VERKÍS

Geothermal Binary Power Plants

Preliminary study of low temperature utilization, cost estimates and energy cost

With funding from

iceida ICELANDIC INTERNATIONAL DEVELOPMENT AGENCY
ÞRÓUNARSAMVINNUSTOFNUN ÍSLANDS

Geothermal Binary Power Plants

Preliminary study of low temperature utilization, cost estimates and energy cost

Prepared by Verkis Consulting Engineers 2014, www.verkis.is
With funding from the Icelandic International Development Agency (ICEIDA),
www.iceida.is, under the Geothermal Exploration Project

Executive summary

This report was prepared in November 2013 - August 2014 by Verkís Consulting Engineers and is funded by the Icelandic International Development Agency (ICEIDA). It is intended to contribute to discussions on the possibilities for electricity generation from geothermal resources in East Africa Rift Valley States, as a part of the ICEIDA and NDF funded Geothermal Exploration Project. The objective is to explore the feasibility, and factors that influence feasibility, of electricity production from binary power plants in the context of low temperature geothermal areas, providing a reference point for further discussions once the resource potentials in the various countries are recognized. The main task is to evaluate the economy of producing electricity with water below 150°C.

The binary technology allows for the production of electricity from resources that could otherwise not be used for such a purpose, typically at reservoir temperatures between 100°C and 200°C In a conventional steam power plant, the turbine is driven directly by the steam whereas in a binary plant, the geothermal fluid is used indirectly by heating up the working fluid above its boiling point. The binary production technology has recently become competitive due to higher energy prices and subsidies to electricity generated with renewable energy resources. The binary technology for production of energy from geothermal resources is therefore an option worth assessing in low and medium temperature geothermal fields.

The characteristics of the geothermal resource is the basis for the design of the power plant and has to be carefully investigated before the commissioning of the project. The most important parameters are:

- Extent of the resource
- Temperature
- Flow from each well versus depth to water table in wells
- Depth of wells
- Chemical composition of the geothermal fluid

In this report the following assumptions are set as a base case for a geothermal field:

- Flow from each well: 40 l/s
- Depth of wells: 1.400 m
- Depth to water table: 150 m
- Pumps installed at depth: 200 m
- Distance between wells: 250 m
- Temperature of the geothermal fluid: 90°C – 150°C

In the report a study was performed on two working cycles, one and two stage, see Figure 1 and Figure 2.

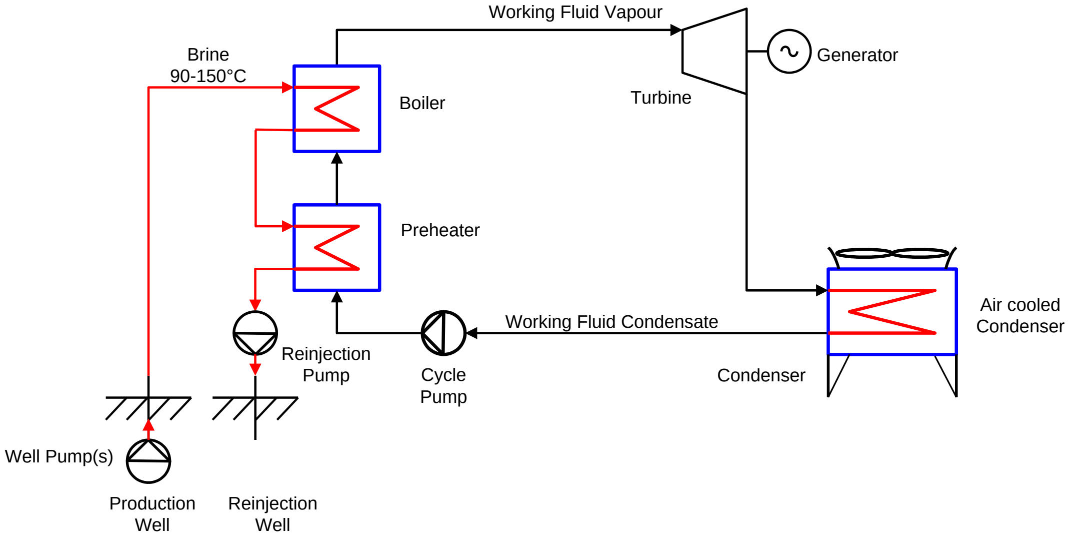


Figure 1 **One stage binary cycle**

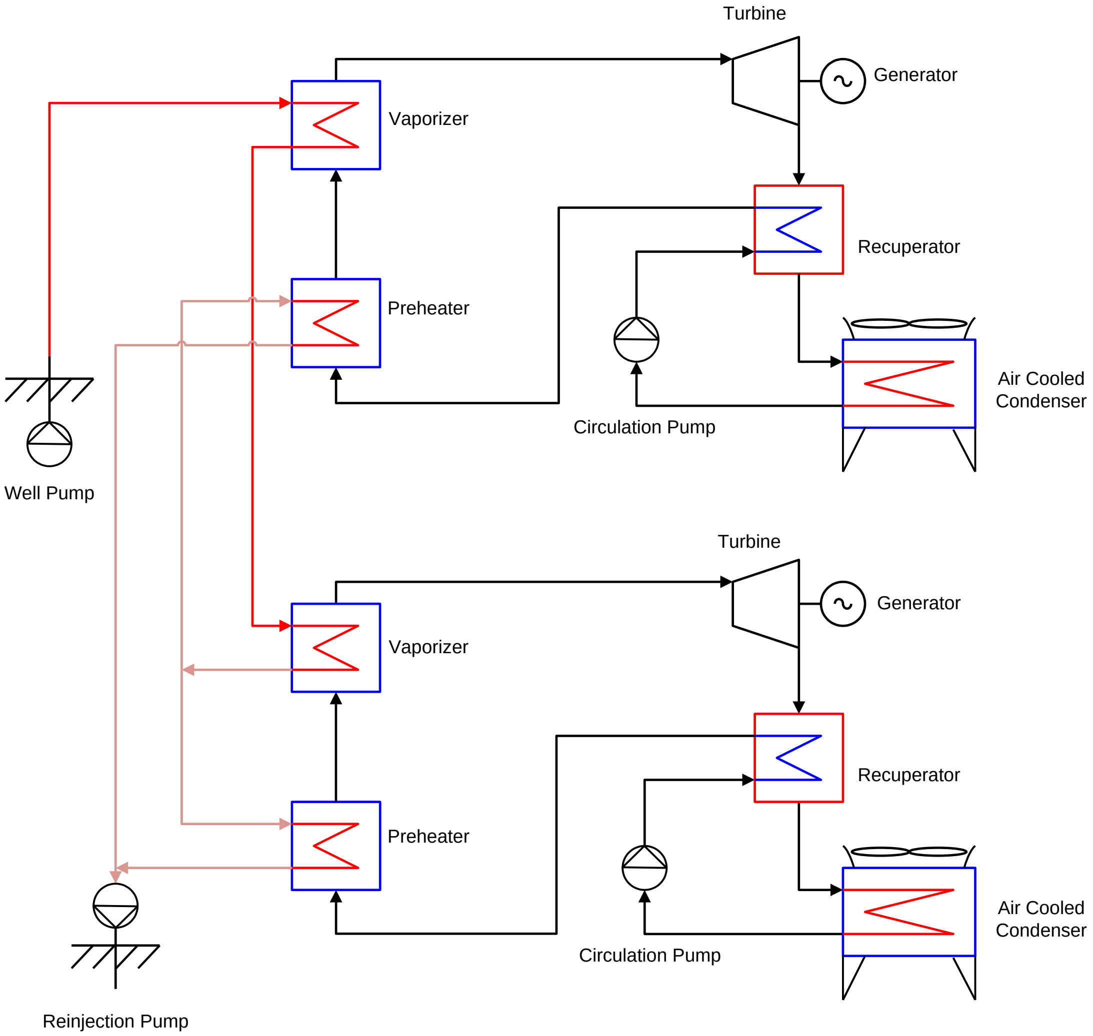


Figure 2 **Two stage binary cycle**

Five different sizes of power plants with 250 kW, 1000 KW, 2.500 kW, 5.000 kW and 10.000 kW generator output were introduced.

In Figure 3 the net production of the power plants is plotted as a function of the resource temperature. The net power production is the electricity which can be sold. All parasitic loads of the power plant have been subtracted from the gross generated power (well pumping not included).

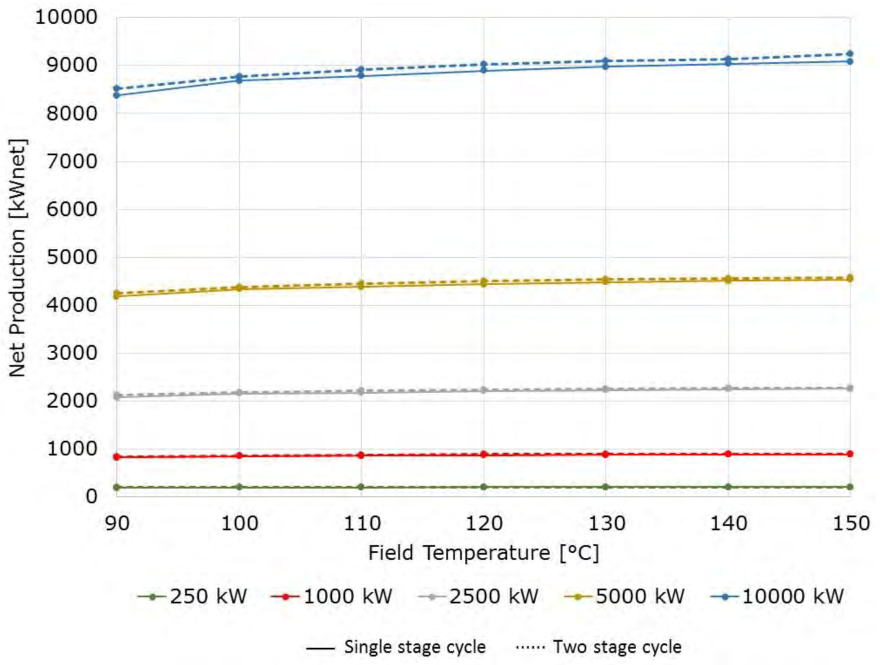


Figure 3 Net power as a function of temperature. The colored lines indicate the generator size (gross product).

The annual production of electricity as well as requirements for control of the electrical production highly depend on the type of electrical network. An island operation with the binary plant as the only producer is not recommended. Connection to a strong network where a binary plant will be a base load producer is the best way to operate the plant. An island operation in a smaller isolated network in combination with a diesel generator is also possible.

In this study it is assumed that the turbine and generator will be located under a weather shield and the electrical equipment and service facilities situated in a container or a building close to the turbine. The whole area will have to be fenced off to shield it from animals and fend off trespassers. Often geothermal areas are situated far from developed areas and often in rugged volcanic terrains, and requires drill site preparation which involves road construction for heavy equipment and transportation of employees.

Cost summary

The investment cost is divided into two parts, power plant and steam field respectively.The cost estimate for the power plant is relatively secure although it may vary from one place to another and from time to time. The cost of the field development may vary a lot due to the uncertainty in acquiring an adequate amount of water. The cost estimate in this report is based on the base assumptions mentioned previously. The actual cost of field development may deflect ±50% from the base case due to different conditions. Figure 4 shows the investment cost estimate for the 5 different plant sizes and resource temperature from 90°C – 150°C

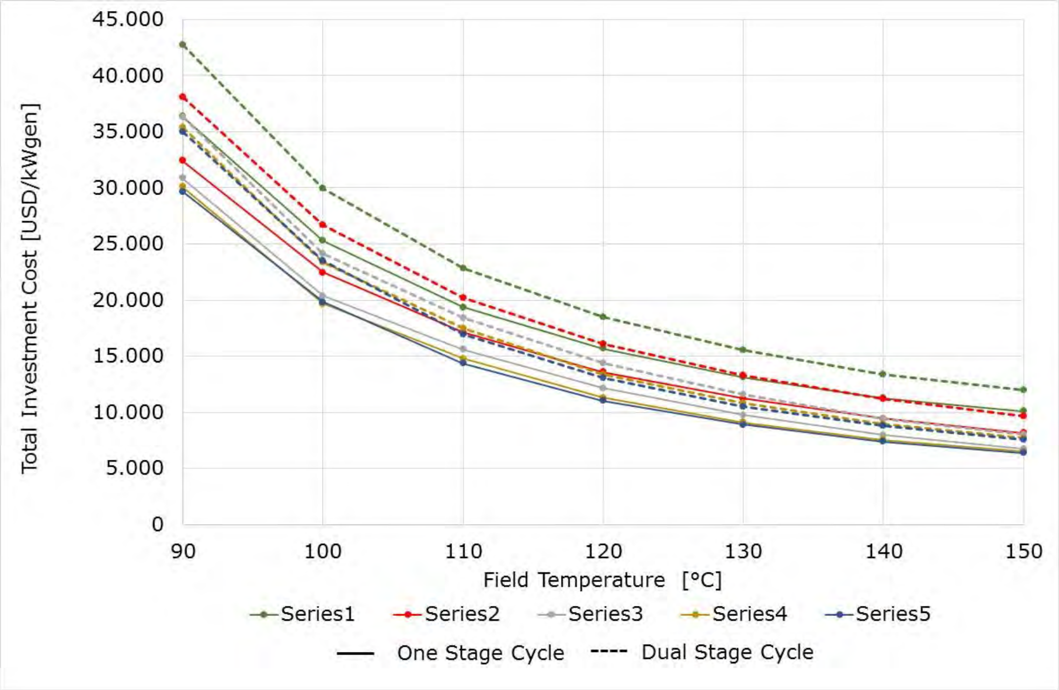


Figure 4 Investment Cost of the plants, USD/kW generated

Table 1 shows the total annual cost i.e the annual operation and financial cost. Operation cost includes all cost of personnel, maintenance and other conventional cost of operation.

The financial cost includes depreciation, loan interest and return on equity. For simplification the annual financial cost is defined as a percentage of investment cost. The percentage is based on depreciation period, estimated interest rate, required rate of return and equal distribution of total financial cost, annuity. Two alternatives are presented for financial cost:

Fin 1

- Depreciation period 25 years
- Interest rate of loans 3,71%
- Rate of return of equity 15%
- Equity/loan ratio 30%/70%
- Average rate equity/loan 7,1%

Fin 2

- Depreciation period 25 years
- Interest rate of loans 3,71%
- Rate of return of equity 15%
- Equity/loan ratio 15%/85%
- Average rate equity/loan 5,4%

Table 1 **Total annual cost**

Power Plants - Total Annual Cost

		Single stage ORC cycle						Two stage ORC cycle				
		Cost, MUSD /Year						Cost, MUSD /Year				
	Generated Power kW	O&M Cost	Fin. Cost I	Fin. Cost II	Total I	Total II		O&M Cost	Fin. Cost I	Fin. Cost II	Total I	Total II
90°C	250	0,3	0,6	0,5	0,8	0,8		0,3	0,7	0,6	1,0	0,9
	1000	0,6	2,3	2,0	2,9	2,5		0,6	2,8	2,4	3,4	3,0
	2500	1,3	5,6	4,7	6,8	6,0		1,5	6,7	5,7	8,1	7,1
	5000	2,2	10,8	9,2	13,1	11,5		2,6	13,0	11,1	15,6	13,7
	10000	4,1	21,5	18,3	25,6	22,5		4,9	25,8	22,0	30,7	26,9
100°C	250	0,2	0,4	0,4	0,7	0,6		0,3	0,5	0,4	0,8	0,7
	1000	0,5	1,7	1,4	2,1	1,9		0,5	2,0	1,7	2,5	2,2
	2500	1,0	3,9	3,3	4,9	4,3		1,1	4,7	4,0	5,8	5,1
	5000	1,7	7,6	6,4	9,2	8,1		1,9	9,1	7,7	11,0	9,6
	10000	3,0	15,0	12,8	18,0	15,8		3,5	18,0	15,3	21,5	18,8
110°C	250	0,2	0,3	0,3	0,6	0,5		0,2	0,4	0,3	0,6	0,6
	1000	0,4	1,3	1,1	1,7	1,5		0,4	1,5	1,3	2,0	1,7
	2500	0,8	2,9	2,5	3,7	3,3		0,9	3,5	3,0	4,4	3,9
	5000	1,3	5,5	4,7	6,8	6,0		1,5	6,6	5,7	8,1	7,2
	10000	2,3	11,0	9,4	13,4	11,7		2,7	13,3	11,3	16,0	14,0
120°C	250	0,2	0,3	0,2	0,5	0,4		0,2	0,3	0,2	0,6	0,5
	1000	0,3	1,0	0,8	1,3	1,2		0,4	1,2	0,8	1,6	1,2
	2500	0,7	2,3	2,0	3,0	2,7		0,8	2,8	2,0	3,6	2,7
	5000	1,1	4,3	3,7	5,4	4,8		1,2	5,2	3,6	6,4	4,9
	10000	1,9	8,7	7,4	10,6	9,3		2,2	10,4	7,2	12,6	9,4
130°C	250	0,2	0,2	0,2	0,4	0,4		0,2	0,3	0,2	0,5	0,5
	1000	0,3	0,8	0,7	1,1	1,0		0,3	1,0	0,8	1,3	1,2
	2500	0,6	1,9	1,6	2,5	2,3		0,7	2,3	2,0	3,0	2,7
	5000	0,9	3,5	3,0	4,5	4,0		1,1	4,2	3,6	5,3	4,7
	10000	1,6	7,0	6,0	8,7	7,6		1,9	8,5	7,2	10,3	9,1
140°C	250	0,2	0,2	0,2	0,4	0,4		0,2	0,2	0,2	0,4	0,4
	1000	0,3	0,7	0,6	1,0	0,9		0,3	0,9	0,7	1,2	1,0
	2500	0,6	1,5	1,3	2,1	1,9		0,6	1,9	1,6	2,5	2,2
	5000	0,8	2,9	2,5	3,8	3,4		1,0	3,5	3,0	4,5	4,0
	10000	1,4	5,9	5,0	7,3	6,4		1,6	7,0	6,0	8,6	7,6
150°C	250	0,2	0,2	0,2	0,4	0,3		0,2	0,2	0,2	0,4	0,4
	1000	0,3	0,6	0,5	0,9	0,8		0,3	0,7	0,6	1,0	0,9
	2500	0,5	1,3	1,1	1,8	1,6		0,6	1,6	1,3	2,2	1,9
	5000	0,8	2,5	2,2	3,3	2,9		0,9	3,1	2,6	3,9	3,5
	10000	1,3	5,0	4,3	6,3	5,5		1,4	6,0	5,1	7,5	6,6

The production cost per kWh electricity is calculated from the total annual cost presented in Table 1 divided by the net annual energy production. The net energy production is defined as the net power presented in Figure 3 multiplied by the maximum annual production time defined as 0,96 x 8760 = 8.410 hours. This is the maximum production which can only be achived if the plant is operated as a base plant connected to a large grid compared to plant size.

Table 2 shows the production cost based on the annual operation cost only and the total production cost that includes annual operation and finance cost (two alternatives) as presented in Table 1.

The total cost of production of electricity according to Table 2 is: 7,3 to 61,9 UScent pr. kWh, where of the operation (variable cost) is 1,7 to 17,9 depending on temperature and plant size. For comparison the cost of oil for electricity produced in diesel engine is estimated to be 25,5 UScent/kWh.

Table 2 Production Cost pr. kWh of net energy production

Power Plants – Production cost UScent/kwHnet

		Single stage ORC cycle					Two stage ORC cycle			
	Generated Power kW	Annual Energy sale kWh	Cost, UScent/kWh				Annual Energy sale kWh	Cost, UScent/kWh		
			O&M Cost	Total I	Total II			O&M Cost	Total I	Total II
90°C	250	1.596.983	17,3	54,7	49,2		1.632.135	17,9	61,9	55,4
	1000	6.893.349	8,5	41,9	37,0		7.032.948	9,4	48,7	42,9
	2500	17.483.558	7,6	39,3	34,6		17.836.762	8,4	45,8	40,3
	5000	35.135.309	6,6	37,6	33,1		35.816.486	7,5	44,0	38,6
	10000	70.447.219	6,2	36,7	32,2		71.675.021	7,0	43,0	37,7
100°C	250	1.661.737	14,6	40,7	36,8		1.680.406	15,4	46,3	41,7
	1000	7.152.365	6,6	29,7	26,3		7.227.210	7,3	34,7	30,7
	2500	18.131.098	5,6	26,8	23,7		18.318.632	6,2	31,4	27,7
	5000	36.438.797	4,7	25,2	22,2		36.808.819	5,3	29,7	26,1
	10000	73.037.376	4,3	24,7	21,7		73.785.830	4,9	29,1	25,6
110°C	250	1.681.920	13,4	33,4	30,4		1.712.026	13,9	37,4	33,9
	1000	7.233.097	5,5	23,1	20,5		7.351.672	6,0	26,8	23,7
	2500	18.332.928	4,6	20,6	18,3		18.633.992	5,0	24,0	21,2
	5000	36.834.048	3,7	18,9	16,7		37.439.539	4,1	22,1	19,5
	10000	73.844.698	3,2	18,0	15,8		75.030.451	3,7	21,1	18,5
120°C	250	1.706.308	12,6	28,8	26,4		1.732.966	13,0	32,1	26,8
	1000	7.328.966	4,8	18,8	16,7		7.435.768	5,2	21,8	17,0
	2500	18.576.806	3,9	16,4	14,6		18.843.391	4,3	19,1	14,6
	5000	37.321.805	3,0	14,7	13,0		37.855.814	3,4	17,1	12,9
	10000	74.803.392	2,6	14,0	12,3		75.871.411	2,9	16,4	12,2
130°C	250	1.723.968	12,1	25,6	23,6		1.746.842	12,4	28,4	26,1
	1000	7.399.607	4,4	15,9	14,2		7.493.795	4,7	18,4	16,4
	2500	18.753.408	3,5	13,6	12,1		18.982.149	3,7	15,7	14,0
	5000	37.666.598	2,6	12,0	10,6		38.141.741	2,9	14,0	12,3
	10000	75.509.798	2,2	11,3	10,0		76.451.674	2,5	13,3	11,7
140°C	250	1.736.582	11,7	23,3	21,6		1.757.018	11,9	25,7	23,7
	1000	7.450.906	4,0	13,8	12,3		7.532.479	4,3	15,8	14,1
	2500	18.879.552	3,1	11,3	10,1		19.083.905	3,3	13,1	11,6
	5000	37.927.296	2,3	10,1	8,9		38.336.003	2,5	11,8	10,4
	10000	76.022.784	1,9	9,5	8,4		76.838.515	2,1	11,2	9,8
150°C	250	1.745.833	11,4	21,8	20,3		1.763.577	11,7	24,0	22,2
	1000	7.488.749	3,7	12,1	10,9		7.558.212	4,0	14,0	12,5
	2500	18.972.058	2,9	9,8	8,8		19.149.500	3,0	11,3	10,1
	5000	38.120.717	2,1	8,8	7,8		38.459.624	2,3	10,2	9,1
	10000	76.401.216	1,7	8,3	7,3		77.701.340	1,9	9,6	8,5

Figure 5 shows the total production cost (Fin I) pr. net kWh in a binary power plant and the corresponding cost of production in a diesel plant.

