THE CASE STUDY OF BINARY POWER PLANT BASED ON THERMOECONOMICS IN SICHUAN, CHINA

by

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In China, renewable energy power plant will be built from the year 2016 to 2020, because of CO_2 emission assignment and energy company demand. A geothermal power plant will be designed in Sichuan province. The wet temperature 15 ºC is selected for cooling temperature. Thermoeconomics of geothermal power system are analyzed using the engineering equation solver. The results show that the capacity of binary power system is 3506 kW and optimum vaporizing pressure is 28 bar, the thermal and exergy efficiency is 13% and 45%. The turbine shaft work of flash power system is 2301 kW and the parasitic load is 71 kW, the optimum flash pressures is 0.95 bar, the thermal and exergy efficiency is 7.9% and 34.7%. the total capital investment of binary system is about 9,767,000 US$, the average annual profit is 1,308,000 $/year; the average rate of return is 13.39%; the payback period is less than 6 years. Condenser destruction and loss exergy is more than other components in the power system. The geothermal power production cost is 0.04 US$/kWh in Sichuan province.

Key words: *geothermal power plant, binary cycle, thermoeconomics, capital cost, engineering equation solver*

Introduction

In China, urban populations are provided with their electricity requirements. However, the people in rural areas have to generate electricity for local socio-economic development. Fortunately, mid-low temperature geothermal resources are located proximal to rural areas without access to grid electricity. Small-scale geothermal power plants can support electricity as well as create employment opportunities for the rural area. Many big corporations begin to invest into the geothermal power projects because of CO_2 emission assignment and governments inspire energy policies in China [1, 2].

Dry-steam system, flash system, and binary cycle are the main kinds of commercialization technologies. Dry-steam power generation, which is applied for dry-steam geothermal resource and accounts for about 22.7% of all installed geothermal power capacity. Flash power

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generation, which is applied for wet-steam or water-dominated geothermal resource and accounts for about 61.8% of all installed geothermal power capacity. Binary cycle power generation, which is applied for mid-low temperature water-dominated geothermal resource and accounts for about 14.2% of all installed geothermal power capacity at the end of 2014 [1, 2].

Based on the temperature and property of geothermal resources, different energy conversion system can be utilized to maximize the extraction of energy from the geothermal fluid. Optimization of the plant can yield improvements of up to 30-40% in terms of reduction of brine specific consumption compared to conventional design. The best working fluids of binary cycle are R152a and isobutene, while there are no apparent advantages in the use of multicomponent fluids for the range of conditions studied [3]. The net power generated from plants varies of depending on the air temperature. For moderate ambient temperatures (⩾1.7 ºC) superheat maximizes net power output of the system. Optimal operation strategies provide the same scale increase in net power (up to 117%) as incorporation of more fans in the air-cooled condenser system [4, 5]. Thermodynamic and technoeconomic assessment and optimization of organic Rankin cycle (ORC) were presented based on different cycle configurations (subcritical/supercritical, saturated/superheated, regenerative/non-regenerative), operating with a variety of working fluids, for the exploitation of low-medium enthalpy geothermal fields (120-180 ºC) in the 2-15 MW power output range [6, 7]. Exergy analysis is a very useful method to evaluate the performance of renewable energy resources. Based on the exergy analysis, a comparative study was done to clarify the best geothermal power cycle configuration. The performance of each cycle has been discussed in terms of the second-law efficiency, exergy destruction rate, and first-law efficiency [8-11]. The ORC technology, acting as *topping* or *bottoming* cycle, has an enormous potential, from the technical and economical point of view, for the production of heat (for heating, domestic hot water, drying processes in industry, absorption cooling, *etc.*) and/or for mechanical and electrical energy (from a few kWe to some MWe) from renewable energy sources [12-14]. The production cost and payback period of different geothermal power system have been discussed from the calculation procedure in Simav, Turkey. An economic analysis of four cycles considered indicates that the cost of producing a unit amount of electricity is 0.0116 $/kWh for double flash and Kalina cycles, 0.0165 $/kWh for combined cycle and 0.0202 $/kWh for binary cycle. Consequently, the payback period is 5.8 years for double flash and Kalina cycles while it is 8.3 years for combined cycle and 9 years for binary cycle [15, 16]. The performance of the binary cycle steam power plant (SPP) degrades slightly with SPP load, turbine inlet temperature variations, turbine inlet pressure variations and cooling water variations. When the load was reduced from 100% down to a minimum load of 25%, the efficiency was reduced by only 0.97%. When the turbine inlet temperature dropped from 235 ºC down to 125 ºC, the SPP-2BCP (SPP-Two-Stage Binary Cycle Plant) efficiency was reduced by only 6%. When the turbine inlet pressure dropped from 30 bar down to 5 bar, the efficiency was reduced by only 7%. Finally, when the cooling water temperature increased up to a maximum site condition temperature of 37 ºC, the efficiency was reduced by only 0.3%. Net power output, thermal economics, energy efficiency and exergy efficiency have an effect on geothermal resource temperature, flow rate and pinch point [17, 18].

