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Preliminary Cost Calculation of Geothermal ORC Power Plant in KarKar

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REPORT TITLE:

Preliminary Cost Calculation of Geothermal ORC Power Plant in KarKar

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ABSTRACT:

The KarKar geothermal are is under development in Armenia. Verkis has made a preliminary cost schedule with estimated design parameters for the geothermal project, including well field development and power plant. The estimated geothermal fluid temperature is between 120-160°C and each well is estimated to yield 30-70 l/s. In the report is a summary on the main parts of the Organic Rankine Cycle used to produce electricity from low temperature resources and well field development. The geothermal fluid temperature and flow rate from the wells are the most important parameters in the cost calculation. Also the pumping from wells influence the cost of electricity because it will take up electricity which could be sold,

The total investment cost for 10 MW power plant is calculated 41 – 130 MUSD and the production cost of electricity delivered to the grid varies from 10 to 45 UScent/kWh depending on flowrate from each well and resource temperature.

KEYWORDS (ENGLISH): Geothermal, low-temperature, Armenia, binary power plant, estimated design parameters, electricity generation, costs.	KEYWORDS (ICELANDIC): Jarðhiti, lághitasvæði, Armenía, tvívökvavirkjanir, áætlaðar reikniforsendur, raforkuframleiðsla, kostnaður

PROJECT MANAGER´S SIGNATURE:	REVIEWED BY: David Orn Benediktsson

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1 Introduction

This report is prepared in April – May 2017 by Verkis according to a contract entered into on April 10, 2017 with Armenia Renewable Resource and Energy Efficiency Fund. The contract is under the project " Geothermal Exploratory Drilling Project, Grant No. P152039"

The aim of this study is to conduct a preliminary cost calculation for a $10MW_{gross}$ binary power plant at the KarKar geothermal field in Armenia. The cost estimate will include

- Capital cost for the power plant and geothermal field.
- Operation and maintenance cost
- Financial cost
- Production cost

This report is based in informational data supplied by Armenia Renewable Resources and Energy Efficiency Fund. All design parameters have been estimated and can been found in Appendix 1. In geothermal projects like this there are many parameters that influence the cost and economy of the project. The most important parameters are the temperature of the reservoir and flow from each well They are taken into calculation in the report. Other parameters like size of power plant unit, location of the wells, well depth, water level height, chemical composition of the geothermal fluid, number of reinjection wells versus production wells etc. will influence the cost. The calculations in this report are base cases and need to be reviewed when actual characteristics of the geothermal field have been clarified by further exploration and drilling.

The KarKar geothermal area is situated in southern Armenia, at 3,000 meters elevation close to the border with Nagorno-Karabakh. The site is in the development phase with the objective to intercept the faults located at 1,200-1,500 depth and to identify up-flow zones of the geothermal resource. Two exploration wells have been drilled, the results from well measurements can be seen in Table 1. Well locations and contour lines at site can be seen on Figure 1.

Table 1 Exploration wells, preliminary coordinates and properties

Well	Latitude	Longitude	Elevation	Depth	Water level depth	Temperature
B1	39°46’54”N	45°57’37”E	3,000 m	1,500 m	400 m	115 °C
B2	39°47’03”N	45°56’50”E	3,000 m	1,680 m	400 m	125 °C

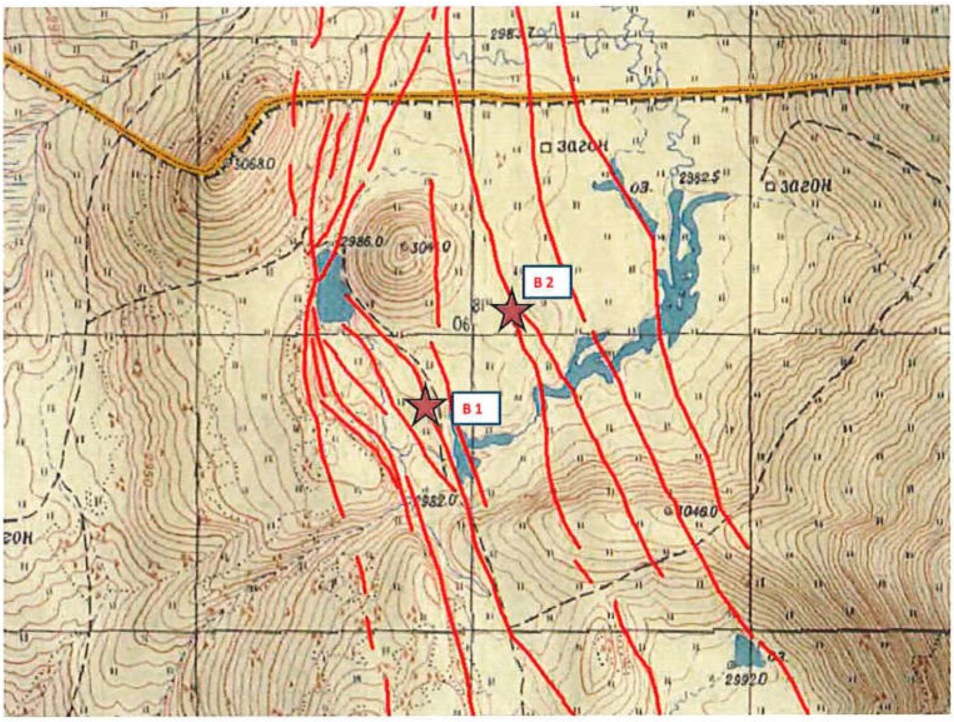

Figure 1 Map showing the existing well locations

2 Geothermal Field

As in all geothermal projects, the characteristics of the geothermal reservoir is the fundamental issue for further development. Detailed investigations of the geothermal field before decision making is therefore of utmost importance.

An investigation starts with surface exploration followed by test drilling. Two test wells have been drilled so far and are used as basis in the calculations, see section 0.

Typical information gathered by field investigations includes (list non exhaustive):

- Extent of the geothermal field.
- Capacity of the geothermal resource.
- Temperature of the resource.
- Estimated flow rate from each well v.s drawdown in the well or well head pressure.
- Estimated distance between wells.
- Chemical composition of the geothermal fluid.
- Influence of reinjection on flow rates from well and field capacity.

Geothermal fields are generally categorized in three categories by the highest temperature measured above 1000m depth. Low temperature (<100°C), medium temperature resources (100-200°C) and high temperature resources (>200°C). The KarKar geothermal area is a low/medium enthalpy resource.

2.1 Production Wells

Drilling is one of the substantial operations from financial point of view. It is risky due to the uncertainty in acquiring hot fluid and sustain production for years to come.

Low/medium temperature drilling as in this case is less complicated than high temperature due to a lower pressure in the reservoir and less risk of steam blowouts during drilling.

The depth of wells varies from 500 to 3,000 m and even up to 5,000 m in extreme cases. Most of the wells are 1,000 to 2,000 m in depth as will be the case in this study. The wells are lined with casings which have the purpose of sealing off unwanted aquifers and support the well walls. The material cost, building and set up of the casing is high. An increased casing depth can increase the price dramatically.

Low/medium temperature wells are nowadays cased down to an approximately 300-800 meter depth. If the water level in the well is lowered, the well needs to be cased further down. There are three main types of casing in low temperature wells

- Surface casing 4-20 m
- Anchor casing 60-100 m
- Production casing 100-800 m

Figure 2 shows a typical casing program for a low/medium temperature well, showing the casing structure and levels of depth.