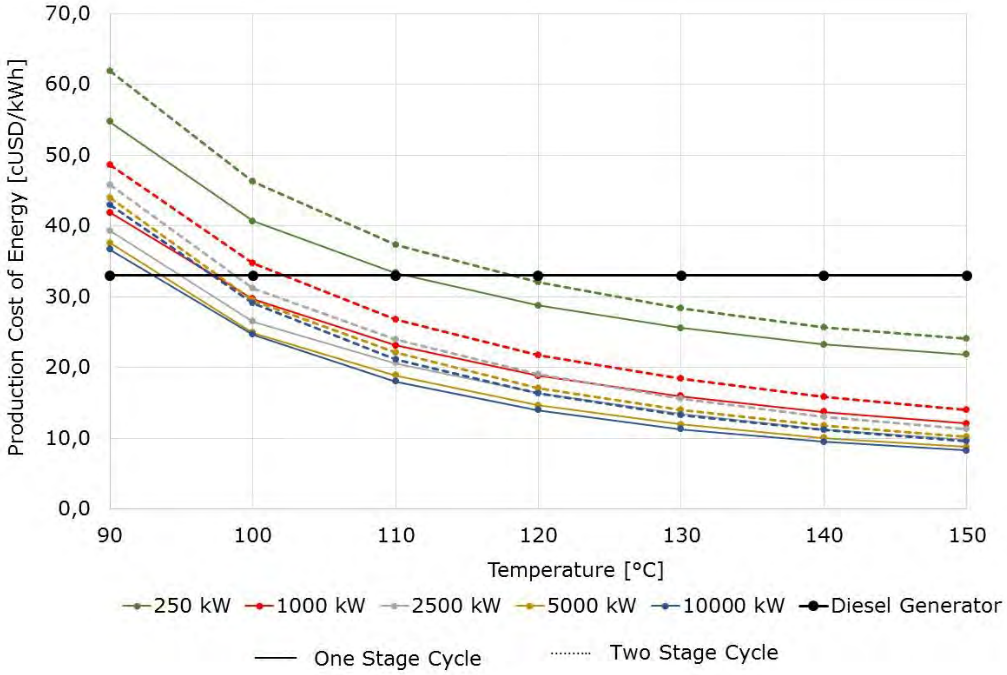


Figure 5 **Comparison of total production cost per net kWh produced in a binary plant and the corresponding cost for each kWh produced in a diesel plant. The colored lines indicate the generator size (gross product).**

Figure 6 shows the operation cost pr. net kWh in a binary power plant and the corresponding operational cost in a diesel plant. The graph shows that operation of a binary plant costs less than the oil in a diesel plant in all cases expect for a 250 kW plant using 90°C water. Therefore if a diesel plant and a binary plant have been installed it is beneficial to produce as much electricity as possible in the binary plant.

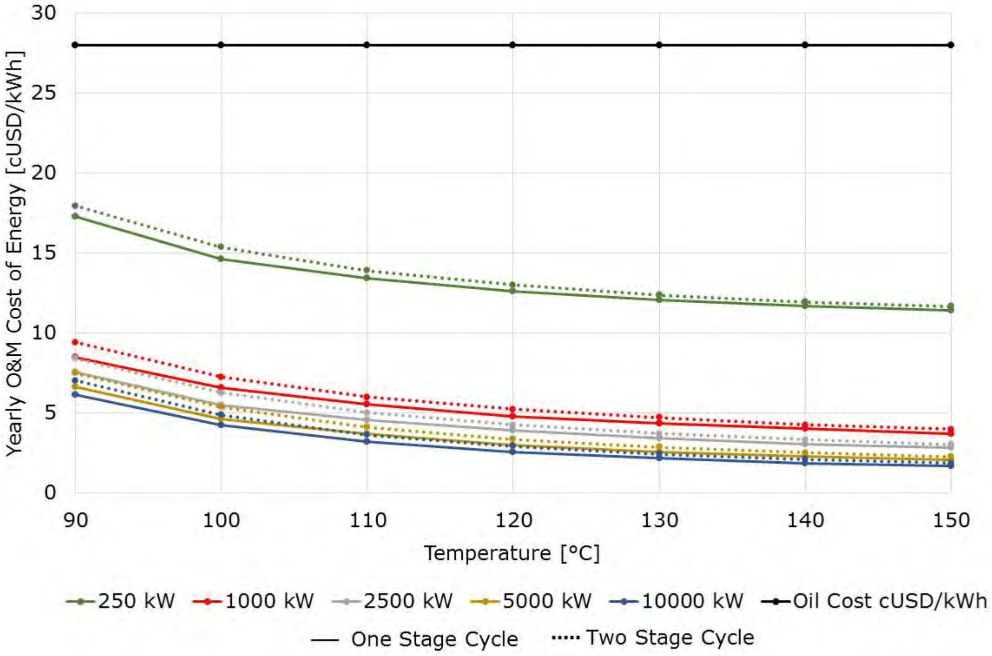


Figure 6 **Operation cost per net kWh in a binary plant and the corresponding operational cost of a diesel plant. The colored lines indicate the generator size (gross product).**

The power delivered to the grid is the net power minus the power needed for pumping of wells.

In Figure 7 it is shown how water level and pumping depth affect the production cost. The price is higher as the water level is lower as more energy is required to drive the pumps, thus leaving less electricity to be sold.

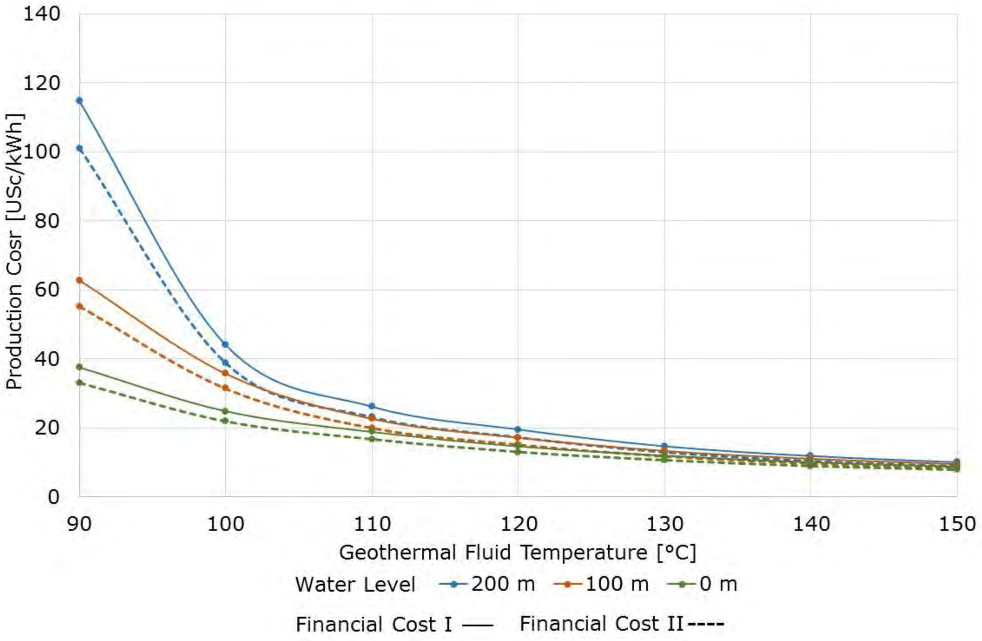


Figure 7 **Effect of water level and well pumping on production cost of energy delivered to the grid in a 5 MW plant. The colored lines indicate the water level depth.**

Figure 8 shows the cost of power to the grid for the base case defined in Table 5-1. The pumping depth is 200 m and the water level at 150 m.

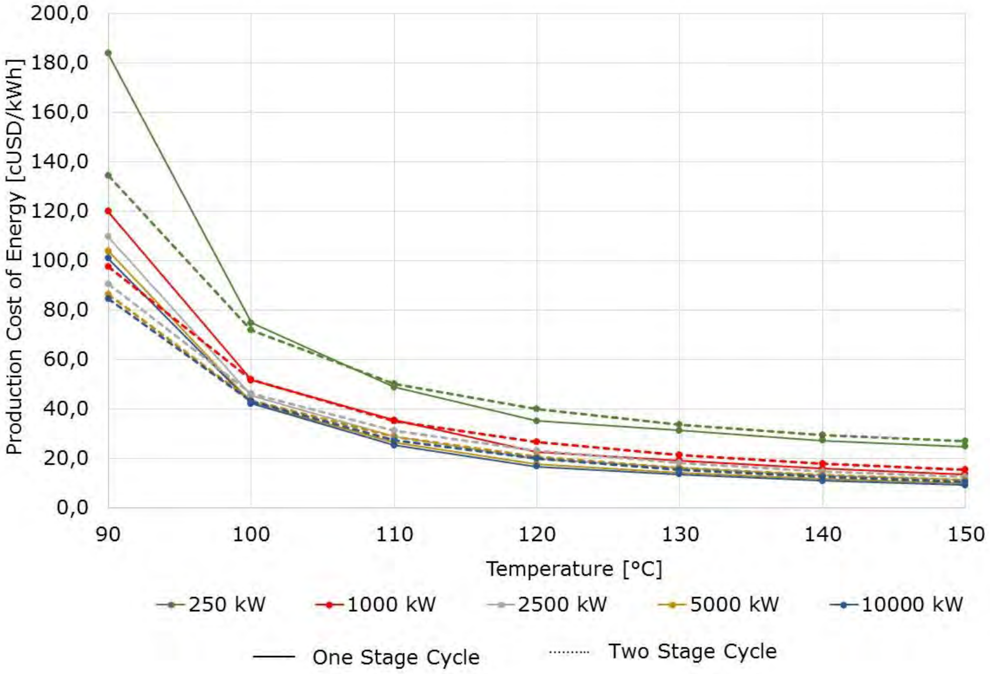


Figure 8 Production cost of electricity delivered to the grid for a case where the well pumping depth is 200 m and the water level at 150 m.

Contents

List of figures

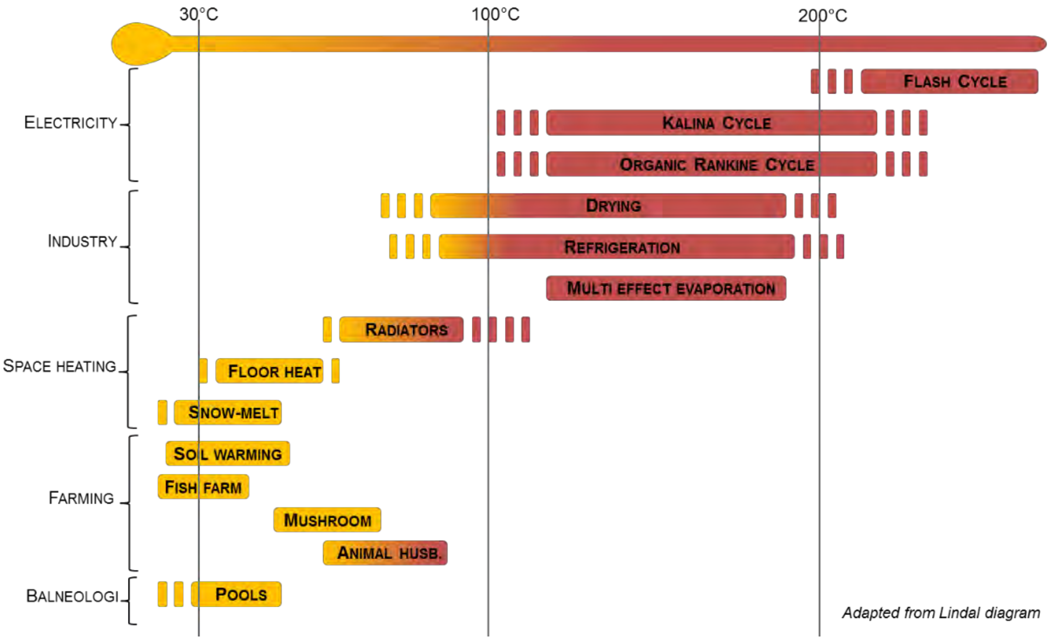
List of tables

1 Introduction

This report was prepared in November 2013 - September 2014 by Verkís Consulting Engineers and is funded by the Icelandic International Development Agency (ICEIDA). It is intended to contribute to discussions on the possibilities for electricity generation from geothermal resources in East Africa Rift Valley States, as a part of the ICEIDA and NDF funded Geothermal Exploration Project. The objective is to explore the feasibility, and factors that influence feasibility, of electricity production from binary power plants in the context of low temperature (<150°C) geothermal areas, providing a reference point for further discussions once the resource potentials in the various countries are recognized.

1.1 Geothermal energy and the binary technology

Geothermal energy is thermal energy which is generated and stored in the Earth. Utilization of geothermal resources has been known for over 2000 years. The utilization of geothermal energy depends highly on the resource temperature as is shown in Figure 1-1 below.



Adapted from Lindal diagram

Figure 1-1 Geothermal utilization (adapted from the Lindal diagram)

Geothermal resources are usually divided into two categories:

- Low temperature <150°C at the depth of 1000 m.
- Intermediate-temperature 150-200 °C at depth of 1000 m.
- High-temperature >200°C at the depth of 1000 m.

Figure 1-1 shows the Lindal diagram where utilization at different resource temperature is presented. Utilization of geothermal water 20 – 50°C for bathing has been well known for ages. Geothermal water at temperature 50 – 100°C is well suited for space heating and as tap water. Water in the same temperature range is also suitable in various kinds of farming, green houses etc.

The utilization of geothermal energy for the generation of electricity is more recent, with the first geothermal power plant established in 1904 in Lardarello.High temperature resources are suitable for generation of electricity by steam condensing turbines, i.e. similar types of turbines as in conventional coal and oil fired power plants. The technology for harnessing geothermal energy is now considered mature and geothermal energy offers nowadays one of the most competitive sources of renewable energy. As a result, the world installed geothermal power capacity has increased rapidly over the past decade and in 2012, installed geothermal power plant production capacity in the world was approximately 11.200 MW (Jennejohn, Hines, Gawell, & Blodgett, 2012). Contribution from geothermal steam condensing power plants to energy production worldwide is expected to grow significantly in the next 20 years. The locations of such plants will however be limited to high temperature areas, i.e. where the temperature of the geothermal resource is higher than 200°C. Medium to low temperature geothermal fields, with temperatures between 100°C and 200°C, can be found all over the world. Such fields cannot be utilized for power generation with steam condensing turbines. However binary technology has opened up new opportunities for producing electricity from low and medium temperature geothermal fluids. The technology is based on the use of a working fluid with a low boiling point where the geothermal water is used to heat up the organic fluid.

The first binary units for generation of electricity by geothermal resources were installed around 1980. The production cost in binary plants is higher than that of conventional steam plants and therefore such power plants have long been uncompetitive compared to coal and oil fired plants. However, both conventional and binary production technology have recently become more competitive due to higher energy prices and subsidies to electricity production from geothermal resources.

Geothermal fluid at temperatures as low as 75°C can be used in binary power plants. The binary cycle technology is also a viable option where the chemical composition of the geothermal brine is not suitable for direct use in steam turbines. The use of binary cycles has also increased in high temperature geothermal field where reinjection of geothermal fluid is essential to manage the reservoir over time or if reinjection is mandatory.

Low temperature fields are more common than high temperature fields and often more accessible and/or closer to potential end-users. Binary technology is expected to play a significant part in the future development of power generation from geothermal resources. Binary units can be as small as 250 kW and can even be provided as container modules, contributing to reduced risks related to the geothermal resource.

Utilization of the binary technology for production of power from geothermal energy is therefore an option worth assessing for project developers having medium or low temperature geothermal resource fields in their portfolio. This report is meant to explore this option.

Report context and case study

High temperature fields with great potential for electricity generation with steam turbines can be found in the northern part of the Great Rift Valley in East Africa, Djibouti, Ethiopia, Eritrea and Kenya. Geothermal fields with lower temperature are located in the south-western part of the Rift Valley and might be suitable for power production from binary cycles given that the temperature and size of the reservoirs are sufficient.

The Icelandic International Development Agency (ICEIDA) and the Nordic Development Fund (NDF) launched in 2012 a project to support geothermal exploration in East Africa. The report has been prepared in this context.

The report features a case study where the temperature of the geothermal resources and the plant production capacity are variable parameters. The geothermal resource parameter range selected is 90-150°C and the production capacity (installed generator capacity) varies from 250 kW – 10 MW.

The report is structured to present an overview of the main elements of a geothermal binary power project and present results from the case study:

- Overview of the binary technology
- Description of the main elements of a geothermal binary power plant project
- Process Diagrams
- Capital Cost Estimate
- Operation and Production cost estimate
- Environmental and risk management
- Project implementation

For clarification, a few definitions are convenient to keep in mind while reading the report:

Gross Power is the rated generated power produced, generator size.

Net Power is the power from the power plant left when the plants own consumption (parasitic loads) has been substracted from the gross power (does not include well pumping).

Power to the grid is the net power produced by the power plant where the well pumping power has also been subtracted.

2 Overview of the binary technology

In this chapter a general description of the binary power plant cycle and the design premises used in the case study are described. The chapter also covers the main factors, plant parameters and environmental conditions, which may affect the cost and efficiency of the plants.

2.1 Binary Process Description

The binary technology allows for production of electricity from low temperature resources that otherwise could not be used 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. It vaporizes in a closed-loop a working fluid that is then used 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 90-200°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 (ORC) technology is commonly used for electricity production from low enthalpy reservoirs or for bottoming plants in steam power plants. Most of the geothermal binary cycle power plants currently in operation in the world are of the ORC type.

Figure 2-1 below features the most basic binary cycle. The diagram describes a single stage ORC cycle with an air cooled condenser.

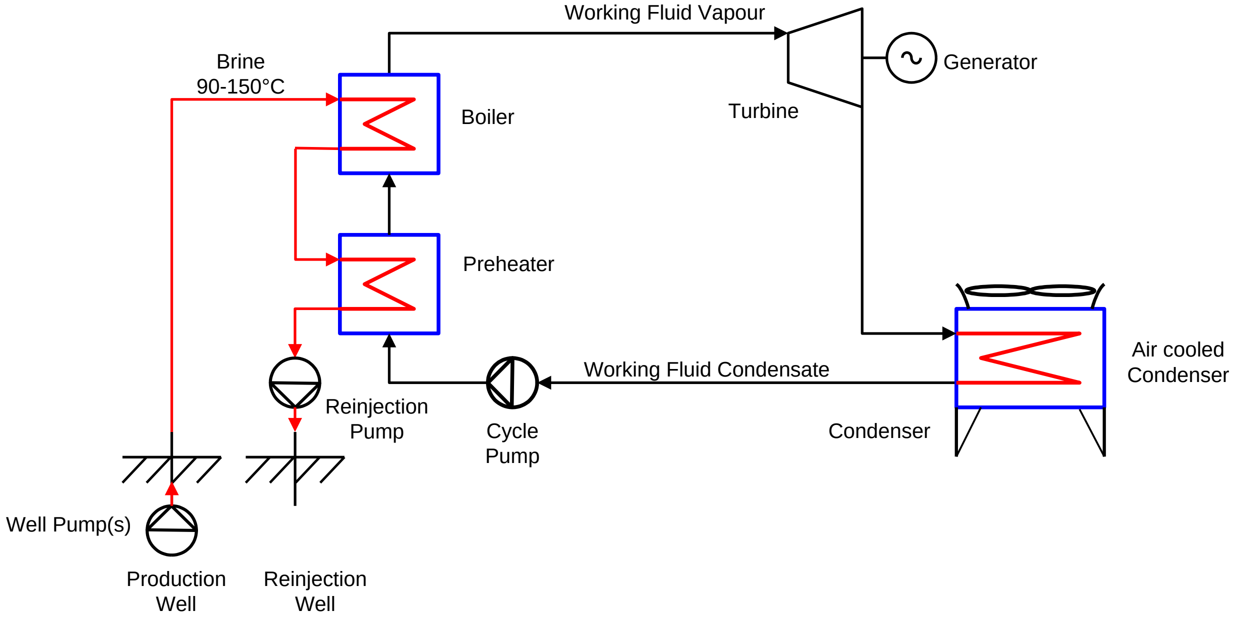


Figure 2-1 Single stage ORC cycle

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 and is presented in Figure 3

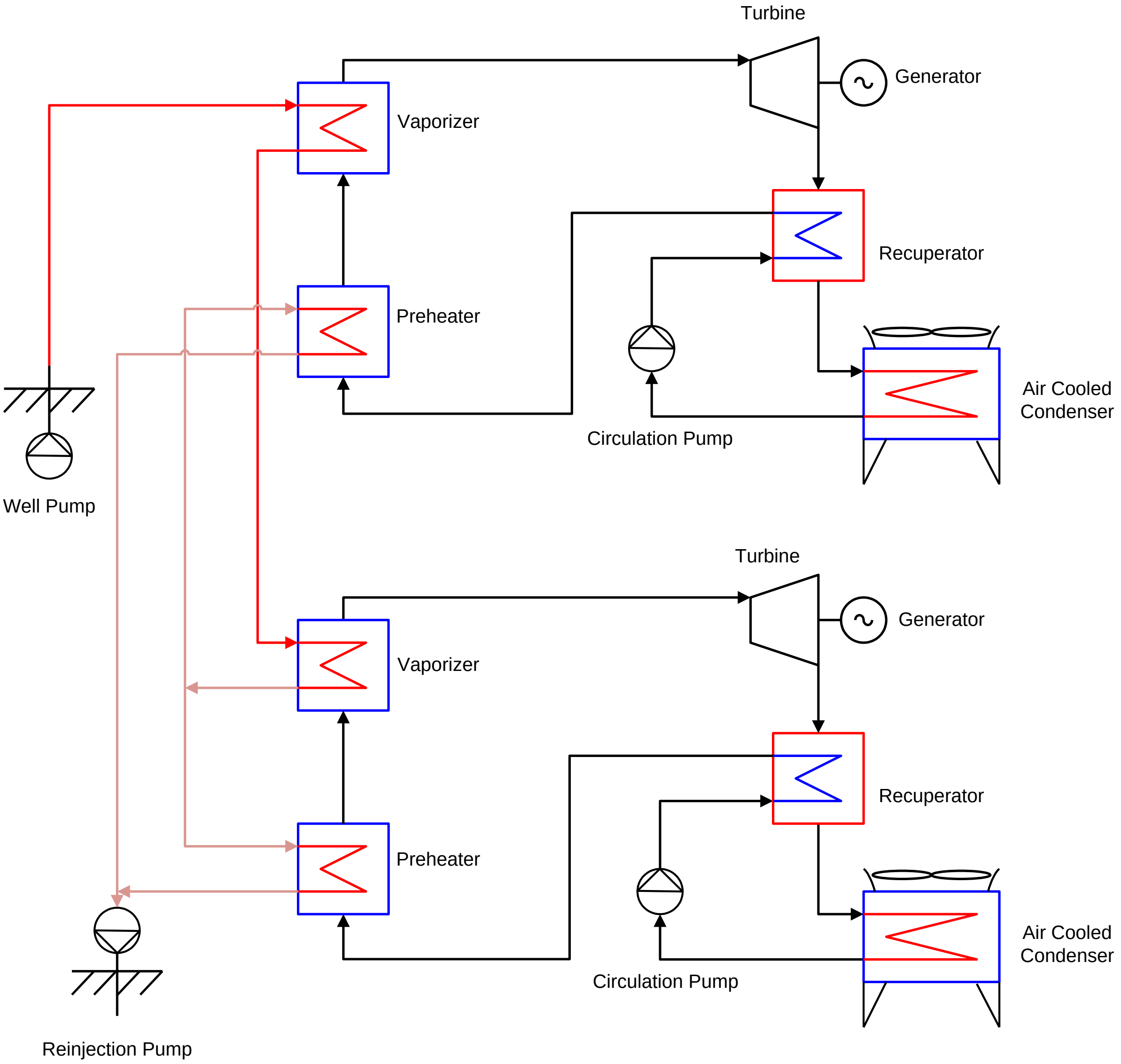


Figure 2-2 Two stage ORC cycle with an air cooled condenser

The Kalina cycle 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.