Geothermal resource assessments and weather condition in Sichuan

The area of a new binary power plant will be selected in Ganzi-Litang geothermal field, near Tibet, in Sichuan province. Figure 1 shows the geothermal resource distribution in Sichuan province. Batang-Xiangcheng, Ganzi-Litang, Luhuo-Kangding, Shimian-Dechang, Yuexi-Ningnan, Ebian-Jinyang, and Dayi-Anxian are the main geothermal areas in Sichuan [19]. In Batang-Xiangcheng, they evaluated reservoir temperature and mass-flow rate as 160 ºC and 35 kg/s, in Ganzi-Litang, they evaluated reservoir temperature and mass-flow rate as 170 ºC and 50 kg/s, in Luhuo-Kangding, they evaluated reservoir temperature and mass-flow rate as 140 ºC and 30 kg/s. Mid-high temperature geothermal resources are distributed in the western of Sichuan; Ganzi-Litang area is in the middle of Batang-Xiangcheng and Luhuo-Kangding areas.

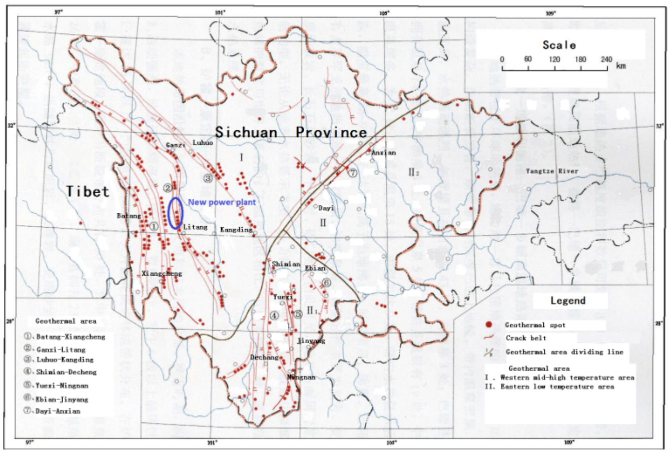

Figure 1. Geothermal assessment in Sichuan (revised)

Weather data was taken from 2012. The data was at 1 hour interval. There were 7 hours missing from the dataset and the data was extrapolated to 8760 hours. The data had dry bulb temperature and relative humidity. The wet bulb temperature was then calculated from all valid data points. The dry and wet bulb temperatures from low to high were given in fig. 2.

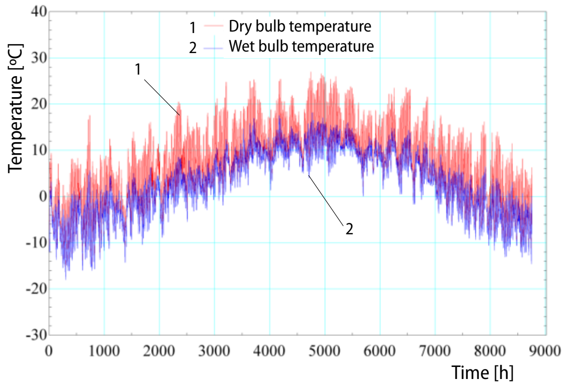

Figure 2. Dry bulb and wet bulb temperature
(*for color image see journal web site*)

Figure 3 gives the cooling water temperature which is estimated by the wet temperature. The 15 ºC is selected for cooling temperature (the green line). The dry bulb temperature is from the lowest to highest. The conditions of the geothermal reservoir and technical characteristics of power plant system are shown in tab. 1 [19].

