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POWER PRODUCTION USING LOW-TEMPERATURE HEAT SOURCES IN EL SALVADOR

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ABSTRACT

The report gives the reader an insight into geothermal development in El Salvador; it also describes research and calculations done for low-temperature power production development. An organic Rankine cycle (ORC), a Kalina cycle power plant and research on thermoelectricity-based geothermal projects are primarily considered. A description is also given on why a Kalina cycle is much more efficient than a simple or even a regenerated binary power plant and why this particular cycle does not work for the analysed conditions. In addition, it explains the phenomena on which thermoelectric devices are based and why harnessing the true potential of devices based on these principles is still prohibitive, given the extremely difficult process involved in nano-scale manufacturing.

1. INTRODUCTION

Since the industrial revolution, the world's ever increasing energy demand has led man on a quest for an efficient power source. Power generation with fossil fuels has been practiced since olden times, but these resources are scarce and getting even more expensive to access; current technologies are focused on producing more efficient processes and machines but this does not diminish the need for more energy sources, and fossil fuel reserves are being depleted (Colorado River Commission of Nevada, 2002). Even if these depletion estimates are not so accurate, we have less fossil fuel than we used to and eventually we will not have any at all.

Today, not just big industries consume bigger amounts of energy. Average households are consuming more energy, too. As a matter of fact, by the year 2030 in Latin America, house electrification is scheduled to be 1336% of that in the year 2000 (Letschert and McNeil, 2009). Including heating, cooling, transport, communication and many other needs, the energy requirement for 2030 could be a lot bigger, but this energy does not come without an additional cost, which includes pollution and environmental problems.

The global climate is going through many changes and it is always a matter of debate among many scientists as to whether it is due to human or natural effects. One thing that is certain is that energy consumption affects the environment at least on a local level. For example, the smoke produced by coal or bunker power plants is very toxic for living organisms and it is just waste material. Pollution and the lifetime of these power sources are only two of many related problems. Partly for these reasons, there has been an interest in developing green and sustainable power energies, like wind, solar and geothermal power production.

Worldwide, geothermal energy is one of the cleanest energy sources known. There are several ways to assess and even use geothermal energy, although it is mostly used to generate electricity. However, in many countries geothermal energy is used not only to produce electricity but also for district heating, swimming pools, heating vegetable nurseries and many other uses. El Salvador is one of the countries in Central America that produces electricity with geothermal energy, mostly from high-temperature sources, but given the opportunity to improve overall efficiency of the power plants, low-temperature power production is an option that needs to be considered.

The focus of this report is on renewable energy sources, specifically on geothermal power production in El Salvador. El Salvador is trying to increase the renewable energy production in the country to assess the problem of contamination and fossil fuel prices in a more aggressive way, and geothermal energy as a very reliable and constant power source over the years comes into the picture. Based on the current conditions of a geothermal field in operation in El Salvador, the conditions and the output for a proposed power plant will be given according to the types of power plants that will be analysed.

2. GEOTHERMAL UTILIZATION IN EL SALVADOR

2.1 Overview of geothermal development in El Salvador

El Salvador has two main geothermal fields that are currently used for power production. As shown in Figure 1, Ahuachapán geothermal field is located in the western part of the country and Berlin geothermal field in the eastern part.

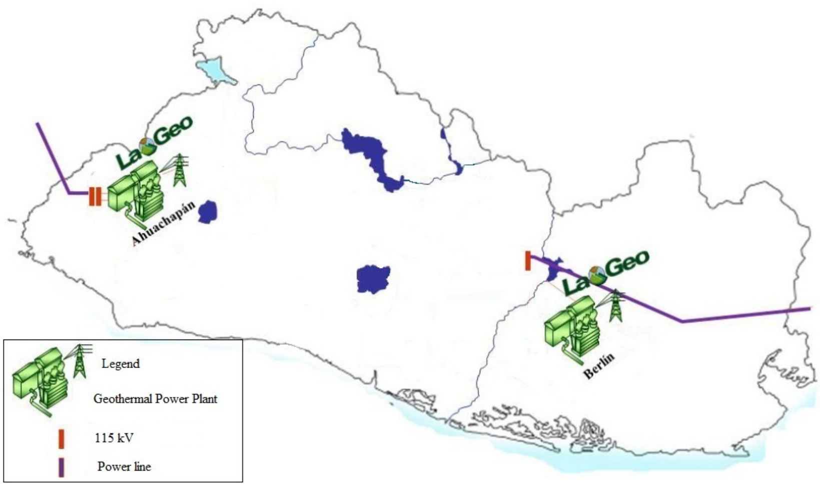

FIGURE 1: El Salvador geothermal power plants

Geothermal exploration in El Salvador began in the mid 1960s; a programme for geothermal studies started in 1965. The first well drilled was AH-1 in the Ahuachapán geothermal field in 1968. This well showed successful production results, so the drilling of more wells was continued. Power production began in 1975 with the installation of a single-flash unit and a second one in 1976. By 1980 a third unit was installed in the field giving a combined installed field capacity of 95 MW. El Salvador has also had another geothermal field in full operation since the end of the 1990s, the Berlin geothermal field, currently in operation with 3 single-flash units and a binary cycle power plant.

Since the mid 1970s, El Salvador has relied on geothermal power production to get electricity. Around that period of time, El Salvador´s bet for future power production was based on renewable energy sources and so geothermal power production became one of the main energy sources. A few years later, a civil war started in the country and a lot of electricity projects came to a halt. Eventually, after the war ceased, the country needed electricity and many fossil fuel power plants started operating. That is why, as of today, almost half of the country's power generation is based on fossil fuels, and prices are going nowhere but up.

A rough estimate in the middle of 2012 made by SIGET – the Energy and Telecommunications authority in El Salvador (SIGET: Superintendencia General de Electricidad y Telecomunicaciones) showed that 23.55% of the total power consumption in El Salvador came from geothermal sources, 22.30% from hydroelectrical generation, 49.39% from thermal generation and the rest was imported from other countries. In terms of installed capacity, renewable sources comprise around 45% of the total installed capacity of the country whereof geothermal sources comprise 13%. This shows the scope for additional renewable energy power production in El Salvador, given the increasing prices of fossil fuels, not only in America but around the world (SIGET, 2012).

2.2 The Ahuachapán geothermal power plant

By 1972, construction of the Ahuachapán geothermal power plant began, located in the western part of El Salvador; the first of its kind in the country. The power plant started operating in 1975. In 1981, the power plant was forced by the government to produce around 41% of the national electricity required; this impacted quite badly on the geothermal resource. By 1983, a sustainable extraction-generation plan was established which allowed the field to preserve the reservoir's geophysical, thermodynamic and geochemical characteristics within sustainable limits.

Near the end of the 1980s an extensive reservoir engineering study was conducted to determine new extraction and reinjection zones that could allow better geothermal fluid management. Another purpose of this study was to establish allowable levels of power generation close to the installed capacity of the power plant. As a result of this study, it was possible to develop a programme to stabilize the Ahuachapán geothermal field.

In mid-2000, another project was developed in Ahuachapán called "Ahuachapán total reinjection" (Reinyección total Ahuachapán). This project was conceived to move the reinjection zone of the field 6 km to the east along with a pumping station. Currently, the power production in this geothermal field is around 80 MW.

2.3 The Berlin geothermal power plant

Between 1976 and 1981, research called "Development for a geothermal project in the eastern-centre zone" was financed by the World Bank. After getting the results from that research, the national energy institute conceived the project "Wellhead Berlin I", and in 1992 a small geothermal power plant was commissioned, also known as "Central El Tronador" (this was the first unit of the wellhead project).

In the beginning of the 1990s a feasibility study called "Feasibility study for the first geothermal-electric condensing unit in Berlin geothermal field" was developed by an Italian company called Electroconsult. This study proposed the installation of two single-flash condensing units of 25 MW each. A year after the study, well drilling started and the building of the steam and reinjection pipeline along with the power plant construction began.

The power plant was commissioned in July 1999 and is currently used as a base load generator, with two single-flash units (25 MW each). In late 2000, a third 40 MW single-flash unit was installed, increasing the installed capacity of the power station. In 2008, a 10 MW ORC binary power plant was installed using isopentane as a working fluid, using reinjection water as the heating fluid as shown in Figure 2.

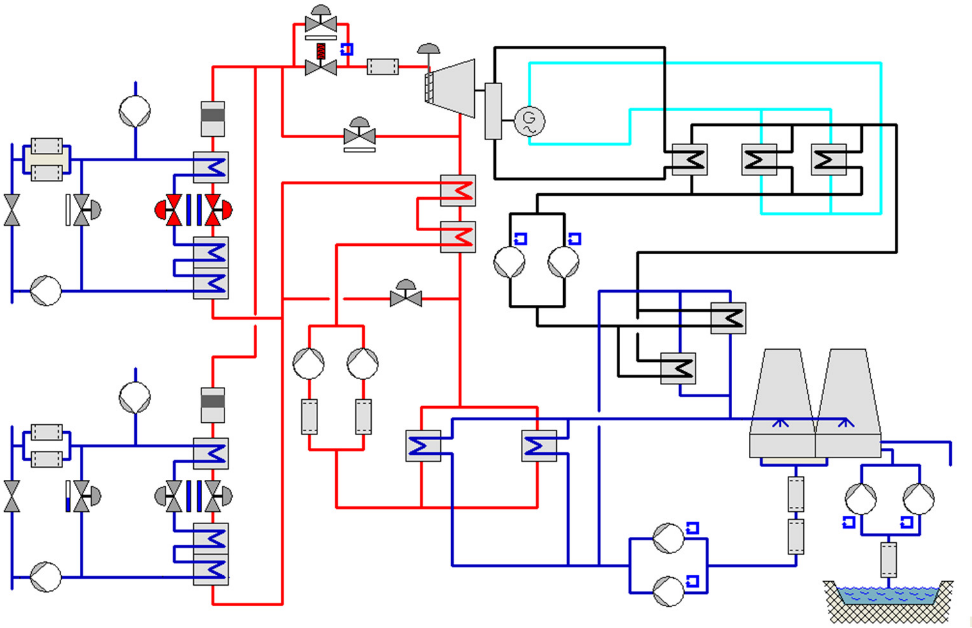

FIGURE 2: Berlin binary cycle power plant using isopentane as working fluid

2.4 Low-temperature utilization

Most of the geothermal resources in the world are classified as low-temperature resources. For a geothermal fluid of 150°C or less, it is quite difficult and expensive to build a steam flash power plant that will use the working fluid in an efficient manner. The lower the temperature of the geothermal resource, the harder it becomes for flashing technology. A lot of scaling is expected for those temperatures in geothermal fluids (DiPippo, 2005).

For low-temperature geothermal utilization, there are several applications that can use the resource. Swimming pools are an example of low-temperature utilization for leisure and even medical purposes. District heating is widely used in colder countries with known geothermal resources. For example, Iceland has almost stopped relying on fossil fuel heating and now relies mostly on geothermal heating. Applications range from aquaculture to agriculture, and several other uses. The main focus of this report it though on power production.

Usually a low-temperature geothermal resource of 150°C or less is used in a power plant of a binary type power conversion system which uses a secondary working fluid in a closed loop Rankine cycle, in which the geothermal fluid just heats up the secondary working fluid. There are many variations of these types of power plants: there are single- and dual-pressure binary cycles, dual fluid binary cycles and Kalina cycles.

When it comes to geothermal power production, binary cycle power plants are thermodynamically the closest to conventional fossil or nuclear power plants in that the actual working fluid is processed on a closed loop. The kind of binary cycle and working fluid must be selected carefully for its thermodynamic properties; it undergoes several processes such as receiving heat from the geothermal fluid, evaporation, then an expansion on the turbo machine, condensation and eventually is pressurized again to gain heat from the geothermal fluid before starting all over again.

The first geothermal binary power plant produced electricity and heat for a small village and some farms in Paratunka near the city of Petropavlovsk on Russia's Kamchatka peninsula in 1967 (DiPippo, 1980). It was rated at 670 kW; it ran successfully for many years and proved that the concept of power generation using a binary cycle power plant was right and could be done.

