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Numerical modeling and optimizing of geothermal CCHP integrated energy system in Xiaoreshui, Kangding county in Sichuan Ganzi Prefecture.

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ABSTRACT

This study presents a numerical modeling of geothermal CCHP integrated system. To improve efficiency of energy utilization, an integrated system with Organic Rankine Cycle (ORC) is designed for generating electricity and providing heating in winter. The ORC unit is the core part the integrated energy system.

An ORC numerical model is established to optimize the design of the power generation system. Key parameters of the system, including the type of working fluid, evaporation pressure, condensation pressure and pinch point temperature difference, are optimized in the numerical model. The return flow from the ORC plant is used as a heat source for a district heating network.

For the effective utilization of geothermal resource, aquifer energy storage unit is applied in the system to store the return flow from the plant during summer, so that the injected water can be extracted during the heating season. The economy is the objective function of this cogeneration of power, heating and cooling system optimization.

The most economic feasible design of the system is achieved through optimization.

1. INTRODUCTION

The name of the studied geothermal field is Xiaoreshui and is close to Kangding Lucheng city in Ganzi Prefecture, Sichuan, China.

There are several exploratory wells drilled in the area, and wells ZK201 and ZK203 indicate that the reservoir may have up to 210 °C temperature. The wells have produced a mixture of non-condensable gas, steam, and brine with a mixture total flow of up to 200 m^3/h.

The weather data used for the calculation of the plant performance and for estimation of the heat load are taken from the International Weather for Energy Calculations (IWEC) for Kangding (World Meteorological Organization weather station number 563 740), see ASHRAE (2012).

The plant is calculated with a thermodynamic plant model. The performance of the plant is calculated, and the size of the plant components is estimated. This is done with the help of the Thermus thermodynamic plant modeling library which is under development by the company P.Vald ehf (https://pvald.com/) in Iceland. The Thermus library is still under development, so no public information on the library as such is available. Instead, the modeling approach will be explained step by step in this paper.

The plant cost is estimated with heuristic values of specific component cost, installation, and overhead cost. These heuristic values are based on the experience of the authors and are very much dependent on the location and market in which the proposed plant is to be located.

2. LOCATION

The field is around 220 km west-south-west from Chengdu, and 5 km south of Kangding Lucheng city, which has around 130 000 inhabitants and is therefore a logical candidate for a district heating system.

The location of Kangding Lucheng city relative to Chengdu is shown on Figure 1

Figure 1: Location of Kangding Lucheng city relative to Chengdu. The distance is around 200 km as the crow flies.

Kangding Lucheng city is in a narrow valley, and the Xiaoreshui geothermal field is located around 5 km further south in the valley.

The location of the Xiaoreshui field relative to Kangding Lucheng city is shown on Figure 2.

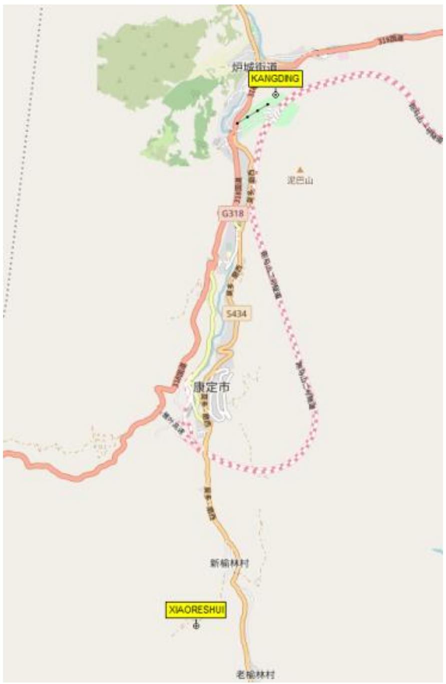

Figure 2: Location of Xiaoreshui geothermal field relative to Kancheng Lucheng city.

3. WEATHER DATA

The dry bulb outdoor air temperature for Kangding is shown on Figure 3. The heating season is assumed to start on November 15th and end on March 15th. The start and end of the heating season is marked on the graph. The length of the heating season is thus 2 880 hours.

The average temperature for the design year in Kangding is 7,6 °C. Based on that the design outdoor temperature for the ORC plant is selected as 8 °C.