Geothermal power system design

Binary power cycle and single flash power system are designed to build a new power plant in Sichuan province. The detail fundamentals and mathematic model are found in DiPippo [20]. Quadratic approximation is applied for the optimization. The Quadratic approximations optimization method is one of two methods used in engineering equation solver (EES) to find a minimum or maximum when there is one degree of freedom. The EES requires that you specify the possible range for the independent variable before the search begins. The EES evaluates the objective function at the bounds of this range and at one point within the range. The objective function is then assumed to depend on variable in a quadratic manner. The point having the largest value of the objective function is eliminated and the process is repeated until convergence is achieved.

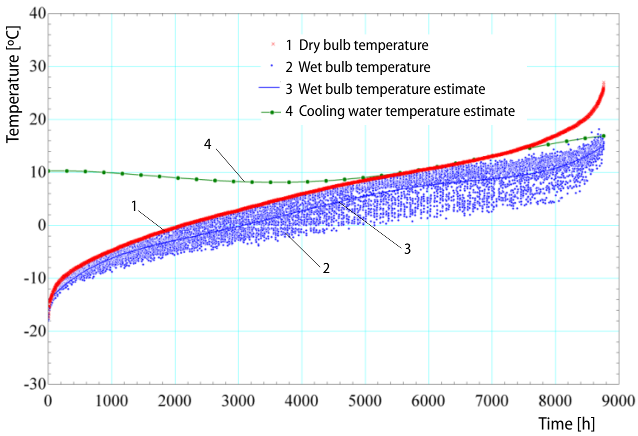

Figure 3. Cooling water temperature estimate
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The evaporator pressure and separator pressure are the design variables. The maximum net power output and minimum cost rate are the optimization objective. When the net power output gets maximum value, the energy efficiency and exergy efficiency is calculated and compared in tab. 6. The energy efficiency and exergy efficiency of binary system is 13% and 45%, and higher than flash system. Binary power system is selected for Sichuan because higher efficiency and output.

Table 1. Parameters and boundary conditions of the power plant model

	Parameter		Unit	Value
Geothermal reservoir	Ganzi-Litang	Temperature of reservoir	ºC	170
		Mass-flow rate	kgs^{-1}	50
		Gas mass fraction	%	0
	Well 1#	Depth	m	1842
Power plant system	Cooling water temperature		ºC	15
	Temperature difference of cooling water		ºC	10
	Turbine isentropic efficiency		%	80
	Pump isentropic efficiency		%	75
	Vaporizer heat transfer coefficient		kWm^{-2}ºC^{-1}	1.1
	Preheater heat transfer coefficient		kWm^{-2}ºC^{-1}	0.7
	Recuperate heat transfer coefficient		kWm^{-2}ºC^{-1}	0.7
	Condenser heat transfer coefficient		kWm^{-2}ºC^{-1}	1

Binary power cycle

The parameters and boundary conditions of binary cycle model are shown in tab. 1. Vaporizer, preheater, recuperator, working pump, turbine, condenser, and cooling tower are the main components in the system.

Figure 4 shows the scheme of binary power cycle. The working fluid (isobutane) is vaporized by the geothermal water from production well in the vaporizer. The vapor expands in the turbine, and then condensed in a water-cooled condenser before being pumped back to the vaporizer to complete the cycle (1-2-3-4-5-6-7-8-9-10). The vaporizer pressure and condenser area are the main parameters to analyze the turbine shaft work.

Figure 5 shows the T-s diagram of binary power cycle. In fact, they are not isotropic process from state 6 to state 7 and state 10 to 1, the isentropic efficiency of turbine and pump is 0.8 and 0.75.