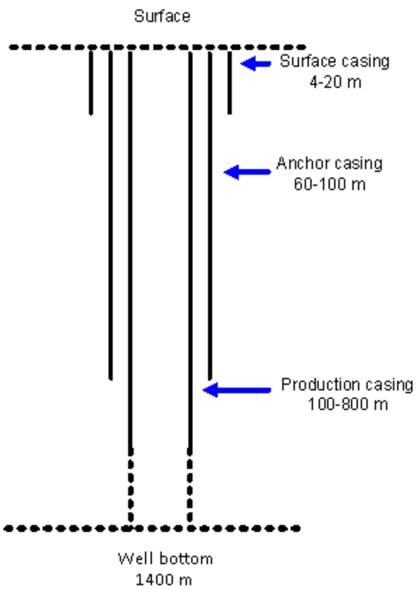

Figure 2 Casing program for a low temperature well

On the top of the well are a flange and a valve. The water can either flow freely from the well or require pumping. Well pumps are classified in two categories:

- Submersible pumps
- Line shaft turbine pump

Both submersible and line shaft pumps are centrifugal pumps. The main difference is the location of the motor. In submersible pumps, the pump and the motor are submerged in the well. This makes it possible to pump water from deeper levels, and from inclined wells.

The motor used in a line shaft pump is placed on a flange on the wellhead. The motor is used to drive a pump on a composite shaft which can reach a few hundred meters down the well. Working temperature of the pumps depends on material especially in the bearings and lubrication. The line shaft pumps can be designed s for temperatures up to 250°C and submersible pumps up to 150°C. Figure 3 presents the main components of a line shaft pump where the line shaft bearings are lubricated with geothermal water.

The clearance between pump house and impellers limits the depth for installation of line shaft pumps. Until recently the maximum depth was 250 – 300 m. In recent years there has been developed pumps with up to 60 mm clearance which allows installation at up to 600 m depth.

At this stage, the type of pump is not fixed and the price is assumed to be the same. The selection will be based on economical evaluation (price and efficiency) of available pumps.

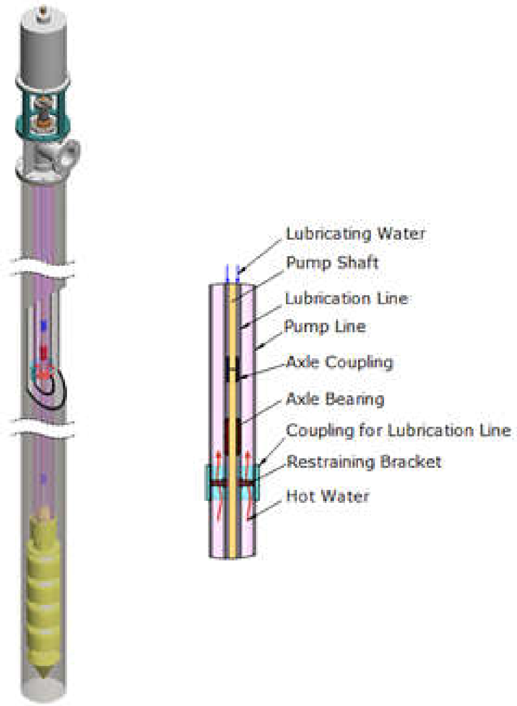

Figure 3 Line shaft deep well pump

The pump height and the flow of water decide the amount of power needed to drive the pump. The power for the pump is taken from the production and thus decreases the amount of salable power.

2.2 Reinjection Wells

Reinjection of geothermal fluid into a reservoir after its utilization has become a subject of debate. The idea of reinjection is to sustain pressure in the reservoir and to prolong its lifetime. The choice of location for reinjection wells is a delicate matter due to the cooling effects that reinjection may have on the reservoir or its effects if encountering groundwater. Additionally, the number of reinjection wells and reinjection pressure depend highly on reservoir conditions. In this case, it is assumed one reinjection well for one production well and that no pumping is required for reinjection.

2.3 Chemical Composition

The concentrations of minerals will affect the design of the heat extraction process. Upon cooling and/or degassing of the geothermal fluid, minerals can precipitate and cause scaling in the equipment. The scaling can clog equipment and injection wells, making them inoperable. Also, high salinity solutions may be corrosive especially at low pH and when put in contact with atmospheric oxygen. There was no information on the chemical composition other than use of inhibitors is expected. Inhibitors can be used to delay scaling and prevent it will occur in the equipment or wells.

2.4 Well Field Piping

The most economical way of well field planning and plant location is to locate the plant in the middle of the field. Such configuration minimizes distances between gathering and reinjection pipelines. It results in a lower capital cost and a minimized pressure drop in the pipeline.

In this report the average distance between the wells is assumed to be 250 m. Locations of the wells and the topography of the field are among the main parameters impacting the well field piping systems. If the wells are drilled in line, it is possible to have one collective pipe with branches connecting each well to the main pipe. If however they are distributed around the power plant, the pattern will be more complicated.

The gathering and reinjection pipes can be both above ground and underground. Pre-insulated steel pipes are available for underground piping with temperatures up to 150°C. The most common surface pipes are steel pipes isolated with rock wool and aluminium cladding.

3 Technical Details

3.1 Electrical Power Plant

The binary technology allows for production of electricity from low/medium temperature resources that otherwise could not be utilized for such a purpose. In a conventional steam power plant, the turbine is driven directly by the steam for power production whereas in a binary plant, the geothermal fluid is used indirectly. A secondary working fluid is vaporized in a closed-loop to drive the turbine for power generation. Various working fluids are available and are presented further in the section on cycles.

Typical heat sources suitable for electricity production with binary plants are:

- Geothermal two phase source.
- Geothermal water between 90 and 200°C, and even with temperatures as low as 75°C depending on the cooling potential of the cold end.
- Waste heat from industrial processes and geothermal single flash cycles (bottoming plants).

The binary technology is usually split into two categories:

- Organic Rankine cycle (ORC)
- Kalina cycle

The Organic Rankine Cycle and its derivatives have been popular for the application and the largest equipment manufactures offer this solution. In this report, the focus will be on the Organic Rankine Cycle (ORC).

The Kalina cycle which utilizes ammonia and water as working fluids where the concentration of ammonia is changing during the process. It is based on a closed cycle in which a mixture of water and ammonia (NH_3-H_2O) serves as the heat transfer medium (refrigerant). The Kalina process is most suitable at 100-140°C. Only few Kalina plants have been built worldwide despite an advantageous thermodynamic efficiency. Plant and equipment manufacturers have few references and some of the plants put into operation using the Kalina cycle have encountered severe start-up and/or operational problems. Due to such limited experience of the process and the equipment, the Kalina process will not be discussed further in this report.

3.2 The Organic Rankine Cycle

The Organic Rankine Cycle (ORC) technology is common practice used for electricity production from low enthalpy reservoirs or for bottoming plants in steam power plants.

Figure 4 features a basic binary cycle. The diagram describes a single stage ORC cycle with an air cooled condenser.

In an ORC plant where geothermal fluid is the heat source, the fluid is passed through a closed heat exchanger. The geothermal fluid is used to heat the working fluid on the other side, which vaporizes during the process. The vapour created is admitted to and expanded in a turbine, similar to the geothermal steam in a steam plant turbine, producing shaft power to a generator. After this step, the working fluid is exhausted to a condenser where the working fluid/vapour is condensed and then pumped back to the heat exchangers for the cycle to be repeated. The condenser is a closed heat exchanger in which the cooling medium is usually cold water or air.

The thermal efficiency of binary cycles is typically between 7-15%, that is 7-15% of the heat supplied to the system by the geothermal fluid is converted to electrical energy compared to 10-23% in single flash plants. The thermal efficiency of a single stage ORC cycle can be improved by adding another cycle with lower pressure. This type of cycle is called a two-stage cycle or a cascade cycle.