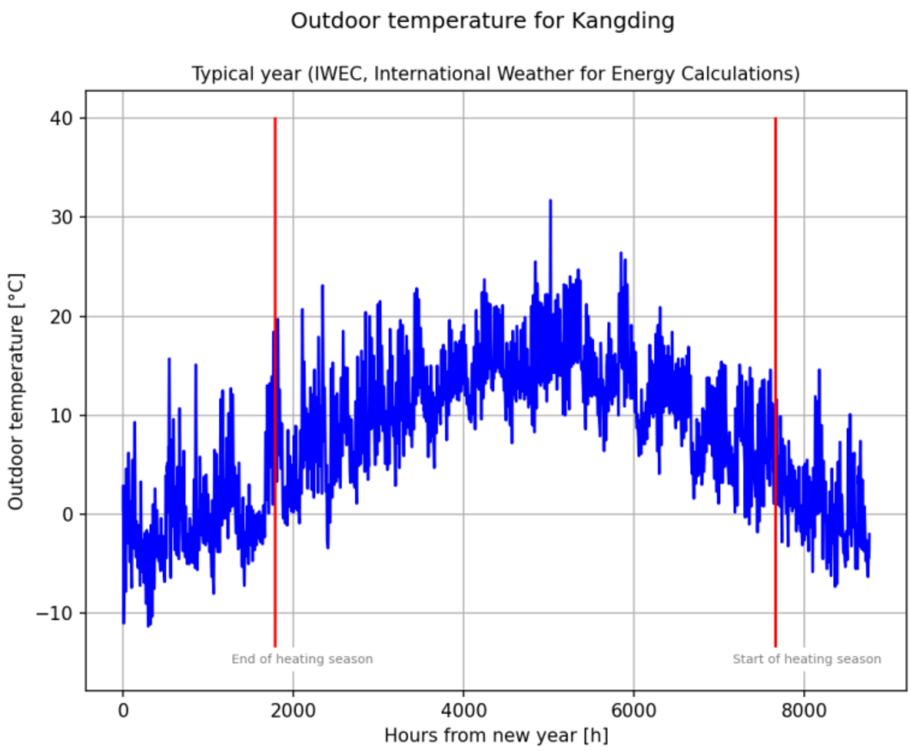

Figure 3: The dry bulb outdoor air temperature for the design year in Kangding.

4. THE RESOURCE

The available data indicates a good resource. However, some assumptions regarding the resource have to be made.

The design reservoir temperature is selected at 150 °C, which is lower than the expectations from the exploration wells. This is just an attempt to be on the cautious side, and not oversell the idea of an ORC power plant.

The well flow is selected as 100 kg/s. This will then require 4 wells with 25 kg/s flow each, which may be taken as an average value for similar fields.

It is known that some non-condensable gas will be present in the geothermal fluid mixture. This will influence the ORC plant design, and a value of the amount of gas has to be selected for the fluid. After some considerations, a gas content of 0.15 % of the total well flow is selected.

The mineralization and heat capacity of the liquid part of the mixture is not known, so the liquid component is assumed to have the same properties as pure water.

The fluid from the well will be separated into a gas-steam mixture on one hand and mineralized brine on the other hand when it has reached the surface. The separation pressure must be is lower than the wellhead pressure, so knowledge of the well productivity curves is necessary to optimize this separation pressure together with the plant. As the productivity curves are not known, a separation pressure of 2 bar-abs is selected.

The ORC plant will then have separate inlets for the steam – gas mixture on one hand and the liquid brine on the other hand.

A calculation of the plant source system is shown on Figure 4.

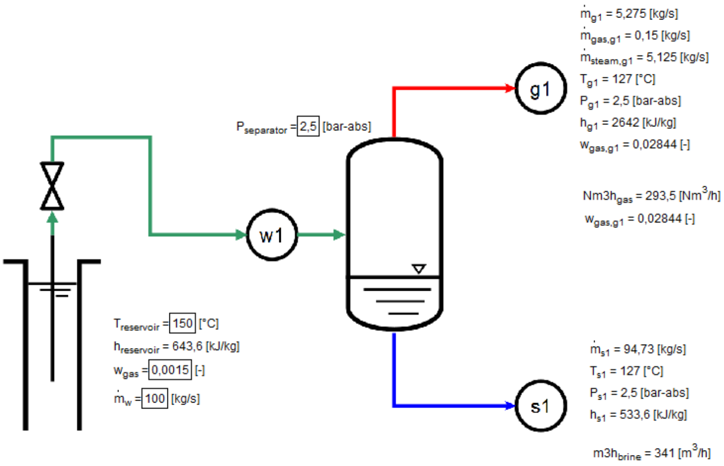

Figure 4: A calculation of the plant source system according to the assumed resource properties.