3. BOUNDARY CONDITIONS FOR A LOW-TEMPERATURE POWER PLANT IN THE BERLIN GEOTHERMAL FIELD

3.1 General guidelines

For every power plant development, regardless of its nature, there are some conditions that must be fulfilled. The types of conditions with which a power plant needs to comply can be environmental, economical, or technical in nature, amongst others. For the current research, the conditions that will be considered for the design will be mostly technical, regarding the nature of the geothermal fluid and the use of it in the geothermal field. For this analysis the most important factor to be considered will be the disposition of the geothermal fluid.

3.2 Power plant location

A very important condition for any power plant design is its proposed location. Location can affect in many ways the development of such a project as land is not always available, accessible or affordable. For instance, if a geothermal company has the possibility of installing a power plant with an estimated output of 15 MWe due to the available heat in the geothermal fluid but the available location has only a certain amount of cooling water available, then location becomes a critical issue for power plant design, as moving the plant closer to a water source can assure the estimated power production, but also will increase the land acquisition costs. For this example an optimization analysis must be done in order to obtain the best relationship between power output and plant location.

For this research two preliminary power plant locations were considered: Location 1 is along a reinjection pipeline recently commissioned in Berlin geothermal field in an area shown in Figure 3. This location was selected due to the accessibility of a considerable volume of geothermal water, because this pipeline gathers reinjection brine from two different production wells for a reinjection well near the power plant.

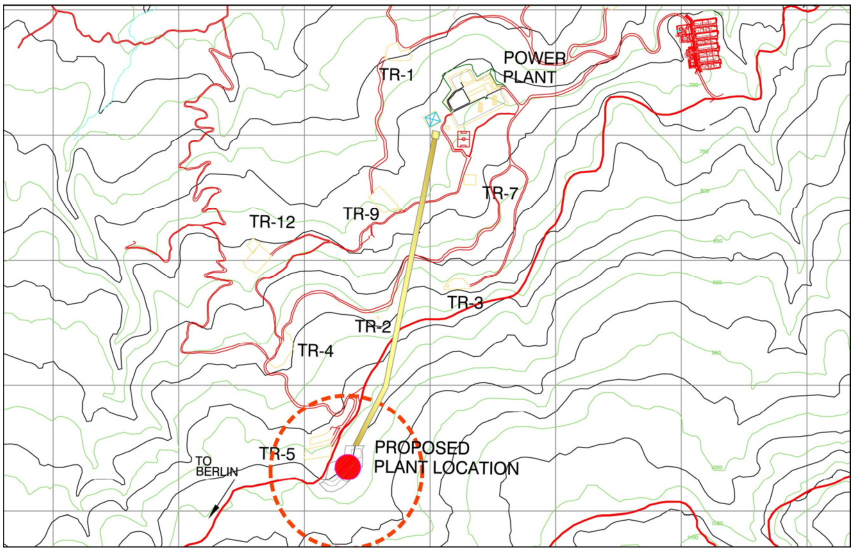

FIGURE 3: Proposed plant location 1

Location 2 for the proposed power plant is on the platform of a reinjection well further away from the existing power plant; here the geothermal mass flow available for heating up the working fluid is lower than that of Location 1, but has a clear advantage over the former choice in that the amount of civil works would be reduced because of the already installed well platform. Civil works for land preparation can represent a high percentage of the total cost of installing a power plant.

Studies have started for the feasibility of selecting Location 1 as a new power plant location. An Environmental Impact Assessment study is already in the works. The fact that this spot is closer to the binary power plant, for operational and maintenance purposes, is another advantage for selecting this location for a power plant.

3.3 Geothermal fluid scenarios

Having defined mass flow availability, the next step is to consider the temperature range for the geothermal water that may be used by the power plant. It is important to note that regardless of the location, the lowest temperature that this specific geothermal fluid can have is 135°C; this limit is imposed by the chemical composition of the reinjection water and was determined by the geochemical department at LaGeo, as a limit to prevent silica scaling problems.

For the proposed Location 1, a higher geothermal fluid mass flow is available which, in consequence, represents a much higher amount of heat extraction capacity, assuming similar extraction temperatures as shown in Table 1. It is important to note that the values used in this table and later tables are average values that represent a parameter for a preliminary design.

TABLE 1: Mass flow available for each location for the proposed power plant (mass flow in kg/s)

Location 1		Location 2	
Well no.	**Mass flow**	**Well no.**	**Mass flow**
TR-3	34	TR-19	40
TR-7	6	TR-19A	9
TR-19	40	TR-19B	102
TR-19A	9	TR-19C	34
TR-19B	102		
TR-19C	34		
Total	**225**	**Total**	**185**

Having figured out the mass flow availability, one important matter is to consider the temperature available for each location. Given that this is reinjection water, regardless of the location selected, it is very important to control the geothermal outlet temperature after the heat exchange process; if the outlet temperature goes too low, a possible scaling process may occur, diminishing the power plant's performance and lifetime.

The proposed mass flow for each location comes partly from the same geothermal wells. In this case, the temperature and consequently the heat available for any process is determined by the distance from the extraction point to the production point, as temperature losses along the pipeline affect the final temperature in the proposed location.

These reinjection mass flows are constantly monitored and, for the purposes of this research, the temperature values are known at least for the two locations considered here, due to the constant measurements taken. The proposed power plant location will be a consequence of the available energy for the heat exchange process between the working fluid and the geothermal water. For a calculation of available heat, Equation 1 is used considering each location's utilization temperature: 175°C for Location 1 and 170°C for Location 2, giving rough estimates of the available thermal energy. It is though important to clarify that thermal energy for a geothermal power plant is much bigger than the net power output:

$$\dot{W}_{th} = \dot{m} * C_p * \Delta T \tag{1}$$

where $\dot{W}_{th}$ = Heat available [kW];
$\dot{m}$ = Mass flow [kg/s];
C_p = Specific heat at constant pressure of a fluid [kJ/kg-°C];
ΔT = Temperature difference between inlet and outlet [°C].

Using the embedded fluid properties in Engineering Equation Solver - EES (F-Chart Software, 2012) the available heat is calculated, assuming total heat exchange. Table 2 shows an analysis of the two scenarios.

TABLE 2: Comparison of heat available for each location

Location	c_p **(kJ/kg°C)**	$\dot{m}$ **(kg/s)**	$T_{geo,in}$ **(°C)**	$T_{geo,out}$ **(°C)**	$\dot{W}_{th}$ **(kW)**
1	4.385	225	175	135	39,466
2	4.368	185	170	135	28,286

From the calculations in the table above, an approximate result of available heat is obtained, resulting in the selection of Location 1 due to the fact that it has almost 40% more energy available. In the following sections, these parameters will be analysed among different technologies, to get an idea of the optimum technological and also a practical solution for a power plant.

4. ORC POWER PLANT

An organic Rankine cycle binary power plant uses a secondary fluid (instead of steam) with a lower boiling point and different thermodynamic properties than water as a working fluid. The organic fluid receives heat from the geothermal fluid in a heat exchanger and ultimately is vaporized before entering the turbine to produce mechanical work and eventually electricity in the generator. After the organic fluid leaves the turbine it is condensed and then pumped again in a closed circuit to be vaporized again.

A binary cycle power plant does not have steam condensate to serve as makeup for a cooling tower. Binary plants usually have a separate cooling medium that can be fresh water or air. Air cooled condensers are usually a solution for power plants with no fresh water availability.

Many binary power plants rely on organic fluids with a retrograde behaviour. With these kinds of fluids, the thermodynamic state at the turbine outlet is superheated steam. This allows a regeneration phase as shown in Figure 4, in which heat exchange of superheated steam raises the temperature of the fluid at the pump outlet in the high-pressure end of the cycle. By adding a regenerator the load on the condenser is lowered, as it has to remove less heat when getting the superheated steam to the saturated area and then start the actual condensation process.

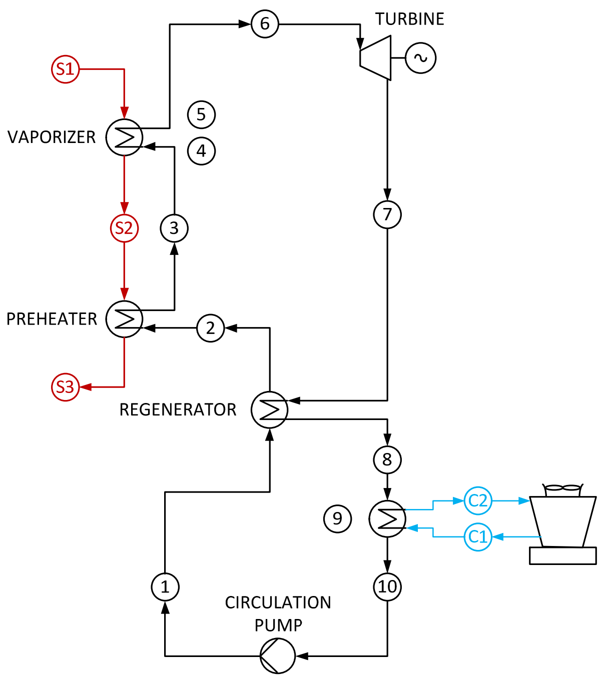

FIGURE 4: Binary cycle power plant diagram with a regeneration stage

As many of the geothermal resources available in the world are in the low-temperature category, binary cycle power plants are increasing in number as well as technology as they allow the use of geothermal fluid in liquid phase without flashing, thus requiring less management.

Currently, a binary cycle power plant is operated in the Berlin geothermal field using isopentane as the working fluid; overall, this has resulted in an increased efficiency of the geothermal field, as it uses heat from reinjection water for the heat exchange process with the organic fluid.

4.1 Advanced binary power plants

4.1.1 Dual-pressure cycles

These kinds of cycles are designed to minimize the thermodynamic losses in the geothermal fluid heat exchangers in basic binary cycles. These kinds of losses occur in the heat transfer process due to a large temperature difference between the cooler working fluid and the hotter geofluid. If the process has a closer match between the geofluid's cooling curve and the working fluid's heating and boiling curve, the thermodynamic losses can be reduced. The thermodynamic process is shown in Figure 5.

A dual pressure binary cycle allows the two fluids to have a smaller temperature difference than a one stage process using a two-stage heating and boiling process. A dual admission turbine is usually considered for the design process in which low-pressure saturated steam is admitted into the turbine to mix with a partially expanded high-pressure steam to obtain a superheated steam. Turbines using organic fluids are usually of small size compared to steam turbines. Many practical solutions using dual-pressure binary cycles consider having two different turbines instead of a single-pressure one.

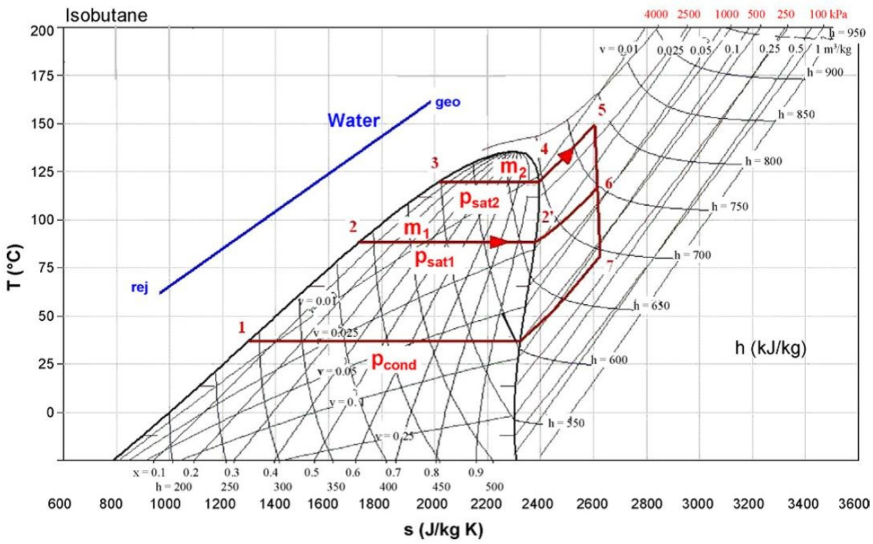

FIGURE 5: Thermodynamic diagram of a dual pressure binary cycle (Franco and Villani, 2009)

4.1.2 Dual-fluid binary cycles

Dual fluid binary cycles are similar to dual-pressure cycles, as both cycles try to create a close match between the geofluid and the organic fluid heating-boiling curves. In this particular cycle a heat transfer between the two working fluids is also intended as the lower-temperature working fluid is doing the condensation process for the higher-temperature working fluid at the same time as the higher-temperature fluid is doing the vaporization process for the lower-temperature working fluid, as shown in Figure 6.

