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Optimization of a Geothermal Multi?Generation Energy System: Energy, Exergy and Cost for Use in Coastal and Tropical Environments

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ABSTRACT

A considerable increase in global warming and climate change has seen in recent years; Resulting in effects as desertification of agricultural lands, changes in monsoon season, increase of floods, filling of land by rising sea level etc. At the same time, energy requirements are growing with the exponential increase of population, which most of the demand is covered by energy produced through fossil fuels. Fossil fuels has major drawback of releasing substantial amount of carbon emission, which is a major player in deteriorating the environment. As a result, extensive research is carrying on nowadays on utilizing renewable energy resources which provides clean energy with decreased emissions. In this paper, a multi-generation system is proposed to produce five outputs: electricity, hot water, cooling, drying-air and fresh water. Aim of the research is to design a stand-alone multi-generation system that can fulfill the energy needs of a small scale community/industry in the coastal or tropical areas in the region. This system uses isobutane-based, organic rankine cycle driven primarily from low/ moderate temperature geothermal resource to produce more than 0.8 MW of power and 150 tons of cooling capacity. Energy, exergy and cost analysis has been carried out to optimize the system. Being a coupled system, it maintains an efficiency of more than 20% under all ambient conditions with an overall exergic efficiency of more than 65%. Moreover, the effects of changing environmental temperature, changes in temperature of geo-water. Along with this, the effects of three different refrigerants have been studied.

1. Introduction.

The present day lifestyle has seen various appliances contributing to the better standard of living which were unavailable in the past and became an essential part of modern-day house. Many of these appliances give rise to higher energy demands. For all these developments, energy remains one of the major requirement; its security, abundant and an unconstraint availability in face of ever-growing populations poses major challenges to nations, all around the globe. The two major threats to energy are: Constrained amount of earth's resources, especially fossil fuels, which are being consumed at ever-rising rate and the amount of degradation being caused to environment. The second problem is particularly associated to carbon emission in form of carbon dioxide, the amount of which in atmosphere reached its highest in past 800,000 years, crossing 410 parts per million (ppm) [1]. As carbon dioxide acts as a greenhouse gas, it traps additional heat resulting in increased temperatures.

Owing to such concerns, a lot of efforts are being put in towards renewable energy resources with insignificant or negligible carbon emissions. Hence, much research has gone into using systems based on solar, wind, ocean and geothermal sources. As per the statistics published by International Renewable Energy Agency (IRENA) in 2018, the global renewable energy generation capacity has doubled from 1,057,962 MW in 2008 to 2,179,099 MW in 2018 [2]. Many of these renewable energy power plants have used multi-generation systems which produce a number of useful outputs from one single or mul-

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tiple primary energy inputs. In other words, it is a smart use of primary energy sources to enhance the efficiency of energy generation processes for better sustainability [3].

Almost all the renewable energy resources are marred by a distinct disadvantage of 'inconsistent' availability; thus additional investment is required in form of hybrid energy sources or energy storage to overcome such inconsistencies. The exception in this regard is geothermal energy, electrical power generation from which was first demonstrated in Larderello, Italy in 1904 [4]. Geothermal resources source their energy content from internal heat of the earth (i.e. magma) which maintains itself on a constant temperature due to almost unlimited energy from interior of earth. Such heat sources are located in the Earth's crust, in active geothermal areas which can be located on the surface, near the surface or at deep depths. By drilling intodeep wells, heated rocks by internal heat of earth, heats the water or mud [5]. Thus, in case water is already present and making contact with the heated rocks, steam or heated water may be readily available to harness the energy; alternately, water is injected through wells to extract the energy from otherwise dry rocks [6]. The global weighted average, levelised cost of electricity from a geothermal plant was reported to be at 0.07/kWh in 2017, which is only 2 cents more than hydropower projects [7, p. 16]. The usable geothermal systems are frequently categorized based upon the temperature ranges [8]; the categorization by Balta [9] is shown in Table 1.

Table 1: Categorization of Geothermal Energy Resources.

S. No	Category	Temperature Range	Approximate Depths
a.	Low-temp systems	< 90 °C	< 3.5 km
b.	Intermediate-temperature systems	90–150 °C	
c.	High-temperature systems	>150 °C	> 3.5 km

Source: Authors.

As the table 1 indicates, a high temperature system is ideal as it can be directly used to heat abundantly available water to make steam which will in turn be used to power a turbine. On the other hand, an intermediate or even lower temperature systems can also be used to produce electrical power by utilizing a low boiling point materials as working fluid such as alcohols, ethers, amines and even some fluids mixtures (such as zeotropic and azeotropic) etc. [10, p. 3964]. Thus, these fluids allow for use of heat energy from a wide range of temperature sources (32 – 232 ^{o}C) [10, p. 3973]. In other words, we can say that an 'open cycle dry steam plants' (or flash plants) are used with the naturally produced fluids to produce electricity using a steam turbine. On the other hand, for lower temperature heat sources (i.e. <150 ^{o}C), a binary plant can be installed in which an organic fluid can be used to run a turbine; this organic fluid takes heat from geothermal fluid [10, p. 3965]. A considerable amount of effort is being put in all around the world in ORC technology, which is clearly indicated from the figures by Imran et al. [11].