5. THE UTILIZATION SYSTEM

The central component of the utilization system is the ORC plant. The return flow from the ORC plant has sufficient temperature to be a heat source for a district heating system during the heating season.

An aquifer storage is also considered. Then the ORC plant return flow is injected into the storage aquifer during the summer. During the heating season the ORC plant return will be fed to the district heating, if there is any surplus of return water it will be injected into the aquifer storage. If more water is needed for the district heating than what the return flow form the ORC plant can supply, then additional water is harvested form the aquifer storage. The aquifer storage wells will ideally have a reservoir temperature around 60 °C. If the reservoir temperature of the aquifer storage wells is higher, then additional heat mining from the field will happen in the storage, but if they are colder, then storage loss will be encountered.

The district heating system is not analyzed in detail in the paper. It is assumed that the district heating system will require 60 °C supply temperature and have 37 °C return temperature. The district heating return water is then injected into cold re-injection wells. An estimation of the possible district heating system size will be made later in this paper.

A block diagram of the utilization system is shown on Figure 5. Geothermal fluid flow streams having steam or gas component are shown in red color. Liquid only geothermal fluid flow streams are shown in magenta color. The ORC plant working fluid flow streams are shown in green color, and cooling air flow streams are in blue color.

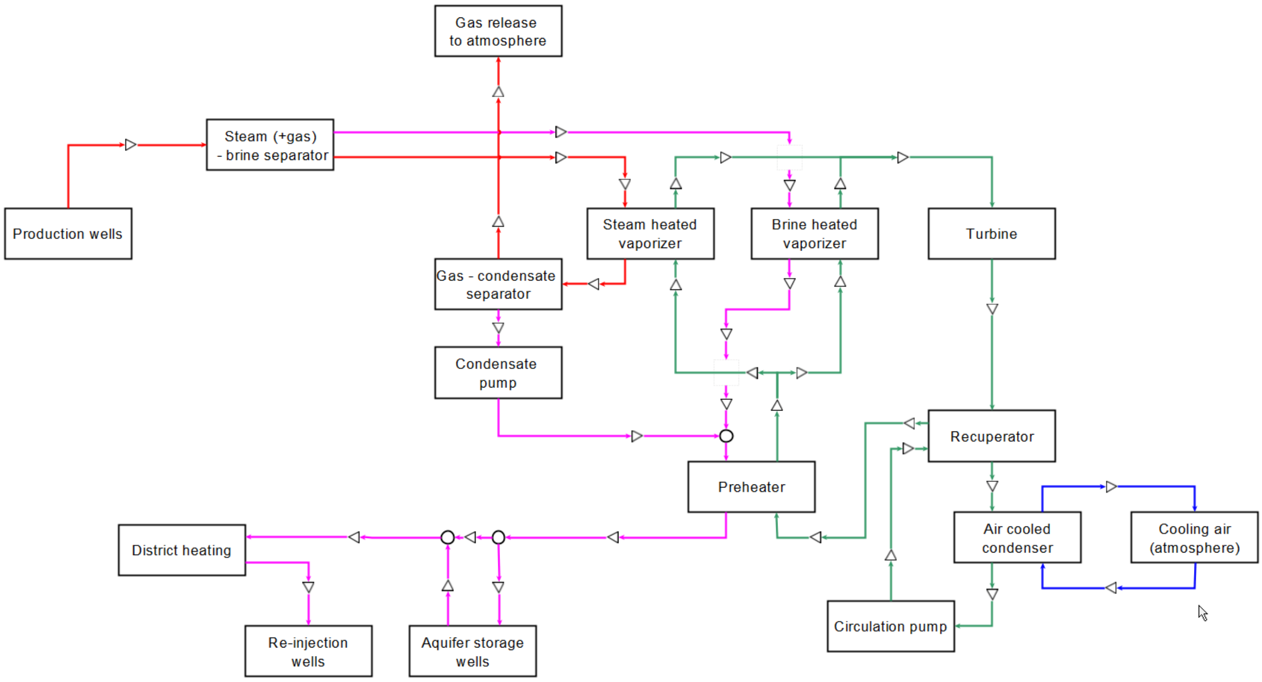

Figure 5: A block diagram of the proposed utilization system.