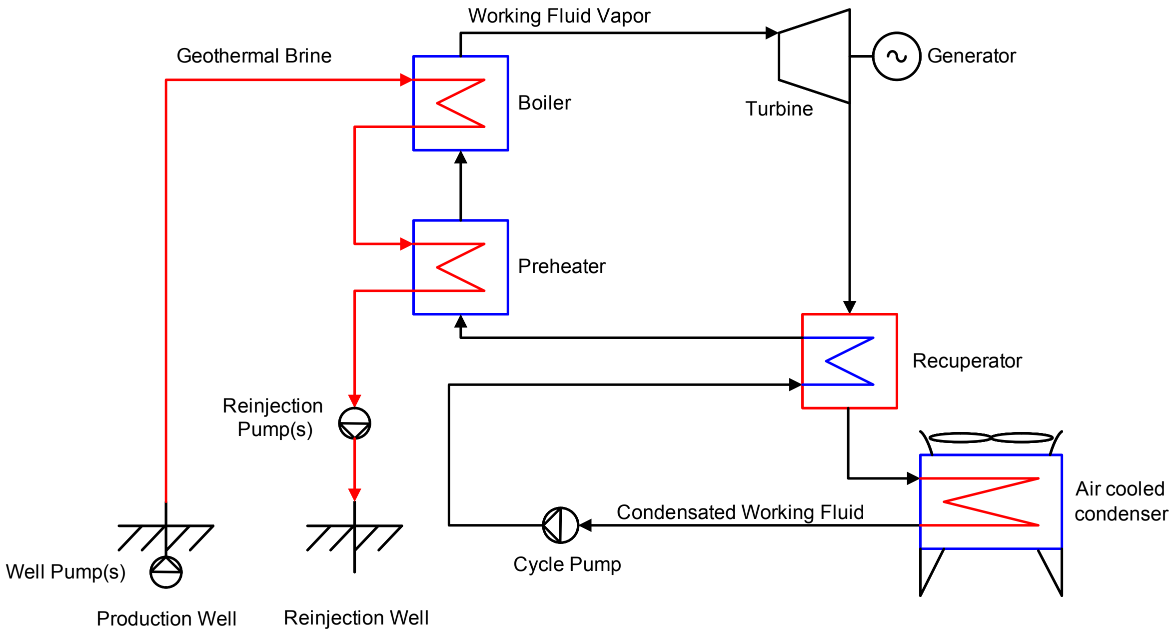

Figure 4 Binary Power Plant utilizing the Organic Rankine Cycle

3.2.1 Preheater and Vaporizer

Both the preheater and vaporizers are closed heat exchangers, meaning there is no contact between the geothermal fluid and the working fluid. They can either be shell & tube or plate heat exchangers. The shell and tube heat exchangers are preferred for the binary application because they are easier to operate. The pressure at the shell and tube heat exchangers is easier to control, an important property to control to avoid escape of gases from the geothermal fluid and precipitation. They are furthermore easier to clean. Shell and tube heat exchangers are however more expensive and take up more space than the plate type.

3.2.2 Heat Exchanger Pinch

Pinch temperature in the heat exchanger is the minimum temperature difference which can be attained between the two sides on a certain heat exchanger area, i.e. the minimum temperature difference between the working fluid and the geothermal brine.

Low pinch values will contribute to higher plant efficiency but at the same time as it will contribute to higher capital costs. The lower the pinch value, the higher the price of the heat exchangers. A low pinch value implies a larger heat exchanger area and eventually the selection of more expensive material.

For the case study featured here, a heat exchanger pinch of 3-7.5°C has been assumed.

In practice, the choice of pinch temperature is an optimization exercise, between cost and efficiency and the final choice is in the hands of plant vendor.

3.2.3 Turbine

Although buying and installing individual equipment is an option, most binary plants are nowadays supplied as turn-key plants, i.e one company supplies the equipment: heat exchangers, turbine(s), generator, cooling system, control and instrumentation.

The choice of material depends on the working fluid used in the loop. The case study features a 10,000 kW plant. Standard turbines are available on the market for this range and it is common to have a single or a double flow turbine, the single/double flow corresponding to the number of inlets.

3.2.4 Working Fluid

The working fluids used in ORC cycles are organic compounds with a low boiling point. The fluids in use are commonly isomers of the hydrocarbons pentane and butane, others include ammonia, carbon dioxide and R134a and R245fa

The choice of working fluid is usually up to the equipment manufacturer. The main problem with using pentane and butane is that they are extremely flammable. R245fa is relatively new at the market and is non-toxic and non-flammable. Others are commonly known in the refrigerant industry as their main use is in refrigeration equipment.

3.2.5 Cooling

Access to a cold sink is as important as access to a heat source for a binary power plant. The temperature of the cold source influences the power output of the plant significantly: the greater the temperature difference between the two media, the more the energy can be extracted from the system.

All condensers in binary plants are closed, with no contact between the working fluid and the cooling agent. There are three main types of cooling: direct water cooling, evaporative cooling towers and air cooled condensers. They all involve a closed heat exchanger due to the closed working fluid loop.

3.2.5.1 Air Cooled Condenser

Air cooled condensers are used in places where no water is available or in places where water cannot be used due to environmental restrictions. The efficiency of air cooled condensers is highly dependent on the ambient conditions. Such cooling systems present good efficiency in places where the weather is cold. They are suitable where ambient air (dry bulb) temperatures are low and are most effective during winter when temperatures are below 0°C.

The largest drawback of air cooled condensers is their dependency on air temperature and humidity level. Variation in the outdoor condition over the year may cause the output of the plant to drop for instance during hot summer days due to insufficient cooling capacity of the cold sink. Losses in cooling capacity of the condenser decrease the production capacity of the power plant. In locations where continental climate is dominant the output drop can be up to 50% during the day due to insufficient cooling. Air cooled condensers furthermore occupy a large area. They also require high fan power to run the system, and this might affect the performance of the plant. The size of the heat exchanger area is a matter of optimization after the final design requirements have been set.

It is possible to increase the cooling capacity by adding water spraying equipment. The water spray system is added to increase the humidity of the incoming air, therefore lowering its dry bulb temperature. This method can be useful when air temperatures are high and relative humidity is low. It is however only feasible if access to water is already in place.

3.2.5.2 Wet Cooling

Water cooled condensers provide better cooling than air-cooled condensers during warm summer days. There are two types of wet cooling:

- Direct cooling
- Cooling tower

Direct cooling is in general the most efficient type of cooling for a binary plant. It requires access to a large amount of cooling water at a low temperature, usually from a river or a lake. The water is pumped through the condenser and then back to the cold sink. To minimize the energy required to pump the cold water, a binary plant using direct cooling should ideally be located as close as possible to the cold sink. This is however seldom the case and direct cooling is not common.

The efficiency of cooling towers is in between air cooling and direct wet cooling. The cooling water is circulated between the cooling tower and the condenser. Such systems are highly efficient. Access to makeup water is however required. Various types of cooling towers are available although they are all based on the same principle, i.e. to cool the water with an air stream passed through the tower by fans or natural draft. The cooling towers require steady supply of make-up water which is used to compensate for water which is evaporated or blown down in the cooling tower.

There are a few things to consider when considering the use of a cooling tower. The water in the cooling tower may have to be chemically treated to prevent the growth of fungi or algae in the tower. Environmental issues such as visible steam plums could be an issue for the implementation of a binary plant.

Selection of the type of cooling system should be assessed on a case by case basis. The case study featured here is based on air cooling because it is available everywhere even though it is not very effective in warm areas.

3.2.6 Efficiency

Various elements impact the efficiency of a binary power plant:

- Temperature of the geothermal fluid
- Depth to water level
- Cooling technology and ambient temperature
- Size of the plant

Thermal efficiency of the cycles is typically 7-15% depending on size and equipment quality. The efficiency decreases as the source temperature decreases. As explained in section 3.2.5, the cooling system also plays an important role in the thermal efficiency of the plant. Fluctuations in temperature of cooling fluid, be it air or water depending on the cooling devices selected, might significantly impact the plant output.