The outputs can be in form of "energy products" (such as heating, drying, cooling etc.) as well as by-products such as gases (hydrogen, oxygen etc.), carbon fibers and various other chemicals. Thus, multigenerational systems, specially the combined cooling, heat and power (CCHP) systems, offer a more efficient, cost effective, environmentally better solution for multiple products creation [3].

The geothermal based multi-generation systems have been studied by various researchers in past, a few works pertinent to our work are mentioned here. Hettiarachchi et al. [12] studied the design criterion an Organic Rankine Cycle (ORC) for 10 MWe gross power for use with low temperature geothermal heat sources with geothermal water temperature of 90 ^{o}C. They concluded that although ammonia based ORC system will have relatively better performance followed by HCFC 123, n-Pentane and PF5050, respectively. However, the higher-pressure requirements for evaporation of ammonia will result into an exorbitant and infeasible initial costs. Liu et al. [13] carried out an optimization study for four different working fluids (i.e. R123, R245fa, R134a and R152a) for four different configurations of a binary ORC operating at low temperatures (80 -95 ^{o}C). The results showed that R123 when used in superheated cycle gives an optimal cost; thermal efficiency is highest for R123+regenerative cycle. R152a, in superheated cycle can give highest work output and exergy efficiency (with geothermal temperature of 80-85 ^{o}C). Gozdur and Nowak [14], covered the significance of geothermal mass flow rate in the geothermal power plant to increase power of organic rankine cycle. In his analysis, he found that there exist a temperature in which variation of mass flow rate gives highest power for the specified conditions. Guzovic et al. [15], focused on the feasibility of power generation through geothermal plants in Republic of Croatia. In the analysis, he got 4% better thermal efficiency and 8% exergic efficiency in Organic Rankine Cycle.

T.Guo et al. [16], presented the analysis of 27 fluids and its optimization according to net power produced, proportion of heat transfer area to the net work produced and cost. It is determined that an optimized evaporator temperature gives the best of these parameters in each fluid. Sauret and Rowlands [17], studied suitability of radial-inflow turbines for geothermal power plants. He obtained initial design of radial-inflow turbine by one-dimensional analysis then carried out the study on working fluids and concluded that R134a was the best working fluid while the n-Pentane was the least in terms of net power produced. Ghasemi et al. [18], carried out the simulation of an existing geothermal power plant on aspen plus. According to the results, the low ambient temperatures of the turbine inlet should be at saturation vapor condition for maximum power but the case differs in high ambient temperatures where optimum degree of superheat is required for the maximum output from the turbine. El Emam and Dincer [19], explored geothermal – regenerative organic Rankine cycle (ORC) through the analysis of energy, exergy and exergo-economic analysis of a 5 MWe system. They calculated an energy efficiency of 16.37% and exergy efficiency of 48.8%.

Rustovic et al. [20], simulated through excel spread sheets for medium temperature geothermal plant in Velika Ciglena. He deduced from the results that Binary Organic Rankine Cycle is superior to Kalina Cycle thermodynamically and economically. Cheng et al. [21], proposed a double pipe heat exchanger and did numerical analysis of it. He concluded that the geothermal fluid is constantly heated through conduction from the formation of abandoned well and its temperature decreases with the operating time until a point of equilibrium. Zhai et al. [22], investigated the effect of molecular structure of HC (Hydro Carbon and HFC (Hydro Fluorine Carbon) working fluids on the system performance. The results exhibit that optimized evaporation temperature are same for all the selected fluids for a given geothermal well production temperature. F. Heberle and Bruggemann [23], did comparison study of zeotropic mixtures over pure fluids as a working fluid in geothermal organic rankine cycle. From the analysis, he evaluated that zeotropic mixtures has 20.6% increase in second law efficiency over pure fluids. Akrmai et al. [24], aimed on thermodynamic analysis of a geothermal-based multi-generation system using isobutene as working fluid with three energy outputs: electricity, hydrogen and domestic water heating. Effect onto the system efficiencies have been portrayed with variation in the input rate of geofluid, turbine inlet pressures, turbine inlet temperature on system efficiencies.

Bicer and Dincer [25] proposed and analyzed a combined geothermal-solar system for provisioning of cooling, heating, power generation and hydrogen production through a high temperature geothermal resource at 200 ^oC. Since the efficiency of photovoltaic (PV) solar cells is directly affected by the module and the environment conditions [26], cooling (through recovery of waste heat) is used to increase the PV cells efficiency; the whole system being called as Photovoltaic/Thermal (PVT) technology. Moreover, they also studied the effect of ambient temperature from 15 – 55 ^oC and found the isobutane to be superior to R123 and R245fa in terms of exergy and energy efficiency and turbine work output. Behzadi et al. [27] proposed a geothermal-solar system, similar to that of [25] for provisioning of power and cooling at a cost of 35USD/GJ. It may also be noted that isobutene (R600a) offers several other benefits as well [5]: it is a useful tracer, it exhibits chemical stability for longer time periods at the temperatures and pressures experienced in geothermal systems and is probably not appreciably adsorbed onto solid surfaces as well.