6. THE CALCULATION MODEL

A thermodynamic model of the whole system has ben set up. The model is implemented in the programming language Python with the help of the CoolProp thermodynamic properties library and the Thermus library of P.Vald ehf for the component models. See Python Software Foundation (2023), Bell et al. (2014) and Valdimarsson (2011a/b/c):

The first step in any thermal engineering calculation model is to define the thermodynamic stations in the system to be modeled. They are grouped in the following groups:

- Prefix w: Wells and reservoir
- Prefix g: Steam – gas mixture and condensate
- Prefix s: Source brine
- No prefix: ORC working fluid
- Prefix c: Cooling (atmospheric) air

The process flow diagram for the calculation model is shown on Figure 6.

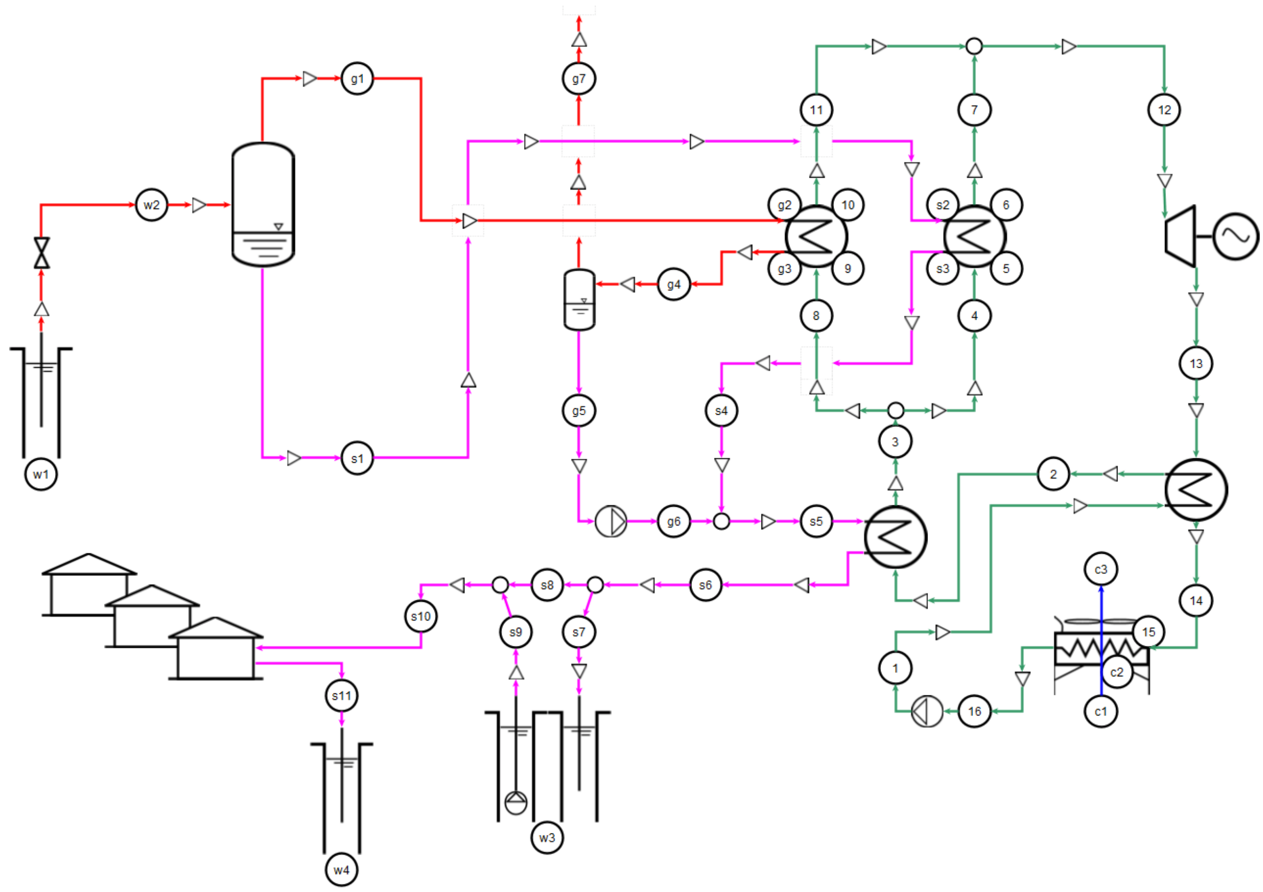

Figure 6: The process flow diagram of the calculation model.