Efficiency of plant equipment used in the case study:

- Isentropic efficiency of the turbine: 80%. Isentropic efficiency describes the ratio between the actual work of the turbine and the maximum theoretical work as if the entropy during the process would remain constant during the process
- Generator efficiency: 95%. It includes the losses in the generator and gears
- Efficiency of pumps and motors: 70%

3.2.7 Auxiliary systems

Presence of hydrogen sulfide H2S is often a problem in geothermal areas due to its effect on the electrical equipment. In order to limit the effect of H2S on the equipment, the concentration in the air surrounding it may not be higher than 3 ppb. To be able to keep the concentration down, the equipment is placed in an overpressurized container supplied with purged air from the pressurized air system. The air is filtered in with coil filters in an effort to remove H_2S from the air.

3.2.8 Plant arrangement

The plant owner must decide to some extent which equipment should be inside shelters or buildings. The equipment manufacturer will suggest a solution where some equipment might be outside, commonly heat exchangers and Turbine/genarator unit. Still it is advised to have this equipment inside/under some shelter since maintenance work is hard in extreme weather conditions. See Figure 5 for an example of setup of a 10 MW power plant with 150°C geothermal fluid temperature as source.

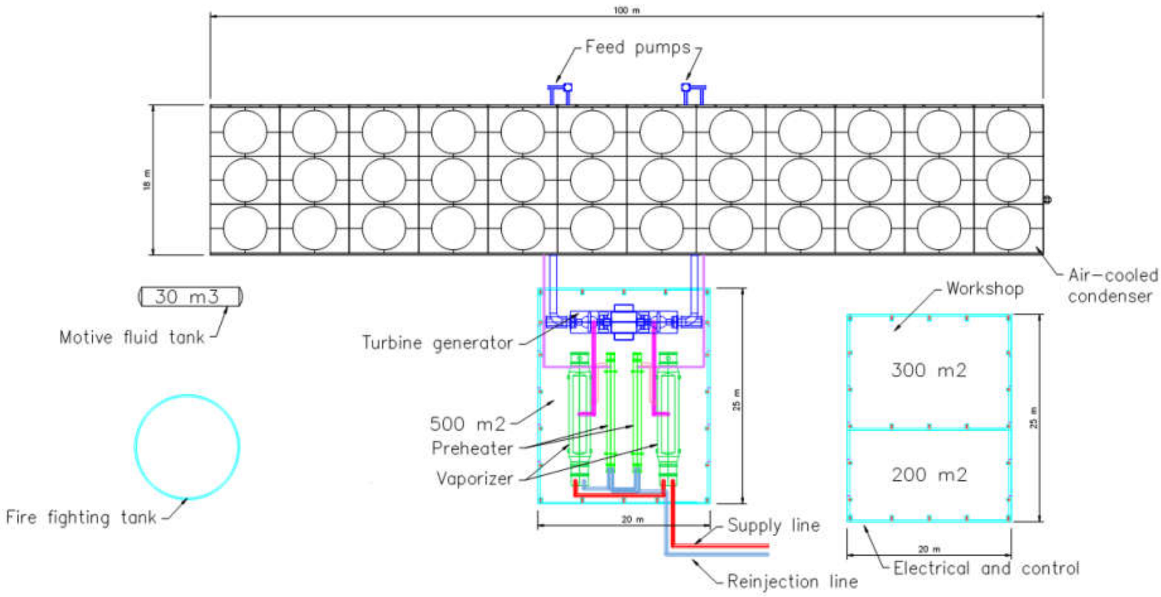

Figure 5 Simplified setup of a 10 MW power plant with 150°C geothermal fluid temperature as a source.

The total footprint of the plant exclusive wells and gathering system is approx. 6000 m^2.

3.2.9 Electricals and Controls

3.2.9.1 Generator

The turbine generator in geothermal power plants are generally, three phase, 2 pole, synchronous 50 or 60 Hz, enclosed, self-ventilated and closed cycle air cooled type with air to water heat exchangers or air to air heat exchangers.

The generator should be sufficiently rated with contingencies above the Maximum Continuous Rating (MCR) of the turbine and can operate over the power factor range required by defined grid interference conditions without the loss of stability and control. The generator nominal voltage is in the range between 10 kV and 14 kV for generator sizes above 2 MVA. For smaller generators, a voltage range between 400 V and 690 V is commonly used. The output circuit comprises a generator circuit breaker and an isolated phase busbar system. The generator circuit breaker is used for synchronizing the generator with the grid; prior to synchronization the parasitic power used for operation of the cooling system and other auxiliary systems necessary for no-load operation of the turbine is drawn from the grid. The basic layout of the electrical equipment is shown in Figure 6.

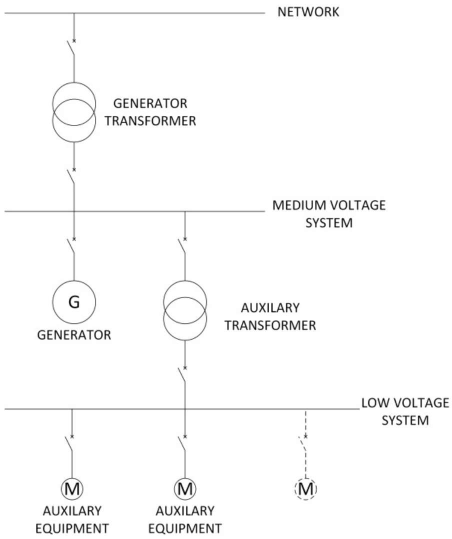

Figure 6 Basic layout of electrical equipment

3.2.9.2 Transformers

For each geothermal powered steam generator there is a respective step up power transformer. The generator transformer is a 3-phase, two winding, oil immersed, air cooled suitable for outdoor operation. The transformer voltage ratio depends on the generator voltage and the network voltage. The auxiliary transformers for a parasitic load is a 3-phase, two winding, oil immersed, air cooled suitable for outdoor operation. The voltage ratio of auxiliary transformers is typically 11/0.4 kV, size is a matter of detail design.

3.2.9.3 Medium Voltage System

The medium voltage basic design is metal clad switchgear. Each cubicle will consists of four compartments, a cable- and measuring transformer compartment, a switching device compartment and a low-voltage for secondary equipment. The voltage level of a main medium voltage distribution system is typically 11 kV.

3.2.9.4 Low Voltage System

The low voltage system serves the plant auxiliaries e.g. condenser fans, feed pumps and other auxiliaries. The voltage level of a low voltage distribution system is typically 400 V. The low voltage basic design is metal enclosed switchgear.

3.2.9.5 Direct Current System

The DC system supplies power to the plant control system. The DC system basic design is standard station type batteries connected to switch mode charging devices. UPS devices are also commonly used. The capacity of the batteries will be based on a DC system load. The voltage level of a DC system is in the range between 24 VDC to 110 VDC.

3.2.9.6 Control and Protection

The power plant level of automation depends on whether the plant is unmanned or manned, i.e. whether skilled operators will be at the power plant at all times. All processes critical to the production of electricity are to be controlled by PLCs. The plant shall be equipped with necessary protection systems to ensure that the plant primary equipment turbine, generator etc. are protected against overload and breakdown.