2.2 Case study

The report covers 5 different plant sizes defined as generator net outputs,

- 250 kW
- 1000 kW
- 2500 kW
- 5000 kW
- 10000 kW

Each plant was simulated with different geothermal fluid temperatures

- 90°C
- 100°C
- 110°C
- 120°C
- 130°C
- 150°C

Part of the generator net output is required for the plant's own consumption. In wells which require pumping power, requirements can vary between locations. Effects of well pumping on production will be introduced in chapter 7.3 for a 5 MW_{gross} plant.

The working cycles were optimized so as to use as little geothermal fluid as possible. Heat loss in well field piping is neglected in the calculations.

The working fluid used in the calculations is isopentane, which is the most common working fluid used in binary applications.

It was decided to use air cooled condensers as a base case in this study although water cooling is the best cooling source if it is available. The reason is that access to cooling water in remote areas can be costly in terms of installation costs and energy demand, especially when pumping is required and access to water might also be limited or restricted in the areas chosen.

The ambient temperature chosen for the case study is 30°C and the effect of temperature fluctuations between day and night is neglected.

3 Geothermal field

As in all geothermal projects, the characteristics of the geothermal resource are fundamental issues for binary power plants and will be the basis for the design of the power plant. Detailed investigations of the geothermal field before decision making is therefore of utmost importance.

An investigation starts with surface exploration followed by test drilling. Geothermal exploration has to be carried out before drilling can start. 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.

3.1 Geothermal Exploration

The exploration phase is extremely important for evaluation of the field capacity and successful siting of wells. The exploration process might be lengthy but is relatively cheap compared to drilling and the construction of a plant. The phases related to identification and exploration of the geothermal field are aimed at confirming the existence of a geothermal reservoir suitable for power production. This subject will not be discussed any further here as it is not directly related to binary technology. As described in section 7.1 on project development phases and planning, the bankability of the project will be assessed during these phases since the extent, characteristics and expected output of the geothermal resource are key elements for the project.

Geothermal exploration has to be carried out before drilling can start. Geothermal exploration assesses the subsurface of a geothermal area. The goal of the exploration is to estimate the extent of the utilization area, locate permeable fractures, possible production locations and capacity. Major geothermal exploration activities are listed in Table 3-1 (list non exhaustive)

Table 3-1 Geothermal Exploration Summary

Exploration Activity	**Details**
Geological mapping	Mapping of: • Hot springs, fumaroles and other surface manifestations which might indicate geothermal activity • Mapping of strike and dip of lava piles • Mapping of dykes, faults and fissures
Chemical analysis	Chemical analysis of cold groundwater, hot spring water and rocks.
Ground magnetic measurements	To estimate locations of faults and fractures in the rock.
Resistivity measurements	Changes in resistivity in the rock indicating flow lines and distribution of water in the system.
Test drilling	Drilling of temperature gradient wells in an effort to estimate temperature of the reservoir and possible flow rate.
Soil temperature measurements	Indicators of geothermal activity.

3.2 Production Wells

Drilling is one of the most expensive operations in preparing a geothermal power plant. It is also related to the development phase that is the most risky from the financial point of view due to uncertainty in acquiring hot fluid.

The technique of geothermal well drilling is initially adapted from the oil-and gas drilling industry. The depth of conventional high temperature geothermal well varies from 500 to 3000 m and even up to 5.000 m. Most of the wells are 1.000 to 2000 m in depth. 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 temperature drilling is slightly less complicated due to a lower pressure in the reservoir and less risk of steam blowouts during drilling.

Low 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 3-1 below features a typical casing program for a low temperature well, showing the casing structure and levels of depth.

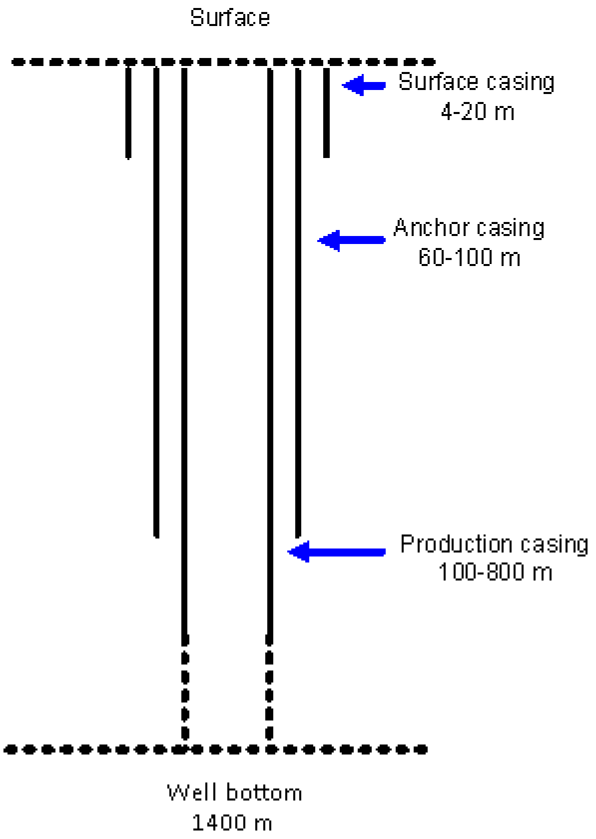


Figure 3-1 Casing program for a low temperature well

On the top of the well are a flange and a valve. The water can either flow freely from the well or require pumping. Flow from a self-flowing well is sometimes enhanced by adding a pumping unit. Well pumps are classified in two categories:

- Submersible pumps
- Deep well pumps (line shaft turbine pump).

Both submersible and deep well 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 in inclined wells.

The motor used in deep well pumps 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. The deep well pumps are suitable at higher temperatures (200°C). Figure 3-2 presents the main components of a deep well pump where the line shaft bearings are lubricated with geothermal water.

In this study, it is assumed that a line shaft deep well pump is used because of the temperature range.

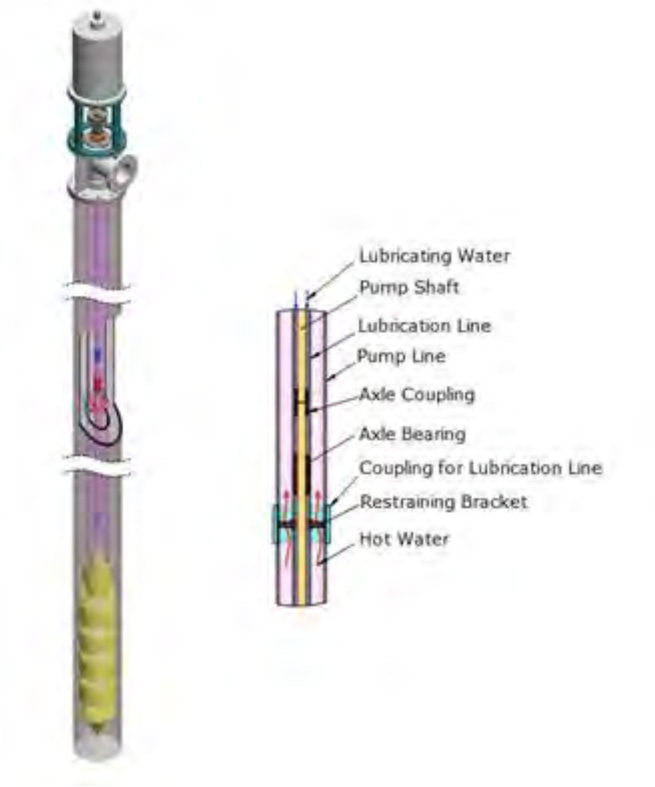


Figure 3-2 Line shaft deep well pump

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. Figure 3-3 shows the effect the pumping height has on the pump power and the net power in a 5 MW power plant with a geothermal resource temperature of 120°C. Increased pumping height results in a decrease in a net output of the plant and an increased startup cost due larger pumps.

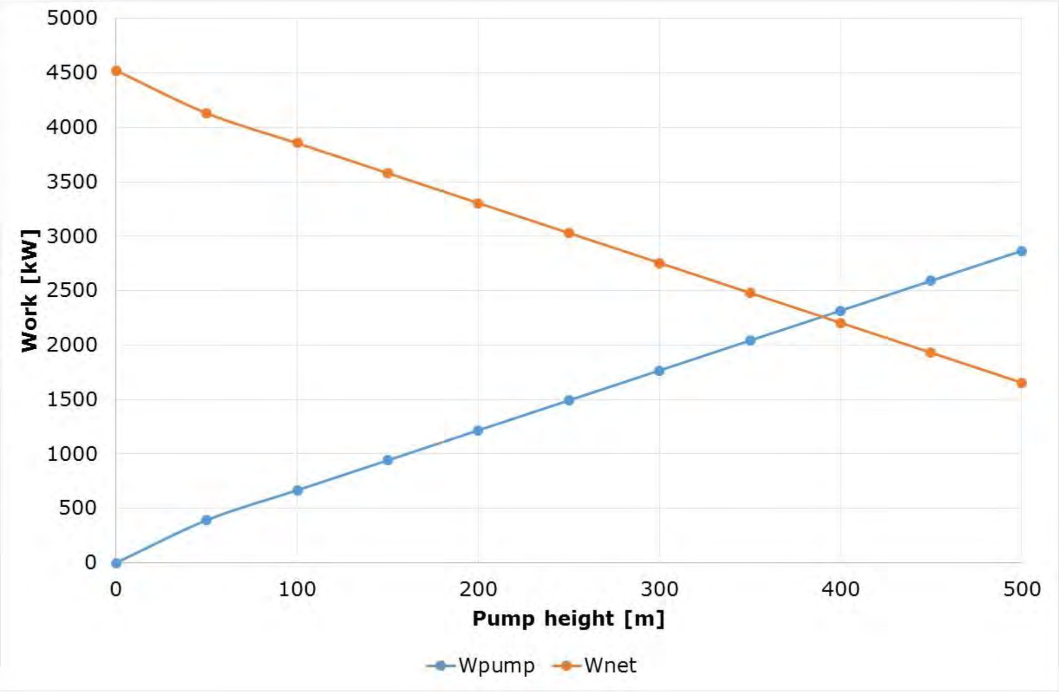


Figure 3-3 Effect of pumping height on net output of 5 MW binary plant. Geothermal resource temperature 120°C.

3.3 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 coming in contact with groundwater.

In some countries reinjection is required by law. In some cases it is necessary to reinject the geothermal fluid due to its chemical composition and the effect of its disposal on nearby ecosystems.

Reinjection wells are similar to production wells. In some places free flow down the reinjection wells is possible whereas it might be necessary to pump the water down elsewhere. Determination of necessary wellhead pressure at the reinjection wells has to be based on exploration and well testing.

3.4 Chemical Composition

The chemical composition of the geothermal water has to be taken into account when designing a geothermal binary power plant. 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.

Geothermal brine usually contains non condensable gases which escape from the brine when the pressure decreases. These gases are commonly, in order of concentration, Carbon dioxide (CO_2), hydrogen sulphide (H_2S), methane (CH_4), hydrogen(H_2), Argon (Ar)and nitrogen (N_2). The escape of the latter two does not affect the acidity of the fluid. A common scaling problem is the formation of calcite. Calcite scale is highly dependent on the pH of the brine which is mostly controlled by the concentrations of CO_2 and H_2S. CO_2 is usually in higher concentration and therefore has a greater effect on the pH. Degassing of CO_2 from the brine increases with lower pressure. Escape of CO_2 from the fluid will elevate the pH, thus inducing the formation of calcite. If the degassing begins inside the production well, the well may clog up and become inoperable and if the pressure in the surface equipment drops below water saturation pressure, the geothermal fluid will boil inside the equipment. The steam and CO_2 are then separated from the fluid, leaving the fluid supersaturated with calcite. The calcite will accumulate in the surface equipment which may result in damage and/or decrease the efficiency of the heat exchangers.

It is technically possible to prevent or minimize calcite scaling. There are three main methods:

- Firstly, alkalinity of the fluid can be reduced by addition of acid.
- Secondly, the pressure can be controlled to avoid degassing of CO_2.
- Thirdly, calcite scaling can be inhibited by addition of specific inhibitors prior to degassing.

The solubility of calcite increases with lower temperature. Therefore calcite scaling in the reinjection system is not likely to become a problem. The situation is different regarding silica scaling where the solubility decreases with lower temperature. High temperature geothermal liquid often has a high silica content. When the geothermal liquid is cooled down it may become supersaturated with consequent scaling problems. The silica content of the geothermal liquid often puts a limit on how much the liquid may be cooled down, i.e. how much energy it is possible to extract from the geothermal resource. For the temperature range dealt with in this report silica scaling is not likely to become a problem.

Proper design and availability of relevant chemical data are key factors to handle scaling and avoid operational problems.

3.5 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 pipes. It results in a lower capital cost and a minimized temperature 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.

4 Power Plant

This section presents the main components of geothermal binary power plants and describes the design premises used in the case study.

A simple layout of a binary power plant is shown in Figure 4-1. This layout describes a single cycle plant which has two turbines and a joint generator in the middle. Double flow turbines are used to minimize the effect of forces on the support which can be a problem with larger single flow turbines where the flow is only in one direction. The large green area represents the air cooled condensers which occupy the largest area of the plant site. A more detailed layout drawing is shown in Appendix A.

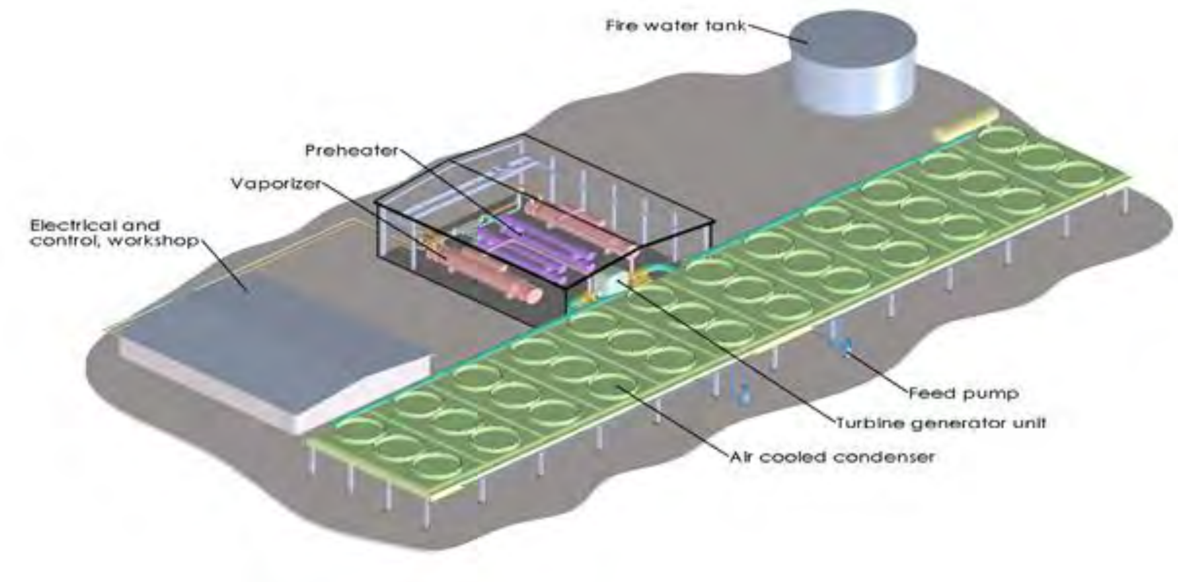


Figure 4-1 Typical layout of a 10 MW two stage cycle binary power plant

4.1 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.

4.2 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 7,5°C has been assumed to reflect the most common value used for binary plants

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.

4.3 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. As introduced in section 9, there are more and more equipment manufacturers able to supply binary plants.

The choice of material depends on the working fluid used in the loop. The case study features relatively small plants ranging from 250 to 10.000 kW. 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. Single flow is usually considered sufficient for smaller power plants. Double flow turbines are often used for larger plants and have the advantage of allowing for shutdown of one inlet without a complete production shutdown. It is common to have two turbines to drive one generator installed on one shaft between the turbines for binary plants larger than 5 MW.

4.4 Working Media

The boiling point of the working fluid in an ORC cycle has to be lower than the temperature of the geothermal fluid. The most common working fluids used for binary application are hydrocarbons such as isopentane and isobutane. Others include ammonia, R134a and R245fa, the last two being hydrofluorcarbons well known in the refrigeration industry as they are mainly used in refrigeration equipment.

In Figure 3.2 a comparison of fluids is shown, for each fluid the process is optimized for maximum net output in a 5 MW plant.

Isopentane and isobutane are the most widely used organic working fluids for binary applications despite their high flammability.

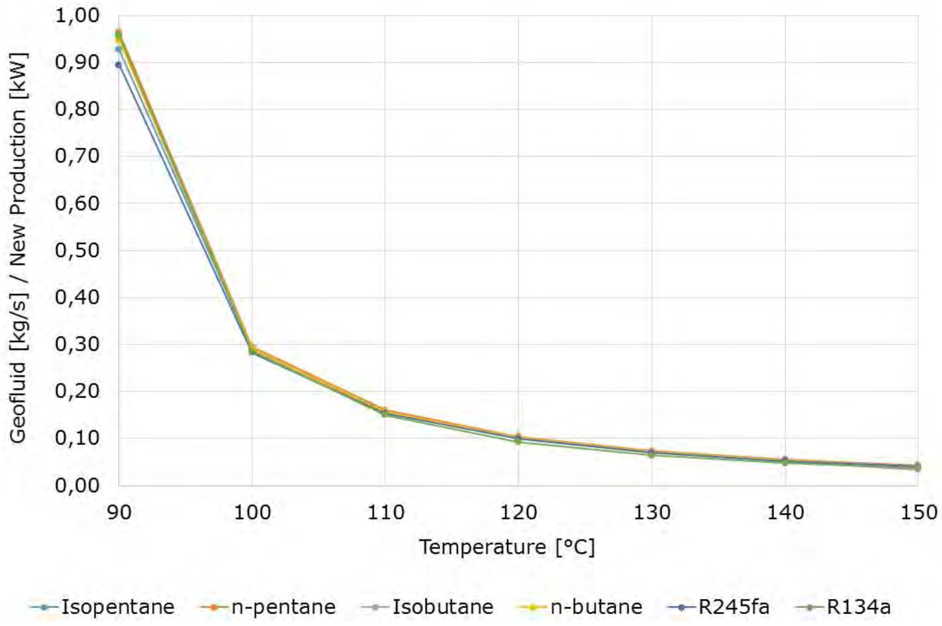


Figure 4-2 Working fluid comparison

4.5 Cooling Systems

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.

4.5.1 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. Their function is hampered during hot summer days when humidity is low. 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 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 wet 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.

4.5.2 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. In order 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.

A binary plant with direct water cooling will heat up the cooling water by 15°C and use 90 l/s pr. MW. If enough water is available and it is allowed to release it to the surroundings at additional 15°C, direct water cooling is the most economically feasible cooling method.

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 take into account 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 despite the fact that it is not very effective in warm areas.

4.6 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 9-15% depending on size and equipment quality. The efficiency decreases as the source temperature decreases. As explained in section 4.5, 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.

Keeping the pressure drop over the turbine as high as possible without excessive use of geothermal fluid is one of the most important parameters impacting the power plant efficiency. Excessive use of geothermal fluid compared to the plant output may imply high pumping power from the production wells or for reinjection, resulting in uneconomical operation of the plant.

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%

4.7 Auxiliary systems

Presence of hydrogen sulfide H_2S is often a problem in geothermal areas due to its effect on the electrical equipment. In order to limit the effect of H_2S 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.

4.8 Electricals and Controls

4.8.1 Generator

The turbine generator in geothermal power plants are generally, three phase, 2 pole, synchronous 50 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 be able to 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 4-3.

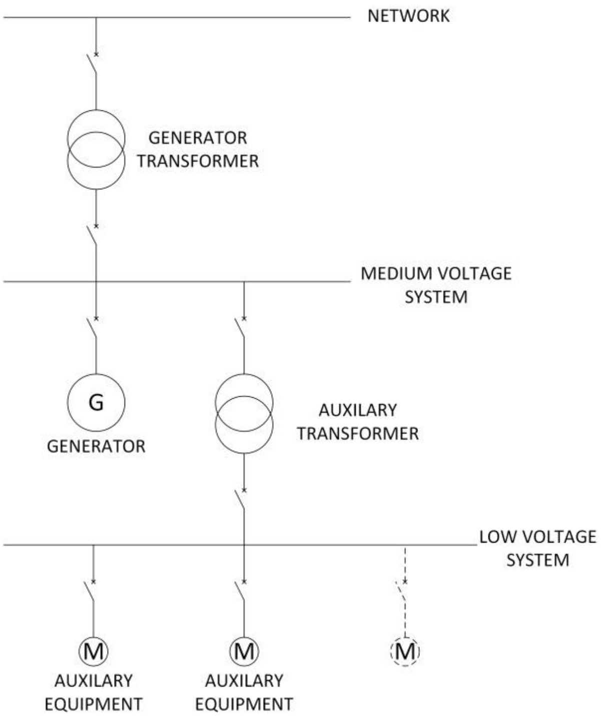


Figure 4-3 Basic layout of electrical equipment

4.8.2 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.

4.8.3 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.

4.8.4 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.

4.8.5 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.

4.8.6 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 and etc. are protected against overload and breakdown.

4.9 Plant Electrical Production Options

The requirements to the control of the electrical production are dependent on the type of electrical network the generator is connected to. It is assumed that there could be three types of electrical networks the plant would be connected to:

- Parallel operation with a large and stable network (National or regional grid). The plant is then normally operating at full output.
- Island operation where the plant is alone supplying electricity to a small isolated network, small town or a village. The plant is operating with variable output depending on the network load.
- Parallel operation with diesel generators. This could apply to small networks with diesel generators already installed. The plant is operating at full or partial loads.

For a binary plant the most feasible operating mode is parallel operating with a large strong network where the network takes care of frequency control and reactive power control. The plant can be continuously operated at full output. This operating mode does not require fast and accurate speed and load control. As the plant output is constant, the binary media and heat input will also be quite stable.

There are mainly four parameters that determine the electrical output of a binary plant:

- The heat input to the binary media from wells by brine or steam. This is controlled by well pumps, control valves and in some cases reinjection pumps.
- Evaporation of binary media. To keep a constant turbine inlet pressure the binary system has to control the heat input to the evaporators and release the excess heat in the binary media directly to the air cooled condensers.
- Opening of turbine inlet valves controls the power output of the generator and speed when running in an island operation (frequency control).
- Generator excitation current controls the generator voltage and reactive power.