7. SELECTION OF WORKING FLUID FOR THE ORC CYCLE

A simplified plant model is made to select the best working fluid. This model is run for a set of working fluids in order to find the best working fluid. The ORC plant return temperature is as well calculated and the results presented in a “nose diagram”, where the “nose tip” of the curve for each candidate working fluid gives the best performance.

The simplified model ignores the parasitic work of the air fans of the condenser and assumes instead a fixed condensation temperature of the working fluid in the condenser. This is possible because the fan parasitic work will be very similar for all working fluids. Other plant design parameters are set at default values for pinches in the heat exchangers, which are common in European plants.

Some of the fluids do not display a “nose tip” and have instead high power at a very low return temperature. These are fluids which are not at all suitable, because their critical pressure is too low relative to the source temperature. A plant with these fluids will not be possible.

The “nose diagram” is shown on Figure 7. There it can be seen that the plant return temperature for highest power production for Isobutane working fluid is 64.5 °C whereas the return temperature for R236a is 63,0 °C. The best internal net power for both fluids is 3 702 kW.

The selected fluid is therefore Isobutane. It has higher return temperature and is cheaper than the refrigerant R236a.

The ORC plant will be optimized for Isobutane, so the final return temperature will change somewhat. A new net power for the whole optimized plant will also be calculated.

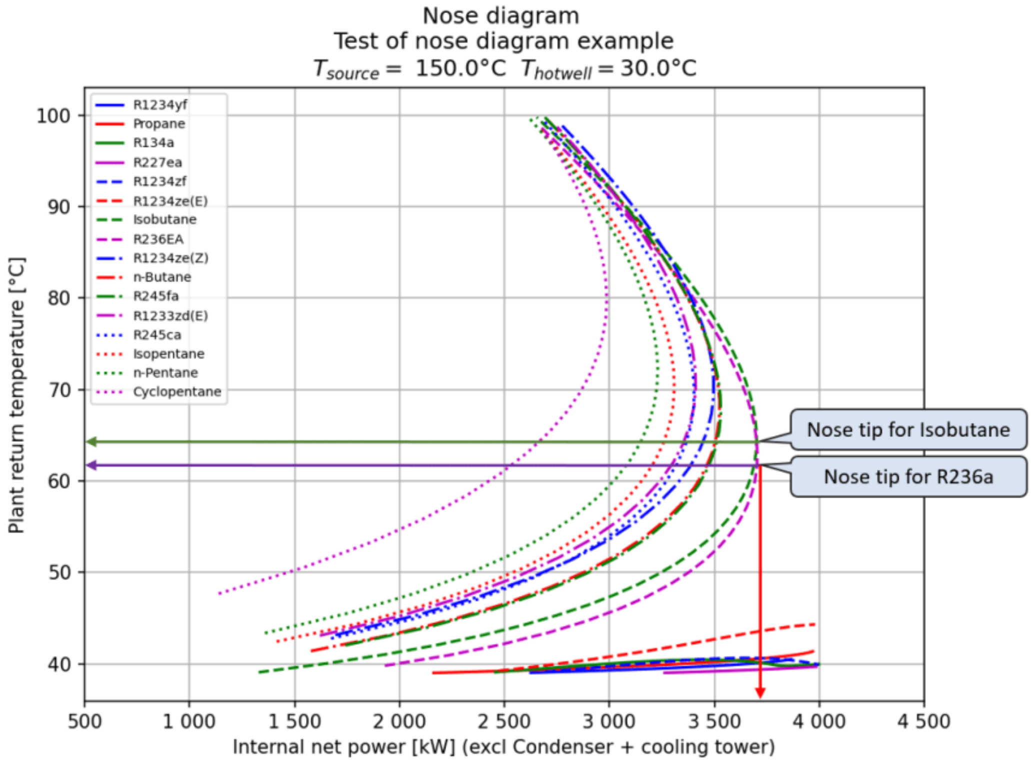

Figure 7: The "nose diagram" for working fluid selection.