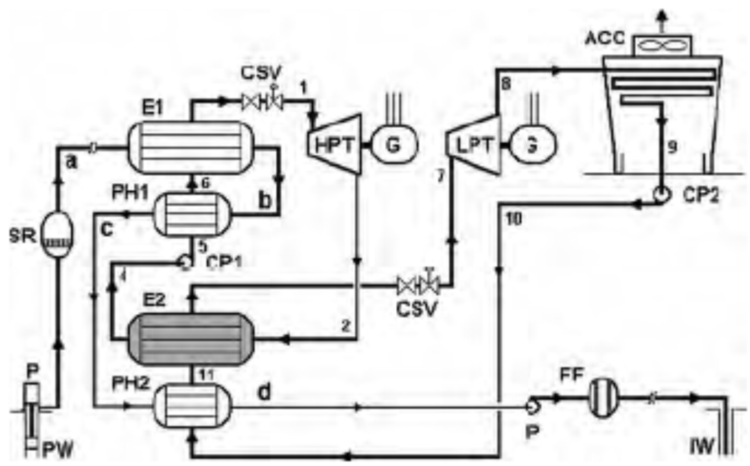

FIGURE 6: Diagram of a dual-fluid binary cycle (DiPippo, 2005)

The cycle is designed so that the boiling curves of the organic fluids and the geofluid are almost parallel in the preheaters. In that way the thermodynamic irreversibility in the process is lowered, as also will be the loss of exergy during the heat transfer in those components of the system. However, there will be a higher loss of exergy in the evaporator of the higher fluid, due to relatively larger mean temperature differences.

The first binary power plant in the United States used this kind of binary cycle, using two hydrocarbons, one in a subcritical cycle and the other in a supercritical cycle. However, there are some difficulties in using a supercritical cycle, as the vaporizing pressures may require thicker tubing in the heat exchangers, unless the design establishes almost equal pressures on both sides of the components. Also, going for thicker components increases the thermal resistance for the heat transfer components, which increases the size of said components, making them more expensive.

4.2 Organic fluid selection

A very important consideration for a binary cycle power plant is the fluid selection as the organic fluid has a great impact on the performance of a binary plant. There are several choices for working fluids in a binary plant but not every available fluid can be used for a given power plant; regardless of its thermodynamic properties for efficiency purposes, as there are other considerations for safety, health and environmental impacts.

Five fluids were studied for the proposed binary cycles. Below, in Table 3, some properties regarding health and environmental properties are shown. When selecting the fluid: toxicity and flammability are two very important factors regarding human safety; the ozone depletion potential (ODP) and global warming potential (GWP) reflect environmental issues. For both the ODP and GWP, the lower the values of these two numbers, the safer for the environment they are.

TABLE 3: Environmental and health properties of studied working fluids (DiPippo, 2005)

Fluid	Formula	Toxicity	Flammability	ODP*	GWP**
R134a	CH_2FCF_3	Low	Non-flam	0	1430
R245fa	$C_3H_3F_5$	Low	Non-flam	0	1030
n-pentane	C_5H_{12}	Low	Very high	0	3
isopentane	i-C_5H_{12}	Low	Very high	0	3
isobutane	i- C_4H_{10}	Low	Very high	0	3

*Ozone depletion potential; **Global warming potential

For an initial approach to the fluid selection problem, R134a and R245fa are the safer bet regarding human safety factors but, nonetheless, an existing binary cycle power plant is currently working in the Berlin geothermal field, in which isopentane is used with very satisfactory results; isopentane is a flammable fluid with low toxicity. However, the field operators have experience in handling highly flammable fluids.

Concerning the environmental factors, the five fluids presented above have zero ODP. The GWP measures how much heat a greenhouse gas traps in the atmosphere; it is a relative measurement because it compares the amount of heat trapped by a similar mass of carbon dioxide. GWP is higher among the Refrigerants but still in the safe zone for industrial utilization, and are approved for current standards. For both safety and environmental issues, all five considered fluids are feasible for utilization. Thus, the selection of fluids becomes a technical issue.

In this research, four retrograde fluids were considered: Isopentane, isobutane, n-pentane and R245fa. Retrograde fluids are those with a saturated vapour line with a positive slope, and so regeneration is possible because the working fluid at the turbine outlet will always be in the superheated zone. R134a, a non-retrograde fluid, was considered for this study but it was not able to exchange enough heat with the cold end fluid due to the restrictions imposed on the condenser in the design phase and, also, like in the preheater, boiling is supposed to be avoided in these kinds of components due to design restrictions and to prevent early failure. In Figure 7, a schematic of the T-s diagram for the abovementioned fluids is shown; the retrograde or non-retrograde behaviour of the fluids is quite noticeable.

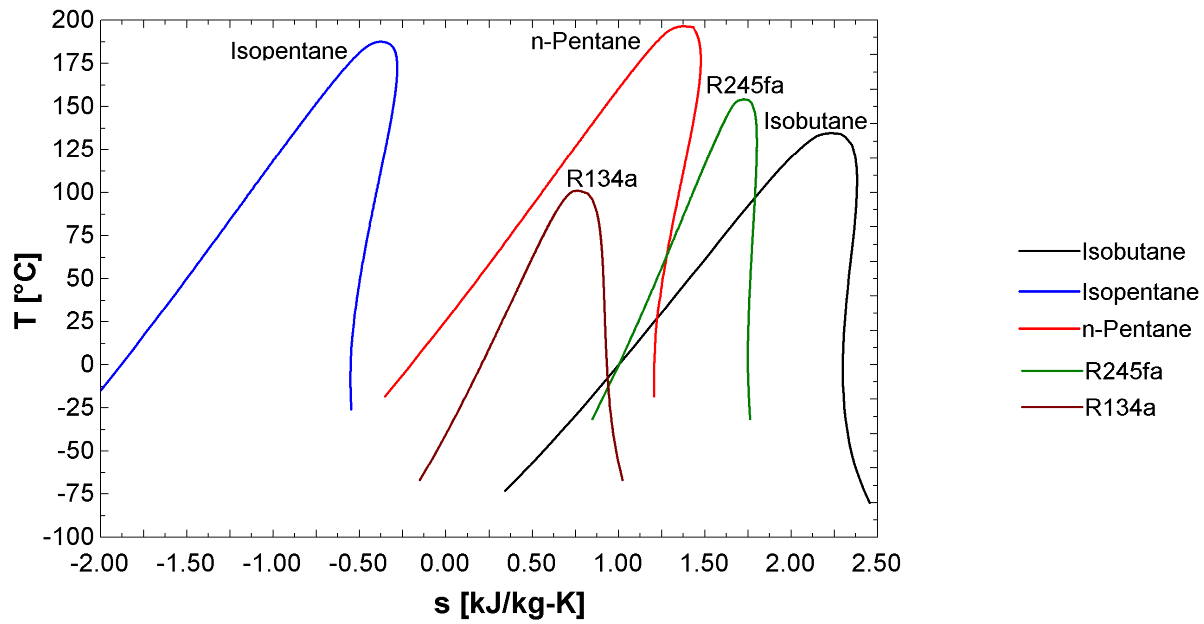

FIGURE 7: Temperature-Entropy (T-s) diagrams of calculated organic fluids

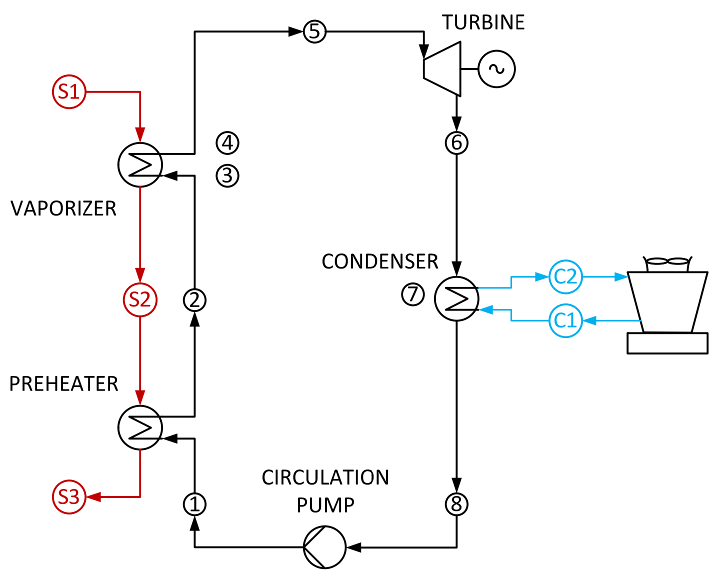

FIGURE 8: First scenario cycle (ORC without regeneration)

To be able to compare the fluids, two scenarios were created involving an Organic Rankine Cycle. The first one is an 8 state working fluid scenario, shown in Figure 8. In the first state, the fluid is in liquid form and has been pressurized in the pump (meeting the vaporization pressure). In state 2 the fluid has left the preheater where it increased its temperature in a heat exchange process with the geothermal fluid that just left the vaporizer. In the preheater, the organic fluid raised its temperature to a point close to the boiling temperature but a safe margin is considered to prevent boiling in the preheater. States 3 and 4 are saturated liquid and vapour points, respectively. In these points, the organic fluid is just changing phase at a constant temperature and pressure in the vaporizer. State 5 is where the fluid is in a superheated vapour state and is about to enter the turbine. In state 6 the fluid has just left the turbine and, depending on the fluid behaviour (retrograde or non-retrograde), it may still be in its vapour phase. The turbine has done its mechanical work and the working fluid is about to enter the condenser. The turbine outlet and the condenser inlet appear separated in the diagram but, in reality, the condenser inlet and turbine outlet are practically in the same place. States 7 and 8 are saturated vapour and liquid points, respectively, at condenser pressure. State 7 is inside the condenser while state 8 is the condenser outlet. In the condenser, the remaining heat is removed from the working fluid after leaving the turbine; it is de-superheated and then condensed.

The second scenario considers an Organic Rankine Cycle with regeneration after the turbine outlet, where the regenerator exchanges the heat of the turbine outlet fluid with the pump outlet fluid, increasing the overall efficiency of the cycle, due to the fact that the condenser removes a smaller amount of heat. The regeneration is possible because the fluid at the turbine outlet is in a superheated vapour phase so there is no mixing in the turbine outlet, which could cause an early failure in the last stages of the turbine.

In Figure 9, state 7 depicts the turbine outlet working fluid that enters the regenerator and leaves it again with a lower temperature but still in the superheated zone. It will enter the condenser at a temperature that is set by the design process. The condenser now only needs to remove the smaller amount of heat related to the de-superheating and condensing processes. States 9 and 10 represent saturated vapour and liquid, respectively, at the temperature of the condenser. State 1 is the pump outlet and the colder fluid regenerator inlet; for the calculation process, there are no heat losses in the component. The amount of heat removed is equal to the amount gained by the colder fluid. As the cycle increases in efficiency, a smaller condenser and preheater is required for a fixed amount of heat. In a case where the geothermal fluid cannot go below 135°C, and keeping in mind that maximizing the cycle efficiency is important, one of the key elements for fluid selection is fluid performance.