Island operation is the least feasible operating mode for a binary plant as the plant output is continuously changing with the load. Sudden load changes affect all four parameters mentioned above. The thermal systems, encompassing both the geothermal fluid and the working fluid, must therefore always operate with extra capacity to be able to quickly react to load changes. Binary plants are furthermore not able to start up without external power for their auxiliaries. In practice the binary power plant is proven to be most suitable for generating base load power.

A combination of binary plants and diesel generators could be an attractive solution for small isolated networks. In this case the binary plants would generate base load power and the diesel generators would handle the load changes and frequency control thanks to their ability to respond quickly to changes. This could in practice be implemented by coordinating the governor control of the binary plant and diesel generator. The layout of a binary plant and diesel generator combination can be seen in Figure 4-4.

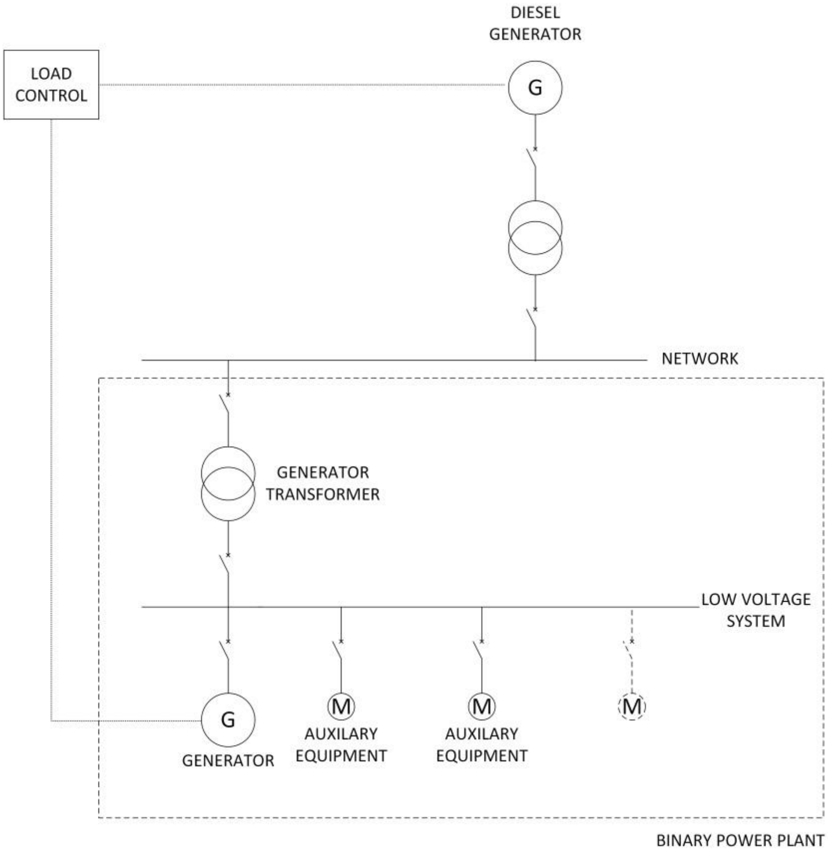


Figure 4-4 Binary plant and diesel generator combination

Key findings:

It is recommended to operate the plant in parallel with a strong network or in a smaller isolated network in combination with a diesel generator. Island operation is not regarded suitable for a binary power plant.

4.10 Buildings and Roads

Geothermal fields are often far from developed areas and often in rugged volcanic terrains. This requires site preparation before drilling can begin. Drill site preparation involves construction of roads that can carry heavy equipment and handle transportation of employees on site. The drill pad can be a few dozen meters long.

It is assumed for the case study that the turbine will be located in a weather shield and the electrical equipment is situated in a container or a building close to the turbine.

Figure 4-5 Weather shield over a turbine at the Olkaria field in Kenya

Service facilities will also be included in the container. Service facilities include an operation station with office space for operators, sanitary facilities and storage for spare parts. Air cooled condensers will be located on a concrete basin. The whole area will be fenced off to shield it from animals and fend off trespassers.

Figure 4-6 presents a simple binary plant layout with 150°C geothermal fluid and 10 MW installed power. The layout is also included in Appendix A.

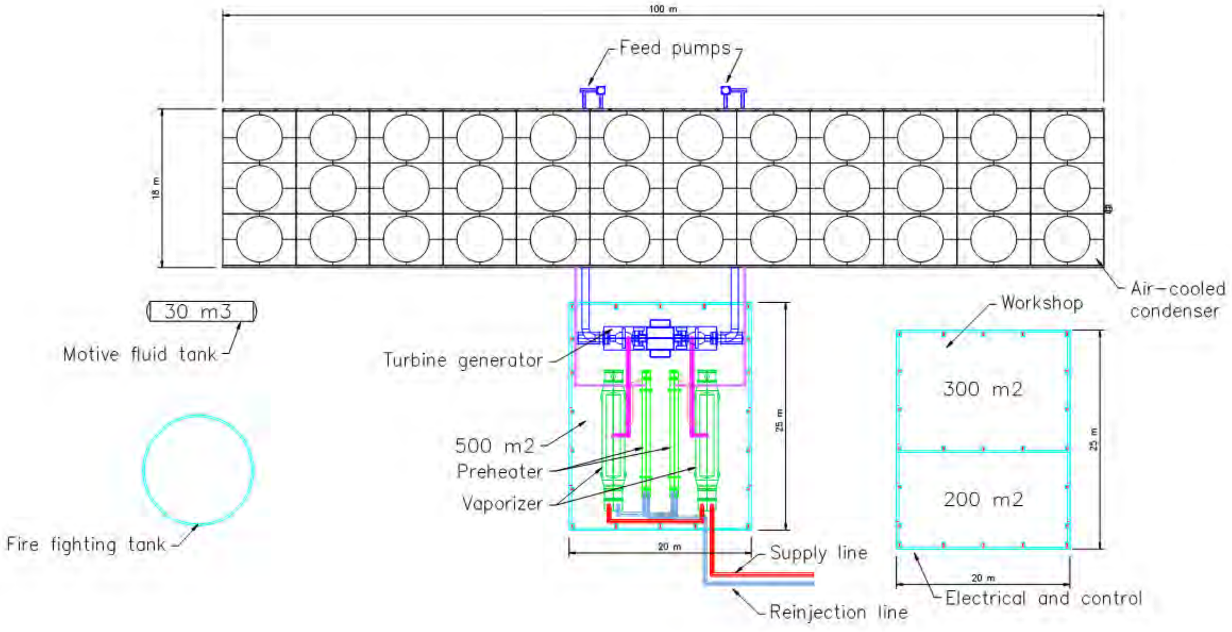


Figure 4-6 Simple layout of a 10 MW plant, 150°C geothermal fluid.

5 Process diagram

The results of a heat and mass balance calculation for the case study are presented here. The design premises are listed in Table 5-1.The vaporizer pressure is optimized using the method of quadratic approximations where the process is optimized for minimum uptake of geothermal fluid in order to minimize the required well pump size and deliver the highest net output

Table 5-1 Design premise of the ORC cycles.

Design parameter	Units	Value
Geothermal fluid temperature	°C	90,100,110,120,130,140,150
Well depth	m	1400
Water level depth	m	150
Generator output	kW	250, 1000, 2500, 5000, 10000
Isentropic efficiency of the turbine	%	80
Generator efficiency	%	95
Cycle pump efficiency	%	70
Air cooled condenser fan efficiency	%	60
Outdoor temperature	°C	30

5.1 Single Stage ORC Cycle

A sample of a heat and mass balance diagram used in the calculations is shown in Figure 5-1.

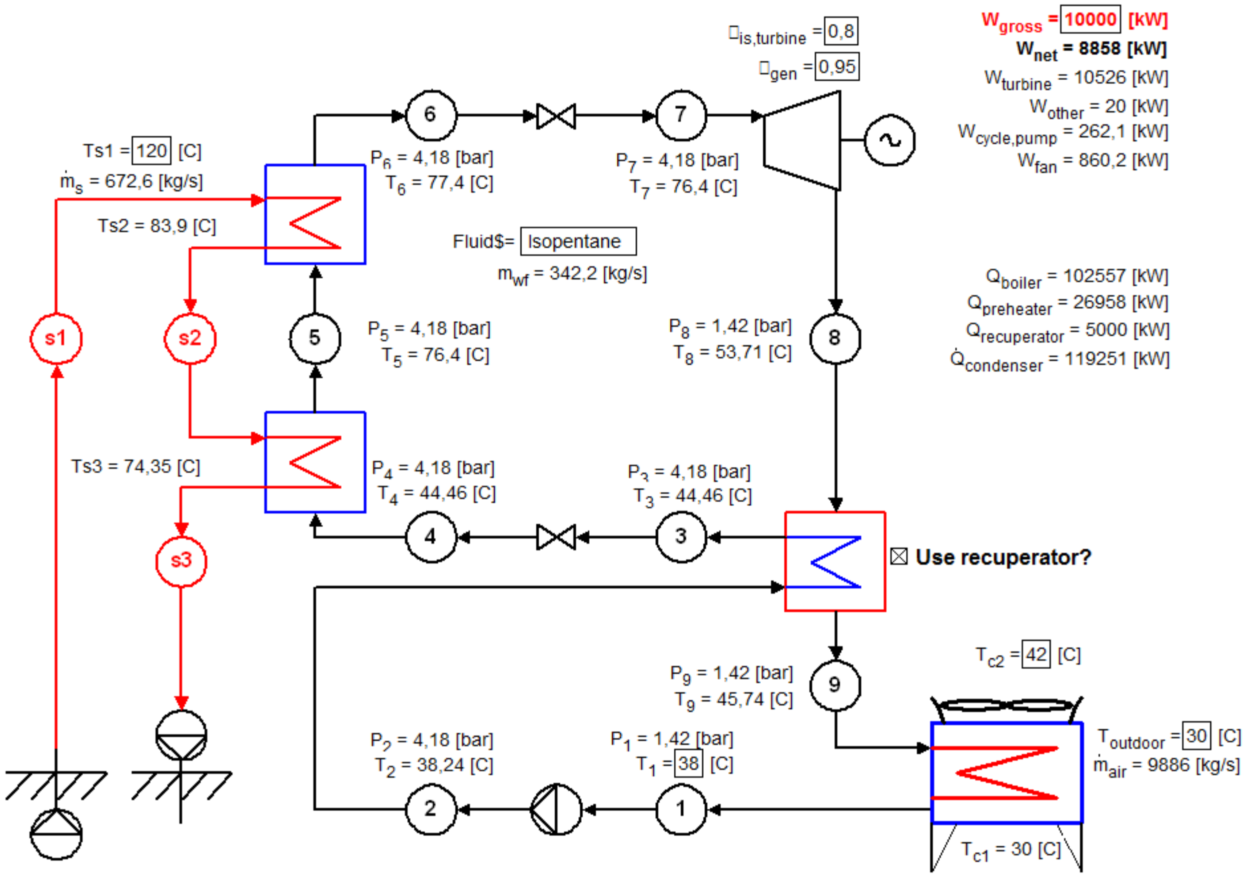


Figure 5-1 Heat and mass balance diagram of a 10 MW single stage ORC cycle. Geothermal fluid temperature is 120°C.

Details concerning the case study simulations and the amount (mass flow) of geothermal fluid needed for generation of electricity at temperatures 90°C, 100°C, 110°C, 120°C, 130°C, 140°C and 150°C respectively are presented in Appendix B. The tables also show various parameters in the process cycle and the electricity delivered to the grid (net power production)

The net power delivered to the grid and accordingly the economy of the power production depends highly on the temperature of the geothermal fluid. A guideline for the economy may be to have at least 50% of generated power as net power. Other factors that influence the efficiency of the plants are:

- Size of the plant
- Depth to water level and pumping requirements.
- Cooling technology and ambient temperature.

As shown in Table 5-1 the water level is assumed to be at 150 m depth, outdoor temperature 30°C and air cooling. The net production under these conditions is shown in Figure 5-3

5.2 Two-Stage Cycle

A sample of a heat and mass balance diagram used in the calculations is shown in Figure 5-2.

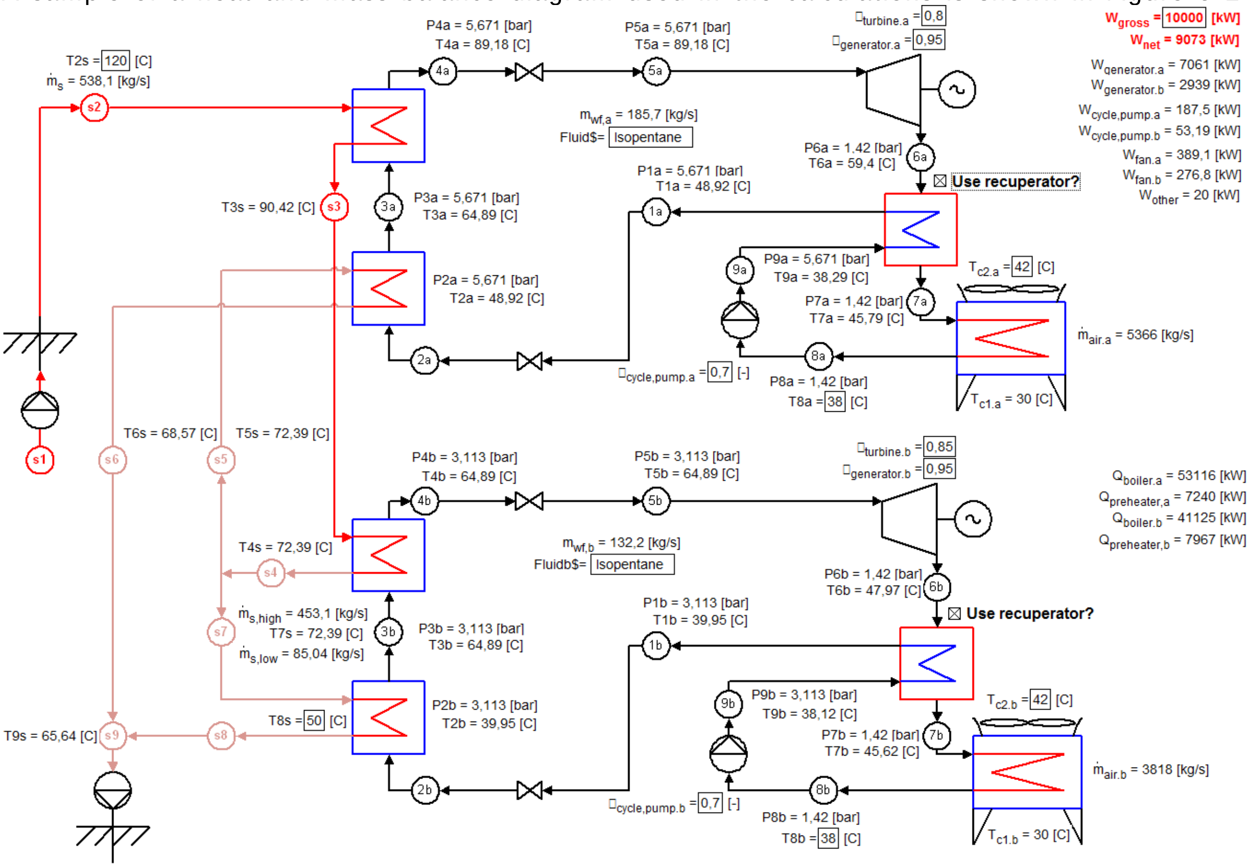


Figure 5-2 Heat and mass balance diagram for a 10 MW two stage ORC cycle. Geothermal fluid temperature is 120°C.

Details concerning the case study simulations and the amount (mass flow) of geothermal fluid needed for generation of electricity at temperatures 90°C, 100°C, 110°C, 120°C, 130°C, 140°C and 150°C respectively with a two stage ORC cycle are presented in Appendix B.

5.3 Results

The net power is the power remaining when parasitic loads of the plant itself have been subtracted from the total generated power. In Figure 5-3, the net power is plotted against temperature of the heat source for each generator unit.

It is likely that utilization of water at this temperature for power production will only be feasible if the water flow is artesian and the energy price is very high or feeds in tariffs are available from governmental organizations.

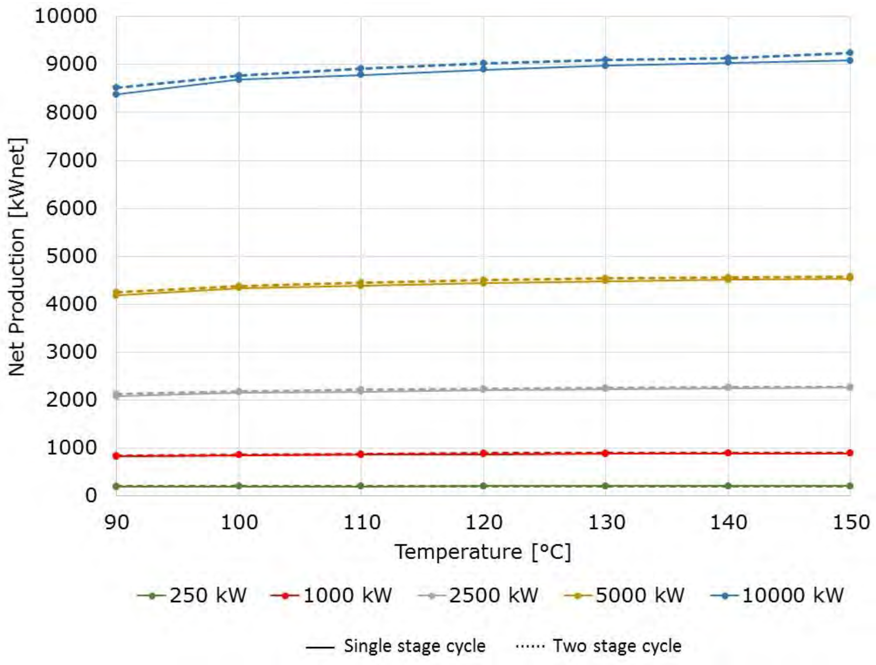


Figure 5-3 Net power as a function of temperature. The colored lines indicate the generator size (gross product)

In Figure 5-4 the mass flow of geothermal fluid required for each unit is shown for both working cycles. The thermal efficiency of the two stage cycle is greater than efficiency of the single stage cycle. The mass flow of geothermal fluid required in the two stage cycle is lower and also the reinjection temperature.

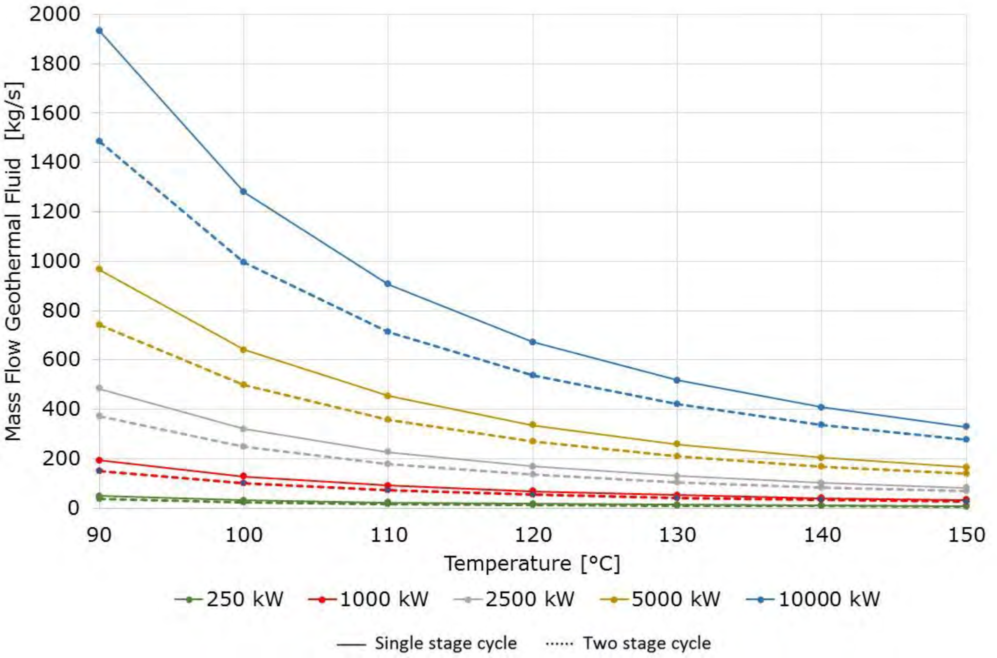


Figure 5-4 **Mass flow of geothermal fluid in kg/s required per each unit. The colored lines indicate the generator size (gross product)**

The ratio of net power to generated power is higher in the two stage cycle, due to a more efficient use of geothermal fluid. If pumping is required to extract water from the well, the ratio between net power and generated power is lowered due to power consumed by the well pump. It is possible to increase the overall efficiency, and therefore the net power sale, by gaining access to a better cooling system. If accessible, direct cooling with water from a nearby river will likely provide better cooling than the air cooled condenser.

6 Capital Cost Estimate

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

The following cost items were not assessed for the 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 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 October 2013.

The case study currency is US dollars (USD).

6.1 Geothermal Field – cost estimates

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 set forth in consultation with Iceland GeoSurvey, ISOR:

Depth of wells:	1.400 m.
Average output from each well:	40 l/s.
Depth of water level in wells:	150 m.
Line shaft pump installed at:	200 m depth.
Average distance between wells:	250 m.

- One reinjection well will be drilled for each 2 production wells.

Table 6-1 below presents the detailed cost estimates for individual wells, including supply and installation of a line shaft pump.

Table 6-1 Capital cost of individual well, incl. pump

Item	**Total (MUSD)**
Well, 1.400 m deep	2,00
Line shaft pump	0,25
Miscellaneous, 15%	0,20
Design, supervision, commissioning	0,15
Total, one well	**2,60**

Cost of exploration of geothermal fields varies a lot. The average cost of exploration of harnessed geothermal fields is assumed to be included in the figure above. The cost of exploration of unsuccessful fields is not included and has to be handled as a sunken cost.

The average cost for a gathering system is estimated 80.000 USD pr. well.

Table 6-2 proposes cost estimates related to the geothermal field for 40 l/s supplied for production to the binary power plant. The cost estimates are given for the base case, 40 l/s, and cover the production and reinjection wells and piping required for each production well as defined in the case study.

Table 6-2 Capital cost for 40 l/s supplied from the geothermal field

Item	**Total (MUSD)**
1 production well with installed pump	2,60
0,5 reinjection well	1,30
Gathering system	0,08
Reinjection system	0,04
Total, for 40 l/s	**4,02**

On this basis, the case study will use the total capital cost for the geothermal field development: 100.500 USD per l/s supplied from the geothermal field

The cost estimates above are assumed to be independent of the temperature of the geothermal fluid assessed in the case study, or 90°C – 150°C.

Figure 6-1 and Figure 6-2 show the cost of field development (wells and gathering system) pr. net kW generated in the power plant, for different plant sizes and resource temperature, for a single stage cycle and a 2 stage cycle respectively.