8. THE COST MODEL

The cost items for an ORC power plant can be divided into three groups:

1) The cost of the main components of the plant
2) The cost of connecting the components and auxiliary systems (control, fire protection) as well as the building itself and the civil works. This is sometimes referred to as "Balance of plant".
3) The cost of connecting the plant to the source system.

The cost of the wells and the source system is ignored in this optimization. It will influence the optimal plant design, because if it is expensive to supply the source fluid to the plant, it will be feasible to invest more in the plant and get higher efficiency for the expensive system. This means that the plant presented here is only optimal if somebody else is paying for all wells and the supply system.

9. THE OPTIMIZED ORC PLANT

The plant return temperature is sufficiently high to feed the district heating network. As a result of that the optimization process puts the recuperator size to zero, that is that the recuperator is not needed and is removed from the plant.

9.1 Main results

- Working fluid: Isobutane
- Turbine inlet pressure [bar-abs]: 23.94
- Source flow [kg/s]: 100
- …thereof brine [kg/s]: 94.725
- …thereof steam-gas mixture [kg/s]: 5.275
- Cooling system: Air
- Air inlet temperature [°C]: 8
- Net power [kW]: 4 405
- Turbine wheel power [kW]: 5 407
- Plant return temperature [°C]: 69.93
- Cost of connection to the source system [$]: 1 000 000
- Cost of "balance of plant" [$]: 5 000 000
- Cost of main components [$]: 6 509 639
- Total plant cost [$]: 12 509 639
- Specific main component cost [$/kW]: 1 477
- Specific plant total cost [$/kW]: 2 839

9.2 Thermodynamic station data for the optimized plant

Working fluid thermodynamic station data							
StationNumber[i]	P_wf[i]	T_wf[i]	h_wf[i]	s_wf[i]	rho_wf[i]	m_dot_wf[i]	V_dot_wf[i]
	[bar_abs]	[°C]	[kJ/kg]	[kJ/kg/°C]	[kg/m^3]	[kg/s]	[m^3/s]
1	25.01	27.54	266.8	1.219	551.3	85.89	0.1558
2	24.61	27.55	266.8	1.219	551.2	85.89	0.1558
3	24.06	108.6	494.7	1.886	410.3	85.89	0.2093
4	24.06	108.6	494.7	1.886	410.3	29.6	0.07216
5	24.05	110.6	502	1.905	403.4	29.6	0.07339
6	24.05	110.5	684.8	2.381	73.54	29.6	0.4026
7	24.04	112.5	691.8	2.399	71.28	29.6	0.4153
8	24.06	108.6	494.7	1.886	410.3	56.28	0.1372
9	24.05	110.6	502	1.905	403.4	56.28	0.1395
10	24.05	110.5	684.8	2.381	73.54	56.28	0.7654
11	24.04	112.5	691.8	2.399	71.28	56.28	0.7896
12	23.94	112.4	691.8	2.4	70.83	85.89	1.213
13	3.677	47.25	628.8	2.435	8.721	85.89	9.848
14	3.627	47.45	629.3	2.438	8.585	85.89	10
15	3.617	26.11	590	2.312	9.404	85.89	9.133
16	3.6	25.92	261.7	1.214	548.7	85.89	0.1565

Source liquid thermodynamic station data			
StationNumber[i]	T_s[i]	h_s[i]	s_s[i]
	[°C]	[kJ/kg]	[kJ/kg/°C]
1	127.4	691.8	2.399
2	126.9	684.8	2.381
3	114.2	502	1.905
4	113.7	494.7	1.886
5	113.5	494.7	1.886
6	69.63	266.8	1.219

Steam-gas-liquid thermodynamic station data							
StationNumber[i]	P_g[i]	T_g[i]	h_g[i]	m_dot_g[i]	m_dot_gas_g[i]	m_dot_vap_g[i]	m_dot_liq_g[i]
	[bar_abs]	[°C]	[kJ/kg]	[kg/s]	[kg/s]	[kg/s]	[kg/s]
1	2.5	127.3	2642	5.275	0.15	5.125	0
2	2.3	124.3	2568	5.275	0.15	4.957	0.168
3	2.1	116.5	617.5	5.275	0.15	0.3344	4.791
4	1.9	110.6	539.2	5.275	0.15	0.2049	4.92
5	1.9	110.6	463.9	4.92	0	0	4.92
6	2.5	110.6	464	4.92	0	0	4.92
7	1.9	110.6	1586	0.3549	0.15	0.2049	0