Hydrogen bears some significant advantages as a non-pollutant, energetic material which can be produced at industrial scales. Although it has a low volumetric energy content, yet it has a very high combustion efficiency and the highest mass energy content. Thus, as world moves towards renewable energy generation, Hydrogen remains in focus of engineers as a potential energy carrier in energy industry of future [28, pp. 521–522]. Hydrogen can be mass produced using three techniques: electrolysis (which can produce 99.99% pure Hydrogen, a requirement for use in fuel cells), bio mass conversion and solar conversion [29]. However, it is the electrolysis that is mature and is being widely employed. Although it is environmentally very clean, this process requires large amount of electricity: an ideal system would need 39 kWh per kg whereas 48 kWh per kg is being used by actual Hydrogen plants, resulting in a cost of 2.40 USD/kg (@ USD 0.06 per kWh) from electricity alone [30]. Thus, low cost electricity is sine qua non for production of hydrogen gas which is quite possible through use of renewable sources. Balta et al. [9], in their study of geothermal-hydrogen systems for Iceland; also indicated the similar problem while indicated the use of 'Geothermal, steam assisted, high-temperature electrolysis' as a promising mean of reducing hydrogen production cost, albeit this option can be exploited by countries where geothermal sources are abundantly available. Reference [28, pp. 525–537] has comprehensively covered the energy analysis of several of the hydrogen production methods driven by electricity whereas reference [31] specifically discusses the production of hydrogen from solar energy in detail. Christopher and Dimitrios [32] carried out a comparison of several hydrogen production methods based upon their exergy efficiency; while incorporating the post-production, liquefaction requirements. Marino et al. [33] explained and analyzed the electrolytic Hydrogen production system installed at Mediterranea University of Reggio Calabria, Italy.

This paper aims at studying the design of a multi-generation system to produce five outputs: electricity, hot water, cooling, drying-air, fresh-water for use as an independent stand-alone system for a remote community. This paper uses the geothermal energy from an intermediate temperature source at 100 -150 ^oC.

2. System Description.

The whole system and its components derive energy from the geothermal source. This system can be divided into four cycles; 1) Geothermal Cycle, 2) Isobutane based Organic Rankine Cycle (ORC), 3) R22 based Vapor Compression Cycle and 4) LiBr based Absorption Cycle. The schematic diagram of the multi-generation system is given in the Figure 1. Flow in each of these systems are described below:

2.1. Geothermal Cycle.

Geothermal energy is used as the primary heat source to extract heat from underground hot water and utilize the heat for productive purposes through energy recovery processes as described hereafter. Hot water is extracted (state-G-1) from geothermal well at a temperature of approximately 90 – 150 ^oC. Hot water from geothermal well is made to enter a Heat Recovery Unit (HRU) (state-G-2). Here, the extracted heat is used to power an Organic Rankine Cycle. The relatively cool but still hot geothermal-water at outlet of Heat Recovery Unit (state-G3) is then fed to another heat exchanger i.e. Domestic Water Heater (DWH). It has been assumed that the incoming domestic water is at ambient temperature (i.e. T_o) and the DWH increases the water temperature (T_{D2}) to 60 ^oC. After extracting the useful heat content in the DWH, the relatively cooler outlet of geothermal-water is then rejected back towards earth in a geo-well (state-G6).

2.2. Organic Rankine Cycle.

The geothermal energy is exchanged in the HRU with a secondary fluid. The secondary fluid used here is Iso-Butane which has a low boiling temperature (-11.7 °C). In the ORC, the superheated working fluid at output of HRU (state-O3) is used to power the turbine. An isentropic efficiency of 80% has been considered for the pump and the turbine. At outlet of the turbine (state-O4) the working fluid is still in superheated form. After passing through condenser, which is rejecting the heat (Q) to atmosphere, the working fluid condenses to liquid (state-O1). The liquid is then pumped into the HRU (state-O2). Inside the HRU, the secondary-fluid extracts heat from the geothermal water to become superheated again at the outlet. In this way the ORC continues to operate in a steady state. The ORC turbine directly powers a generator which in turn is being used to produce electricity as well as to run a compressor (of Vapor Compression Cycle).

2.3. Vapor Compression Cycle.

Vapor Compression Cycle is used for producing cooling effect as an output of the system. The compressor of the VC-Cycle is driven by turbine of the ORC. Compressor takes 15% of the turbine power to run its cycle. Refrigerant R-22 is used as the working fluid of VC-Cycle. The refrigerant enters the compressor (state-V3) at low temperature and pressure in gaseous state. Compression takes place to raise the temperature and refrigerant pressure. The refrigerant leaves the compressor and enters to the condenser (state-V4). In condenser heat is rejected from the refrigerant to ambient air. As the refrigerant flows through the condenser, it is in a constant pressure. At outlet of condenser it is at (state-V1), where it enters the expansion valve. Here, it expands and releases pressure. Consequently, the temperature drops at this stage. Because of these changes, the refrigerant leaves the expansion valve as a liquid vapor mixture (state-V2).