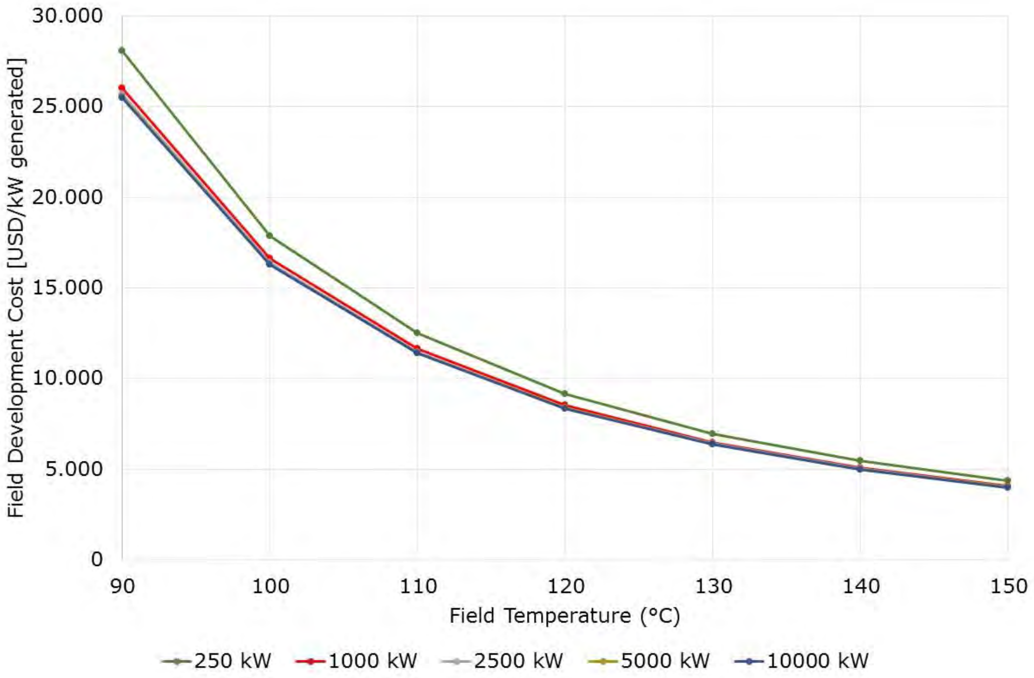


Figure 6-1 Cost of field development per net kW generated - single stage cycle. The colored lines indicate the generator size (gross product).

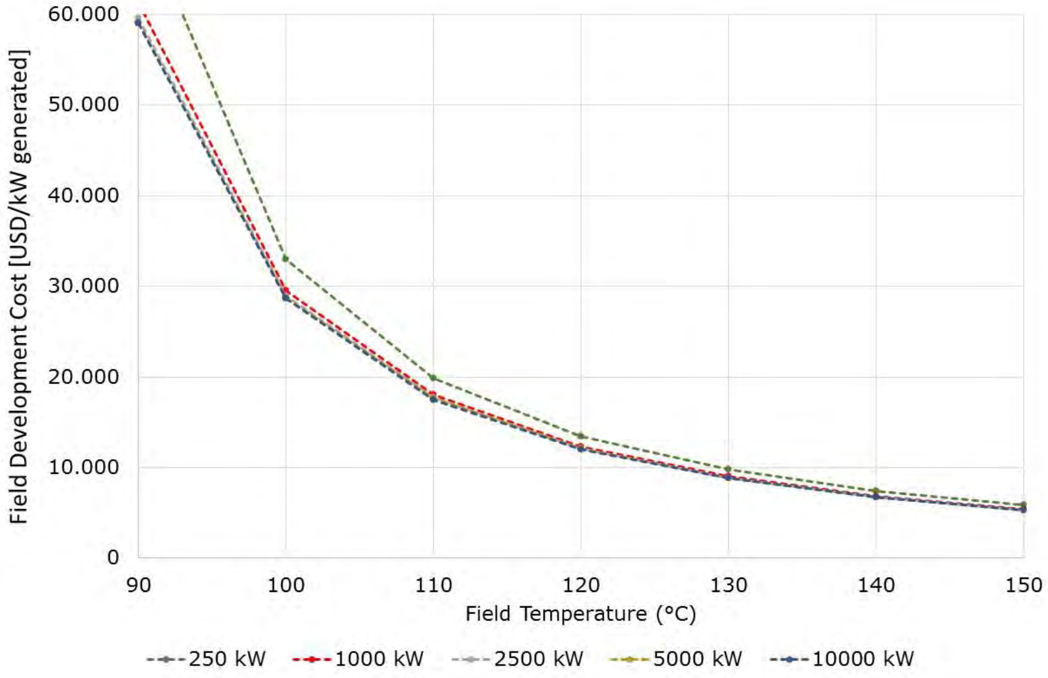


Figure 6-2 **Cost of field development per net kW generated - two stage cycle. The colored lines indicate the generator size (gross product).**

The cost calculation is based on a calculated mass flow of geothermal fluid according to previous sections and a unit price pr. l/s 100.500 USD. As may be expected the cost goes significantly down as the temperature goes up. The cost of net power for the field development is also lower for a large unit compared to small one due to higher efficiency.

As mentioned before the cost may vary a lot from one place to another. As a rough estimate, deviation up to ± 50% from the calculated base cost is to be expected.

Details of the field development costs pr. kW are provided for both installed generator power and net power in appendix C.

6.2 Cost of 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 6-3 below.

Table 6-3 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

Figure 6-3 and Figure 6-4 show the power plant cost pr. net kW generated, for different plant sizes and resource temperature, for a single stage cycle and a 2 stage cycle respectively.

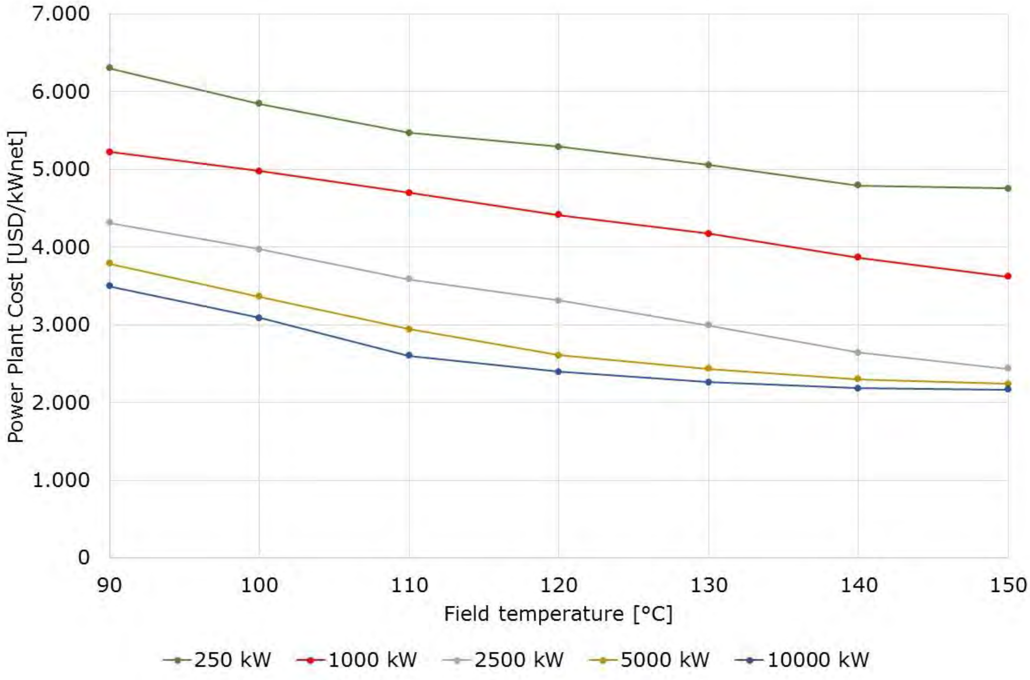


Figure 6-3 **Cost of power plant per net kW generated - single stage cycle. The colored lines indicate the generator size (gross product).**

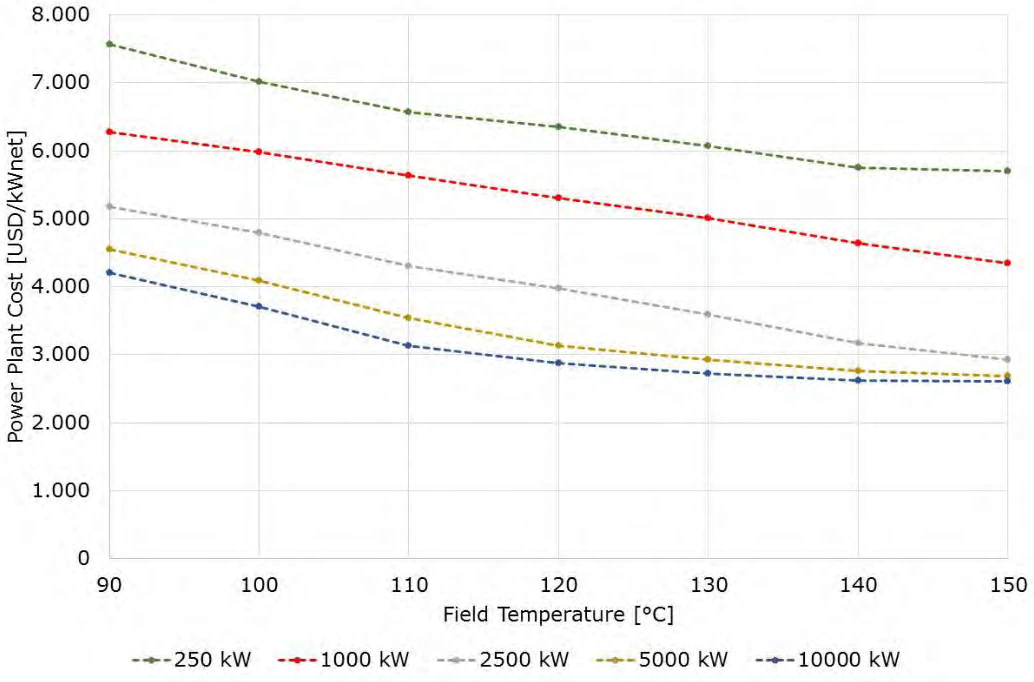


Figure 6-4 Cost of power plant per net kW generated - 2 stage cycle. The colored lines indicate the generator size (gross product).

Details of the plant costs pr. kW are provided for both installed generator power and net power in Appendix C. The main cost items have been detailed per kW for different plant sizes and resource temperature, both for installed generator power and net power.

6.3 Total Investment Cost

The total cost is divided into:

- Cost of field development
- Cost of power plant

The cost is detailed in Table 6-4 where total cost is also summed up

Table 6-4 Investment cost of power plant and steam field (base case)

Total Investment Cost								
		Single stage ORC cycle				**Two stage ORC cycle**		
	Generated Power kW	**Cost, MUSD**				**Cost MUSD**		
		Power Plant	**Steam Field**	**Total**		**Power Plant**	**Steam Field**	**Total**
90°C	250	1,6	8,2	9,7		1,9	5,3	7,2
	1000	5,2	21,6	26,9		6,3	16,3	22,6
	2500	10,8	54,2	65,0		13,0	40,8	53,7
	5000	19,0	103,2	122,1		22,7	78,7	101,4
	10000	35,0	201,0	236,0		42,0	154,9	196,9
100°C	250	1,5	5,3	6,8		1,8	5,3	7,1
	1000	5,0	16,3	21,3		6,0	13,5	19,5
	2500	8,6	37,9	47,1		12	29,8	40,7
	5000	14,6	70,6	86,4		20,4	54,2	73,3
	10000	30,9	135,8	166,7		37,1	103,2	140,3
110°C	250	1,4	5,3	6,7		1,6	5,3	7,0
	1000	4,7	13,5	18,2		5,6	8,2	13,8
	2500	9,0	24,5	33,4		10,8	21,6	32,4
	5000	14,7	48,9	63,7		17,7	37,9	55,6
	10000	26,1	95,0	121,1		31,3	73,4	104,7
120°C	250	1,3	5,3	6,7		1,6	5,3	6,9
	1000	4,4	8,2	12,6		5,3	8,2	13,5
	2500	8,3	21,6	29,9		9,9	16,3	26,3
	5000	13,1	37,9	51,0		15,7	29,8	45,4
	10000	24,0	70,6	94,5		28,8	57,1	85,9
130°C	250	1,3	5,3	6,6		1,5	5,3	6,8
	1000	4,2	8,2	12,3		5,0	8,2	13,2
	2500	7,6	16,3	23,9		9,2	13,5	22,6
	5000	12,2	29,8	42,0		14,6	24,5	39,1
	10000	22,6	54,2	76,9		27,2	46,1	73,3
140°C	250	1,2	5,3	6,5		1,4	5,3	6,8
	1000	3,9	8,2	12,0		4,6	5,3	10,0
	2500	6,6	13,5	20,1		7,9	13,5	21,4
	5000	11,5	24,5	36,0		13,8	21,6	35,5
	10000	21,9	46,1	68,0		26,3	37,9	64,2
150°C	250	1,2	5,3	6,5		1,4	5,3	6,8
	1000	3,6	5,3	8,9		4,3	5,3	9,7
	2500	6,1	13,5	19,6		7,3	8,2	15,5
	5000	11,2	21,6	32,8		13,4	16,3	29,8
	10000	21,7	37,9	59,6		26,0	29,8	55,8

Figure 6-5 andFigure 6-6 show the total investment cost pr. net kW generated, for different plant sizes and resource temperature, for a single stage cycle and a 2 stage cycle respectively.

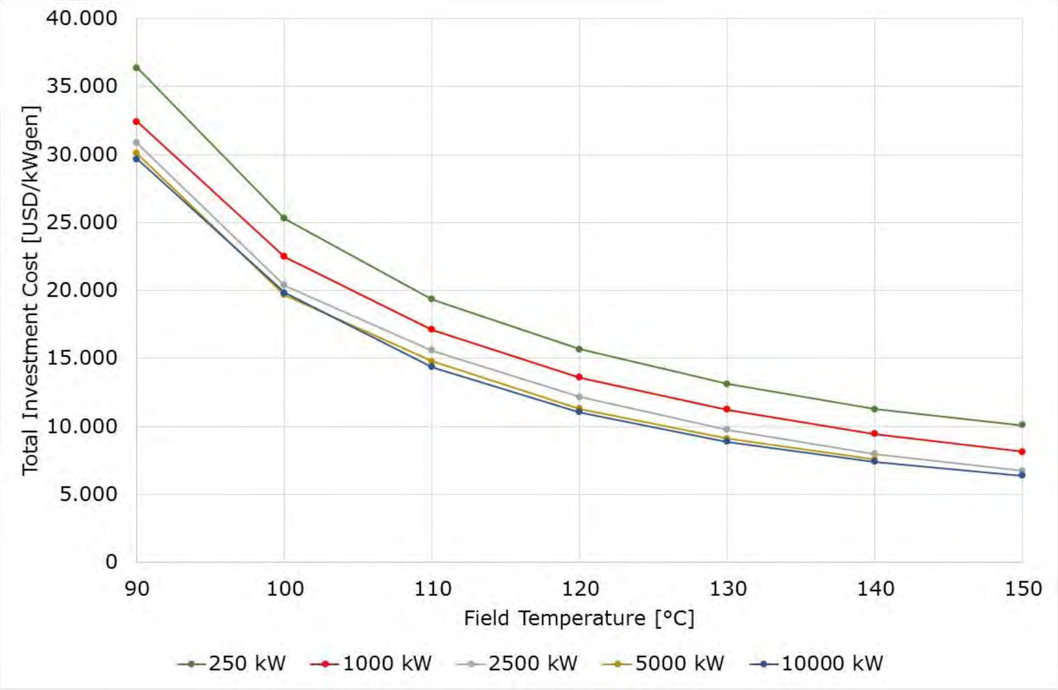


Figure 6-5 Total investment cost per kW generated - single stage cycle. The colored lines indicate to the generator size (gross product).

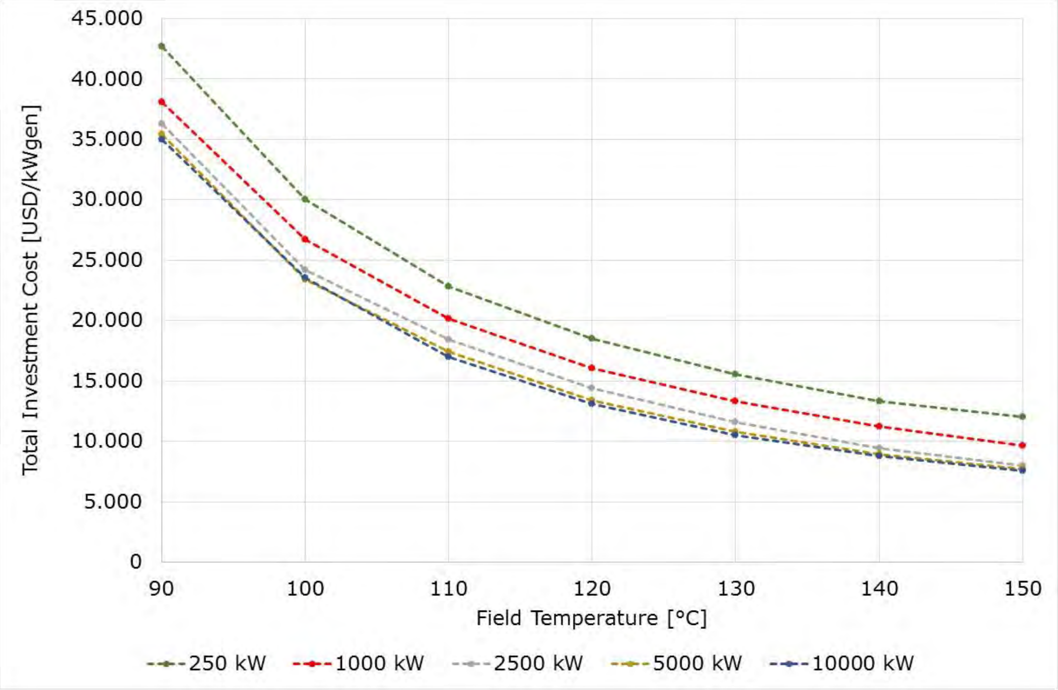


Figure 6-6 Total investment cost per net kW generated - 2 stage cycle. The colored lines indicate the generator size (gross product).

Details of the total cost pr. kW are provided for both installed generator power and net power in Appendix C. The main cost items have been detailed per kW for different plant size and resource temperature, both for installed generator power and net power.

The cost of high voltage transmission line(s) for connection of the plant to an electrical grid is not included in the calculated investment cost. That cost may vary a lot due to distance to the grid, voltage and terrain. To give an idea on such a cost a HV-line or cable for small plants may cost 0,1 – 0,2 million USD pr. km and for larger plants 0,2 – 0,3 million USD.

7 Operation and Production

7.1 Plant Operation and Maintenance Overview

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.

7.1.1 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 capable of performing on-line supervision, maintenance and repair work. The operators need to divide night stand-by duties between them.

In small ORC plants it is not necessary to have operators and workers full time. Security personnel is on the other hand considered necessary to prevent trespassers from entering dangerous areas and/or damage the plant. It may be an outsourced task.

In advanced plants the production is automatic and there is not much need for full time employees except security personnel. All maintenance services for the plant can be purchased from a service provider with adequate education and experience. Security personnel will have to be on site 24-hours with back-up to seal off unwanted visitors. In Table 7-1 a likely requirement for employees is listed per shift. It is assumed that to be able to maintain a 24-hour shift, the manning of 5 shifts is required.

Table 7-1 Requirement for employees per shift

Plant size (kW)	**Operators (24 hours)**	**Skilled Workers (8-hours, weekdays)**	**Security (24 hours)**	**Support services**	**Total number of employees**
250	1		1		**10**
1.000	1		1		**10**
2.500	2	1	1		**17**
5.000	2	2	1	1	**18**
10.000	2	2	1	2	**19**

Managers and office employees fall under the category of management staff. In plants smaller than 5 MW, it is assumed that management will be shared with other companies. In the cost schedule it is assumed that the management cost will be 50% of the cost estimated for larger plants.

Cost per employee includes salary and related expenses is listen in Table 7-2

Table 7-2 Yearly cost of per employee

	$USD/year
Management staff total	40.000
Operators	24.000
Workers	12.000
Security	4.500

7.1.2 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.

7.1.3 Scheduled Maintenance

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.

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 and consumables is estimated as 1,6% of the capital cost per.

7.1.4 Well Replacement

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.

Well replacement is assumed to be 1% of well cost per year.

7.1.5 Total Operation and Maintenance Cost

Items included in the plants operation and maintenance cost is listed in the cost schedule in Table 7-3.

Table 7-3 Cost schedule for plant operation and maintenance cost

	Definition
Capacity factor	96%
Fixed costs	
Personnel	See table 7.1.11
Temporary contractors	Production stops one week per year.
Maintenance	
Inclusive spare parts and consumables	1,6% total capital cost of the plant and well pump.
Production wells	
Well replacement	1% capital cost of wells

In Table 7-4 the operation and maintenance cost for each unit is listed on an annual basis.

Table 7-4 Operation and maintenance cost for each unit

	O&M cost			
	Single stage ORC cycle		Two stage ORC cycle	
	Power	Cost /Year $USD	Power	Cost /Year $USD
90°C	250	276.076	250	292.936
	1.000	587.165	1.000	663.733
	2.500	1.321.952	2.500	1.504.022
	5.000	2.335.037	5.000	2.690.739
	10.000	4.332.870	10.000	5.039.152
100°C	250	243.063	250	258.339
	1.000	470.919	1.000	525.075
	2.500	999.167	2.500	1.151.623
	5.000	1.690.733	5.000	1.979.310
	10.000	3.119.315	10.000	3.608.816
110°C	250	226.078	250	237.957
	1.000	400.402	1.000	441.291
	2.500	838.316	2.500	937.879
	5.000	1.362.863	5.000	1.547.551
	10.000	2.380.444	10.000	2.743.083
120°C	250	215.717	250	225.524
	1.000	352.892	1.000	389.297
	2.500	726.563	2.500	804.611
	5.000	1.129.885	5.000	1.274.669
	10.000	1.935.287	10.000	2.222.278
130°C	250	208.323	250	216.651
	1.000	323.315	1.000	353.805
	2.500	645.191	2.500	707.801
	5.000	979.076	5.000	1.099.554
	10.000	1.639.270	10.000	1.874.585
140°C	250	202.749	250	209.962
	1.000	300.330	1.000	322.040
	2.500	581.838	2.500	636.797
	5.000	873.837	5.000	974.103
	10.000	1.438.357	10.000	1.635.162
150°C	250	199.313	250	205.839
	1.000	279.072	1.000	301.550
	2.500	540.768	2.500	583.330
	5.000	798.953	5.000	885.079
	10.000	1.295.664	10.000	1.465.604

7.1.6 Financial cost

The financial cost includes depreciation, loan interest and return on equity. For simplification the annual financial cost is defined as a percentage of the investment cost. The percentage is based on depreciation period, estimated interest rate, required rate of return and equal distribution of total financial cost, annuity. Two alternatives are presented for financial cost, see Table 7.5.

Table 7-5 Financial Cost Assumptions

	Financial Cost I	**Financial Cost II**
Equity	30%	15%
Return on equity	15%	15%
Loan ratio	70%	85%
Depreciation rate	25 years	25 years
Average Interest rate (loan 3,71% and equity 15%)	7,1%	5,40%

7.1.7 Total annual Cost

Table 7-6 shows the total annual cost i.e the annual operation cost according to table 7.4 and financial cost as defined in table 7.5 (2 alternatives).