4 Energy production

The results of a heat and mass balance calculation for the case study are presented here. The design premises are listed in Table 2. The vaporizer pressure is optimized using the method of quadratic approximations where the process is optimized for minimum uptake of geothermal fluid to minimize the required well pump size and deliver the highest net output

Table 2 Design premise of the ORC cycle

Design parameter	Units	Value
Geothermal fluid temperature	°C	120,130,140,150,160
Well depth	m	2,000
Water level depth	m	450
Generator output	kW	10,000
Isentropic efficiency of the turbine	%	80
Generator efficiency	%	98
Cycle pump efficiency	%	70
Air cooled condenser fan efficiency	%	60
Design temperature	°C	30

4.1 Heat and mass balance diagram

A sample of a heat and mass balance diagram used in the calculations is shown in Figure 7. The net power delivered to the grid and accordingly the economy of the power production depends highly on the temperature of the geothermal fluid and well pumping requirement. A guideline for the economy may be to have at least 50% of generated power as net power.

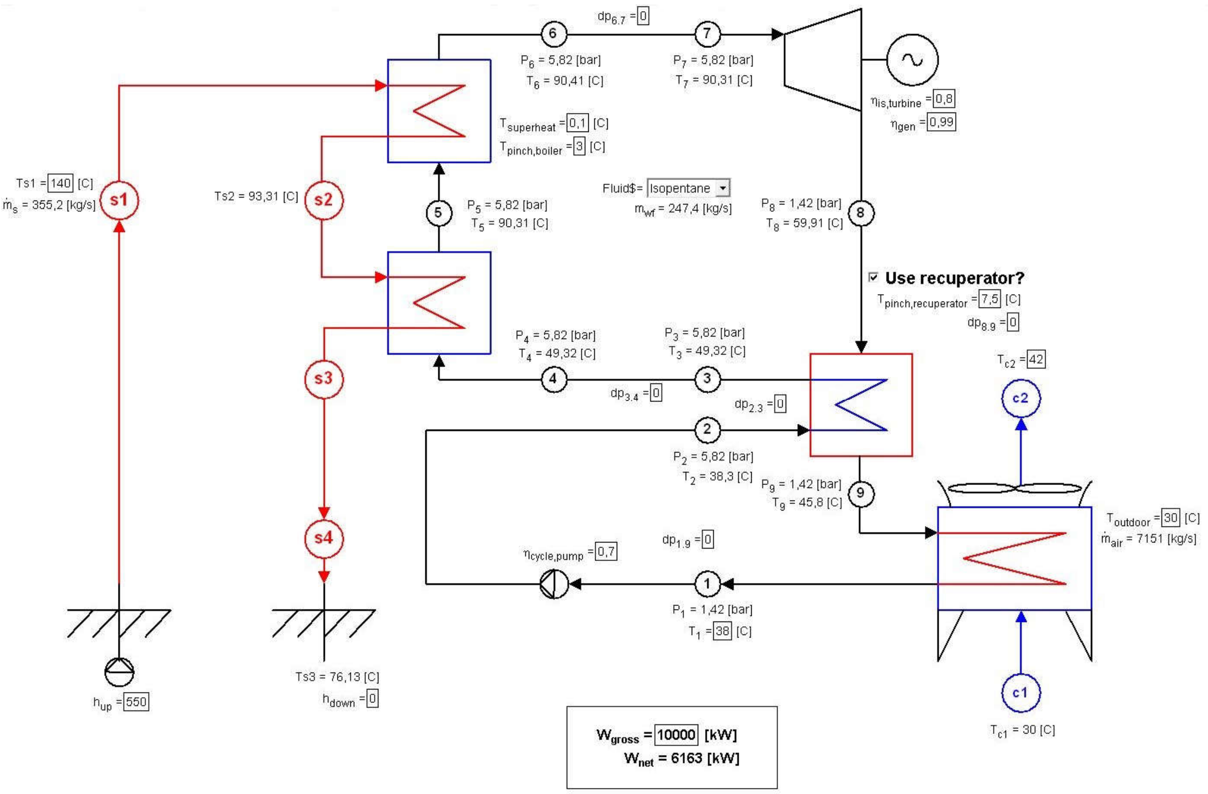

Figure 7 Heat and mass balance diagram of a 10 MW single stage ORC cycle. Geothermal fluid temperature is 140°C.

Other factors that influence the efficiency of the plants are:

- Size of the plant
- Cooling technology and ambient temperature.

As shown in Table 2 Design premise of the ORC cycle the water level is assumed to be at 450 m depth and an estimated lifting requirement is 550 m, design temperature 30°C and air cooling is the assumed cooling method.

4.2 Results

The results from the heat and mass balance calculations of the ORC cycle can be viewed in Table 3. The net power production is the power remaining when parasitic loads of the plant itself have been subtracted from the total generated power. The net power delivered to the grid is net power produced minus power used for pumping from wells. With increasing temperature, the mass flow from the well decreases, thus decreasing the pumping power required to extract the water from the wells. Furthermore, it is estimated the loss from generator to the grid is 3%.

Table 3 Result from heat and mass balance calculations of the ORC cycle

10 MW_{gross}						
Resource temperature [°C]	**Mass Flow Geothermal Fluid [kg/s]**	**Reinjection Temperature [°C]**	**Mass Flow Working Fluid [kg/s]**	**Vaporizer Pressure [bar-a]**	**Condenser Pressure [bar-a]**	**Net Power delivered to grid [kW]**
120	572.2	71.1	310	4.44	1.42	4,264
130	445.5	73.78	275.4	5.09	1.42	5,267
140	355.2	76.13	247.4	5.82	1.42	5,978
150	288.5	78.18	224.2	6.67	1.42	6,498
160	237.8	79.9	204.4	7.66	1.42	6,886

In Figure 8, the net power production and the power delivered to the grid are plotted against temperature of the heat source.

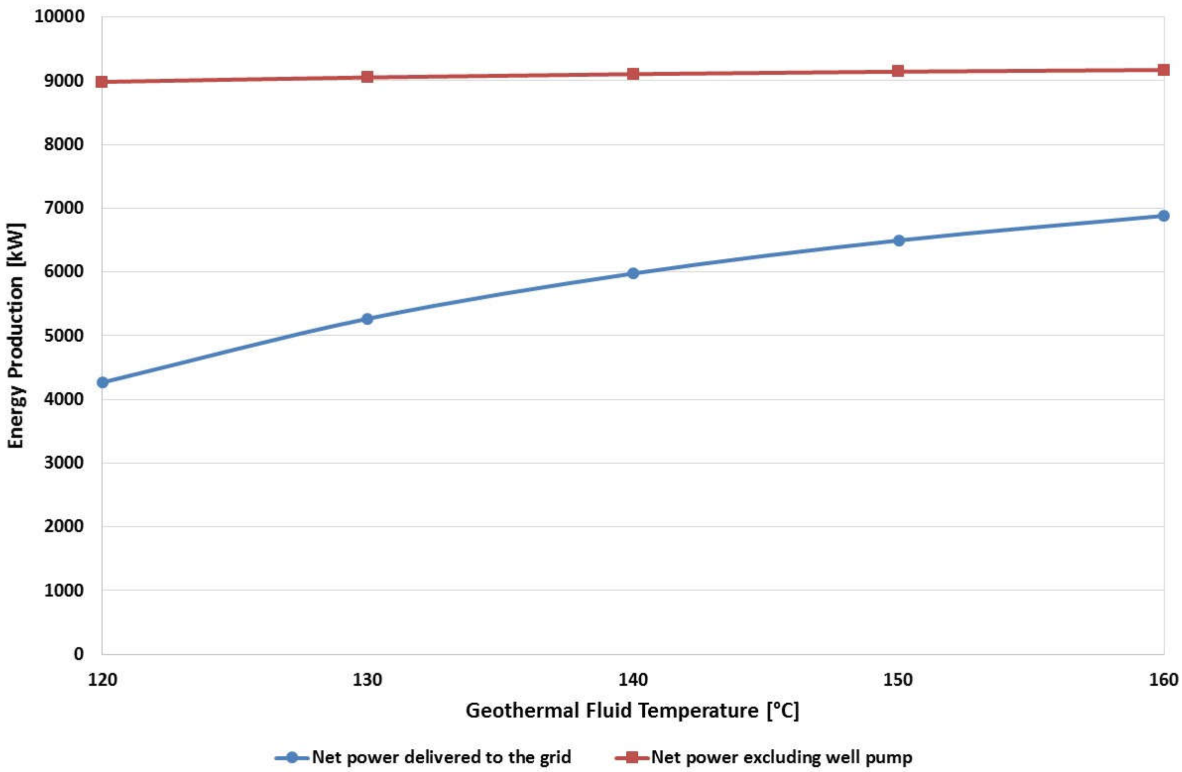

Figure 8 Net power produced and delivered to the grid as a function of temperature

4.3 Electricity delivered to the grid

Estimated annual electricity production is shown in Table 4. The delivered energy is net power delivered to the grid multiplied with the up time of the power plant which is assumed to be 95%.

