Proceedings 20th NZ Geothermal Workshop 1998

COMBINED, MIXED, FLASH AND BINARY CYCLES FOR ELECTRICITY GENERATION FROM GEOTHERMAL SOURCES

PART B: TECHNICAL ECONOMIC ANALYSIS

P.BOMBARDA[1]

[1]Department of Energetics, Politecnico di Milano, Italy

SUMMARY - The principal economic constraints, basic assumptions and objectives of the optimization process are discussed. The results of parametric calculations for the various feasible plant schemes are presented and examined. Different geothermal sources, having different liquid/steam ratios or noncondensable gas contents are considered.

1.0 ECONOMIC ANALYSIS

1.1 Objective

Several economic indicators are used to assess the potential of an investment. The most common are the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Pay Back Time (PBT); and among these the IRR was chosen as the objective to be maximized in this work. Note that the choice of one indicator over all others may lead to a different optimum solution and depend on the assumed economic constraints.

1.2 Assumptions

Two kinds of assumption will be made in order to proceed with the analysis: the first group concerns the general economic parameters (Table. 1), and the second one involves the various component costs (Table. 2). It is always difficult to find universally acceptable assumptions, and these are considered further below:

plant lifetime: the value indicated refers to an average condition; one should not forget that the well exploitation must guarantee the assumed constant conditions at well head throughout the lifetime

yearly operating hours: the value indicated refers to base load operation

interest rate: the value is assumed to be the average value in the period considered (relies on future expectations)

electrical energy price: care must be always taken in considering this value, which can vary greatly fiom one situation to another. The energy price is the result of many circumstances (market conditions, possible monopolies, etc.) and in the specific case of geothermal energy it may be altered by particularly favorable conditions or incentives for renewable energy. As a matter of fact, data collected fiom the Geothermal Research Council Database (1998), show a huge scattering (fiom 0.015 $US/kWh to 0.235 $US/kWh).

geothermal cost: it represents the sum of costs related to well drilling and geothermal field preparation; it depends on local conditions, therefore its variation fiom site to site can be relevant and it has a heavy influence on the optimum solution: if the geothermal cost is high, the optimum solution will be complex and expensive but will ensure increased power output.

operating and maintenance costs (O.&M.), both fixed and variable, are assumed equal for steam and ORC section and given by a linear relation

balance of plant cost (B.O.P.) a fixed amount is added to the component costs so as to represent the cost of all minor components

plant lifetime	10 y
yearly operating hours	7500 h/y
interest rate	6 %
electrical energy sale price	0.0386 e/kWh
geothermal cost	10300000 e
O.&M. fixed cost (steam and ORC section)	77250 e
O.&M. variable cost (steam and ORC section)	0.0015 e/kWh
B.O.P. cost (steam and ORC section)	51500 e
component cost multiplier	1.25

Table I General economic assumptions; values are given in Euro currency.

component cost multiplier: it accounts for assembling, transport and as a safety factor on costs of both steam and ORC plants.

	fixed costs	variable costs
steam turbine	257500 e	200-100 e/kW
electric generator	25750 e	50 e/kW
gas compressor	77250 e	300-200 e/kW
compressor intercooler	5150 e	150 e/m^2
cooling tower	-	10 e/kW,
steam condenser (water)		5150 e/(m^3/s)$^{2/3}$
flash chamber	-	5150 e/(m^3/s)$^{2/3}$
steam condenser (air)	51500 e	230 e/m$^2_{surface}$ 128 e/m$^2_{fr.area}$
ORC turbine & generator	309000 e	118.5 e/kW
ORC condenser (air)	51500 e	140 e/kW
air condenser fan	-	50 e/kW 250 e/m^2

T'able 2. Assumed basic component costs.

In order to estimate the cost of every component in the general analysis, a linear rule is selected; costs are given by the sum of a fixed cost plus a variable cost, the latter being proportional to the particular characteristics of the component considered. A few comments are relevant when considering the values reported in Table 2, because the general rule is sometimes modified:

for the turbine and compressor cost, it is impossible to find a variable cost accurate over the full range of machine power, therefore the variable cost is gradually modified according the component size; moreover a correction factor is applied for both components if the volumetric flow differs fiom a standard value and the number of stages calculated exceeds a standard value

for the cooling tower the fixed cost is assumed negligible in respect to variable cost

- flash chamber and direct contact condenser costs have a negligible fixed cost, and a variable cost proportional to the external surface through the component volume$^{2/3}$, assumed proportional to the volumetric flow at the component inlet

air condenser: 2 variable costs are added, one proportional to the heat exchanger surface and one to the frontal area.

For the ORC heat exchanger an existing detailed procedure (Zoggia, 1997) was employed to evaluate the cost, which is given by the sum of material cost (shell and tubes) plus industrial transformation cost (tube production, possible finning, assembling, see Table 3)

shell - steel	0.77 e/kg
tubes - stainless steel	3.1 e/kg
transformation cost (depending of finning)	1.85-13 e/Kg
assembling cost	4 e/kg

2. ASSUMPTIONS FOR PARAMETRIC ANALYSIS

All the plant configurations described in part A are investigated by means of a parametric analysis, by varying the g e o t h e d source characteristics.