Table 7-6 Total Annual cost

		Single stage ORC cycle					**Two stage ORC cycle**				
	Generated Power kW	**Cost, MUSD /Year**					**Cost, MUSD /Year**				
		O&M Cost	**Fin. Cost I**	**Fin. Cost II**	**Total I**	**Total II**	**O&M Cost**	**Fin. Cost I**	**Fin. Cost II**	**Total I**	**Total II**
90°C	250	0,3	0,6	0,5	0,9	0,8	0,3	0,7	0,6	1,0	0,9
	1000	0,6	2,3	2,0	2,9	2,5	0,7	2,8	2,4	3,4	3,0
	2500	1,3	5,6	4,7	6,9	6,1	1,5	6,7	5,7	8,2	7,2
	5000	2,3	10,9	9,3	13,2	11,6	2,7	13,1	11,1	15,7	13,8
	10000	4,3	21,5	18,3	25,8	22,7	5,0	25,8	22,0	30,9	27,0
100°C	250	0,2	0,4	0,4	0,7	0,6	0,3	0,5	0,4	0,8	0,7
	1000	0,5	1,7	1,4	2,1	1,9	0,5	2,0	1,7	2,5	2,2
	2500	1,0	3,8	3,2	4,8	4,2	1,2	4,6	3,9	5,7	5,0
	5000	1,7	7,4	6,3	9,1	8,0	2,0	8,9	7,6	10,8	9,5
	10000	3,1	14,9	12,7	18,0	15,8	3,6	17,9	15,3	21,5	18,9
110°C	250	0,2	0,3	0,3	0,6	0,5	0,2	0,4	0,3	0,6	0,6
	1000	0,4	1,3	1,1	1,7	1,5	0,4	1,5	1,3	2,0	1,7
	2500	0,8	2,9	2,5	3,8	3,3	0,9	3,5	3,0	4,5	3,9
	5000	1,4	5,6	4,8	7,0	6,1	1,5	6,7	5,7	8,3	7,3
	10000	2,4	10,9	9,3	13,3	11,7	2,7	13,1	11,2	15,8	13,9
120°C	250	0,2	0,3	0,2	0,5	0,5	0,2	0,3	0,2	0,6	0,5
	1000	0,4	1,0	0,9	1,4	1,2	0,4	1,2	0,9	1,6	1,3
	2500	0,7	2,3	2,0	3,1	2,7	0,8	2,8	1,9	3,6	2,7
	5000	1,1	4,3	3,7	5,5	4,8	1,3	5,2	3,6	6,5	4,9
	10000	1,9	8,5	7,3	10,4	9,2	2,2	10,2	7,1	12,4	9,3
130°C	250	0,2	0,2	0,2	0,4	0,4	0,2	0,3	0,2	0,5	0,5
	1000	0,3	0,9	0,7	1,2	1,1	0,4	1,0	0,9	1,4	1,2
	2500	0,6	1,9	1,6	2,5	2,3	0,7	2,3	1,9	3,0	2,6
	5000	1,0	3,5	3,0	4,5	4,0	1,1	4,2	3,6	5,3	4,7
	10000	1,6	6,9	5,9	8,5	7,5	1,9	8,3	7,1	10,2	8,9
140°C	250	0,2	0,2	0,2	0,4	0,4	0,2	0,2	0,2	0,5	0,4
	1000	0,3	0,7	0,6	1,0	0,9	0,3	0,9	0,7	1,2	1,1
	2500	0,6	1,5	1,3	2,1	1,9	0,6	1,9	1,6	2,5	2,2
	5000	0,9	2,9	2,5	3,8	3,4	1,0	3,5	3,0	4,5	4,0
	10000	1,4	5,8	4,9	7,2	6,4	1,6	7,0	5,9	8,6	7,6
150°C	250	0,2	0,2	0,2	0,4	0,4	0,2	0,2	0,2	0,4	0,4
	1000	0,3	0,6	0,5	0,9	0,8	0,3	0,8	0,6	1,1	0,9
	2500	0,5	1,3	1,1	1,9	1,7	0,6	1,6	1,3	2,2	1,9
	5000	0,8	2,5	2,2	3,3	3,0	0,9	3,1	2,6	3,9	3,5
	10000	1,3	5,0	4,3	6,3	5,6	1,5	6,0	5,1	7,5	6,6

7.2 Production cost

The production cost per kWh electricity net is calculated from the total annual cost presented in Table 7-6 divided by the net annual energy production. The net energy production is defined as the net power presented in Figure 5-3 multiplied by maximum annual production time defined as 0,96 x 8760 = 8.410 hours. This is the maximum production which can only be received if the plant is operated as a base plant connected to a large grid compared to plant size.

Table 7-7 shows the production cost based on the annual operation cost only and the total production cost that includes annual operation and finance cost (two alternatives) as presented in Table 7-5

Table 7-7 Production cost per net kWh

Power Plants - Cost of Net Energy Production

		Single stage ORC cycle					Two stage ORC cycle			
	Generated Power kW	Annual Energy sale kWh	Cost, UScent/kWh				Annual Energy sale kWh	Cost, UScent/kWh		
			O&M Cost	Total I	Total II			O&M Cost	Total I	Total II
90°C	250	1.596.983	17,3	54,7	49,2		1.632.135	17,9	61,9	55,4
	1000	6.893.349	8,5	41,9	37,0		7.032.948	9,4	48,7	42,9
	2500	17.483.558	7,6	39,3	34,6		17.836.762	8,4	45,8	40,3
	5000	35.135.309	6,6	37,6	33,1		35.816.486	7,5	44,0	38,6
	10000	70.447.219	6,2	36,7	32,2		71.675.021	7,0	43,0	37,7
100°C	250	1.661.737	14,6	40,7	36,8		1.680.406	15,4	46,3	41,7
	1000	7.152.365	6,6	29,7	26,3		7.227.210	7,3	34,7	30,7
	2500	18.131.098	5,5	26,5	23,4		18.318.632	6,3	31,2	27,5
	5000	36.438.797	4,6	24,9	21,9		36.808.819	5,4	29,4	25,9
	10000	73.037.376	4,3	24,7	21,7		73.785.830	4,9	29,1	25,6
110°C	250	1.681.920	13,4	33,4	30,4		1.712.026	13,9	37,4	33,9
	1000	7.233.097	5,5	23,1	20,5		7.351.672	6,0	26,8	23,7
	2500	18.332.928	4,6	20,6	18,3		18.633.992	5,0	24,0	21,2
	5000	36.834.048	3,7	18,9	16,7		37.439.539	4,1	22,1	19,5
	10000	73.844.698	3,2	18,0	15,8		75.030.451	3,7	21,1	18,5
120°C	250	1.706.308	12,6	28,8	26,4		1.732.966	13,0	32,1	26,8
	1000	7.328.966	4,8	18,8	16,7		7.435.768	5,2	21,8	17,0
	2500	18.576.806	3,9	16,4	14,6		18.843.391	4,3	19,1	14,5
	5000	37.321.805	3,0	14,7	13,0		37.855.814	3,4	17,1	12,9
	10000	74.803.392	2,6	14,0	12,3		75.871.411	2,9	16,4	12,2
130°C	250	1.723.968	12,1	25,6	23,6		1.746.842	12,4	28,4	26,1
	1000	7.399.607	4,4	15,9	14,2		7.493.795	4,7	18,4	16,4
	2500	18.753.408	3,4	13,5	12,0		18.982.149	3,7	15,6	13,9
	5000	37.666.598	2,6	12,0	10,6		38.141.741	2,9	14,0	12,3
	10000	75.509.798	2,2	11,3	10,0		76.451.674	2,5	13,3	11,7
140°C	250	1.736.582	11,7	23,3	21,6		1.757.018	11,9	25,7	23,7
	1000	7.450.906	4,0	13,8	12,3		7.532.479	4,3	15,8	14,1
	2500	18.879.552	3,1	11,3	10,1		19.083.905	3,3	13,1	11,6
	5000	37.927.296	2,3	10,1	8,9		38.336.003	2,5	11,8	10,4
	10000	76.022.784	1,9	9,5	8,4		76.838.515	2,1	11,2	9,8
150°C	250	1.745.833	11,4	21,8	20,3		1.763.577	11,7	24,0	22,2
	1000	7.488.749	3,7	12,1	10,9		7.558.212	4,0	14,0	12,5
	2500	18.972.058	2,9	9,8	8,8		19.149.500	3,0	11,3	10,1
	5000	38.120.717	2,1	8,8	7,8		38.459.624	2,3	10,2	9,1
	10000	76.401.216	1,7	8,3	7,3		77.701.340	1,9	9,6	8,5

Figure 7.1 shows the total production cost (Fin 1) pr. net kWh according to table 7.6 and a comparison of the production cost per kWh of electricity produced with a diesel generator.

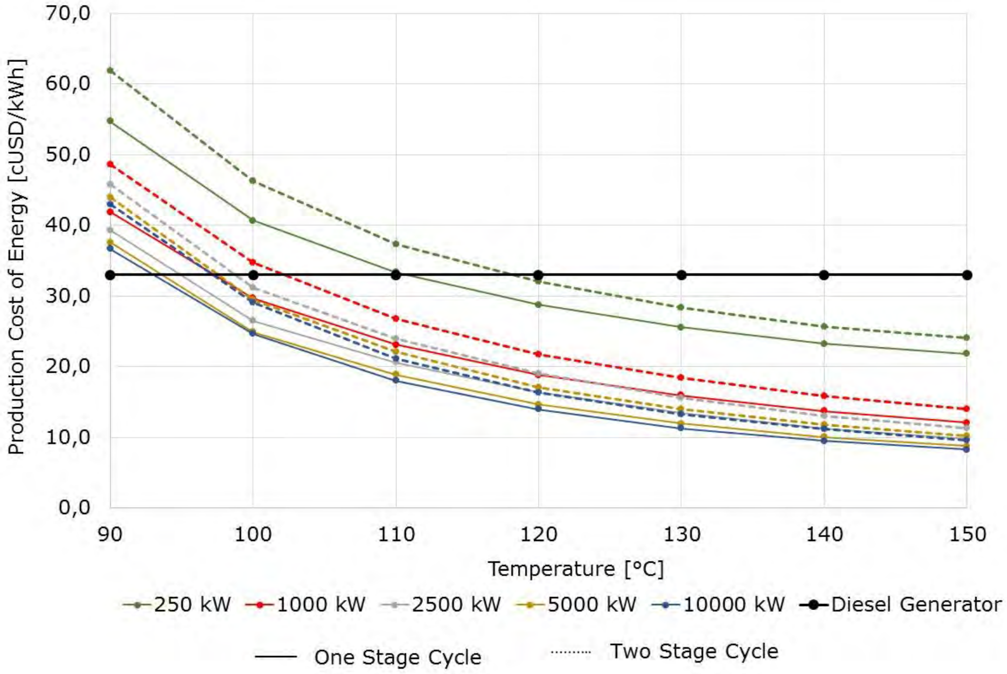


Figure 7-1 Comparison of total production cost per net kWh produced in a binary plant and and the corresponding cost for each produced kWh in a diesel plant. The colored lines indicate the generator size (gross product).

Figure 7.2 shows the operation cost pr. net kWh in a binary power plant and the cost of oil for production in a diesel plant. The graph shows that the operation of a binary plant costs less than the oil in a diesel plant in all cases expect for a 250 kW plant using 90°C water. Therefore if a diesel plant and a binary plant have been installed it is beneficial to produce as much electricity as possible in the binary plant.

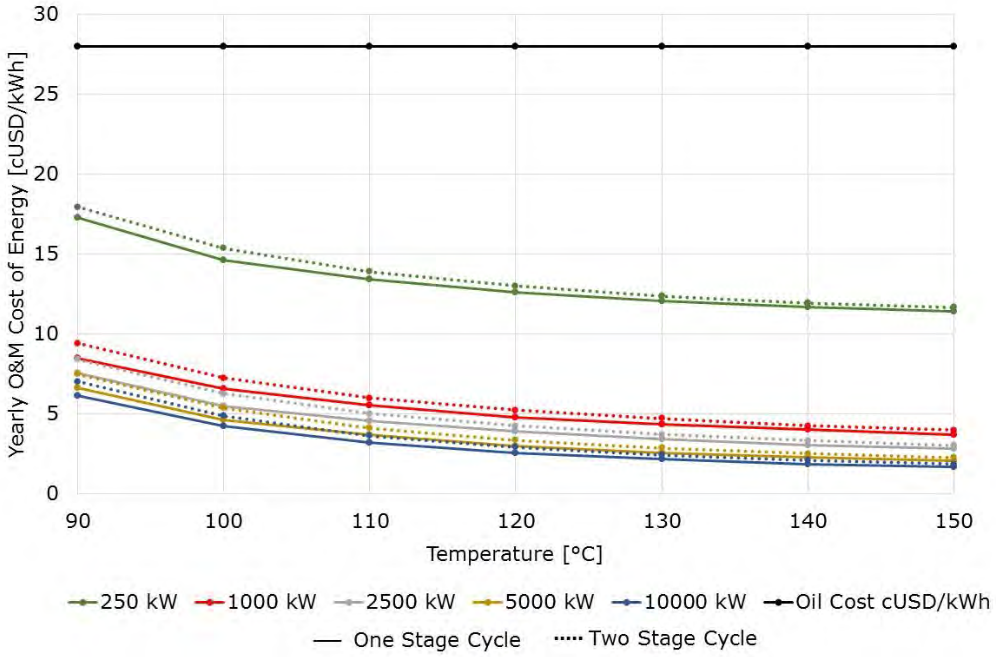


Figure 7-2 **Operation cost per net kWh in a binary plant and the corresponding operational cost of a diesel plant. The colored lines indicate the generator size (gross product).**

7.3 Influence of Well Pumping on Production Cost

A considerable amount of power may be required for well pumping. The well pump consumption of power is subtracted from the net output of the plant. The net production cost increases as the water level sinks as more energy is required to pump from the greater depth.

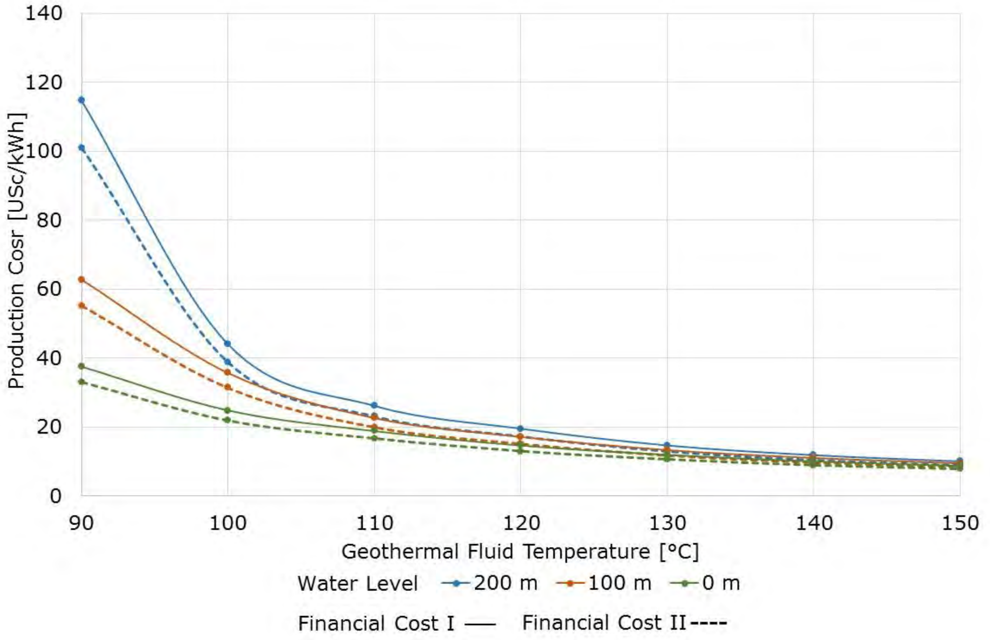


Figure 7-3 **Effect of water level and well pumping on production cost of energy delivered to the grid in a 5 MW plant. The colored lines indicate the water level depth.**

In Tables C-5 and C-6 in appendix C, energy consumption of well pumps is listed in order to make the reader easier to estimate the production cost under different pumping conditions.

Figure 7-4 shows the cost of power to the grid for the base case defined in Table 5-1. The pumping depth is 200 m and the water level at 150 m. It can be concluded that low temperature and smaller units are less economical than the larger ones and performance rises with rising temperature of the geothermal fluid.

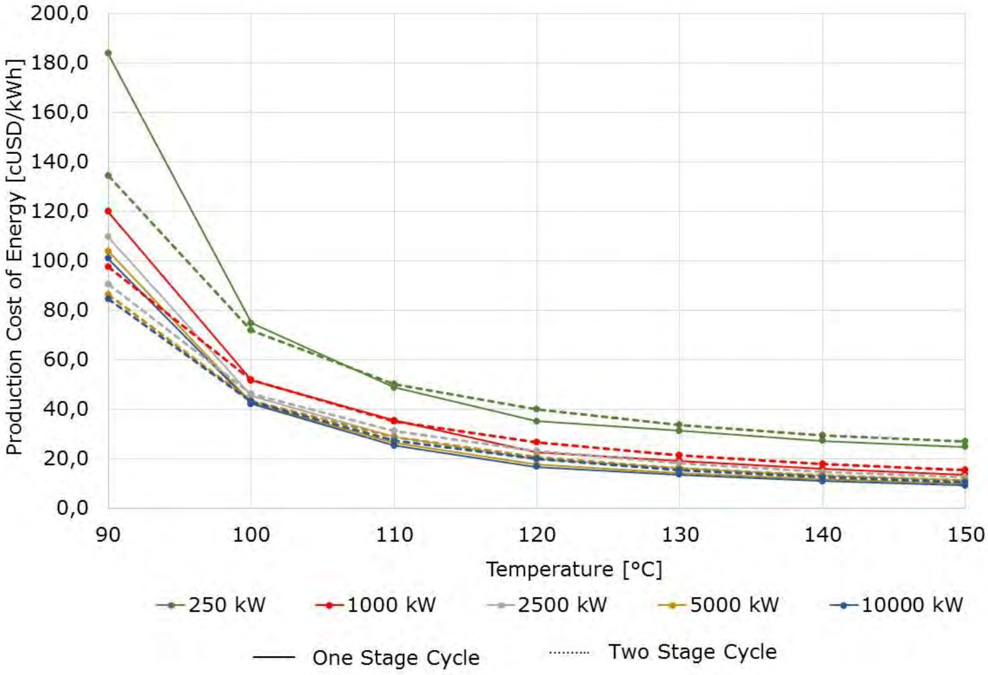


Figure 7-4 Production cost of electricity delivered to the grid for a case where the well pumping depth is 200 m and water level at 150 m.

See Appendix C for more detailed costs schedules

- Annual cost of spare parts, maintenance and insurances
- Annual well replacement cost
- Annual cost of personnel
- Annual operational and maintenance cost
- Production cost at different pump depths

8 Environmental and Risk Management

8.1 Environmental Impact

The development of a binary power plant will always be subject to local regulations with regard to environmental impacts. Table 8-1 gives an overview of the most common environmental aspects related to geothermal power plants with a focus on aspects specific to the binary technology.

Table 8-1 Typical Environmental Impacts.

Environmental aspect	Stage	Possible Impact
Visual impact	Operation	The power plant complex and associated power transmission lines imply changes in the landscape appearance.
Air	Operation	Possible H_2S released. The geothermal fluid will most likely be held under pressure in the heat exchangers, not allowing the gases to escape the fluid. Minor releases might occur in specific circumstances leading to emergency release. The binary plant uses working fluid under vacuum. During operation, some working fluid is purged to the atmosphere in order to prevent air from entering and accumulating in the system.
Flora	Construction Operation	Disruption due to well pad and construction of the power plant complex. Brine released to a pond during plant start/stops during e.g. maintenance.
Fauna	Construction Operation	Nuisance due to well pad and construction of the power plant complex, possible loss of habitat. Obstruction to terrestrial animals' right of way mainly in relation to roads, pipelines or transmission lines.
Noise	Construction Operation	Noise from construction and from blasting wells Noise from the plant in operation, especially near air cooled condensers where it might reach 90 dB(A) which is above acceptable exposure limits.
Water	Construction Operation	Water used during drilling Possible impact on surface and ground water.
Land and soil	Construction Operation	Possible soil erosion due to land disruption. Possible soil erosion and land subsidence.
Archaeology	Construction	Depending on location of the power plant complex, possible impact on archaeological artefacts.
Tourism	Construction	Possible disturbance due to traffic.
	Operation	Possible benefit if the plant is an attraction for tourists.
Economy	Operation	Positive impact on economy.
Social	Construction Operation	Job creation. Temporary residents. Provision of services Cohabitation with other activities. Provision of services
Land acquisition	Construction	Resettlement might be an issue.

Environmental impacts will in all cases need to be further investigated in light of the local law and regulation for any geothermal project. Results and recommendations from the environmental impact assessment have to be taken into account in the design of the plant. Furthermore, an environmental and social management plan is usually required for construction and operation of the power plant. The management plan may tackle training of staff with regard to implementation of mitigation measures and monitoring of aspects relevant to the defined environmental impacts.

8.2 Risk Management

As in any power generation project connected to the grid, a geothermal binary power plant will be exposed to general risks related to:

- Project implementation: delays, changes, design issues, permit issues, etc.
- Market demand and price fluctuation
- Operation: not meeting the demand, blackouts, reliability etc.
- Environment
- Regulation.

These risks will not be discussed further here. Additionally, geothermal power plant projects are exposed risks related to:

- Exploration of the geothermal resource: uncertainty on output from drilled wells and depth leading to uncertainty regarding bankability of the project during the exploration phase.
- Financing risks: long lead time for development of a geothermal project and uncertainty regarding bankability of the project due to difficulty in predicting the productivity of the geothermal resource.

Risk management is considered a good management practice and is generally put into practice by project developers. Such systems include identification and assessment of the project risks, development and implementation of a risk management plan with detailed risk treatment and monitoring.

A list of major technical risks specifically related to the binary technology is proposed in Table 8-2 together with indication of possible risk treatment measures.