For turbine, the turbine shaft work is calculated:

$$W_t = m_{w,f}(h_6 - h_7) \tag{1}$$

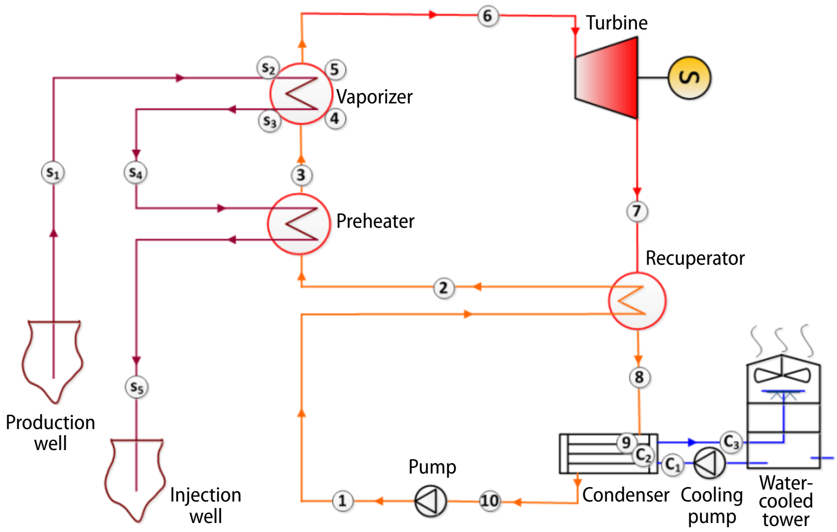

Figure 4. The scheme of binary power cycle

where, W_t [kW] is the turbine shaft work, $m_{w,f}$ [kgs^{-1}] is the mass-flow rate of working fluid, and h_6 and h_7 are the enthalpy at state 6 and 7.

The detail fundamentals and mathematic model are found in DiPippo [20]. The turbine shaft power is 3506 kW and the parasitic load is 484 kW from thermodynamic calculation, the value of first law efficiency, second law efficiency and injection temperature are 12.9%, 45.4%, and 59.7 °C.

Table 2 shows the thermodynamic properties of each state in binary power cycle. The main results of binary cycle are shown in tab. 3.

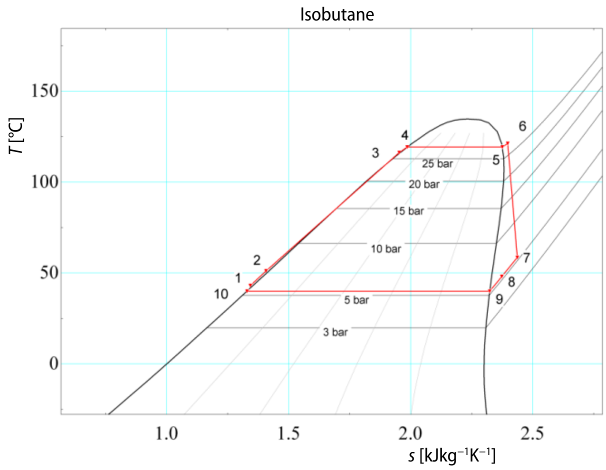

Figure 5. The T-s diagram of binary power cycle

Single flash system

The parameters and boundary conditions of single flash system model are also shown in tab. 1. Throttle valve, separator, turbine, condenser, and cooling tower are the main components in the system. The separation pressure P_2 is the main variable to optimize the turbine shaft work. Figure 6 shows the scheme of single flash system. Figure 7 shows the T-s diagram of single flash system.

The turbine shaft work is 2301 kW and the parasitic load is 71 kW from thermodynamic calculation. Table 4 shows the optimum thermodynamic properties of each state in single flash system. The main results of single flash system are shown in tab. 5. The injection temperature is about 98 °C, the optimum pressures: P_2=0.95 bar, the first and second law efficiency is 7.9% and 34.7%.

