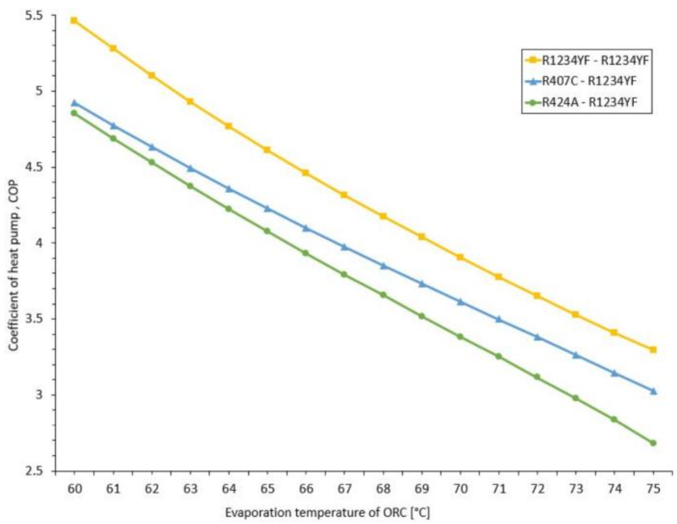

Figure 8: COP of GSHP with source temperature 50°C

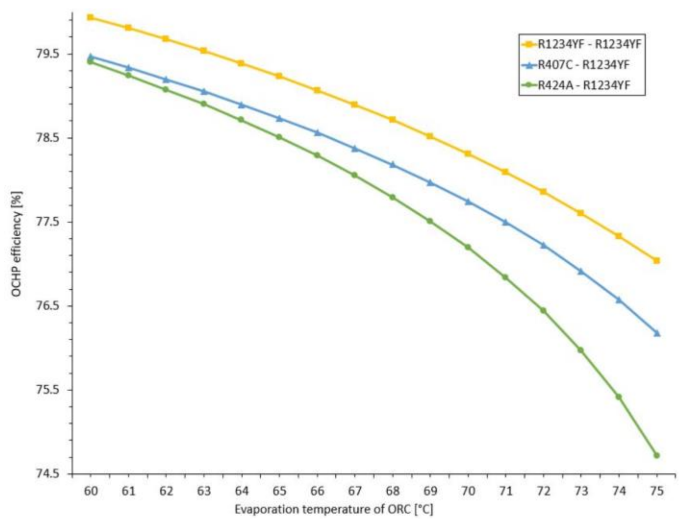

Figure 9: Overall combined heat and power efficiency with source temperature 50°C

CONCLUSIONS

Drake Landing Solar Community (DLSC) heating system is taken as a case study to integrate its borehole thermal energy storage (BTES) with ground source heat pump (GSHP) and organic Rankine cycle (ORC). Different source temperatures of 60°C and 50°C are considered to operate the system. GSHP is introduced to upgrade the heat for the ORC and check for power generation for running the pumps, although part of the power is used by the compressor. At source temperature of T_5=60°C, less cycle work is produced than at T_5=50°C. R1234YF-R1234YF, R407C-R1234YF, and R424A-R1234YF combinations performed well at T_5=50°C and satisfied the criteria of enough power generation but comes at the cost of compressor work. R1234YF-R1234YF provided maximum condenser temperature, less compressor work, highest COP value, and highest combined heat and power efficiency.

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