9.3 Component data for the optimized plant

Steam – gas mixture heated vaporizer data	
Heat Duty [kW]	11 092
Hot side inlet total mass flow [kg/s]	5.275
- thereof gas mass flow [kg/s]	0.15
- thereof steam mass flow [kg/s]	5.125
- thereof liquid water mass flow [kg/s]	0
Hot side inlet temperature [°C]	124.5
Hot side outlet temperature [°C]	110.6
Cold side mass flow [kg/s]	56.28
Cold side inlet temperature [°C]	108.6
Cold side outlet temperature [°C]	112.5
Minimum approach [°C]	2.011
Estimated area [m^2]	1 743

Brine heated vaporizer data	
Heat Duty [kW]	5834
Hot side mass flow [kg/s]	100
Hot side inlet temperature [°C]	127.4
Hot side outlet temperature [°C]	113.7
Cold side mass flow [kg/s]	29.6
Cold side inlet temperature [°C]	108.6
Cold side outlet temperature [°C]	112.5
Minimum approach [°C]	3.633
Estimated area [m^2]	741.7

Turbine data	
Wheel power [kW]	5 407
Mass flow [kg/s]	85.89
Inlet volume flow [m^3/s]	1.213
Inlet pressure [bar-abs]	23.94
Inlet temperature [°C]	112.4
Outlet pressure [bar-abs]	3.677
Outlet Temperature [°C]	47.25
Outlet volume flow [m^3/s]	9.848
Isentropic enthalpy drop [kJ/kg]	74.06
Outlet speed of sound [m/s]	208.1
Estimated efficiency [%]	85

Condenser data	
Heat Duty [kW]	31 575
Hot side mass flow [kg/s]	85.89
Hot side inlet temperature [°C]	47.45
Hot side outlet temperature [°C]	25.92
Cold side mass flow [kg/s]	2 640
Cold side volume flow [m^3/s]	2 131
Cold side inlet temperature [°C]	8
Cold side outlet temperature [°C]	19.91
Minimum approach [°C]	7.472
Estimated area [m^2]	5453

Circulation pump	
Power added to the fluid [kW]	440.9
Mass flow [kg/s]	85.89
Inlet volume flow [m^3/s]	0.1565
Inlet temperature [°C]	25.92
Outlet pressure [bar-abs]	25.01
Outlet Temperature [°C]	27.54
Estimated efficiency [%]	75

10. THE DISTRICT HEATING NETWORK

It is assumed that the district heating network will need a supply temperature of a minimum of 60 °C and gives back a return temperature of 37 °C. The return water from the district heating network is then re-injected in a cold re-injection well.

The plant return water is used for the district heating network during the heating season, but is injected into the aquifer storage during summer and the district heating is not operating.

During the heating season water can be drawn from the aquifer storage and added to the return flow from the plant and supplied to the district heating.

11. CONCLUSION

The optimized ORC plant will deliver 4 405 kW net power to the grid.

The return flow from the plant is 100 kg/s at a temperature of 69.93 °C. There will be some losses in the network, so a cautious estimate of the power delivered to the buildings is based on a supply temperature of 60 °C and a return temperature of 37 °C. With these numbers the ORC plant return flow can deliver 9 630 kW of heat to the buildings. If a 40 W/m^2 specific building heat consumption is assumed, then this will be sufficient for 240 695 m^2 floor space.

The length of the summer is 5 880 hours. Assuming that all the return flow from the plant is injected into the aquifer storage, then 2 116 800 m^3 of water can be stored in the aquifer storage during the summer.

If the effectiveness of the aquifer storage is 100%, which is the same as to say that the aquifer storage behaves like a storage tank without any leaks or heat losses, then all the injected water can be harvested during the heating season.

The water flow from the storage is then calculated as 204 kg/s, taking into account that water is injected for 5 880 hours and harvested for 2 880 hours every year. This makes it possible to heat 731 712 m^2 floor space with the ORC plant and the aquifer storage.

A geoscientific study of such an aquifer storage is needed. The aquifer storage may return less water than what was injected, but it may also happen that the aquifer storage can also give additional water from its reservoir, and more water be extracted than what was injected. This an only be confirmed by a thorough geoscientific study.

Form this it can be concluded that an ORC plant coupled with aquifer storage and district heating is a very interesting option for the Xiaoreshui geothermal field.

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