2.4. Absorption Cycle.

Absorption cycle is used for production of dry cool air. Hot water from geo-thermal well enters the Generator (state-G4) of Absorption Cycle. The Li-Br solution in the generator is heated by hot water. The temperature of the solution increases. The water in the Li-Br solution gets vaporized and it leaves the generator at high temperature. The high pressure and the high temperature refrigerant then enters the condenser (state-A6), where it is cooled to (state-A1) before it enters the expansion valve and then finally into the evaporator (state-A2) where it produces the desired cooling effect. This refrigerant (state-A3) is then mixed again with concentrated Li-Br solution again in the absorber. When the absorbent absorbs the Li-Br refrigerant, weak solution is formed. This solution is pumped by the pump at high pressure to the generator (state-A4). After water has vaporized, the concentrated solution from the generator is passed back to the absorber, via an expansion valve to maintain equalized pressures (state-A5).

2.5. Thermal analysis.

To get an idea of efficiency and quality of energy produced, energy and exergy analysis have been carried out. Following are the assumptions made for the energy and exergy analysis of the multi-generation System:

- All systems / processes are assumed to be in steady state.
- The compressors, expansion valves, pumps and turbines have been assumed to be adiabatic.
- No chemical interaction takes place between refrigerant and the absorbent of absorption Cycle.
- Exergy, kinetic and potential energy changes are negligible.
- R-22 is used as working fluid for Vapor Compression Cycle.
- Isobutane is used as working fluid for Organic Rankine Cycle.
- LiBr and water solution is used as working fluid for Absorption Cycle.
- Environmental conditions are taken as T_0 =25 °C and atmospheric pressure of P_0 = 100 kPa. The same are used as dead state in exergy calculations.

First law of thermodynamics is used for energy balance which is shortly expressed as

$$Energy_{in} = Energy_{out}$$

Exergy analysis is based on second law of thermodynamics. For flow exergies we use

$$h_i = (h_i - h_o) - T\,(s_i - s_o)$$

The work and power equations used in this study are sourced from Cengel and Boles [34]. It has primarily been calculated from the enthalpy and mass flow rate across that particular machine.

Turbine Work:

$$W_{OT} = m_O * (h_{O3} - h_{O4})$$

Turbine Net Power:

$$PN_{OT} = W_{OT} - W_{VCP} - W_{Op}$$

Pump Work:

$$W_{OP} = m_O * (h_{O2} - h_{O1})$$

Compressor Work:

$$W_{VCP} = m_V * (h_{V4} - h_{V3})$$

The energy efficiency is mainly calculated through a ratio of output to input. Following formulas have been used: Organic Rankine Cycle Efficiency.

$$\eta_O = \frac{W_{OT-}W_{OP}}{Q_{OHRU}}$$

Coefficient of Performance Vapor Compression Cycle

$$COP_V = \frac{Q_{VE}}{W_{VCP}}$$

Coefficient of Performance Absorption Cycle

$$COP_A = \frac{Q_{AE}}{W_{AG}}$$

Overall Efficiency of the combined system

$$n_{overall} = \frac{Output_{overall}}{Input_{overall}}$$

Exergic Efficiency Organic Rankine Cycle

$$\eta_{exO} = \frac{W_{OT} - W_{OP}}{m_O * (ex_{O3} - ex_{O2})}$$

Exergic Coefficient of Performance Vapor Compression Cycle

$$COP_{exV} = m_v * \left[\frac{Q_{VE}}{W_{VCP}}\right]$$

Overall System Exergic Efficiency

$$\eta_{exoverall} = \frac{Output_{exoverall}}{Input_{exoverall}}$$

The cost of each cycle were calculated from the following. Geothermal Plant cost from Office of Energy Efficiency & Renewable Energy [35].

$$TonCost_{ABS} = 6000 + (Ton_{ABS} - 50) * ((1800 - 6000)/(1320 - 50))$$

Equation formed from the data given by Absorption Chillers for CHP Systems [36]. Chiller capacity by manipulating the data from Trane Absorption Chiller Series Catalog [37]. Cost of the tonnage by manipulating the data given by Florida Power & Light Company [38]. Chiller capacity from SKM company catalog of SKM Water Cooled Centrifugal Chiller [39].

3. Process Data

The process data at various state points is as shown in Table 2.

4. Results and Discussion.

The exergy has been used as a measure of quality of energy being produced. As the whole cycle is being run practically on the geothermal input, the ratio of output to input is relatively high. With an overall efficiency of ~40%, the exergy efficiency remains above 60% for all variations in ambient temperatures (from 8 to 54 ^{o}C).

Table 2: Parameters at state points of the system.