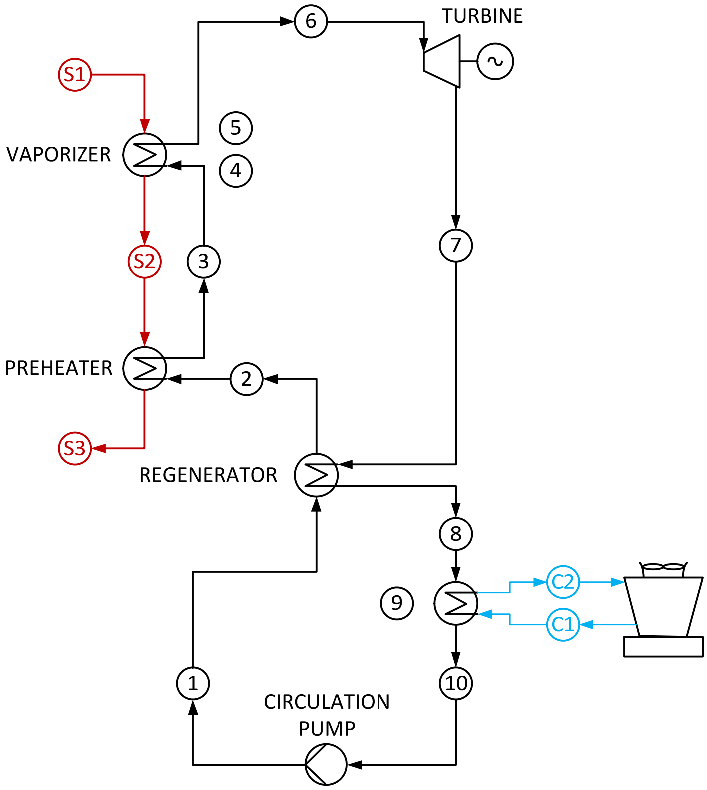

FIGURE 9: Second scenario cycle
(ORC with regeneration)

The EES computer software was used in the cycle calculations. As its name implies, it solves a set of given equations with the same quantity of unknown values and equations. The main advantage of the software is that it includes libraries with the thermodynamic properties of several fluids, including water and the fluids used in this research. Where convergence was not achieved by the software calculation, data tables were compiled with enough information to calculate them in matrix form in the computer program Matrix Laboratory (MatLab), mainly for heat exchange area calculations.

The first approach for fluid comparison was to plot the geothermal fluid outlet temperature for the same range of pressure in the vaporizer, considering the same temperature in the condenser (Figures 10 and 11). In this approach, the behaviour of each fluid was likely to be predicted and easily compared with the others for the same conditions.

In the regenerative cycle shown in Figure 11, calculations for R134a are not shown since the heat exchange process in the regenerator showed that the fluid was not increasing its temperature on the colder side and so the regeneration phase was useless for this particular range and fluid.

As a result of calculations aiming for a geothermal fluid outlet temperature of 135 ºC, an overview of the desired vaporizer pressure required is shown in Table 4. The table shows the data for both the simple cycle and the regenerated cycle.

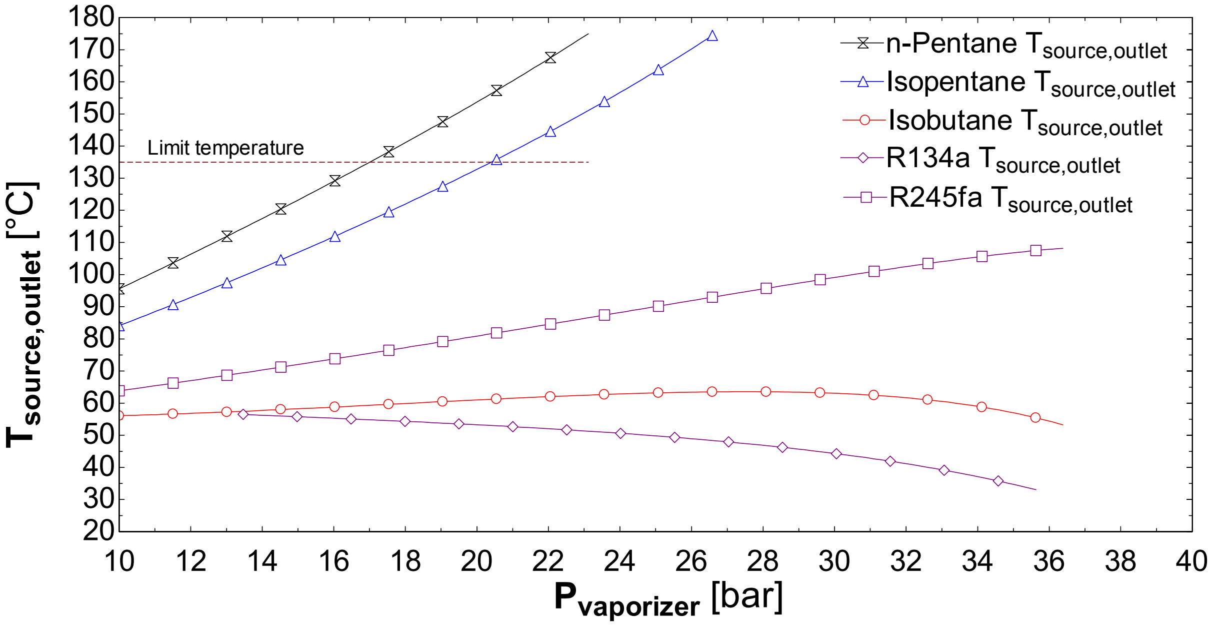

FIGURE 10: Geothermal outlet temperature for the non-regenerative cycle

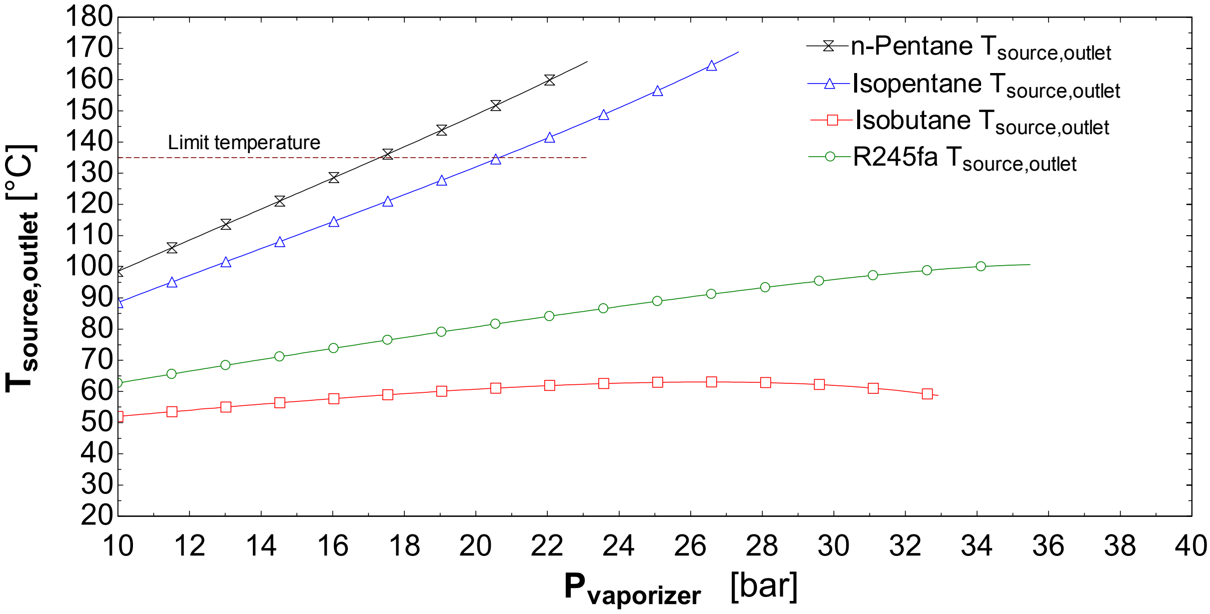

FIGURE 11: Geothermal fluid outlet temperature for the regenerative cycle

As shown in Figures 10 and 11, only two of the selected organic fluids (Isopentane and n-pentane) were able to produce power, managing to get an outlet geothermal temperature at the desired temperature range which is a geothermal fluid outlet temperature of 135 °C. Also from Table 4, it is fair to conclude that with or without regeneration each fluid can be used at almost the same pressure, regardless of the presence or absence of the regenerative component.

TABLE 4: Vaporizer pressure (P) in bars for a 135°C geothermal fluid outlet temperature

Organic fluid	P_{vap} (non-regeneration)	P_{vap} (regeneration)
n-pentane	17	17.24
Isopentane	20.4	20.7
Isobutane	N/A	N/A
R134a	N/A	--
R245fa	N/A	N/A

The next thing to consider for each fluid is the power output that can be obtained. In these calculations all five fluids were considered for the non-regenerative cycle; the cycle with regeneration R134a was not considered due to the problems mentioned above. Even though just two fluids are being considered for the proposed power plant, it is important to include the others for future reference. Also, conditions may be different for different wells and this research can be used as a first approach on how much power may be available for certain conditions. But also, it is important to gather as much information as possible on the conditions as deeper analysis is required for every component of the power plant.

After considering the geothermal fluid outlet temperature, the turbine inlet pressure in the cycle is known and thus the net power output can be calculated. The net power output as a function of the pressure on the vaporizer is shown in Figures 12 and 13. Table 5 compares the net power output for both fluids in regenerative and non-regenerative cycles, where the power output was calculated using Equation 2 and the properties embedded in EES. A noticeable increase in the power output for both fluids is observed in the regenerative cycle compared to the non-regenerative case.