Table 4 Energy production potential

Temperature °C	Net Power delivered to the grid	Annual energy sales
	MW	MWh
120	4,264	35,486
130	5,267	43,833
140	5,978	49,750
150	6,498	54,077
160	6,886	57,306

5 Cost estimate

5.1 Capital Cost

The capital cost estimate is based on European prices and Verkís experience from similar projects.

The following cost items were not assessed for purpose of this report on the binary technology because it is either not possible or not practicable to include them in a generic case study:

- HV- Transmission Line(s)
- Access roads
- Fresh water, sewage
- Land/concession
- Official Permits
- Taxes, duties, connection fee to the grid
- Additional cost because of special environmental constraints

All other costs are included in the cost estimate.

- Direct cost (well, steam/water gathering system, power plant), divided into cost of geothermal field and cost of power plant
- Indirect cost such as engineering and commissioning and general contingency.

The price basis is April 2017.

The case study currency is US dollars (USD).

5.1.1 Geothermal Field

Cost estimates for the geothermal field include:

- Production and reinjection wells, including deep well pumps.
- Gathering and reinjection system.
- The cost of drilling, pumping and gathering system may vary a lot from one field to another. It depends on the depth of wells, flow rate from each well, distance between wells and depth to water level in the wells. The base case for the cost of the geothermal field is based on the following assumptions:
- Depth of wells: 2.000 m.
- Average output from each well: 30, 50 and 70 kg/s.
- Depth of water level in wells: 450 m.
- Pump installed at: 550 m depth.
- Average distance between wells: 250 m.
- One reinjection well will be drilled for each production well.

Cost of exploration of geothermal fields varies a lot. As a rough estimate, deviation up to ± 50% from the calculated base cost is to be expected. The average cost of exploration of harnessed geothermal fields is assumed to be included in the cost estimate. The cost of exploration of unsuccessful fields is not included and should be handled as a sunken cost.

The cost estimates above are assumed to be independent of the temperature of the geothermal fluid assessed in the case study, or 120°C – 160°C.

The unit prices for wells and gathering system are showed in table 5.

Table 5 Unit cost for wells and gathering systems

Flow rate	kg/s	30	50	70
Production well:				
Well	USD	2,500,000	2,500,000	2,500,000
Deep well pump	USD	215,000	359,000	503,000
Steam/water gathering system	USD	100,000	100,000	100,000
Production well, total	**USD**	**2,815,000**	**2,959,000**	**3,103,000**
Reinjection well:				
Well	USD	2,500,000	2,500,000	2,500,000
Deep well pump	USD	0	0	0
Steam/water gathering system	USD	100,000	100,000	100,000
Reinjection well, total	**USD**	**2,600,000**	**2,600,000**	**2,600,000**

5.1.2 Power Plant

The power plant cost estimates are based on quotations, purchasing prices and experience from other geothermal projects.

The cost estimates for different binary plants are based on the design premises and the preliminary concept design presented in previous sections. The power plant cost is divided into:

- Mechanical equipment
- Electrical & control
- Civil work.

The elements included in the power plant cost estimates are detailed in Table 6.

Table 6 Elements included in the main cost items

Direct Cost	
Mechanical Equipment	Turbine, generator, incl. lube oil unit, control etc. Heat exchangers (vaporizers, preheaters and recuperators) Air cooled condensers (excl. foundations) Cycle pump Auxiliary systems Compressed air systems Valves and controls Firefighting system Piping, materials and installation, not icl. in other
Electrical & Control	Transformers (main and auxiliary) Local connection to the grid MV switchgear Control, protection and MCC'a Sensors and transmitters Cables, materials and installation not incl. in other
Civil Work	Excavation Foundations Service facilities
Indirect cost	
	Engineering, supervision and commissioning, 10% of direct cost General Contingency, 15% of direct cost

5.1.3 Total Cost

Table 7 shows the CAPEX of the power plant. The cost estimates is based on the unit cost of geothermal wells shown in Table 5 and the cost estimate for power plant in Table 6 . The number of wells is calculated from the mass flow of geothermal fluid shown in table 3.

Table 7 Total Capital Cost of 10 MW Plant

Temperature, °C	**120**			**130**			**140**			**150**			**160**		
Necessary geothermal flow, kg/s	**572**			**446**			**355**			**289**			**238**		
Flow rates from wells, kg/s	30	50	70	30	50	70	30	50	70	30	50	70	30	50	70
No. of production wells	19	11	8	15	9	6	12	7	5	10	6	4	8	5	3
No. of reinjection wells	19	11	8	15	9	6	12	7	5	10	6	4	8	5	3
Wells and gathering systems, MUSD	103	64	47	80	50	36	64	39	29	52	32	24	43	26	19
Power plant, MUSD	27			24			23			22			21		
Total cost, MUSD	**130**	**90**	**73**	**105**	**74**	**61**	**87**	**62**	**52**	**74**	**54**	**45**	**64**	**48**	**41**

Figure 9 shows the CAPEX for the wellfield and power plant for different flow rates from each well as function of the temperature of the geothermal fluid.