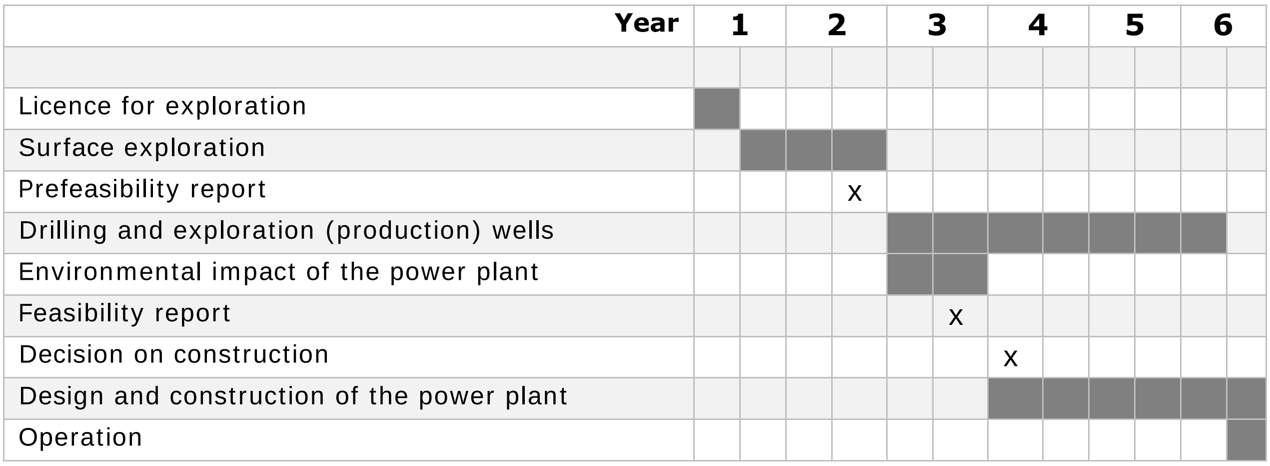
Table 8-2 Typical risks related to geothermal binary power plant projects

Risk title	Description	Risk treatment
Oversizing of the power plant	Brine flow rate and/or temperature overestimated resulting in either a project not viable from the financial point of view or unsustainable extraction rates.	Exploration risk to be tackled by implementing a sound exploration plan and development of the plant in incremental steps.
Unsuccessful drilling	Inabilty to acquire hot geothermal fluid, well collapse	Thorough geothermal exploration and drilling techniquies.
Chemistry of the brine	Project basis is to keep the gas dissolved in the brine by keeping the pressure up. While escape of the gas to the atmosphere is not in itself a problem, scaling due to degasification is a problem.	Exploration plan with among others confirmation by tests a sufficient level of pressure to prevent release of gases from the brine.
Operation and maintenance of the heat exchangers	Heat exchangers fouling on the brine side. Geothermal fluid contains mineral that can precipitate and cause fouling in the heat exchanger. Increased operation and maintenance costs.	Select fouling factors for the heat exchangers taking into account the fouling properties of the brine.
Nature of the binary working fluid	The most common ORC working fluids, isobutane and isopentane are highly flammable. NB: the working fluids R134a and R245fa are not flammable and rank on par with a hydro power plant in regards of fire hazard.	Design the plant to fulfill relevant fire safety and explosion standards in relation to the selected working fluid. Develop and implement safety management plan for the operation and maintenance of the plant. Access to the plant should be restricted.
Technology selection	Selection of a plant with Kalina cycle - limited experience on the process and the equipment.	Should the Kalina cycle be an option for the project, its selection should be the object of a thorough assessment.
Vandalism	Unauthorized access on the plant site is especially risky if flammable working fluids are used. Also theft could be a problem.	Construct an inpenetrable fence and keep under surveillance with 24-hour security back-up.
Selling tariff	Selling tariff is a sensitive item, even if set and decided for a few years to come. Instability in government and economy can swiftly change assumptions made in the beginning.	Vulnerability to changes in government and economic development depends on the selling contract and its clauses on revision.

9 Project Implementation

9.1 Project Development Phases and Planning

Geothermal projects are usually developed in successive phases. The development phases can be divided into 4 major phases: 1) identification, 2) Exploration, 3) Design and construction, 4) Operation and maintenance. They are further described in the figure below with an indication of the main activities undertaken under each phase and the time required for their implementation.



Year	1		2		3		4		5		6	
Licence for exploration	■											
Surface exploration		■	■	■								
Prefeasibility report				X								
Drilling and exploration (production) wells					■	■	■	■	■	■	■	
Environmental impact of the power plant					■	■						
Feasibility report						X						
Decision on construction							X					
Design and construction of the power plant							■	■	■	■	■	■
Operation												■

Figure 9-1 Rough draft of a typical development plan for a binary plant.

Identification and exploration of the geothermal resource constitute the most important part of a geothermal project as they are seen as the riskiest part of the project development. Apart from the aspects related to the assessment of the geothermal field, its size, characteristics and expected output, the bankability of the project will be assessed during these phases. The harnessing technology will inter alia be pre-selected during these stages.

The procurement strategy is one of the tools used by project developers to manage project implementation risks and it is also drafted during the feasibility stage. Well field development and the power plant complex construction can be procured in various manners depending among other things on project characteristics and the project developer’s approach to risk.

- Drilling is usually allotted to a specific package
- Development of the well field (piping, mechanical equipment together with equipment for the control and electrical systems) can be split into individual packages - i.e. design, equipment supply, installation – or be included in one turn-key package. It might in some cases be included in the power plant package.
- Construction of the geothermal power plant is often included in a turn-key package consisting of having one contractor design, construct and deliver a fully operational plant and being responsible for all stages of the design and construction phase. The water / steam gathering system (wells, deep well pumps and pipelines) may be included in the power plant package or procured separately. The same applies to buildings, site preparation, roads etc.

There are several potential contractors for a turnkey binary geothermal power plant:

- ORC power plant equipment manufacturers: they can provide complete solutions and design.
- Consulting engineers specializing in geothermal power, that design, prepare and tender out all necessary project packages and deliver an operating plant
- Consortium consisting of engineering firms, contractors, manufactures, experienced energy companies etc.

It is most practical to at least procure the power plant as a one package including heat exchangers, turbine, generator, electrical and control equipment and cooling system. Lead time for supply of a binary unit is currently 12-24 months depending on size.

9.2 Overview of Technology Suppliers

There is an increasing number of companies that offer complete binary power plants. The list is not exhaustive.

Atlas Copco (Germany)

Atlas Copco is an industrial group producing compressors, construction and mining equipment, power tools and assembly systems. They provide turbo expanders for various uses and were commissioning their first geothermal ORC plant, a 45 MW plant in Turkey at the end of 2013.

Cryostar (France)

Cryostar is a France based company that has produced various cryogenic equipment for decades. They have among other things developer turbo expanders that can be used as turbine/generator units for ORC plants. Cryostar can provide only the turbo expander generator or also procure the whole closed loop binary system. Cryostar has produced equipment for two geothermal projects, a 1,5 MW plant in France and a 3,3 MW plant in Germany.

Exergy (Italy)

Exergy is a producer of modules for heat and power production. It specializes in heat recovery power units, combined heat and power and low temperature geothermal (90-180°C) ORC units.

Fuji Electric (Japan)

Fuji Electric has produced steam turbine generators since 1959. They are one of the most experienced manufacturers of geothermal steam turbines worldwide and have built the largest geothermal steam turbines in the world. They have recently entered the market for ORC power plants, utilizing their extensive knowledge of geothermal steam turbines. They can provide turbines up to 10 MW in size.

Nooter/Eriksen (USA)

Has been a supplier of heat recovery steam generators for over 10 years. It proposes a wide range of boiler types and is expanding to more custom-made solutions. Based in USA and Italy.

Opcon (Sweden)

Opcon is a Swedish energy and environmental technology group that develops, produces and markets systems and products for low resource energy utilization. It produces Opcon Powerboxes which are mobile stand-alone units that transform low and waste heat into emission free power production and new revenues.

Ormat (Israel /USA)

Ormat is an Israel/USA based company. Ormat not only provides binary power equipment but also operates power plants in different locations. Ormat is the most experienced plant vendor in the ORC sector, having built over 1400 MW of geothermal power plants worldwide. These are mostly ORC units but also combined steam and ORC cycles. Ormat has been supplying equipment to geothermal power plants for over 25 years.

TAS (USA)

TAS Energy was founded in the early 1980s and at first specialized in industrial chillers. From 2005 their primary focus has been on low – and waste heat energy solutions such as ORC. TAS has designed and built equipment for an 8,6 MW ORC system at San Emidio Nevada and a 13,2 MW ORC in Turkey

Turboden (Italy)

Turboden has since the 1980's focused on the development and production of ORC equipment to generate heat and power from renewable resources and heat recovered in industrial processes. Turboden is now a part of the Mitsubishi Heavy Industry group. The Turboden ORC units are up to 15 MW. They have built over 200 ORC plants, a total of over 300 MW, mostly biofuel, but 4 geothermal power plants and 3 more that were under construction in 2013. The largest geothermal plant supplied by Turboden so far is 5,6 MW.

9.3 Overview of Installed Binary Power Stations

In this section there is a list of geothermal binary power stations (Bertani, 2010)

Table 9-1 Overview of installed Binary Power Stations (Bertani,2010)

Country	Plant	Unit	Capacity	Operator	Manufacturer
El Salvador	Berlin	4	9,4	LaGeo/Enel Green Power	Enex
France	Soultz-sous-Forets	1	1,5	European EGS Interest	UTC/Turboden
Germany	Unterhaching	1	3,4	Municipality	Siemens
Germany	Landau	1	3	Municipality	ORMAT
Guatemala	Amatitlán	1	24	ORMAT	ORMAT
Japan	Hatchobaru	1	2	Kyushu Electric Power	ORMAT
New Zealand	Ngawha 2	1	15	Top Energy	ORMAT
New Zealand	KA24	1	8,3	ORMAT	ORMAT
New Zealand	Mokai 2	1-5	20	Tuaropaki Power Co	ORMAT
New Zealand	Mokai 2	15-17	14	Contact Energy	ORMAT
Portugal	Pico Vermelho	1	13	Electricidade dos Azores	ORMAT
Turkey	Kizildere Binary	1	6,8	BEREKET	ORMAT
Turkey	Dora	1	7,4	MB	ORMAT
USA	Faulkner	1	50	Nevada Geothermal	ORMAT
USA	Lahendong	3	20	PLN	Fuji
USA	Stillwater	1-2	48	Enel Green Power	Mafi Trench
USA	Salt Wells	1	24	Enel Green Power	Mafi Trench
USA	North Brawley	1-7	49	ORMAT	ORMAT
USA	Thermo Hot springs	1-50	10	Raster Technologies	UTC/Turboden
USA	Galena III	1	30	ORMAT	ORMAT
USA	Raft River	1	13	US Geothermal	ORMAT
USA	Heber South	1	10	ORMAT	ORMAT
USA	Galena II	1	13	ORMAT	ORMAT
USA	Blundell I	2	11	Pacific Corporation	ORMAT
USA	Desert Peak II	1	23	ORMAT	ORMAT
USA	Gould	1-2	10	ORMAT	ORMAT
USA	Richard Burdett	1-2	30	ORMAT	ORMAT

9.4 Operation and Training

One of the basie of a successful operation are skilled operators and workers that operate and maintain the power plant. Geothermal binary power plant operators have to be trained with regard to issues specific to geothermal projects and binary technology.

Operation of geothermal binary power plants includes:

- Supervision of machines
- Operation supplies required for operation of the plant such as inhibitors in cooling towers, oil and grease
- Maintenance of the system
- Maintenance supplies, mainly spare parts
- Supervision of the geothermal resource and reservoir

The operation and maintenance activities might significantly impact the lifetime of a plant. It is important for a plant owner to be aware of this and adopt a strategy for operation and maintenance accordingly. The strategy adopted by the plant owner for operation and maintenance will depend on its internal structure, its staff capability, knowledge and experience in operation of geothermal binary power plants. The size and location of the power plant will also have to be taken into account. For instance, it might not be feasible to have a full operation team for a small power plant located in a remote place. A collaboration with other plant (diesel) owners should be examined.

When planning a geothermal binary power plant, the plant owner should make sure that his operating team will receive appropriate training. Training will first of all be conducted during the commissioning phase and during the first months of operation. The equipment manufacturers usually provide training and operation assistance for the equipment they supply. Training and transfer of knowledge can also be provided by the design team. This is particularly relevant to all matters related to the geothermal resources, its management, monitoring and impact on the equipment operation and maintenance. Another possibility for the plant owner is to send his operation team to places where such plants are already in operation in order to receive training from other operators.

10 Conclusions

The main conclusion of this study is that the economy of a binary power plant depends highly on the characteristics of the geothermal area, i.e. depth to the water level and pumping requirements. Binary technology is feasible for the production of electricity from geothermal resources at temperatures 120° and up. However plants may be viable for temperature down to 90°C if the circumstances are favorable. Larger plants are more economical than smaller units

Binary power plants are best suited as base load plants connected to a large grid, but can also be operated for a small grid in combination with a diesel power plant. Binary power plants are not feasible as the only plant connected to a small grid (island operation).

For a successful geothermal binary power plant project it is important to verify all the main characteristics of the geothermal resource prior to the final design of the plant and selection of equipment. The main characteristics are:

- 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 wellhead pressure.
- Estimated distance between wells.
- Chemical composition of the geothermal fluid.
- Influence of reinjection on flow rates from wells and field capacity.

For a successful operation of a geothermal field and a power plant it is of utmost importance to have skilled, trained operators and maintenance staff.

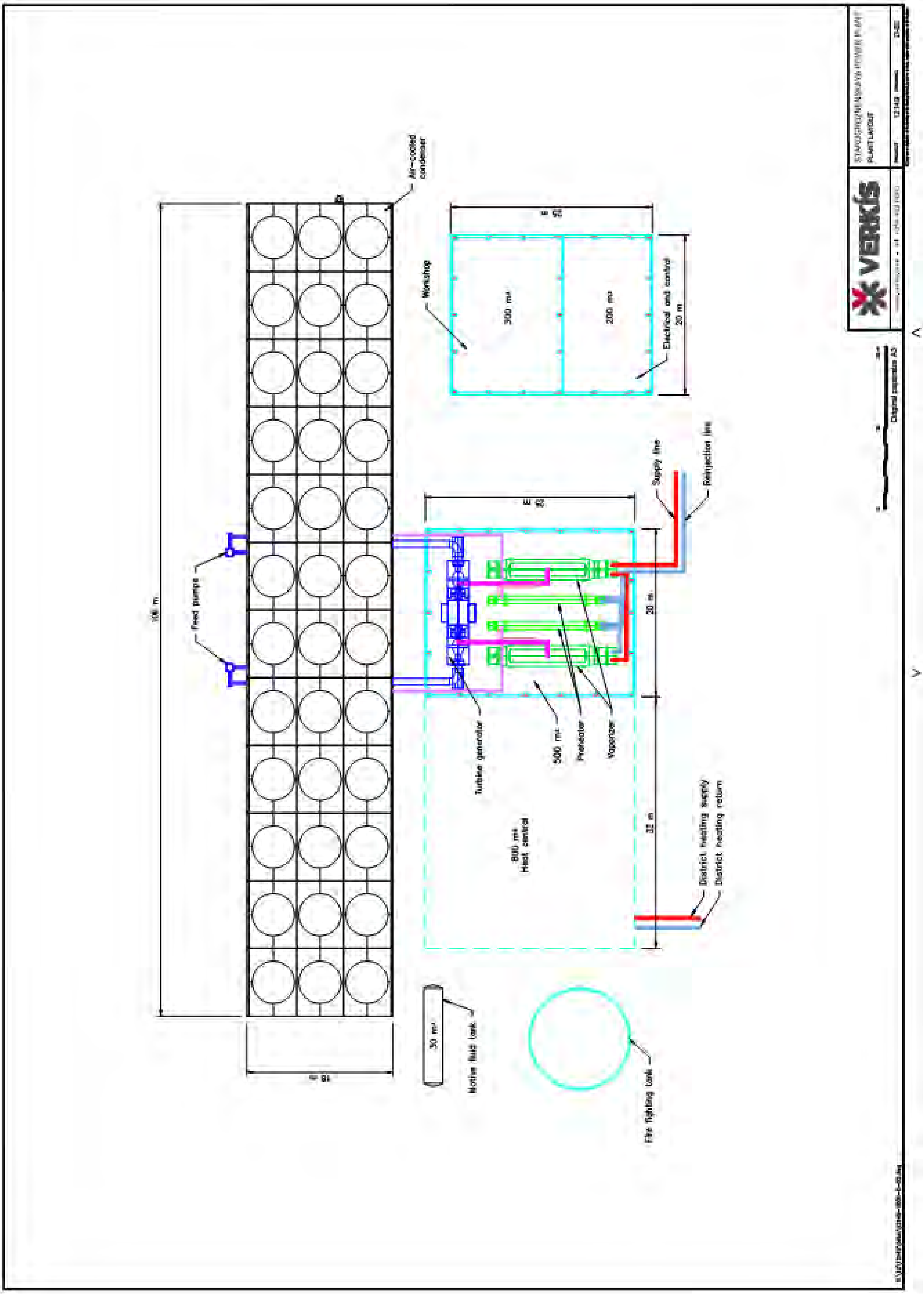
11 Bibliography

Jennejohn, D., Hines, B., Gawell, K., & Blodgett, L. (2012). *Geothermal: International Market Overview Report.* Washington, D.C.: Geothermal Energy Association.

Bertani Ruggero. (2010). *Geothermal Power Generation in the World: 2005-2010 Update Report*. Enel Green Power. Geothermal Energy Association.

Appendices

Appendix A Simple layout of a binary plant, 150°C geothermal fluid and 10 MW



Appendix B Process Diagrams – Detailed simulation results

Single Stage ORC Cycle

The tables below show the amount (mass flow) of geothermal fluid needed for generation of electricity at temperatures 90°C, 100°C, 110°C, 120°C, 130°C, 140°C and 150°C respectively. The tables also show various parameters in the process cycle and the net power production.

Table B-1 Single stage ORC cycle, 90°C geothermal fluid.

90°C						
Gross output	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 Production [kW]
250	48,33	64,41	14,15	2,765	1,42	189,9
1000	193,3	64,41	56,62	2,765	1,42	819,7
2500	483,3	64,41	141,5	2,765	1,42	2079
5000	966,6	64,41	283,1	2,765	1,42	4178
10000	1933	64,41	566,2	2,765	1,42	8377

Table B-2 Single stage ORC cycle, 100°C geothermal fluid.

100°C						
Gross output	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 Production [kW]
250	32,16	70	10,9	3,348	1,42	197,6
1000	128,6	70	43,58	3,348	1,42	850,5
2500	321,6	70	109	3,348	1,42	2156
5000	643,2	70	217,9	3,371	1,42	4333
10000	1286	70	435,8	3,371	1,42	8685

Table B-3 Single stage ORC cycle, 110°C geothermal fluid

110°C						
Gross output	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 Production [kW]
250	22,65	71,29	9,855	3,651	1,42	200
1000	90,62	71,29	39,42	3,651	1,42	860,1
2500	226,5	71,29	98,55	3,651	1,42	2180
5000	453,1	71,29	197,1	3,651	1,42	4380
10000	906,2	71,29	394,2	3,651	1,42	8781

Table B-4 Single stage ORC cycle, 120°C geothermal fluid.

120°C						
Gross output	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 Production [kW]
250	16,82	74,34	8,555	4,183	1,42	202,9
1000	67,26	74,34	34,22	4,183	1,42	871,5
2500	168,2	74,34	85,55	4,183	1,42	2209
5000	336,3	74,35	171,1	4,183	1,42	4438
10000	672,6	74,35	342,2	4,183	1,42	8895

Table B-5 Single stage ORC cycle, 130°C geothermal fluid.

130°C						
Gross output	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 Production [kW]
250	12,93	77,12	7,554	4,788	1,42	205
1000	51,7	77,12	30,21	4,788	1,42	879,9
2500	129,3	77,12	75,53	4,788	1,42	2230
5000	258,5	77,12	151,1	4,788	1,42	4479
10000	517	77,12	302,1	4,788	1,42	8979

Table B-6 Single stage ORC cycle, 140°C geothermal fluid.

140°C						
Gross output	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 Production [kW]
250	10,2	79,61	6,754	5,478	1,42	206,5
1000	40,81	79,61	27,02	5,478	1,42	886
2500	102	79,61	67,54	5,478	1,42	2245
5000	204	79,61	135,1	5,478	1,42	4510
10000	408,1	79,61	270,2	5,478	1,42	9040

Table B-7 Single stage ORC cycle, 150°C geothermal fluid.

150°C						
Heat Source 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 Production [kW]
250	8,22	81,8	6,099	6,272	1,42	207,6
1000	32,88	81,8	24,39	6,272	1,42	890,5
2500	82,2	81,8	60,98	6,272	1,42	2256
5000	164,4	81,8	122	6,272	1,42	4533
10000	328,8	81,8	243,9	6,272	1,42	9085

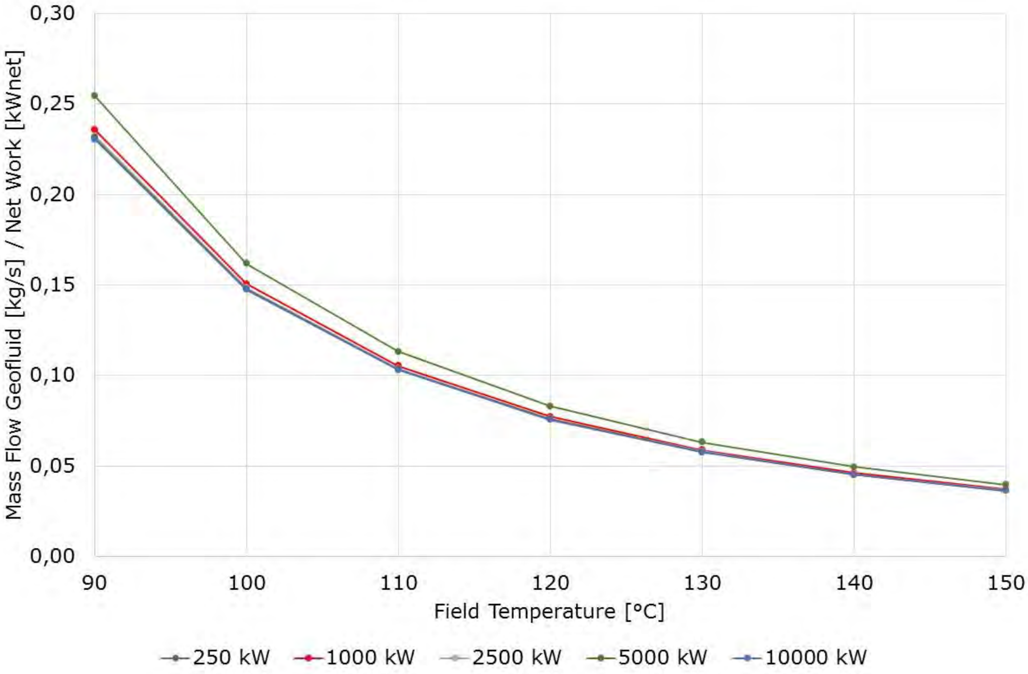


Figure B-1 Mass flow of geothermal fluid required per kW_{net} in a one stage binary cycle. The colored lines indicate the generator size (gross product).