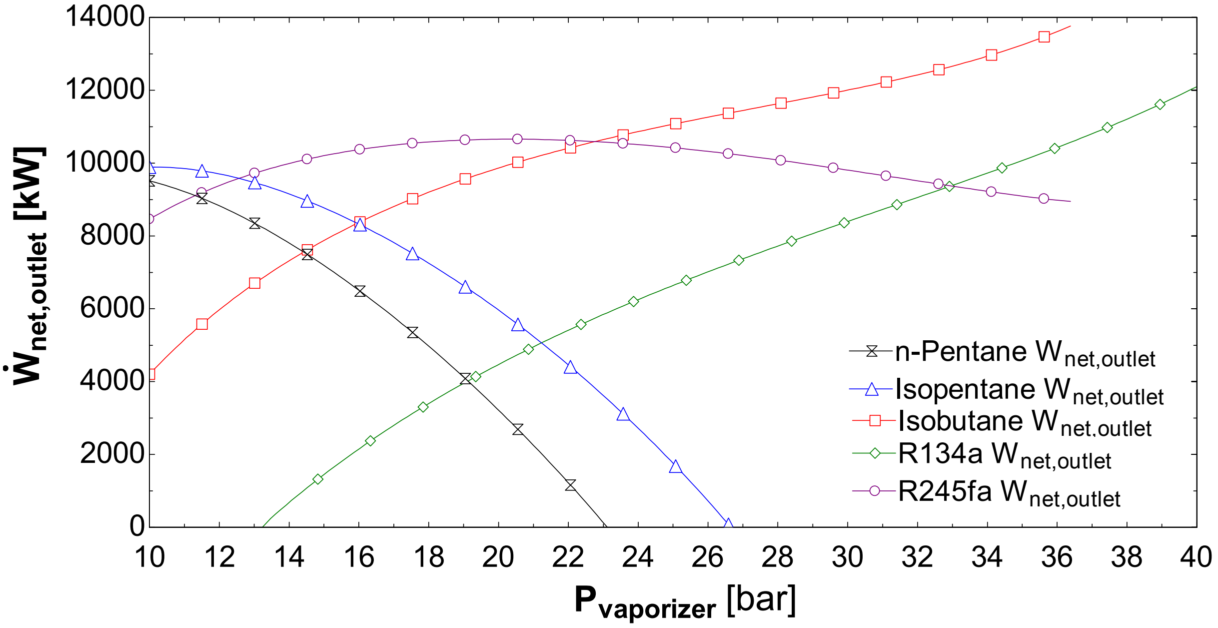

FIGURE 12: Net power output for the binary cycle without regeneration

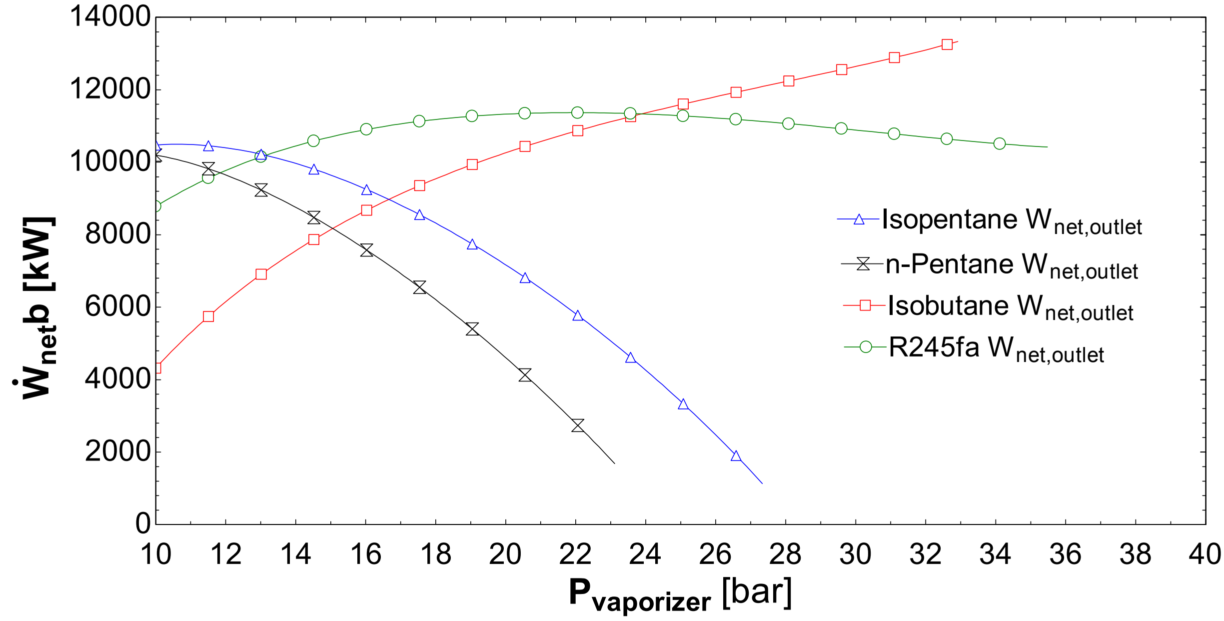

FIGURE 13: Net power output for the binary cycle with regeneration

TABLE 5: Net power output (kW) for isopentane and n-pentane at required vaporizing pressures (bar)

Organic fluid	P_{vap} **(bar) (non-regeneration)**	$\dot{W}_{net}$ **(kW) (non-regeneration)**	P_{vap}**(bar) (regeneration)**	$\dot{W}_{net}$ **(kW) (regeneration)**
n-pentane	17	5769	17.24	6761
Isopentane	20.4	5680	20.7	6721

Both isopentane and n-pentane got an increased power output. The comparison nonetheless was done for all the fluids. It is interesting to see that while isobutane and R134a both increase their outputs with higher vaporization pressure, the complete opposite happens to isopentane and n-pentane. R245fa has a very stable power output along the pressure range considered, where its maximum output occurs around 20-22 bar on the vaporizer.

$$\dot{W} = \dot{m} * (h_{inlet} - h_{outlet}) \tag{2}$$

where $\dot{W}$ = Electric power available [kW];
$\dot{m}$ = Working fluid mass flow [kg/s];
h_{inlet} = Enthalpy at turbine inlet [kJ/kg];
h_{outlet} = Enthalpy at turbine outlet [kJ/kg].

4.3 Power plant performance overview

Having defined the net power output for each fluid, the thermal efficiency of the cycle was calculated to determine which fluid offered a better heat utilization. For the calculations, Equation 3 was used, as it takes into account the amount of heat rejected in the condenser by the working fluid divided by the amount of heat gained in the preheater and the vaporizer in the heat exchange process with the geothermal fluid:

$$\eta_{cycle} = 1 - \frac{h_{turbine\,,outlet} - h_{condenser,outlet}}{h_{turbine,inlet} - h_{pump,oulet}} \tag{3}$$

where h = Enthalpy [kJ/kg].

The thermal efficiency of the cycle was calculated for both non-regenerative and regenerative cycles and also for all fluids considered in the cycle. As shown in Figures 14 and 15, both isopentane and n-pentane show higher efficiency than the other fluids, which is evident when the net power output is compared as well as the lower change in temperature of the geothermal fluid.

When comparing both fluids' efficiencies in the cycles calculated, the increased efficiency of the regenerative cycle is noticeable, as is the similarity in the behaviour of both fluids. The main difference between them is the working pressure range as n-pentane works at a lower vaporizer pressure than the isopentane.

In Table 6, the efficiencies are represented for the selected fluids; as stated before, the main difference between them is the pressure working range. Both fluids are suitable for the current boundary conditions. A deeper analysis of each component should be conducted to determine which is better from a purely thermodynamic point of view. Also, it is important to consider that both isopentane and n-pentane represent no threat environmentally and that, for human safety considerations, there is already experience in the Berlin geothermal field in handling highly flammable fluids.

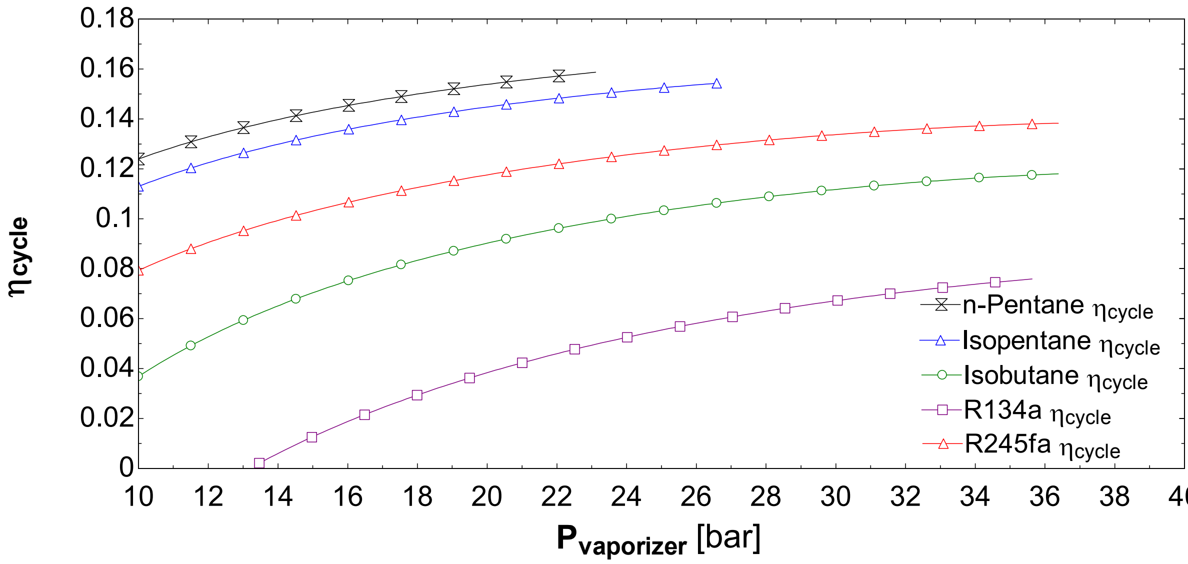

FIGURE 14: Cycle efficiency for a non-regenerative power plant

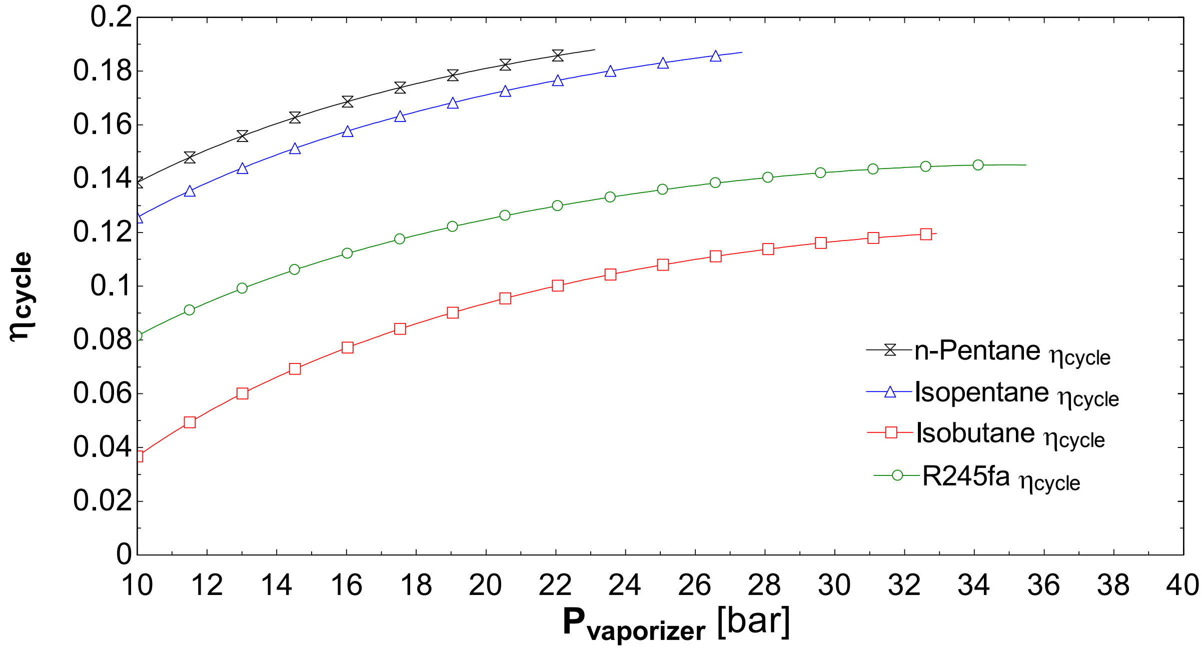

FIGURE 15: Cycle efficiency for a regenerative power plant

TABLE 6: Thermal efficiency (η) of the cycle for isopentane and n-pentane at required vaporizing pressures (P)

Organic fluid	**P_{vap} (bar) (non-regeneration)**	**η_{cycle} (non-regeneration)**	**P_{vap} (bar) (regeneration)**	**η_{cycle} (regeneration)**
n-pentane	17	14.77%	17.24	17.37%
Isopentane	20.4	14.55%	20.7	17.31%

An overview of a proposed ORC with regeneration is shown in Figure 16; this model was done using the EES program. It shows the major properties of the cycle, considering isopentane as the working fluid.

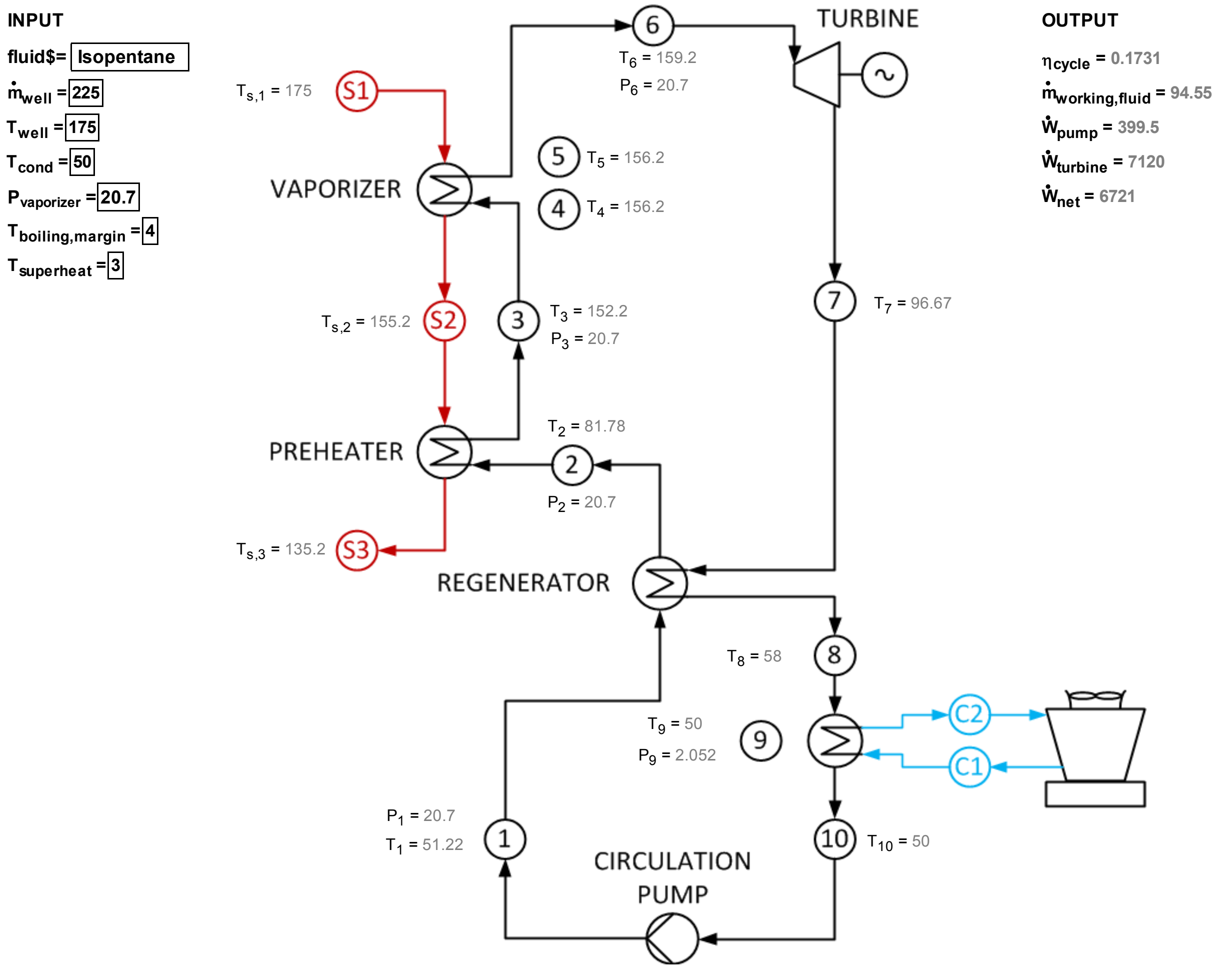

FIGURE 16: Overview of an ORC with regeneration using isopentane as the working fluid