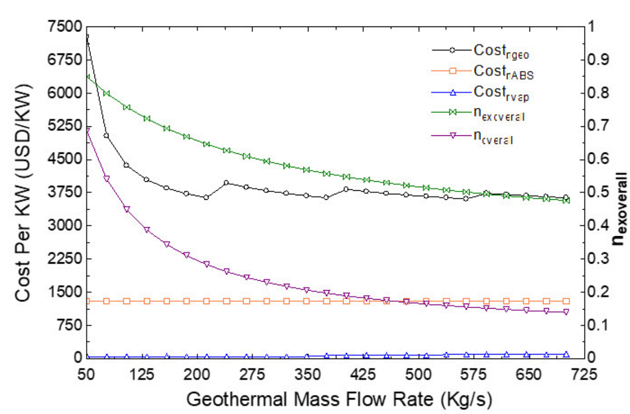
State	Fluid/Gas Type	T(°C)	P (kPa)	ṁ (kg/s)	h(kJ/kg)	s (kJ/kg K)	ėx(kJ/kg)
0	Ambient Values	25	100	-	104.9	0.367	-
A0	Libr Solution	25	100	-	599	0.177	-
A1	Water	40	7.385	0.74	167.5	0.572	1.464
A2	Water	14	1.599	0.74	167.5	0.588	3.361
A3	Water	14	1.599	0.74	2527	8.804	92.5
A4	LiBr Solution	30	7.385	3	61.11	0.297	573.6
A5	LiBr Solution	90	7.385	2.26	206.2	0.523	496
A6	LiBr Solution	90	7.385	0.74	2660	8.512	127.4
G0	Geothermal Water	25	2600	-	104.9	0.367	-
G1	Geothermal Water	100	2600	170	421	1.305	36.58
G2	Geothermal Water	100	2600	143.2	421	1.305	36.58
G3	Geothermal Water	80	2600	143.2	337	1.074	21.53
G4	Geothermal Water	100	2600	26.8	421	1.305	-457.5
G5	Geothermal Water	80	2600	26.8	337	1.074	-472.5
G6	Geothermal Water	70	2600	170	295.2	0.953	15.5
O0	Isobutane	25	100	-	599	2.515	-
O1	Isobutane	50.92	700	33.32	325.4	1.417	53.79
O2	Isobutane	51.26	1200	33.32	326.4	1.417	54.76
O3	Isobutane	90	1200	33.32	687.4	2.459	105.2
O4	Isobutane	71.36	700	33.32	664.4	2.459	82.22
V0	R-22	25	100	-	429.3	1.984	-
V1	R-22	43.11	1492	2.432	248.3	1.162	63.7
V2	R-22	-10.88	386.5	2.432	242.9	1.162	58.3
V3	R-22	-10.88	386.5	2.432	402.1	1.762	38.87
V4	R-22	68.38	1492	2.432	436	1.762	72.76
D0	Domestic Water	25	100	22	104.9	0.367	-
D1	Domestic Water	25	340	22	105.1	0.367	0.246
D2	Domestic Water	60	340	22	251.4	0.831	-138.1

Source: Authors.

4.1. *Optimization of Energy, Exergy and Cost with varying capacity of the unit.*

For this research work, we varied the capacity by varying the geothermal mass flow rate. From the Figure 2, we observe decreasing trends of Cost of geothermal Energy and Exergy efficiencies. On the other hand, the cost of Vapor Compression Cycle increases while Absorption Cycle cost remains cost. The decrease in cost of Geothermal Energy is in our favor while decreasing of Energy and Exergy efficiencies is not favorable.

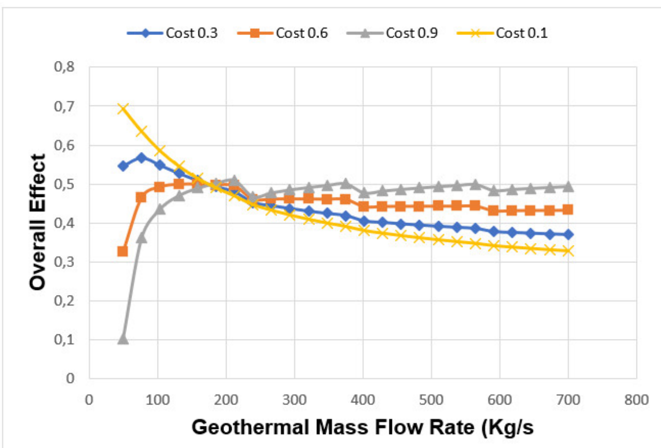
Figure 1: Capacity Variation Effect on different Parameters.



Source: Authors.

In order to optimize the results, we gave weightage to each of the important outputs. We neglected the cost of Vapor Compression Cycle / KW because it is insignificant as compared to the cost of geothermal Electricity. We didn't include the cost of Absorption Cycle in the optimization study because its cost / KW don't vary with mass flow rate, so it doesn't require optimization. By varying weightage from 10% to 90% to the cost of geothermal electricity, we obtained following results. From the Figure 2, it can be concluded that further increase from 190 Kg/s geothermal mass flow rate doesn't increase overall effect, in other words the reduction in cost is in insignificant afterwards with the decrease in performance (overall effect).

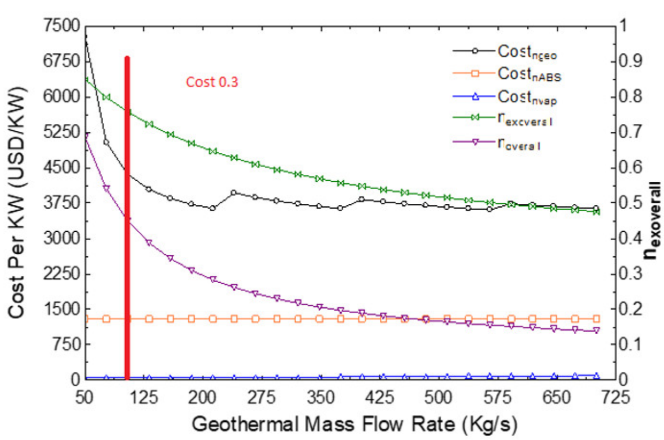
Figure 2: Optimization of Capacity and Cost Weightage.