Table 2. Thermodynamic optimization of binary cycle

State	Pressure	Temperature	Mass-flow	Enthalpy	Entropy	Heat rate	Specific exergy	Exergy rate
	P [bar]	*T* [ºC]	*m* [kgs^{-1}]	*h* [kJkg^{-1}]	*s* [kJkg^{-1}ºC^{-1}]	*Q* [kW]	*e* [kJkg^{-1}]	*Ex* [kW]
1	28.0	35	62.6	284	1.274	17799	6.05	368
2	28.0	45	62.6	311	1.358	19459	8.15	496
3	28.0	117	62.6	525	1.963	32906	48.83	2971
4	28.0	119	62.6	534	1.985	33451	51.12	3111
5	28.0	119	62.6	687	2.375	43039	91.78	5585
6	28.0	121	62.6	696	2.397	43578	94.09	5725
7	4.4	53	62.6	638	2.441	39964	23.61	1437
8	4.4	40	62.6	612	2.359	38311	21.00	1278
9	4.4	33	62.6	599	2.317	37497	20.11	1224
10	4.4	33	62.6	278	1.269	17436	1.60	97
S1	12.9	170	50.0	720	2.041	35980	133.10	6655
S2	12.9	168	50.0	709	2.018	35455	129.50	6473
S3	12.9	124	50.0	523	1.573	26140	71.32	3566
S4	12.9	122	50.0	512	1.546	25610	68.44	3422
S5	12.9	60	50.0	251	0.826	12545	14.45	723
C1	–	15	485.0	63	0.224	30608	0.20	99
C2		25	485.0	103	0.362	50101	0.67	335
C3	–	25	485.0	105	0.368	50877	0.72	361

Table 3. Energy summary of binary system

No.	Item	Units	Optimum value
1	Vaporizer pressure	bar	28
2	Condenser pressure	bar	4
3	Turbine shaft work	kW	3506
4	Cooling pump	kW	129
5	Working pump	kW	355
6	Turbine net output power	kW	3022
7	Condenser temperature	ºC	33
8	Condenser capacity	kW	20284
9	Vaporizer area	m^2	634
10	Preheater area	m^2	2157
11	Recuperate area	m^2	350
12	Condenser area	m^2	1742
13	The first law efficiency	%	13
14	The second law efficiency	%	45

The calculations and optimization work of two kinds of power system have been carried out. The main results of power system are summarized as in tab. 6. Binary cycle is of larger net power output and second law efficiency than single flash system. Therefore, the binary power cycle is selected to build in Ganzi-Litang geothermal field.

Table 4. Thermodynamic optimization of single flash

State	Pressure	Temperature	Mass-flow	Steam quality	Volume	Enthalpy	Entropy	Heat rate	Spec. exergy	Exergy rate
	P [bar]	*T* [ºC]	m [kgs⁻¹]	*x* [–]	*v* [m³kg⁻¹]	*h* [kJkg⁻¹]	*s* [kJkg⁻¹ºC⁻¹]	*Q* [kW]	*e* [kJkg⁻¹]	*Ex* [kW]
1	7.92	170	50.0	0.000	0.001	719	2.04	35965	132.60	6632
2	0.95	98	50.0	0.136	0.243	719	2.12	35965	112.00	5576
3	0.95	98	6.8	1.000	1.777	2673	7.38	18176	550.00	3739
4	0.05	33	6.8	0.907	25.400	2335	7.65	15878	132.00	897
5	0.05	33	6.8	0.000	0.001	138	0.48	938	2.00	15
6	0.95	98	43.2	0.000	0.001	412	1.29	17798	42.00	1837
C1	-	15	357.3		0.001	63	0.22	22510	0.20	71
C2	-	25	357.3		0.001	105	0.37	37481	0.72	259