5. KALINA CYCLE POWER PLANT

In the 1980s, the Russian engineer Alexander Kalina invented and patented the Kalina Cycle. A part of his invention was the development of a contiguous set of ammonia-water mixture with thermodynamic properties. The set of ammonia-water properties provided the ability to design a power plant from different heat sources, from industrial waste heat (as shown in Figure 17) to geothermal heat sources.

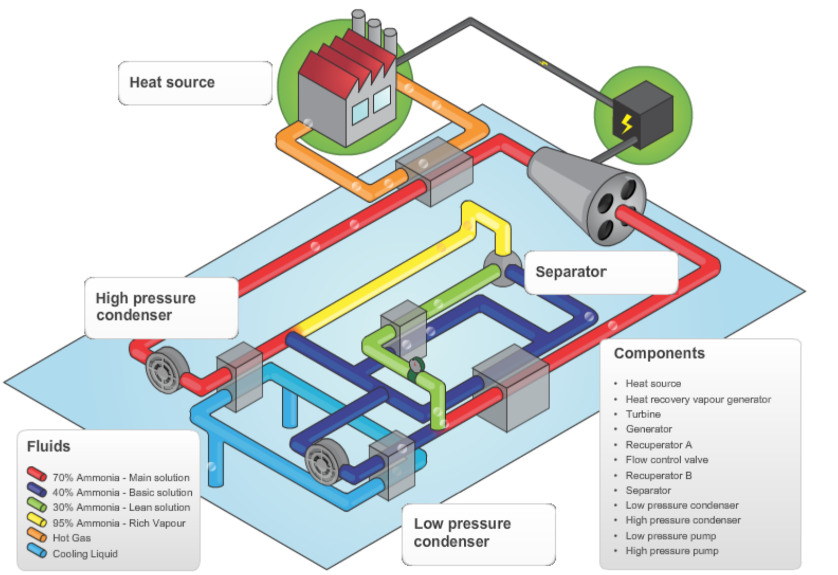

FIGURE 17: Overview of a Kalina power plant cycle, using industrial waste heat as a heat source (Recurrent Engineering, 2010)

The first Kalina cycle ever built was done with the sponsorship of the U.S. Department of Energy. For demonstration purposes, the power plant was constructed between 1991 and 1997 at Canoga Park, California, having a 6.5 MW installed capacity and running for a total of 8600 hours. This period included tests to demonstrate and verify efficiency gains in heat and combined cycle operation (DiPippo, 2005).

Part of the power plant's singular feature that distinguishes it from a Rankine cycle is the distillation condensation sub-system (DCSS). In the condensation process, the DCSS's main purpose is to alter the composition of the working fluid; this way the ammonia-water mixture gets leaner when it comes to the condenser and so the turbine back pressure is reduced, which directly leads to an increased electrical output and higher plant efficiency.

Since 1999 three new commercial Kalina cycle power plants have been commissioned: A 4.5 MW waste-to-energy demonstration facility in Japan, a 3.5 MW waste heat power plant at Sumitomo Steel, and a 2.0 MW geothermal power plant in Húsavík, in N-Iceland.

5.1 Kalina power plant components

A Kalina cycle power plant is essentially an advanced binary cycle. Water-ammonia mixtures have been widely used for absorption refrigeration cycles but not for power generation until Alexander Kalina proposed it. There are several differences between Kalina cycles and other binary cycles; the main ones are presented in Table 7.

TABLE 7: Comparison of Kalina and binary cycles

Binary cycles	Kalina cycles
• The working fluid is usually a single organic fluid or, in case of dual-fluids, each fluid operates on a different closed cycle. • Evaporation or condensation occurs at a single temperature for each process. • There is heat recuperation from turbine exhaust on certain conditions • Usually there is no handling of mixtures.	• The working fluid is a binary mixture of H_2O and NH_3 • Evaporation and condensation occur at variable temperatures • Cycle incorporates heat recuperation from turbine exhaust • Composition of the mixture may be varied during cycle in some versions

Kalina cycles show improved thermodynamic performances of heat exchangers; this is done by reducing irreversibilities associated with heat transfer across a finite temperature difference. The arrangement of heaters is done so that the process maintains a better match between the brine and the mixture at the cold end of the heat transfer process, this part being the most important in terms of exergy preservation in the cycle.

The water-ammonia mixture has a normal saturated vapour line instead of being retrograde as are some organic fluids. This normal line leads to wet mixtures in the turbine and so a reheater is needed. In Kalina cycles more heat is transferred than in a supercritical binary plant; this is why a Kalina power plant relies on good heat exchangers.

As mentioned before, the increased efficiency of the Kalina cycle is gained in the heat exchange process, specifically the heat acquisition in the evaporator and heat rejection in the condenser. Also, increased efficiency is achieved in the recuperators. The reason for these gains is the variable boiling and condensing characteristic of the ammonia-water mixture. The thermodynamic irreversibilities are reduced by the varying temperature during the heat transfer process (Zhang et al., 2012).

The more volatile ammonia vaporizes more easily than pure water, when the ammonia-water mixture is heated. As the concentration of ammonia decreases in the remaining liquid, the saturation temperature arises and provides a better match to a hot heat source. An advantage of using recuperative preheaters is that it may reduce the heat load on the condenser and the cooling tower but, by doing so, a cost comparison between the two choices arises, a smaller condenser and cooling tower compared to bigger recuperators.

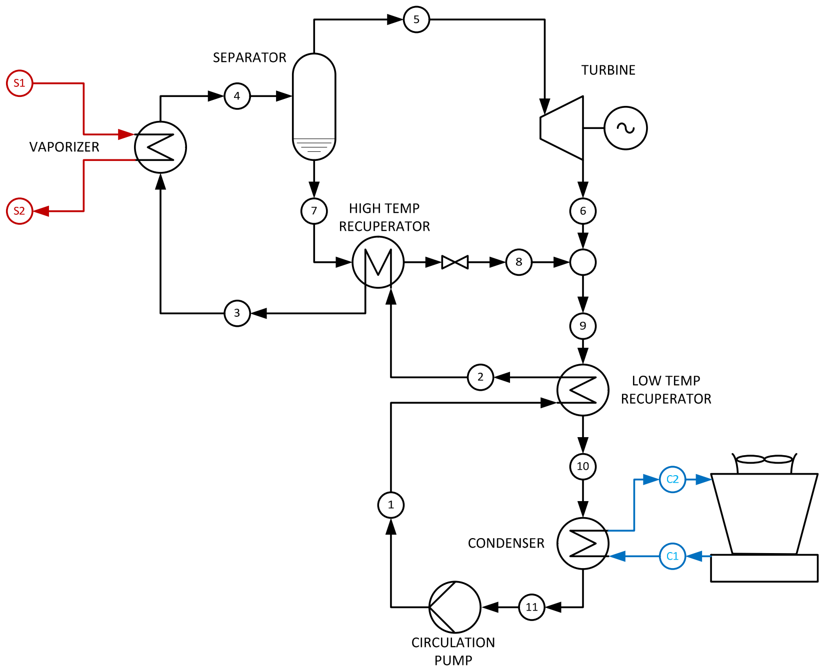

FIGURE 18: Schematic diagram of a Kalina cycle power plant

The separator in a Kalina plant supplies saturated vapour rich in ammonia to the turbine inlet, and this allows for a smaller and cheaper turbine than cycles using any hydrocarbon as a working fluid. The liquid phase in the separation process is used in the high-temperature preheater as shown in Figure 18, and then mixed at the turbine outlet before entering the low-temperature preheater with the initial composition. One of the difficulties in a Kalina power plant is that as a high efficiency cycle, it has to maintain a very close pinch point pass in the heat exchangers and, therefore, the heat exchange area is quite big in comparison to an ORC.

5.2 Kalina cycle power plant overview

Based on the same conditions as for the ORC, a Kalina cycle was calculated in EES, using a calculation program designed by Dr. Páll Valdimarsson. Having defined the mass flow and inlet temperature of the geothermal fluid in the program, the next thing was to define the strength of the ammonia-water mixture and the vaporization pressure of the cycle, as these two are the design parameters for a Kalina cycle (Valdimarsson and Elíasson, 2003). The main difficulty was that there was not a single state where we could achieve 135°C for the geothermal fluid outlet temperature, but many states capable of this temperature for a geofluid outlet, which created a very large amount of information that was very hard to analyse.

Several ways to manage this amount of information were considered. One of those was using MATLAB to produce 3D surfaces, as shown in Figure 19, to get an idea of the best working range for this cycle using Berlin geothermal field boundary conditions. In Figure 19 the net power output is shown in the graph; a similar one was used with the geothermal fluid outlet temperature as a function of the vaporizer pressure and ammonia-water mixture. Using this method, the best working conditions for the cycle were chosen to be between 35 and 60 bar of vaporization pressure in the cycle and with an ammonia-water mixture between 0.45 and 0.60.

After obtaining the working margin for the cycle, a simpler way to analyse it was considered: a net power output diagram versus the vaporization pressure was created for a certain ammonia-water mixture value. Four curves were created to show how the net power output varied with different vaporization pressure, the first curve having a 0.45 ammonia-water mixture with each subsequent curve considering

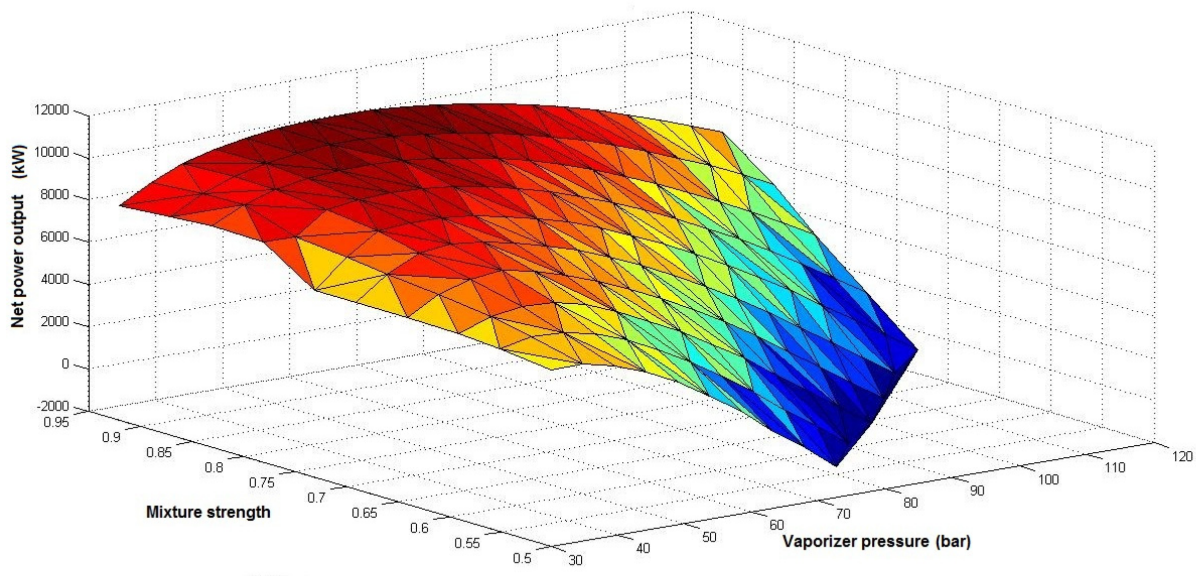

FIGURE 19: Example of 3D surfaces produced with EES and MATLAB for the Kalina model

0.05 more, up to a 0.60 mixture. This analysis showed that by increasing the strength of the mixture, an increased power output could be obtained for the same vaporization pressure. The figure also shows the calculated heat source outlet temperature as a function of the vaporization pressure. This analysis shows that for higher percentage ammonia-water mixtures, a lower source temperature outlet was obtained.