Source: Authors.

We can observe from figure 3 to 5 that we move towards rightward (Increasing geothermal mass flow rate) when giving more weightage to the cost.

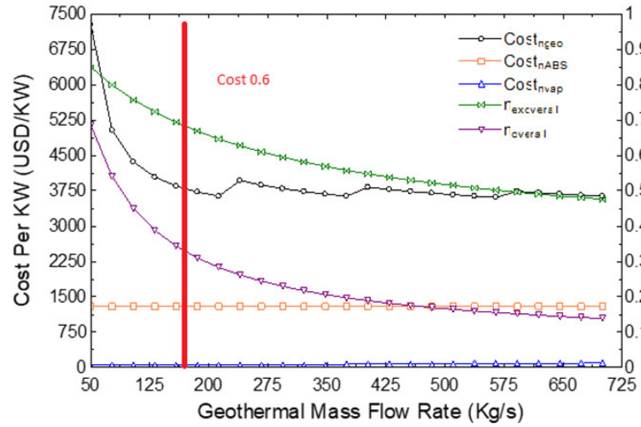
Figure 3: Cost 0.3.



Source: Authors.

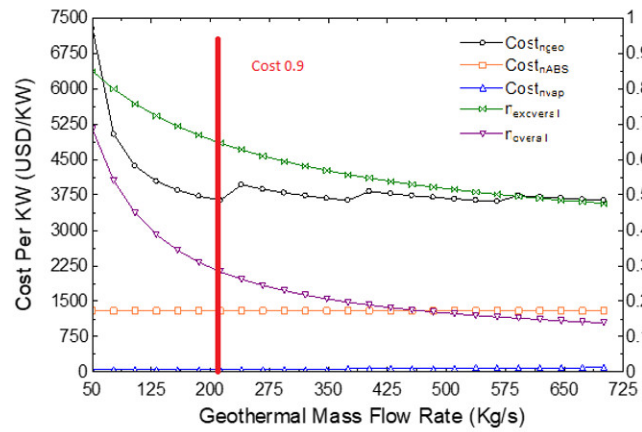
From Figure 6, we can observe that cost and efficiency are inversely proportional to each other. So with the required cost we compromise the efficiency and viceversa.

Figure 4: Cost 0.6.



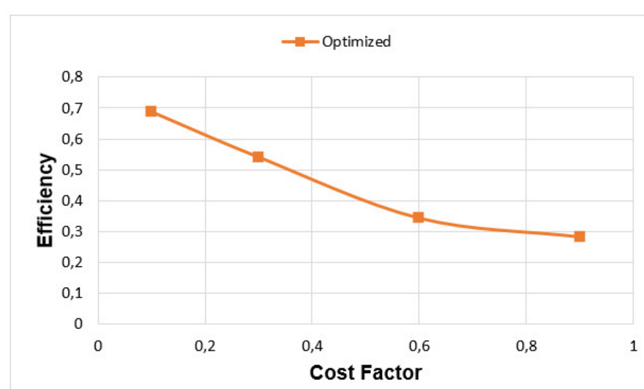
Source: Authors.

Figure 5: Cost 0.9.



Source: Authors.

Figure 6: Compromise Between Cost Factor and Efficiency.

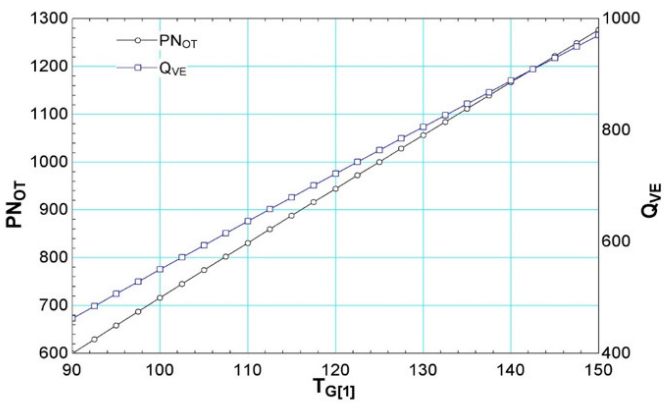


Source: Authors.

4.2. *Effects of Varying Geothermal Temperature.*

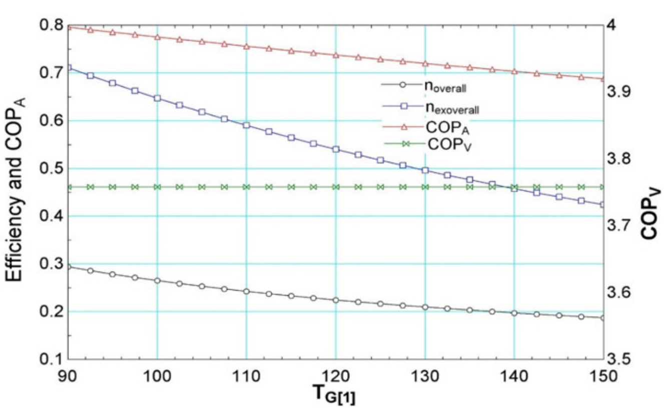
From the categorization of geothermal resource w.r.t temperature as presented in table 1, we know that the subject parameter varies from place to place. So in this part, we investigate the effects onto various parameters by varying the temperature of geothermal resource. Figure 7 presents variations in power w.r.t the changing geo-water temperature. First, we can observe that for constant mass flow rate, the net work done by ORC turbine remains highly sensitive to changes in temperature of geo-water. We can see that the net work done by ORC turbine undergoes a change of almost 11 kW per unit change in temperature; thus the 600 kW of work produced by the ORC system from geothermal source at 90 ^{o}C steeply rises to 1276 kW of output if the geothermal water temperature is increased to 150 ^{o}C.