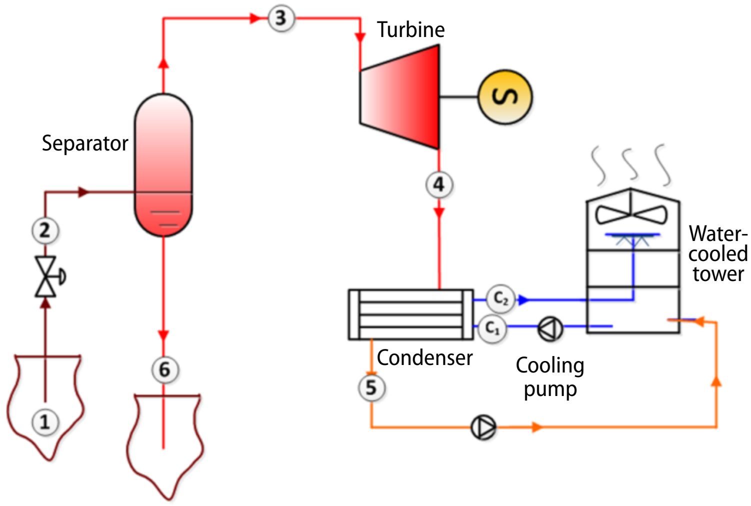

Figure 6. The scheme of single flash system

Table 5. Energy summary of single flash system

No.	Item	Units	Optimum value
1	Separator pressure	bar	0.95
2	Turbine shaft work	kW	2301
3	Cooling pump	kW	71.51
4	Turbine net output power	kW	2230
5	Condenser temperature	ºC	33
6	Condenser capacity	kW	14946
7	Condenser area	m2	1212
8	Second law efficiency	%	34.7

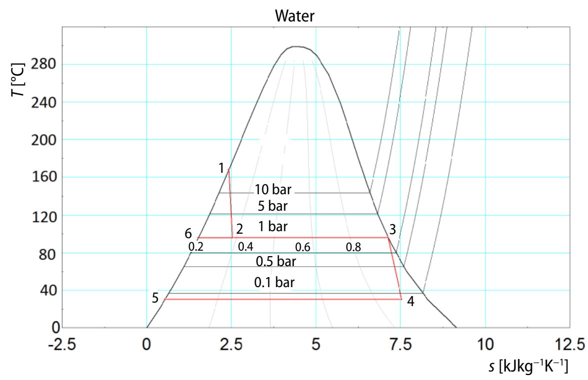

Figure 7. The T-s diagram of single flash system

Table 6. The main results of two kinds of power system

Item	Unit	Single flash	Binary cycle
Net power output, W_{net}	kW	2230	3022
Injection temperature, $T_{injection}$	ºC	98	60
First law efficiency, η_{first}	%	7.9	13
Second law efficiency, η_{second}	%	34.7	45

Thermoeconomic analysis of binary cycle

Thermoeconomic analysis is based on exergy flows, and breaks the power system into individual components, where each component can be analyzed separately. The cost flow of products must be equal to the sum of all incoming cost flow for power system and component. It is usually consider the heat flow as input and work (power) as output. That is the reason for entering the heat cost flow as input and the work (power) cost flow as output [21, 22]. This balance is written:

$$\sum_e C_{e,k} + C_{w,k} = C_{q,k} + \sum_i C_{i,k} + Z_k \tag{2}$$

where C [$\$\text{s}^{-1}$] is cost rate, Z [$\$\text{s}^{-1}$] – the investment cost rate, e – the product or output, i – the feed or input, k – the number of component, q – the heat, and w – the work or power.

Cost estimation of power plant

The cost estimation of the binary cycle is shown in tab. 7 [21]. The cooling tower cost is evaluated from the cooling tower depots [23]. Total initial investment cost 9,767,000 US$ is the sum of total capital cost and fuel cost.

Fuel cost includes subsurface cost and working fluid cost, such as production drilling and testing, exploration drilling well testing pads and appraisal drilling and testing.