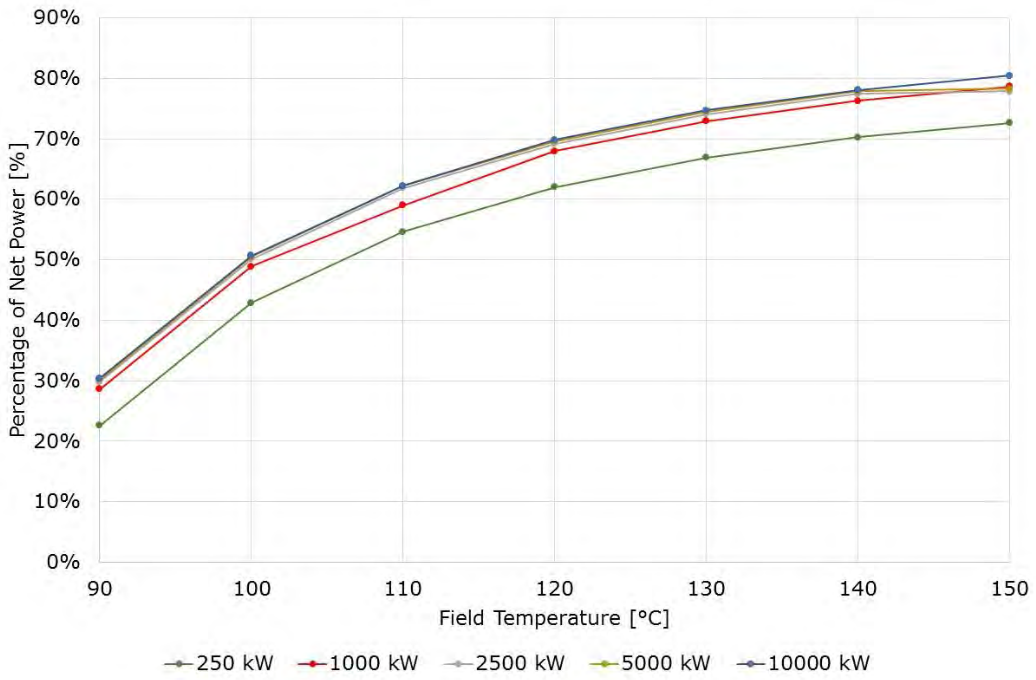


Figure B-2 **Percentage of net power of total generated electricity in the one stage ORC cycle plant. The colored lines indicate the generator size (gross product).**

Two-Stage Cycle

The tables below show the amount (mass flow) of geothermal fluid needed for generation of electricity at temperatures 90°C, 100°C, 110°C, 120°C, 130°C, 140°C and 150°C respectively with two stage ORC cycle. The tables also show various parameters in the process cycle and the net power production.

Table B-8 Two stage ORC cycle, 90°C geothermal fluid.

				90°C				
Generator Output	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 per unitary well flow [kw / kg/s]	Net Power/ Generated power	Net Power Production -Well pump [kW]
250	37,16	58,22	7,11/6,24	3,42/2,28	1,42	5,22	0,78	194,08
1000	148,6	58,22	28,42/24,97	3,42/2,28	1,42	5,63	0,84	836,3
2500	371,6	58,22	71,06/62,42	3,42/2,28	1,42	5,71	0,85	2121
5000	743,2	58,22	142,1/124,8	3,42/2,28	1,42	5,73	0,85	4259
10000	1486	58,22	284,2/249,7	3,42/2,28	1,42	5,74	0,85	8523

Table B-9 Two stage ORC cycle, 100°C geothermal fluid.

100°C								
Generator Output	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 per unitary well flow [kw / kg/s]	Net Power/ Generated power	Net Power Production [kW]
250	24,91	60,77	5,96/4,94	4,08/2,53	1,42	8,02	0,80	199,82
1000	99,63	60,77	23,85/19,75	4,08/2,53	1,42	8,63	0,86	859,4
2500	249,1	60,77	59,62/49,37	4,08/2,53	1,42	8,74	0,87	2178,3
5000	498,1	60,77	119,2/98,75	4,08/2,53	1,42	8,79	0,88	4377
10000	996,3	60,77	238,5/197,5	4,08/2,53	1,42	8,81	0,88	8774

Table B-10 Two stage ORC cycle, 110°C geothermal fluid

110°C								
Generator Output	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 per unitary well flow [kw / kg/s]	Net Power/ Generated power	Net Power Production [kW]
250	17,87	63,24	5,19/4,01	4,83/2,80	1,42	11,39	0,81	203,58
1000	71,47	63,24	20,76/16,03	4,83/2,80	1,42	12,23	0,87	874,2
2500	178,7	63,24	51,91/40,08	4,83/2,80	1,42	12,40	0,89	2215,8
5000	357,4	63,24	103,8/80,16	4,83/2,80	1,42	12,46	0,89	4452
10000	714,7	63,24	207,7/160,3	4,83/2,80	1,42	12,48	0,89	8922

Table B-11 Two stage ORC cycle, 120°C geothermal fluid

120°C								
Generator Output	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 per unitary well flow [kw / kg/s]	Net Power/ Generated power	Net Power Production [kW]
250	13,45	65,64	4,64/3,31	5,67/3,11	1,42	15,32	0,82	206,07
1000	53,81	65,64	18,57/13,22	5,67/3,11	1,42	16,43	0,88	884,2
2500	134,5	65,54	46,53/33,09	5,67/3,11	1,42	16,66	0,90	2240,7
5000	269,1	65,64	92,85/66,11	5,67/3,11	1,42	16,73	0,90	4501,5
10000	538,1	65,64	185,7/132,2	5,67/3,11	1,42	16,77	0,90	9022

Table B-12 Two stage ORC cycle, 130°C geothermal fluid

130°C								
Generator Output	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 per unitary well flow [kw / kg/s]	Net Power/ Generated power	Net Power Production [kW]
250	10,5	67,96	4,241/2,747	6,62/3,45	1,42	19,78	0,83	207,72
1000	41,99	67,96	16,97/10,99	6,62/3,45	1,42	21,22	0,89	891,1
2500	105	67,96	42,41/27,47	6,62/3,45	1,42	21,50	0,90	2257,2
5000	210	67,96	84,83/54,94	6,62/3,45	1,42	21,60	0,91	4535,5
10000	419,9	67,96	169,7/109,9	6,62/3,45	1,42	21,65	0,91	9091

Table B-13 Two stage ORC cycle, 140°C geothermal fluid

140°C								
Generator Output	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 per unitary well flow [kw / kg/s]	Net Power/ Generated power	Net Power Production [kW]
250	8,421	70,22	3,94/2,27	7,67/3,82	1,42	24,81	0,84	208,93
1000	33,69	70,21	15,77/9,42	7,67/3,82	1,42	26,59	0,90	895,7
2500	84,21	70,21	39,43/22,86	7,67/3,82	1,42	26,95	0,91	2269,3
5000	168,4	70,21	78,85/45,72	7,67/3,82	1,42	27,07	0,91	4558,6
10000	336,9	70,21	157,7/91,44	7,67/3,82	1,42	27,12	0,91	9137

Table B-14 Two stage ORC cycle, 150°C geothermal fluid

150°C								
Generator Output	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 per unitary well flow [kw / kg/s]	Net Power/ Generated power	Net Power Production [kW]
250	6,903	72,38	3,72/1,90	8,83/4,23	1,42	30,38	0,84	209,71
1000	27,61	72,38	14,87/7,58	8,83/4,23	1,42	32,55	0,90	898,76
2500	69,03	72,38	37,17/18,95	8,83/4,23	1,42	32,99	0,91	2277,1
5000	138,1	72,38	74,35/37,89	8,83/4,23	1,42	33,12	0,91	4573,3
10000	276,1	72,38	148,7/75,79	8,83/4,23	1,42	33,46	0,92	9239,6

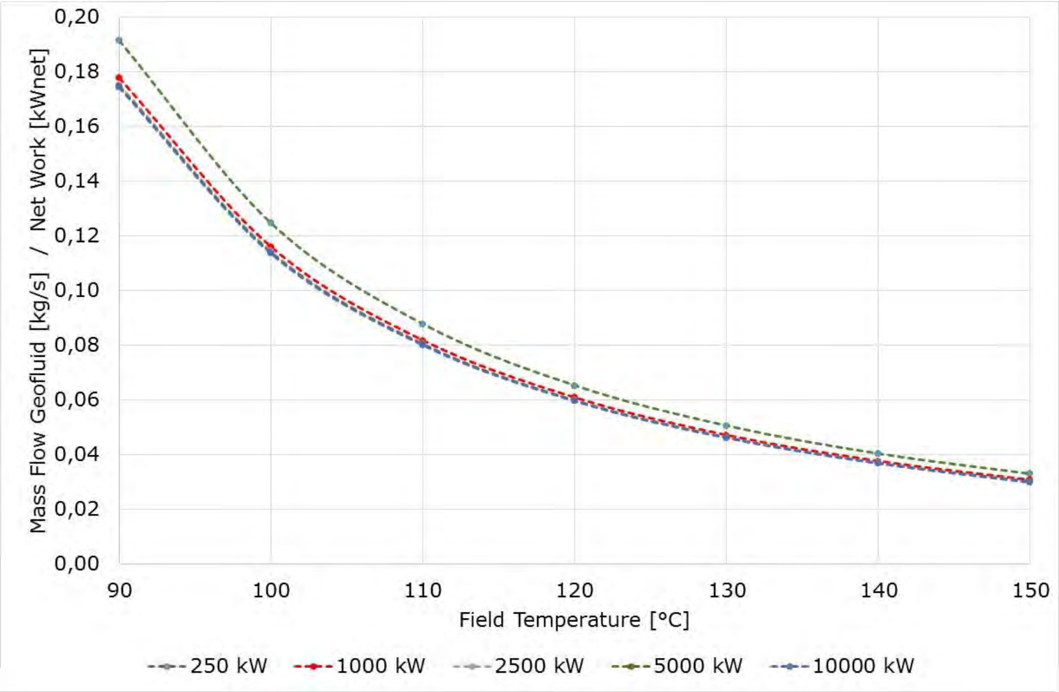


Figure B-3 **Mass flow of geothermal fluid required per kW_{net} in the two stage binary cycle plants. The colored lines indicate the generator size (gross product).**

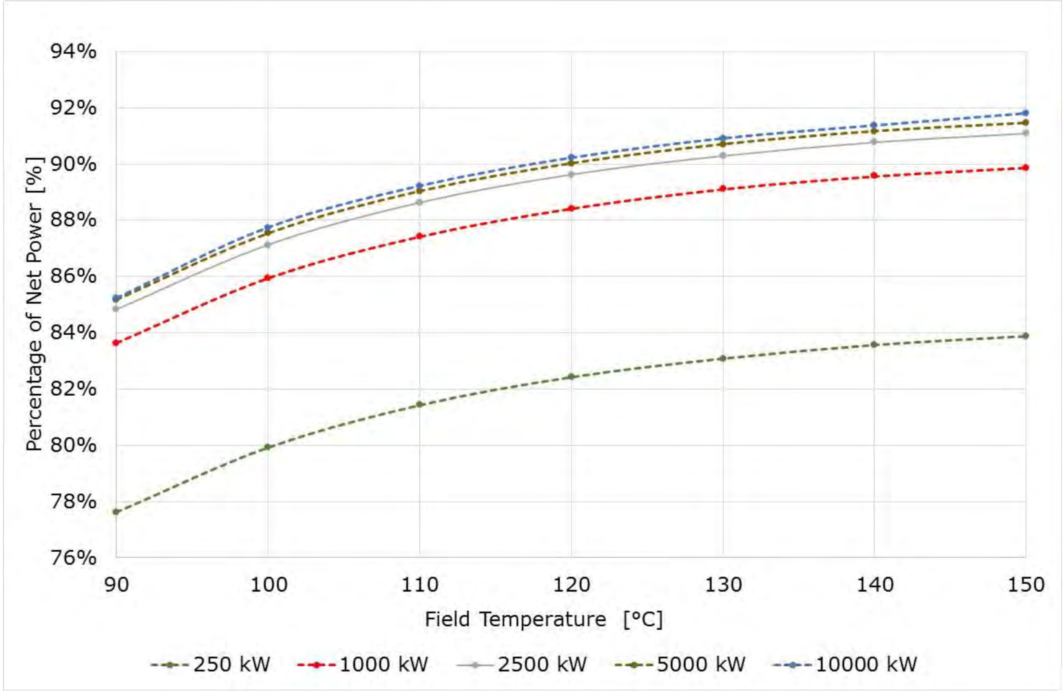


Figure B-4 Percentage of net power of total generated electricity in the two stage ORC cycle plants. The colored lines indicate the generator size (gross product).

Appendix C – Cost Results

Table C-15 Yearly cost of spare parts, maintenance and insurances

	Spare parts, maintainence and insurances				
	Single stage ORC cycle			Two stage ORC cycle	
	Power	Cost /Year $USD		Power	Cost /Year $USD
90°C	250	33.587		250	34.449
	1.000	104.542		1.000	117.086
	2.500	227.063		2.500	249.054
	5.000	407.757		5.000	443.304
	10.000	765.142		10.000	831.179
100°C	250	27.568		250	32.245
	1.000	96.440		1.000	108.199
	2.500	174.717		2.500	221.184
	5.000	304.499		5.000	381.130
	10.000	633.016		10.000	698.557
110°C	250	26.067		250	30.444
	1.000	87.777		1.000	98.641
	2.500	168.711		2.500	193.253
	5.000	285.987		5.000	320.601
	10.000	513.193		10.000	575.681
120°C	250	25.361		250	29.597
	1.000	79.003		1.000	93.131
	2.500	153.508		2.500	175.845
	5.000	246.441		5.000	279.836
	10.000	454.899		10.000	519.112
130°C	250	24.409		250	28.455
	1.000	75.195		1.000	88.561
	2.500	136.558		2.500	156.341
	5.000	224.476		5.000	259.334
	10.000	416.570		10.000	480.645
140°C	250	23.357		250	27.192
	1.000	70.245		1.000	78.438
	2.500	118.417		2.500	139.591
	5.000	209.494		5.000	242.191
	10.000	396.005		10.000	457.641
150°C	250	23.200		250	27.003
	1.000	62.120		1.000	73.707
	2.500	110.137		2.500	125.473
	5.000	200.191		5.000	231.865
	10.000	384.641		10.000	445.676

Table C-2 Annual well replacement cost

Annual Well replacement cost					
	Single stage ORC cycle			**Two stage ORC cycle**	
	Power	**Cost /Year $USD**		**Power**	**Cost /Year $USD**
90°C	250	79.989		250	95.987
	1.000	320.123		1.000	384.147
	2.500	800.390		2.500	960.468
	5.000	1.600.779		5.000	1.920.935
	10.000	3.201.228		10.000	3.841.473
100°C	250	52.995		250	63.594
	1.000	211.980		1.000	254.376
	2.500	529.950		2.500	635.940
	5.000	1.059.734		5.000	1.271.681
	10.000	2.119.799		10.000	2.543.759
110°C	250	37.511		250	45.013
	1.000	150.125		1.000	180.150
	2.500	375.105		2.500	450.126
	5.000	750.376		5.000	900.451
	10.000	1.500.751		10.000	1.800.902
120°C	250	27.855		250	33.427
	1.000	111.389		1.000	133.667
	2.500	278.555		2.500	334.266
	5.000	556.944		5.000	668.333
	10.000	1.113.888		10.000	1.336.666
130°C	250	21.413		250	25.696
	1.000	85.620		1.000	102.744
	2.500	214.133		2.500	256.959
	5.000	428.100		5.000	513.720
	10.000	856.200		10.000	1.027.440
140°C	250	16.892		250	20.271
	1.000	67.585		1.000	81.102
	2.500	168.921		2.500	202.706
	5.000	337.843		5.000	405.412
	10.000	675.852		10.000	811.022
150°C	250	13.613		250	16.336
	1.000	54.452		1.000	65.343
	2.500	136.131		2.500	163.357
	5.000	272.262		5.000	326.714
	10.000	544.523		10.000	653.428

Table C-3 Annual cost of personnel

Personnel cost					
	Single stage ORC cycle			Two stage ORC cycle	
	Power	Cost /Year $USD		Power	Cost /Year $USD
90°C	250	162.500		250	162.500
	1.000	162.500		1.000	162.500
	2.500	294.500		2.500	294.500
	5.000	326.500		5.000	326.500
	10.000	366.500		10.000	366.500
100°C	250	162.500		250	162.500
	1.000	162.500		1.000	162.500
	2.500	294.500		2.500	294.500
	5.000	326.500		5.000	326.500
	10.000	366.500		10.000	366.500
110°C	250	162.500		250	162.500
	1.000	162.500		1.000	162.500
	2.500	294.500		2.500	294.500
	5.000	326.500		5.000	326.500
	10.000	366.500		10.000	366.500
120°C	250	162.500		250	162.500
	1.000	162.500		1.000	162.500
	2.500	294.500		2.500	294.500
	5.000	326.500		5.000	326.500
	10.000	366.500		10.000	366.500
130°C	250	162.500		250	162.500
	1.000	162.500		1.000	162.500
	2.500	294.500		2.500	294.500
	5.000	326.500		5.000	326.500
	10.000	366.500		10.000	366.500
140°C	250	162.500		250	162.500
	1.000	162.500		1.000	162.500
	2.500	294.500		2.500	294.500
	5.000	326.500		5.000	326.500
	10.000	366.500		10.000	366.500
150°C	250	162.500		250	162.500
	1.000	162.500		1.000	162.500
	2.500	294.500		2.500	294.500
	5.000	326.500		5.000	326.500
	10.000	366.500		10.000	366.500

Table C-4 Annual O&M cost

O&M cost					
	Single stage ORC cycle			Two stage ORC cycle	
	Power	Cost /Year $USD		Power	Cost /Year $USD
90°C	250	276.076		250	292.936
	1.000	587.165		1.000	663.733
	2.500	1.321.952		2.500	1.504.022
	5.000	2.335.037		5.000	2.690.739
	10.000	4.332.870		10.000	5.039.152
100°C	250	243.063		250	258.339
	1.000	470.919		1.000	525.075
	2.500	999.167		2.500	1.151.623
	5.000	1.690.733		5.000	1.979.310
	10.000	3.119.315		10.000	3.608.816
110°C	250	226.078		250	237.957
	1.000	400.402		1.000	441.291
	2.500	838.316		2.500	937.879
	5.000	1.362.863		5.000	1.547.551
	10.000	2.380.444		10.000	2.743.083
120°C	250	215.717		250	225.524
	1.000	352.892		1.000	389.297
	2.500	726.563		2.500	804.611
	5.000	1.129.885		5.000	1.274.669
	10.000	1.935.287		10.000	2.222.278
130°C	250	208.323		250	216.651
	1.000	323.315		1.000	353.805
	2.500	645.191		2.500	707.801
	5.000	979.076		5.000	1.099.554
	10.000	1.639.270		10.000	1.874.585
140°C	250	202.749		250	209.962
	1.000	300.330		1.000	322.040
	2.500	581.838		2.500	636.797
	5.000	873.837		5.000	974.103
	10.000	1.438.357		10.000	1.635.162
150°C	250	199.313		250	205.839
	1.000	279.072		1.000	301.550
	2.500	540.768		2.500	583.330
	5.000	798.953		5.000	885.079
	10.000	1.295.664		10.000	1.465.604

Table C-5 Production Cost Estimate (different pumping depths)

Production Cost: 1. Stage Cycle - Power requirements of pumps

	Generator size [kW]	Net Power Production [kW]	Total Production Cost [USD]	Well pump Power [kW] 0m	Well pump Power [kW] 100m	Well pump Power [kW] 200m
90°C	250	189,9	874.293	0	79,02	158,04
	1000	819,7	2.887.590	0	316,1	632,2
	2500	2079	6.876.604	0	790,2	1580,4
	5000	4178	13.216.050	0	1580	3160
	10000	8377	25.843.025	0	3161	6322
100°C	250	197,6	675.520	0	52,31	104,62
	1000	850,5	2.125.895	0	209,3	418,6
	2500	2156	4.800.012	0	523,1	1046,2
	5000	4333	9.070.925	0	1046	2092
	10000	8685	18.034.217	0	2093	4186
110°C	250	200	561.032	0	370,4	740,8
	1000	860,1	1.674.086	0	148,2	296,4
	2500	2180	3.780.742	0	370,4	740,8
	5000	4380	6.970.326	0	740,8	1481,6
	10000	8781	13.299.898	0	1482	2964
120°C	250	202,9	491.121	0	27,49	54,98
	1000	871,5	1.378.129	0	110	220
	2500	2209	3.052.029	0	274,9	549,8
	5000	4438	5.474.684	0	549,9	1099,8
	10000	8895	10.441.974	0	1100	2200
130°C	250	205	441.388	0	21,13	42,26
	1000	879,9	1.179.199	0	84,53	169,06
	2500	2230	2.529.697	0	211,3	422,6
	5000	4479	4.506.548	0	422,6	845,2
	10000	8979	8.541.607	0	845,3	1690,6
140°C	250	206,5	404.019	0	16,68	33,36
	1000	886	1.025.321	0	66,72	133,44
	2500	2245	2.129.831	0	166,8	333,6
	5000	4510	3.821.870	0	333,6	667,2
	10000	9040	7.233.641	0	667,2	1334,4
150°C	250	207,6	380.807	0	13,44	26,88
	1000	890,5	906.922	0	53,76	107,52
	2500	2256	1.854.674	0	134,4	268,8
	5000	4533	3.340.722	0	268,8	537,6
	10000	9085	6.316.644	0	537,6	1075,2

$$Production\ cost\ [\mathrm{USD/kWh}] = \frac{Total\ Production\ Cost\ [USD]}{\left(W_{net,plant} - W_{wellpump}\right)kW \cdot 8409\ h}$$

Table C-6 Production Cost Estimate (different pumping depths)

Production cost: 2. Stage Cycle - Power requirements of pumps						
	Generator size [kW]	Net Power Production [kW]	Total Production Cost [USD]	Well pump Power [kW] 0m	Well pump Power [kW] 100m	Well pump Power [kW] 200m
90°C	250	194,08	1.010.797	0	55,94	111,88
	1000	836,3	3.424.243	0	223,7	447,4
	2500	2121	8.169.604	0	559,4	1118,8
	5000	4259	15.747.955	0	1119	2238
	10000	8523	30.851.338	0	2237	4474
100°C	250	199,82	777.287	0	38,67	77,34
	1000	859,4	2.511.046	0	154,7	309,4
	2500	2178,3	5.712.637	0	386,7	773,4
	5000	4377	10.835.541	0	773,3	1546,6
	10000	8774	21.506.700	0	1547	3094
110°C	250	203,58	639.901	0	28,89	57,78
	1000	874,2	1.969.712	0	115,5	231
	2500	2215,8	4.468.789	0	288,9	577,8
	5000	4452	8.276.507	0	577,7	1155,4
	10000	8922	15.846.428	0	1155	2310
120°C	250	206,07	556.008	0	22,9	45,8
	1000	884,2	1.619.582	0	91,59	183,18
	2500	2240,7	3.595.171	0	229	458
	5000	4501,5	6.488.428	0	458	916
	10000	9022	12.430.303	0	915,9	1831,8
130°C	250	207,72	496.329	0	19,04	38,08
	1000	891,1	1.380.866	0	76,18	152,36
	2500	2257,2	2.969.208	0	190,4	380,8
	5000	4535,5	5.332.520	0	380,9	761,8
	10000	9091	10.157.390	0	761,8	1523,6
140°C	250	208,93	451.487	0	16,49	32,98
	1000	895,7	1.192.030	0	65,97	131,94
	2500	2269,3	2.494.388	0	164,9	329,8
	5000	4558,6	4.511.743	0	329,9	659,8
	10000	9137	8.589.504	0	659,7	1319,4
150°C	250	209,71	423.632	0	14,79	29,58
	1000	898,76	1.054.970	0	59,16	118,32
	2500	2277,1	2.160.017	0	147,9	295,8
	5000	4573,3	3.935.202	0	295,8	591,6
	10000	9239,6	7.490.780	0	591,6	1183,2

$$Production\ cost\ [\mathrm{USD/kWh}] = \frac{Total\ Production\ Cost\ [USD]}{\left(W_{net,plant} - W_{wellpump}\right) kW \cdot 8409\ h}$$