Figure 7: Varation of Geothermal Temperature and Net Power.



Source: Authors.

Figure 8: Variation of Geothermal Temperature over Efficiencies.



Source: Authors.

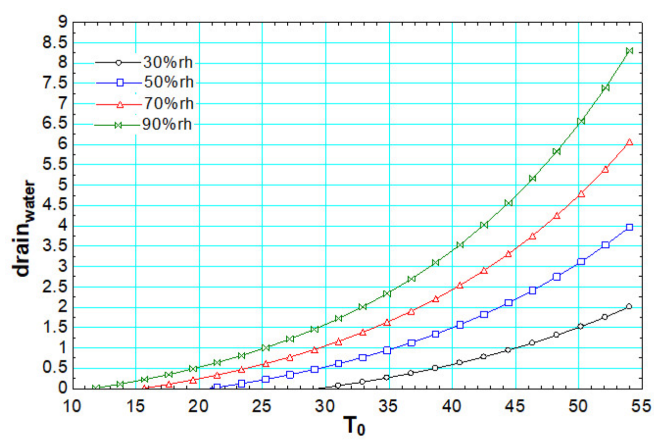
The evaporator of the absorption cycle has constant load and increasing the geothermal temperature increases the generator heat input which rejects in condenser with no increase in evaporator cooling causing decrease in COP. Figure 8 depicts the changes in efficiency as well as COP w.r.t changing the temperature of geothermal source. Here again, the R22 based vapor compression cycle is not getting effected by changes in temperature of geothermal source as the cycle does not come in direct or indirect contact the geothermal energy. The coefficient of performance of LiBr based absorption cycle suffers some degradation with the increase in geo-water temperature.

4.3. *Effects of Ambient Temperature and Relative Humidity on Drain Water Generation Rate.*

This analysis studies the environmental effects on drain water production. As we had to incorporate a significantly large vapor compression system, we have an opportunity to get a significant amount of drain water; albeit it will have to be filtered and purified to be made fit for domestic use or human consumption. Drain water production (in kg/sec) are presented in figure 10 from where we can observe that the rate of production of liquid drain water is highly dependent upon the ambient temperature and humidity thus will undergo significant fluctuations round the year.

Further, it can also be seen that a certain minimum temperature is required for a given relative humidity so that drain water could even be formed. This all results from the increase of water content in air with increase in temperature and humidity. Thus, there will be very less production of drain water on cool, dry winter day i.e. with ambient temperatures less than 20 ^{o}C whereas ~10 tons of water will be accumulating within 12 hours for 25 ^{o}C and 50% RH. On a hot, humid summer day (i.e. 40 ^{o}C and 70% RH), ~216 tons of water will be accumulating in 24 hours. This water, with proper filtering and purification, can be used to meet domestic needs of nearby population or can be directly used to water the corps.

Figure 9: Effects of ambient temperature on drain water production under different relative humidity conditions.

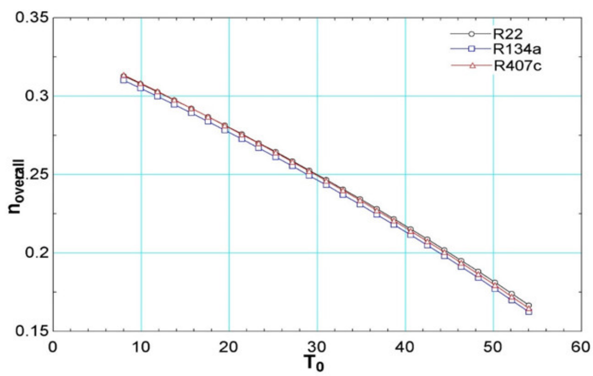


Source: Authors.

4.4. *Effects of Fluids Variation onto Vapor Compression Cycle with Ambient Weather.*

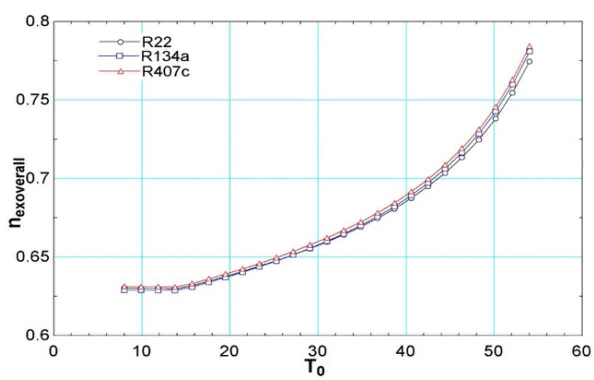
Different fluids have difference performance with respect to specified conditions. Some fluids may perform better at given set of conditions or worse at other sets of conditions. This analysis focuses on three working fluids namely R-22, R-134a and R-407c in Vapor Compression Cycle and the effects on efficiency and performance thereof. From figure 11, it can be noticed for the given conditions the overall efficiency of the three working fluids are nearly the same except that R-22 is slightly more efficient working fluid than the rest. Similarly, the exergic efficiency is nearly the same for the three working fluid with R-407c slightly more efficient. From figure 12, it can be concluded that in winter at temperatures less than 17 °C the COP for R407c is maximum but afterwards, R-22 has maximum COP.