Table 7. Binary power cycle cost

Item		Capacity	Unit	US$/unit	Cost [$]
PEC	Vaporizer	634	m^2	300	52,310
	Preheater	2157	m^2	300	139,360
	Recuperator	350	m^2	300	32,555
	Condenser	1742	m^2	280	109,654
	Organic fluid turbine	3506	kW	1000	302,977
	Working fluid Pump	355	kW	500	54,892
	Cooling water pump	129	kW	400	19,571
	Cooling tower				210,000
PEC:					921,319
Purchased equipment installation		33%	%PEC		304,035
Piping		35%	%PEC		322,462
Instrumentation and controls		12%	%PEC		110,558
Electrical equipment and materials		13%	%PEC		119,772
Land, civil, structural		21%	%PEC		193,477
Direct cost					1,972,000
Indirect cost (engineering, construction)		15%	%DC		295,744
TCC					2,267,000
Fuel cost		50	kg/s	150000	7,500,000
O &M cost		3%	%TCC (per year)		68,021

PEC is purchased equipment cost, DC is direct costs, TCC is total capital cost, and O&M cost is operation and maintenance cost.

Exergy cost

Exergy analysis model of binary cycle is built, which can be referenced to Bejan [21]. Table 8 shows the investment cost rate and destruction exergy cost rate of main components in binary system.

Table 8. Exergy cost rate of the main components in binary system

Component	Capital cost rate [US$/s]	O&M cost rate [US$/s]	Destruction cost rate [US$/s]
Vaporizer	0.0002164	0.00002403	0.005389
Preheater	0.0005766	0.00006402	0.002515
Recuperator	0.0001347	0.00001495	0.0003483
Working pump	0.0002271	0.00002522	0.0009479
Condenser	0.0004537	0.00005037	0.0104
Turbine	0.001254	0.0001392	0.008794

A detailed thermoeconomic evaluation of the binary cycle should be based on the following variables, sum cost rate of destruction and capital investment, exergetic efficiency, and exergetic destruction [21]. The main results of thermoeconomic evaluation of binary cycle are shown in tab. 9.

Table 9. Thermoeconomic evaluation of main components of binary cycle

Component	Sum cost rate of destruction and capital investment [US$/s]	Exergetic efficiency [%]	Exergetic destruction [%]
Condenser	0.1133	21.6	13.91
Turbine	0.01019	81.76	11.76
Working pump	0.00546	76.27	1.267
Vaporizer	0.004491	85.17	7.2
Preheater	0.003395	91.71	3.362
Recuperator	0.001668	80.47	0.47

The condenser cost rate of destruction is of maximum value in all of components in binary power cycle. The variable parameter of vaporizer pressure has to be optimized to decrease the condenser cost rate of destruction.

The main purpose of thermoeconomic results is to achieve a balance between the expenditure on capital costs and the exergy costs which will lead to a minimum cost of the plant product.

The different components in the power system can be categorized:

– *Ready-made* components selected from a manufacturer's catalogue, such as pumps, turbines, *etc.*
– Components specially designed, or *tailor-made* for the plant, *e. g.* heat exchangers, *etc.*

The first type of component is decided by manufacturer. The second type of component is convenient for thermoeconomic analysis. The advantage of using the exergy method of thermoeconomic analysis is that the various elements of the plant can be selected on their own, the effect of the given element on the whole plant could be taken into account by local unit costs of exergy fluxes or those of exergy losses.

Figure 8 shows the relationship between vaporizer pressure and sum cost rate of destruction and capital investment for condenser ($ZC_{\text{condenser}}$). The minimum $ZC_{\text{condenser}}$ is the optimum

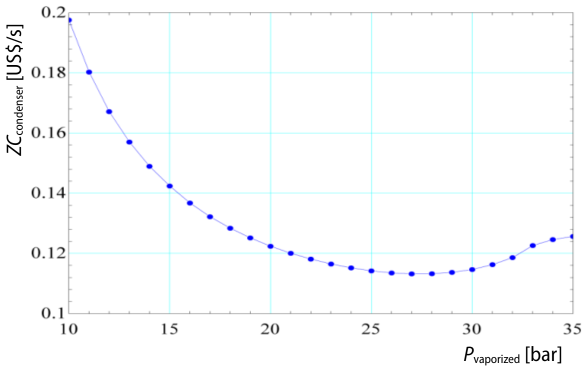

Figure 8. Vaporizer pressure and $ZC_{condenser}$ relationship

value in the power system. The minimum value of sum cost rate $ZC_{condenser}$ is 0.1132 US$/s when vaporizer pressure is 28 bar.