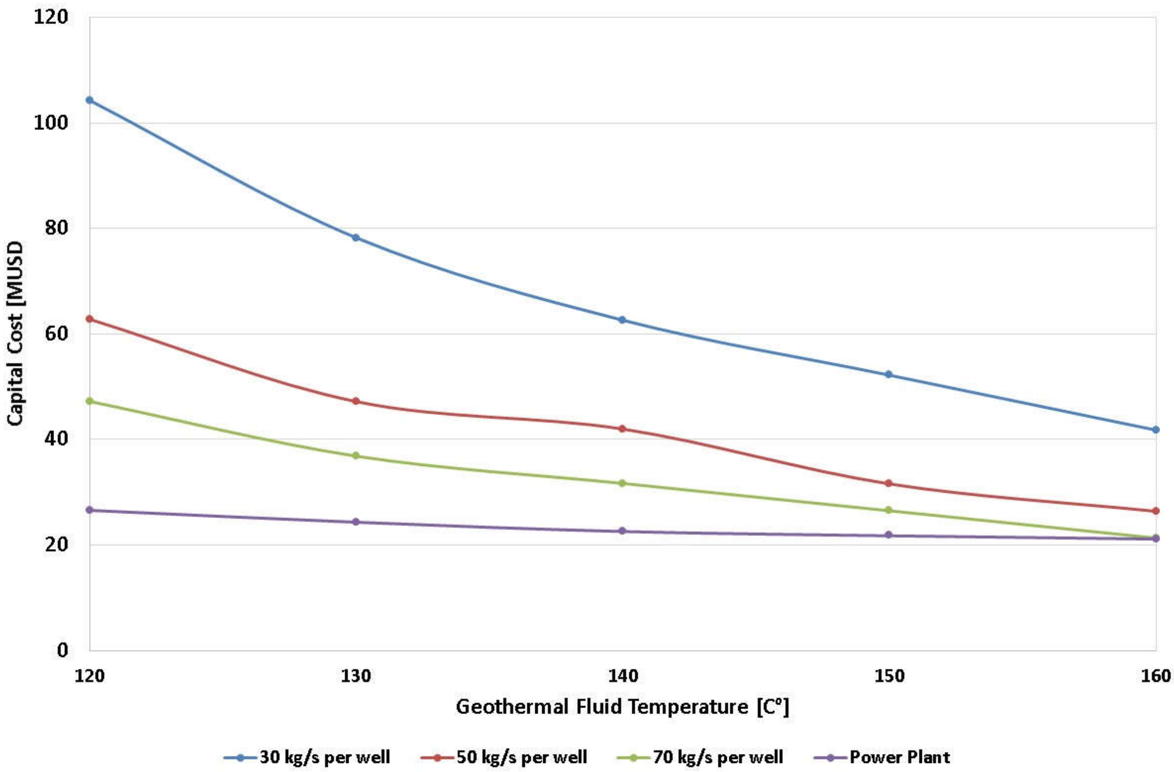

Figure 9 Capital cost per plant and wellfield development.

5.2 Annual Cost

The total annual cost consists of operation and maintenance cost and cost of finance and depreciation of the CAPEX

The power plant will use its own electricity to cover the parasitic load. The parasitic load is not listed as an operational cost; it only reduces the net amount of energy.

5.2.1 OPEX

5.2.1.1 Personnel

The operation of a geothermal binary power plant will require the following staff:

- Operators who perform operation and maintenance.
- Workers who provide general labor and assistance to operators.
- Security personnel to guarantee safety at the plant.

Plant operators need to be skilled and trained for specific tasks. Both electricians and mechanics should be able to perform on-line supervision, maintenance and repair maintenance.

The operators need to divide night stand-by duties between them.

In advanced plants the production is automatic and there is not much need for full time employees. All maintenance services for the plant can be purchased from a service provider with adequate education and experience. It is assumed that 10 employees will be needed for operation of the plant and average cost of each employee is 60,000 USD/year.

5.2.1.2 Spare Parts and Plant Consumables

A decision on spare parts is made during final plant tendering and pre-contract meetings with the manufacturer. In addition, the plant will require some consumables, working fluid refill due to leakage, lubrication oil replacement etc. That cost will increase if inhibitors or acid are required to avoid scaling of the geothermal fluid in the heat exchangers. The cost of consumables is estimated as 500,000 USD/year. Cost of spare parts is included in maintenance cost.

5.2.1.3 Scheduled Maintenance and well replacement

Experience shows that it is reasonable to plan for a week long annual stop of the ORC plant to perform maintenance that cannot be performed with the plant in operation. It includes both maintenance of the plant and of the well field equipment. Since scaling is assumed not to be a problem, taken into consideration in the plant design, there is no single item that requires periodic shutdown of the plant except the mechanical shaft seal of the turbine that needs to be replaced every 5-10 years. Then the stop can be expected to last somewhat longer, 10 days or so, because the seal replacement requires the turbine to be opened.

Usually the geothermal well flow rate can be expected to decrease slowly or not at all. In the case study, no scaling is assumed and all the geothermal fluid is to be re-injected so that well flow rate can be expected to decrease slowly or not at all.

About one week a year should be set aside for external contractor services, mainly associated with heat exchanger cleaning, but also for assistance with other maintenance areas.

The annual maintenance cost inclusive spare parts, well replacement and consumables is estimated as 2.0% of the capital cost per.

5.2.2 Cost of finance and depreciation

The cost is based on the assumptions listed in Table 8

Table 8 Cost assumptions

Equity/loan ration:	30% / 70%
Return on equity:	15% per year
Interest rate on loans:	5%
Depreciation:	25 years or 4% per year

For simplification the annual cost of finance and depreciation is calculated constant (annuitet) over the 25 years lifetime of the power plant. The above assumptions give the annual cost as 9.4% of CAPEX

5.2.3 Total annual production cost

Table 9 shows the estimated total annual cost of the plant for different conditions.

Table 9 Annual production cost

Temperature, °C	**120**			**130**			**140**			**150**			**160**		
Necessary geothermal flow, kg/s	572			446			355			289			238		
Personnel, MUSD/year	0.6			0.6			0.6			0.6			0.6		
Consumable, USD/year	0.5			0.5			0.5			0.5			0.5		
Flow rate from wells, l/s	**30**	**50**	**70**	**30**	**50**	**70**	**30**	**50**	**70**	**30**	**50**	**70**	**30**	**50**	**70**
Maintenance, MUSD/year	2.6	1.8	1.5	2.1	1.5	1.2	1.7	1.2	1.0	1.5	1.1	0.9	1.3	1.0	0.8
OPEX Total, MUSD/year	**3.7**	**2.9**	**2.6**	**3.2**	**2.6**	**2.3**	**2.8**	**2.3**	**2.1**	**2.6**	**2.2**	**2.0**	**2.4**	**2.1**	**1.9**
Cost of finance + depr., MUSD/year	**12.2**	**8.5**	**6.9**	**9.9**	**6.9**	**5.7**	**11**	**8.2**	**7.0**	**9.5**	**7.2**	**6.3**	**8.4**	**6.5**	**5.7**
Total production. cost, MUSD/year	**15.9**	**11.4**	**9.5**	**13.0**	**9.5**	**8.0**	**11.0**	**8.2**	**7.0**	**9.5**	**7.2**	**6.3**	**8.4**	**6.5**	**5.7**

The total annual cost listed in table 9 is shown for comparison in **Figure 10**

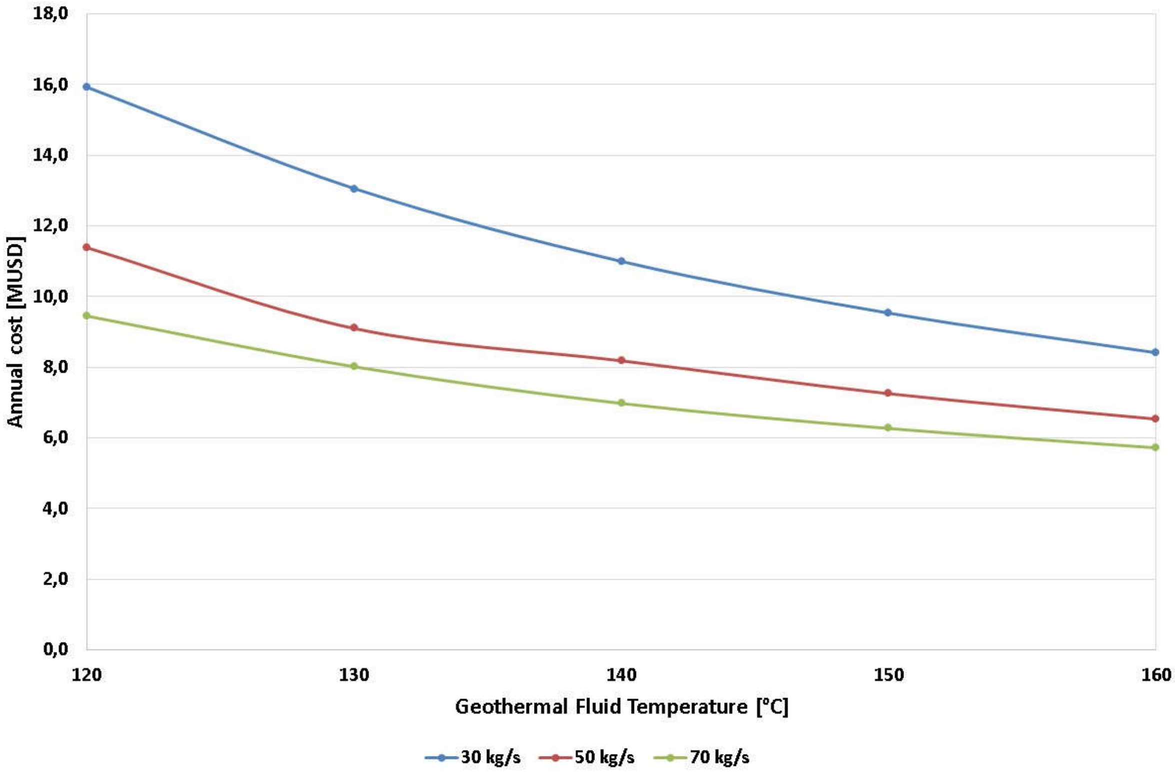

Figure 10 Total annual cost for plants with different well flows.