Figure 10: Effects on efficiency for different refrigerants.



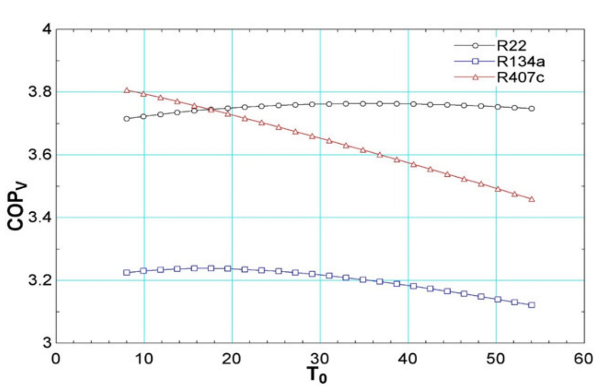
Source: Authors.

Figure 11: Refrigerants and Exergic Efficiency.



Source: Authors.

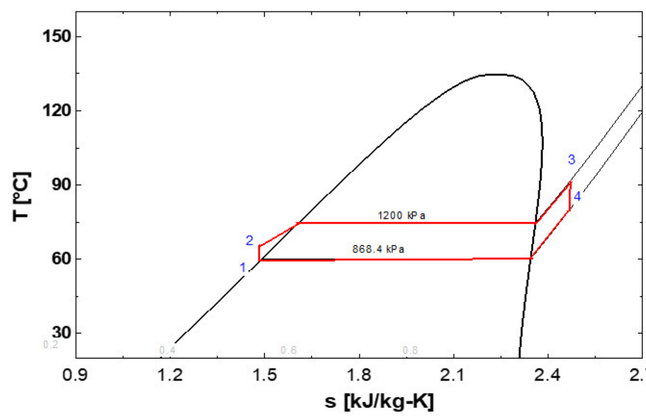
Figure 12: COP of vapor compression cycle for different refrigerants.



Source: Authors.

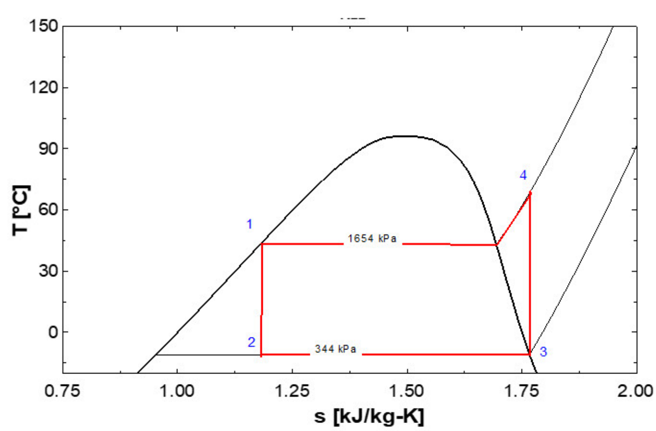
In light of the above-mentioned discussion and three plots, we are of opinion that R-22 is most suited refrigerant for use in such scenarios. The overall T-s diagrams of ORC and vapor compression cycle are presented in figure 13 and 14 respectively.

Figure 13: T-s Diagram for isobutane based Organic Rankine Cycle.



Source: Authors.

Figure 14: T-s Diagram for R22 based vapor compression cycle.



Source: Authors.

Conclusions.

In this paper, we have presented and analyzed a multi - generation system, capable of producing five different outputs. Named as Multi-generation system, it employs a geothermal powered, isobutane bases, Organic Rankine Cycle as primary source of power. The net output of ORC turbine is used for electric power generation; it is most affected by the geothermal water temperature which is capable of producing a change of +11 KW/^{o}C. After imparting energy to isobutane for ORC cycle, the geothermal water is further utilized for heating of domestic water. Three different types of refrigerants have been studied for use in vapor compression cycle; we have found that although the refrigerant R-22 outperforms R-134a and R-407c for most of the temperatures as it require least power consumption thus allowing for a better net power output by turbine. Moreover, as the ambient temperature increases from 8 to 54 ^{o}C; with the same compressor input the Evaporator Heat (Cooling), thus increase in COP of vapor compression cycle. The vapor compression cycle also produces a significant amount of drain water which can be utilized for domestic use after proper filtering and purification. Under hot, humid ambient conditions 70% relative humidity and 40 ^{o}C, ~216 tons of water is produced per day. Air conditioning is done through use of LiBr solution-based absorption cycle. Overall, the system maintains an efficiency of more than 20% under all temperature variations with an exergy efficiency of >65%.

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