The two types of curves were plotted on the same scale in Figure 20 to better determine the power output for a given heat source outlet temperature. For example, selecting 135°C as the outlet temperature and the 0.50 mixture, the resulting operating pressure is 41.58 bar. Now the net power output is known because the operating vaporization pressure is also known; the resulting net power output is 5841 kW, which is considerably lower than the net power output of the ORC operating at half the pressure of the Kalina cycle.

The whole cycle overview appears in Figure 21 and shows that the vaporization pressure in point 1 is slightly lower than the pressure in point 10. This is due to pressure drops on both the low- and high-temperature recuperators. The final selected operating conditions are given in Table 8.

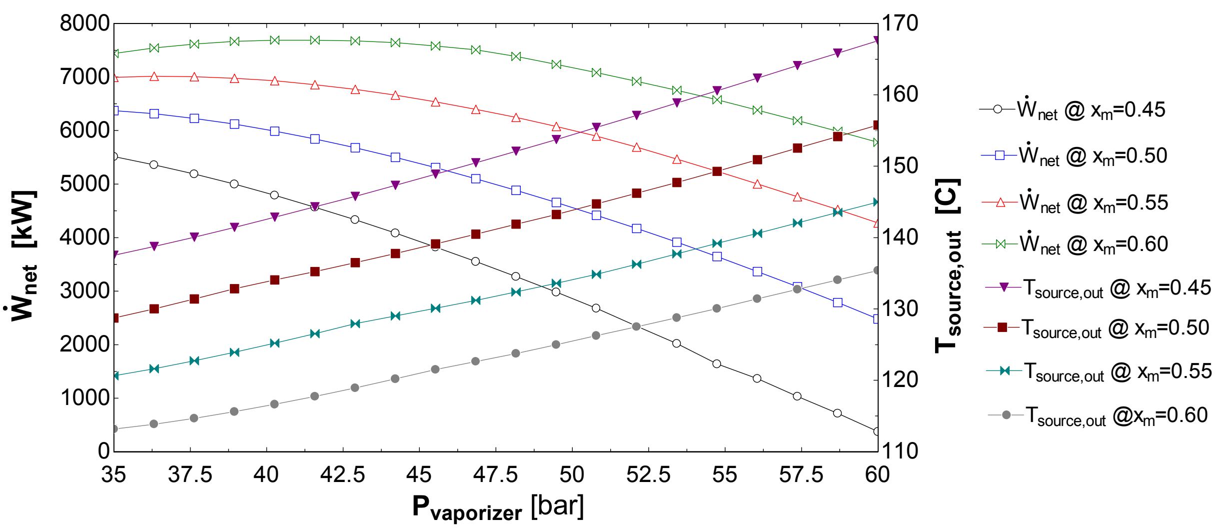

FIGURE 20: Net power output and source fluid temperature outlet plotted versus pressure

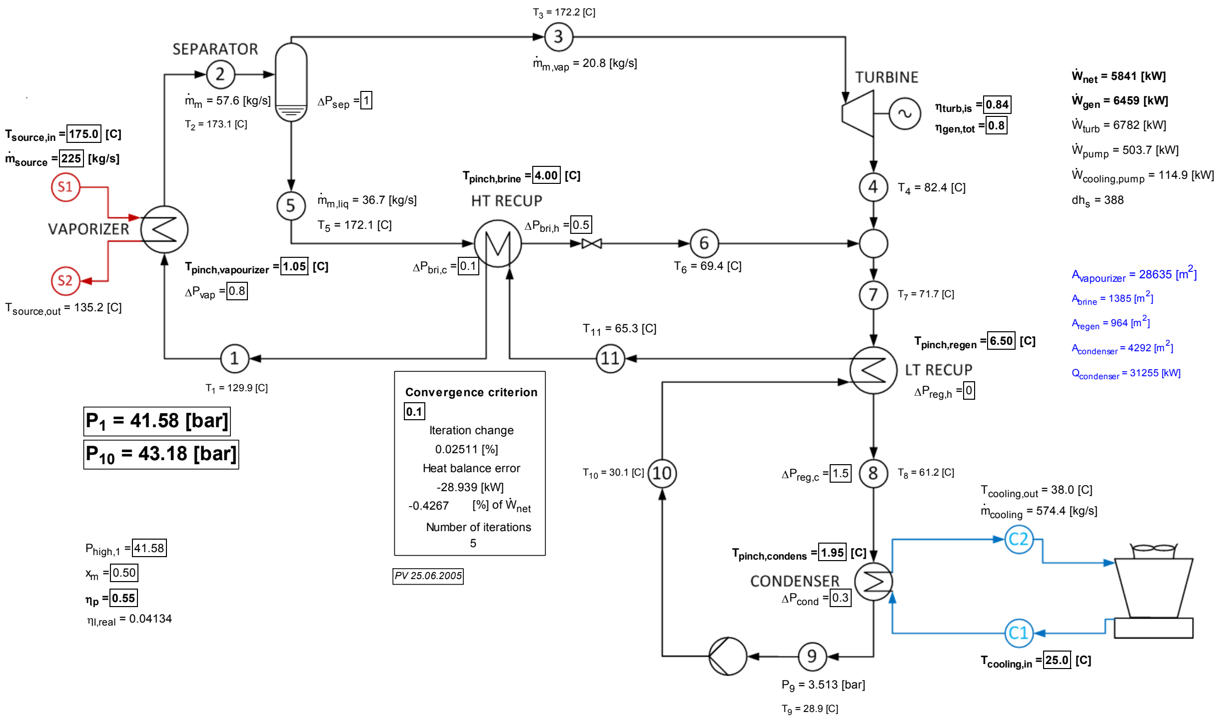

FIGURE 21: Overview of operating conditions for a Kalina cycle power plant

TABLE 8: Operating conditions for a Kalina cycle power plant

Mixture	P_{high} (bar)	$T_{source,outlet}$ (°C)	$\dot{W}_{net}$ (kW)	η_{cycle} (%)
0.50	41.58	135	*5841*	4.13

6. THERMOELECTRICITY

In the early 19th century, the field of what later was known as thermoelectricity began with the discovery of the thermoelectric effect by the Estonian scientist Thomas Seebeck. Seebeck's discovery was that when junctions of two different metals are held at different temperatures, a voltage is generated. When heat is applied to one of the metals, heated electrons flow toward the colder metal. If said metals where connected through an electrical circuit, a DC current flows through it. Voltages produced by the Seebeck effect are usually very small, only a few microvolts per Kelvin of temperature differences at the junction.

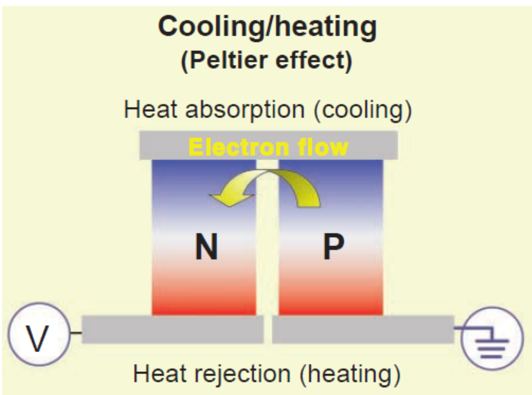

FIGURE 22: Example of the Peltier effect on semiconductors (Bell, 2008)

To have a better understanding of the thermoelectric phenomenon, another physical effect needs to be described that relates to the Seebeck effect. The Peltier effect is named after its discoverer, French physicist Jean-Charles Athanase Peltier. The Peltier effect explains that when a voltage is applied on a material, a temperature difference is produced by the flow of electrons through that material. The opposite effect can be noticed if the voltage is reversed, as Figure 22 shows. Here, the electric current travels by electrons in the n-type material (negative type semiconductors) and by holes in the p-type materials (positive type semiconductors) traveling in the opposite direction.

Having a voltage applied in the right direction across a p-type and n-type material junction, electron-hole pairs are created in the vicinity of the junction. In this case, electrons will flow away from the junction in the n-type and holes will flow away in the p-type. On the opposite end, electrons and holes stream toward junctions where pairs recombine.

In 1821 Seebeck discovered that the needle of a magnet would be deflected in the presence of different metals that are connected electrically in series and thermally in parallel and also when exposed to a temperature difference. The effect observed is the basis for thermoelectric power generation. If the opposite surfaces (thermally in parallel) are exposed to a temperature difference like the one shown in Figure 23 where the bottom one is being cooled and the top one is being heated, a voltage is created. The so-called Seebeck voltage derives from electron-hole flow, which was created by the temperature difference of the hot and cold ends in the thermoelectric materials.

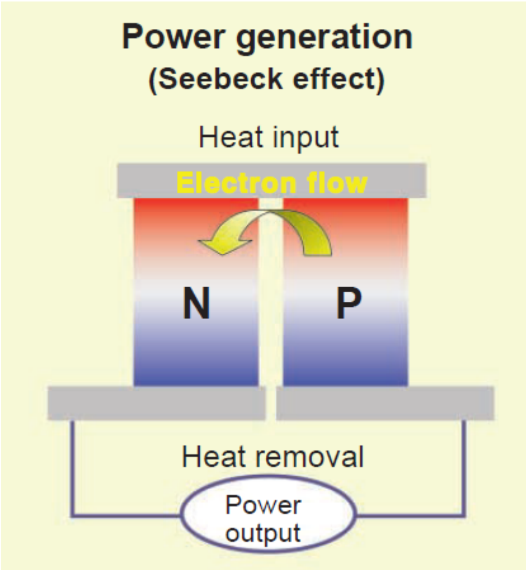

FIGURE 23: Example of Seebeck effect on semiconductors (Bell, 2008)

Thermocouples are extensively based on the Seebeck effect for their temperature measurement systems. If this effect is taken into account, electrical connections can be made from thermocouples to an external load to extract power. But for this process to be efficient, both materials need to have a very good electrical conductivity, otherwise the inherent resistance to the electron flow would dissipate heat along the element. Also, both materials must be poor thermal conductors; otherwise the temperature difference that has to be maintained between both cold and hot sides will produce heat backflow.

The so called electron-holes are charge carriers that in metals and semiconductors are free to move much like gas molecules, and carry charge as well as heat. The maximum efficiency for a thermoelectric material is determined by its figure of merit, which is given by Equation 4:

$$ZT = \frac{\sigma * S^2}{\kappa} * \frac{T_1 + T_2}{2} \tag{4}$$

where σ = Electrical conductivity [Siemens/m];
S = Seebeck coefficient [V/m];
κ = Thermal conductivity [W/m-K];
T_1 = Temperature of the hot end [K];
T_2 = Temperature of the cold end [K].

The best thermoelectric materials are doped (intentionally introduced impurities) semiconductors so that their properties resemble metals. Thermoelectric generators have been used on a small scale for the past 40 years, providing reliable power in remote terrestrial and extra-terrestrial locations, including deep space probes like the Voyager. One of the advantages of thermoelectric generators may be their scalability as waste heat sources can be as small as a home water heater or as large as geothermal sources, and their possibilities may be potentially greater considering enhanced geothermal systems.