5.3 Cost of Energy

The cost of energy is listed in table 10 and shown on the graph in **Figure 11**. The cost of energy is calculated as the annual production cost listed in table 9 divided with annual energy sales shown in table 4.

Table 10 Cost of energy

Temperature, °C	**120**			**130**			**140**			**150**			**160**		
Necessary geothermal flow, kg/s	572			446			355			289			238		
Flow rate from wells, l/s	**30**	**50**	**70**	**30**	**50**	**70**	**30**	**50**	**70**	**30**	**50**	**70**	**30**	**50**	**70**
Totall production cost, MUSD/year	15.9	11.4	9.5	13.0	9.5	8.0	11.0	8.2	7.0	9.5	7.2	6.3	8.4	6.5	5.7
Annual energy sales. MWH	**35,486**			**43,833**			**49,750**			**54,077**			**57,306**		
Energy cost. Ucent/kWh	**44.8**	**32.1**	**26.6**	**29.8**	**21.7**	**18.3**	**22.1**	**16.4**	**14.0**	**17.6**	**13.4**	**11.6**	**14.7**	**11.4**	**10.0**

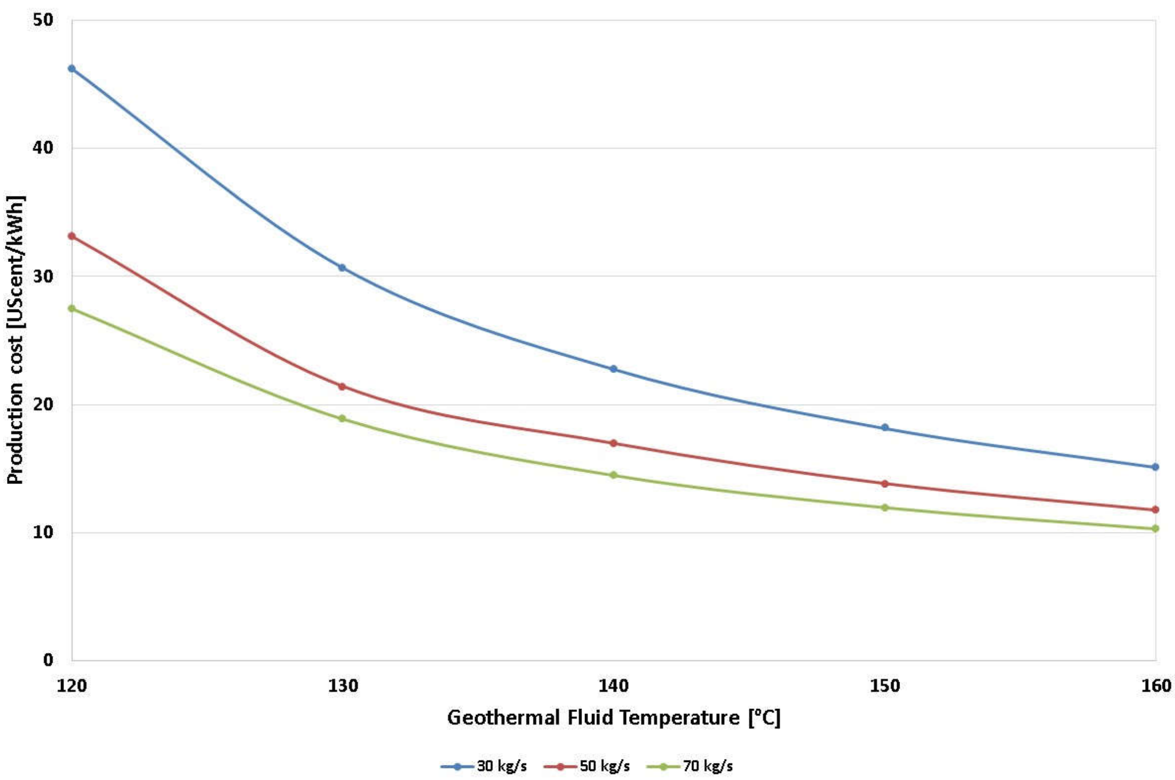

Figure 11 Production cost of electricity delivered to the grid as a function of geothermal fluid temperature for all cases of geothermal fluid temperature and well flow.

6 Summary and Conclusions

In this report a preliminary study on cost of geothermal well field development and a 10 MW power plant has been conducted. In table 11 the main design parameters are listed.

Table 11 Main design parameters

Design parameter	Units	Value
Geothermal fluid temperature	°C	120.130.140.150.160
Well depth	m	2.000
Water level depth	m	450
Generator output	kW	10.000
Design temperature	°C	30

The production cost excludes all taxes. feed in tariffs and local fees. The geothermal fluid temperature and flow rate from the wells are the greatest factors which affect the energy price.

Table 12 Annual net production and production cost

Temperature °C	Annual energy sales	Cost UScent/kwh		
	MWh	30 kg/s	50 kg/s	70 kg/s
120	35.486	44.8	32.1	26.6
130	43.833	29.8	21.7	18.3
140	49.750	22.1	16.4	14.0
150	54.077	17.6	13.4	11.6
160	57.306	14.2	11.4	10.0

The project today is still in its initial phases of test drilling and decisions of project implementation are to wait further research before development of the power plant.

For further consideration

- Ratio of one reinjection well per each production wells seems generous in terms of drilling costs.
- If pumping is required for reinjection the net power output will be less than expected from the study.
- Alternative cooling methods may be applied to increase the efficiency of the plant. information on water resources nearby are limited.
- The assumed water level depth is deep. Assuming higher water level in wells drastically increases the economy of the plant, mainly due to decreased parasitic load. The water level is however a parameter of the reservoir and the assumption made in this study is based on what is measured in the already drilled wells.

Appendices

Appendix 1 Assumptions for Calculations

Items	Assumptions
Geothermal Field	
Average distance between wells, m	250
Depth of production wells, m	2,000
Depth of reinjection wells, m	2,000
Depth to water level in wells, m	450
Temperature in reservoir, °C	120, 130, 140, 150, 160
Flow rate from each well, kg/s	30, 50, 70
Number of reinjection / production wells	1 / 1
Pumps, installation depth, m	550
Power Plant	
Turbine size, gross, MW	10
Ambient design temperature, °C	30
Isentropic efficiency of the turbine	80%
Generator efficiency	98%
Cycle pump efficiency	70%
Air cooled condenser fan efficiency	60%
Economical Calculations	
Number of employees	10
Annual cost per employee, USD	60,000
Annual maintenance cost, % of CAPEX	2%
Annual cost of consumables, USD	500,000
Equity / loan ratio	30% / 70%
Required annual return of equity	15%
Interest rate of loans	5%
Depreciation pr. year	4%