Economic results

The economic evaluation and analysis of binary power plant is implemented based on engineering economic methodology. There are three methods for economic evaluation [21].

The first is average rate of return and payback period method. The payback period is defined as the length of time required for cash inflows received from project to recover the original cash outlays required by the initial investment.

The second is net present value (NPV) method. When the NPV method is used for project selection, the following rules apply: accept any project for which the present value is positive, reject any project with negative present value, the project with highest present value are given the highest preference among various alternatives, if two projects are mutually exclusive, and accept the one having the greater present value.

The third is internal rate of return method. The NPV method uses the interest rate is usually based on the company's cost of money. The internal rate of return method seeks to avoid the arbitrary choice of an interest rate. Instead, it calculates an interest rate, initially unknown, that is internal to the project. The economics conditions of Ganzi-Litang geothermal binary power cycle is shown in tab. 10.

Table 10. Economic conditions

No.	Item	Unit	Value
1	Economic life span	year	25
2	Minimum attractive rate of return	%	10
3	Operation time for one year	h	8000
4	Income tax rate	%	17
5	Price of electricity for user	$\$kW^{-1}h^{-1}$	0.04
6	Effective rate of return	%	10

Figure 9 shows the cash flow of binary power system. The average annual profit is 1,308,000 $/year, the average rate of return is 13.39%, the payback period is less than 6 years [21].

The geothermal water reservoir temperature and flow rate can affect the power production cost and specific net power output. Figure 10 shows that the reservoir temperature affects the power production cost and specific net power output at a constant mass-flow rate of 50 kg/s. For binary power plant, the power production cost, C_p, is about 0.04 US$/kWh in Sichuan province. The net power output, W, blue line 2 in fig. 10, increases with the reservoir temperature, the specific net power output is about 59.76 kW/kgs.

Conclusions

A case of binary power plant is analyzed based on thermoeconomics in Sichuan, China. The conclusions are as follow.

- Binary cycle with recuperator is designed for Ganzi-Litang field in Sichuan, the capacity of turbine shaft work is 3506 kW and net output power is 3022 kW.

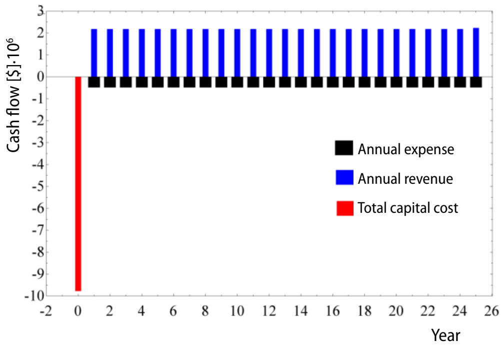

Figure 9. Cash flow of binary power cycle

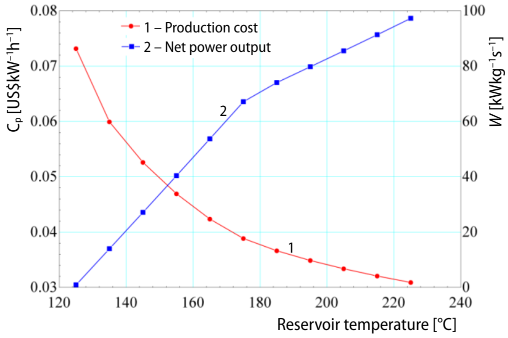

Figure 10. Reservoir temperature effect on power production cost and net power output

- Vaporizer pressure is the key variable parameter for binary power system. Thermoeconomic evaluation shows that the condenser destruction and loss exergy are bigger than other components; the optimum evaporator pressure of binary cycle is 28 bar.
- Economic feasibility of binary cycle with a recuperator is analyzed based on payback period method. The sum of total capital cost and fuel cost is 9,767,000 US$, the payback period is less than 6 years.
- The reservoir temperature and mass-flow rate effect on the power production cost. The higher temperature and larger flow rate are, the lower power production cost will be made. The power production cost of binary power system is 0.04 US$/kWh in Sichuan, China.

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