6.1 Thermoelectrical power production

Use of thermocouples for electricity production is not a new field; they have been employed for many years individually for temperature and in the form of thermopiles for radiant energy measurements. Applications like these use thermocouples as voltage generators instead of power generators.

In vehicles, the heat losses through the exhaust system and radiator are over 50% of the total fuel energy. Early in the 20th century the possibility of recovering those heat losses was considered using a thermoelectric module, but due to the difference in temperature along the sections between the engine and the exhaust, a single module was not considered; a larger array of different modules was designed for specific temperature differences, applying segmented materials. These devices coupled with the electrical system of the vehicle could enhance the overall efficiency while also working as a solution for the car cooling system without using environmentally harmful materials (Zheng et al., 2012).

Many technological developments like advances in medical physics, remote monitoring systems, communication devices on harsh or isolated environments and many more, require a reliable and autonomous power source. Photovoltaic generators are very efficient but their downside is their dependence on weather and atmospheric conditions; that is where thermoelectric generators come into the picture. If a more reliable or constant heat source is available, these types of devices could be an integral part of the power supply system for their modularity, as shown in Figure 24.

In the future, as development of these power production devices increases due to lower costs or less sophisticated manufacturing technologies, thermoelectricity along with photovoltaic power production will be a choice for reliable green energy. A varied number of factors will have to be considered for the selection of any power production technology, such as cost, reliability, conversion efficiency, type and temperature of heat source, type and temperature of heat sink, weight of the components and many more variables. Some of these factors can be compared with other types of electrical power generators, as shown in Table 9.

TABLE 9: Performance of various types of electrical power generators (Wood, 1988)

Type of plant	**Efficiency (%)**	**Output (W/lb)**	**Maintenance interval (h)**
Central station steam plant	20-40	50	5000
Airplane piston engine	30	1000	50
Automobile engine	15	1000	300
Boeing 707 jet engine	20	2000	50
Fuel cell	60	7	~5000
Thermoelectric generator	5	0.8	70000

Thermoelectric generators have a unique set of characteristics: no moving parts, silent operation, operation is unaccompanied by the gyroscopic effects associated with rotating machinery, absence of chemical changes in the materials and potential long life due to the electronic nature in thermoelectric effects and, as described before, flexible design and modularity. This unique set of characteristics makes a thermoelectric generator an ideal efficiency enhancer of an existing power plant.

6.2 Thermoelectricity and geothermal power production

Being a relatively new and expensive field, thermoelectric power production is limited to very few applications. Among those, two stand out as being very promising, one by Japanese technology giant Panasonic, which could economically mass produce a scale of these kinds of devices; the second one was proposed as a joint project between the University of Iceland, an Icelandic company called Varmaraf and a Gibraltar based company called Power Chips PLC.

The Panasonic approach has been called thermoelectric tubes, designed for a hot source fluid of steam or hot water. For efficiency purposes the company chose a tubular design without needing additional heat exchangers and delivering a high density of generated power. Design considerations were to simplify the usual method of trying to harness thermoelectric power production of planar heat exchangers, as they are difficult to scale up.

Panasonic's design is based on an unconventional phenomenon called transverse thermoelectric effect, which takes place in tilted multilayers made up of thermally-resistive thermoelectric materials and thermally-conductive metals. Using this effect in the design makes it possible to control electric current and also heat flow independent of each other in both p and n type materials, ending with simpler structures than electric junctions and planar surfaces.

For these devices Panasonic developed a simulation technology to optimize the tube's design, because performance of the power generator is strongly dependent on many parameters such as its size and the considered heat source. The simulation program calculated the optimum design to maximize the electric power output while considering the surrounding conditions.

As shown in Figure 25 the thermoelectric tube is constructed by stacking conical rings of bismuth telluride as the thermoelectric material and nickel as the metal. Panasonic put great effort into trying to develop conical rings of brittle thermoelectric materials and bonding rings with minimum parasitic electrical and thermal losses.

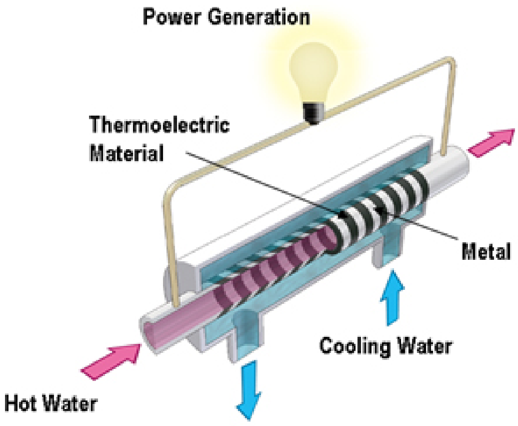

FIGURE 25: Schematic view of Panasonic's thermoelectric tubes (Panasonic, 2011)

A 10 cm thermoelectric tube prototype generated 1.3 W of electricity running hot water of 90°C inside and 10°C on the outside of the tube; the calculated power density corresponds to as high as 10 kW using 1 m^3 of volume. Now Panasonic is looking to develop a system design, manufacturing optimization and feasibility studies to create compact, efficient and economical generators using geothermal resources or waste heat recovery systems. Panasonic holds 29 domestic patents and 12 overseas patents for this type of device, which makes it difficult to get more information than the one that is publicly available (Panasonic, 2011).

The second project involving thermoelectric generation and geothermal resources comes from a joint project, using a new technology called power chips which, unlike thermoelectric devices, exploit a quantum electron tunnelling effect as their primary operating mechanism. The process itself differs from traditional thermoelectric processes in that the electrons involved in the process migrate across a nanometre gap, thus creating useful electric current in the process; the inherent high efficiency of this effect and the actual gap between the electrodes prevent losses from heat conduction. The research indicated that power chips have the potential to deliver power generation at 60-70% Carnot efficiencies across a wide range of operating temperatures (Kilgrow et al., 2003).

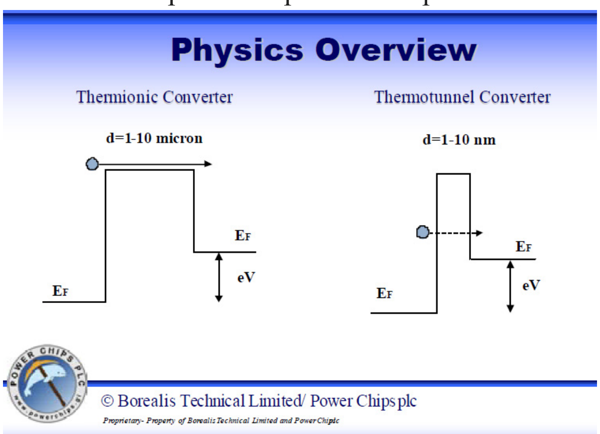

FIGURE 26: Electron flow through a thermionic converter and through a "tunnel" converter (Kilgrow et al., 2003)

Continuous research shows that it is still very difficult to find a material that has very good electrical conduction while being a poor thermal conductor. As a result of this phenomenon, thermal backflow affects the temperature differential across the device and then efficiency is quite degraded. Another approach considered is that of thermionic converters which incorporate gaps between the electrode pairs; these gaps of 1-10 microns impose a high energetic requirement for the electrons to be able to travel through it, high enough for the electron energy to exceed the work function of the material and then escape.

In Power Chips, the gap scale is much smaller, on the order of 1-10 nanometres. Opposed to the thermionic converters, electrons here "tunnel" through the barrier, hopping very short distances from one electron to another, as shown in Figure 26. The greatest challenge to build these types of devices at such infinitesimal precision is to create surfaces that are broadly conformal. And because of the limits of manufacturing and polishing technologies, it is still not possible to create the opposite surfaces by conventional means, which means that even the slightest curvatures in the electrodes would prevent the two surfaces from maintaining such a small gap over their entire surface area.

As with conventional thermoelectric devices, Power chips do not require magnetic induction to generate electricity. Geothermal power plants using this technology would be very different from existing power plants, requiring only heat and no moving parts to work. Future geothermal power plants could use modified steam or binary cycles running at Carnot efficiencies close to 60-70%, which environmentally could lead us to even less dependency on fossil fuels, pairing all green energy sources. With Power Chip performance, even those low-temperature resources at 90°C could be used, increasing even these possibilities with enhanced geothermal systems.

7. COMPARISON BETWEEN TECHNOLOGIES

Having discussed three low-temperature power plant technologies, it is important to summarize and select which of the proposed technologies is best for harnessing the available geothermal resource in the Berlin geothermal field.

Even though the thermodynamic and technological approach for power plant design are very important matters to take into consideration, one important factor that needs to be taken care of is the economic approach. Although no actual figures were given regarding costs, binary cycles remain the cheapest between the three discussed technologies. Kalina cycles are still very expensive, given that they are still a proprietary technology and have more components than a standard ORC. Thermoelectricity is still in its early development and consequently is very expensive.

From the three technologies, thermoelectric generation is not a possibility right now due to manufacturing and the cost limitations of its own development. Thus, the only real possibilities as of now are an organic Rankine cycle and a Kalina cycle. The selection of one technology over the other is purely technical, because the two of them are equally clean, and both require careful operation given the hazardous nature of the working fluids in both the ORC and Kalina cycle, if a hydrocarbon is chosen in the ORC.

Considering cycle complexity, the Kalina cycle is a very much more complicated cycle than a binary cycle; due to the amount of components involved in a Kalina cycle, a very strict installation and commissioning process must be implemented, and its operation involves a very large amount of monitoring and control systems to prevent cycle stops or failures in comparison to even an advanced ORC with a hydrocarbon or refrigerant.

For practical purposes, the calculated power output is shown in Table 10. The cycles' vaporization pressure, net power output and efficiency under the operating conditions for the Kalina, simple ORC and regenerated ORC, considering both isopentane and n-pentane in the ORC cases, are all in the table.

Comparing the performances for the five cycles, even though the Kalina cycle is below its efficiency range, it is clear that overall it is a very efficient cycle and if there was no lower source fluid temperature limit, this cycle could outperform the others. But in this case the Kalina cycle should not be considered for practical purposes, given its complexity and its lower performance for these conditions. Regarding the binary cycles, the efficiency increase on the regenerated cycle compared to the simple cycle is clear.

TABLE 10: Performance overview of calculated power plants for a temperature of geothermal fluid outlet of 135°C

Type of plant / working fluid	P_{high}* (bar)	$\dot{W}_{net}$ (kW)	Efficiency (%)
Kalina cycle	41.58	5841	4.13
Non-regenerated isopentane	20.4	5680	14.55
Non-regenerated n-pentane	17	5769	14.77
Regenerated isopentane	20.7	6721	17.31
Regenerated n-pentane	17.24	6761	17.37

*P_{high} = pressure at pump outlet

After comparing the five cycles, the two best cycles to choose may be the regenerated isopentane cycle and the regenerated n-pentane cycle. They are almost identical and, given the fact that the Berlin geothermal field already has a binary cycle using isopentane as working fluid, the best choice is to consider the installation of a second binary cycle with isopentane as a working fluid.

8. CONCLUSIONS

After comparing these technologies it is important to remark that organic Rankine cycles are a very good solution for harnessing low-temperature heat sources that also work with restricted operating limits. Also, these technologies have been in development for some time and at their current development they are very reliable in operation and safety issues.

Kalina cycles proved to be more efficient cycles than regular ORCs due to their varying boiling temperature, thus reducing the inherent thermodynamic irreversibilities in the cycle. The fact that this is a relatively new technology is one reason why it is still very expensive; also, many of the processes involved in the cycle are not publicly available, which is why its development is quite slow still. But Kalina cycles may be the next logical step toward more efficient thermodynamic cycles.

Thermoelectricity, which has been developed even less than the Kalina cycles in the geothermal power supply field, has a very promising future. With nanotechnology developing very quickly in the past few years, new methods of manufacturing could take nanotechnology prices to a lower scale and so development of these devices may in time be affordable, with an increased efficiency over conventional heat transfer machines. Thermoelectricity could really be the future of power production combined with the development of enhanced geothermal systems, for a long sustainable power production.

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