2.1 Geothermal source

As already discussed in part A, the geotheml brine is identified by:

- salt content
- noncondensable gas content
- steam fraction

For the sake of simplicity, salt content will be maintained constant in all calculations, whereas noncondensable gas content and steam fraction will be varied, resulting in two different series of calculations. All the calculations are performed at constant steam partial pressure, (for example when the noncondensable gas content is increased, steam quality is appropriately increased).

mass flow	75 kg/s
pressure at well head	15 bar
salt content	0.5 mol/kg
noncondensable gas content	0.0 -> 0.25 kg_{gas}/kg_{br}
steam quality	0.2-> 1.0

The brine Characteristics are summarized in Table. 4; the results depend strongly on these characteristics. Note that, with increasing noncondensable gases, the mixture enthalpy decreases.

2.2 ORC cycle

Two basic features of the ORC cycle must be chosen in order to proceed:

- the working fluid
- the cycle

As a general rule, both features should be optimized for the particular source considered. However, this requires a huge calculation, exceeding the scope of the present work (a discussion about the selection of these parameters can be found in Macchi and Bombarda, 1998). Therefore, to simplify the comparison between different plant configurations, the effects of ORC working fluid and cycle variation were neglected, assuming for all the cases:

- working fluid n-pentane. The well known harmful environmental effects of traditional refrigerants preclude their use, so recently constructed plants have used hydrocarbon working fluids.
- thermodynamic cycle: simple cycle (no recuperator or superheater)

The selected cycle is subcritical, so the maximum evaporation temperature cannot exceed the fluid critical temperature *of,* in this case, 173°C.

2.3 Optimum parameters and general assumptions

The key parameters of the various plant configurations have been discussed in part A; the parameters to be optimized are thus the following:

- flash cycle: flash pressures, steam condensation pressure
- binary cycle: ORC evaporation and condensation pressures
- mixed cycle: flash pressures, steam condensation pressure, ORC evaporation and condensation pressures
- combined cycle: flash pressures, ORC evaporation and condensation pressures (condensation pressure was previously found to be optimized at 1.05 bar)

In all cycles the first choice for heat rejection is a water cooled condenser with a cooling tower, using the geothermal fluid as make-up water. The model calculates the water and salt mass balances at *the* tower and shifts automatically to an air condenser if there is insufficient water. Ambient conditions considered are a dry bulb temperature of 18 °C and a wet bulb temperature of 13 "C.

In all cases the optimization procedure was performed using numerical multivariable methods.

3. DISCUSSION OF RESULTS

3.1 Geothermal cost

As already stated, it is rather difficult to find a general value for the geothermal cost: it is therefore interesting to investigate the effect of this cost as a preliminary analysis. The results are given in fig. 1. If the objective is maximization of the IRR very simple plant schemes are generated. In contrast, an objective of maximum plant power requires more complex schemes:

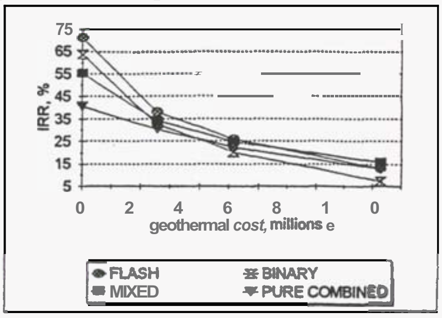

Fig. 1 Effect of the g e o t h e d cost on optimized plant IRR (for brine characteristics see tab. 4; x=0.25, nc = 0.05 kg_{nc}/kg)

- flash cycle: if the geothermal cost goes to zero, the best IRR solution is a very simple scheme, with no gas compressor (a costly item of plant), and consequently the scheme has a low power output.
- the same happens with the mixed cycle, though in this case the impact is smaller due to constant conditions in the ORC section
- the optimum plant conditions remain approximately the same for the binary and the combined cycle, therefore the IRR depends directly on the geothermal cost.

3.2 Investment cost

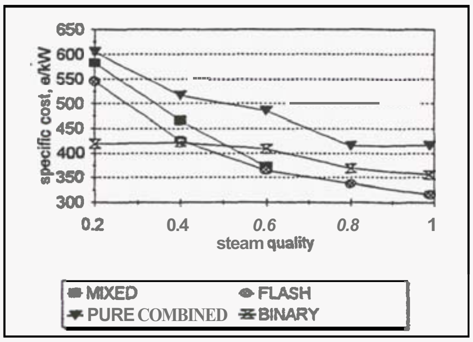

Fig. 2 Plant cost for the considered configurations as a hction of brine steam quality; geothermal cost (10300000 e) is not included.

The different plants have dissimilar specific investment costs (fig. 2); the steam section is characterized by a lower specific cost with increasing steam quality; the ORC section cost depends heavily on source inlet conditions (it is higher for mixed and combined cycles than for binary cycles).

3 3 Cash flow analysis

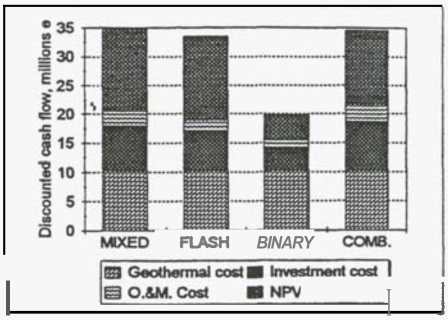

Fig. 3 Discounted cash flows for the **full** life of the plant (brine with x=0.4); the *sum* of the values reported corresponds to the total income.

Prior to proceeding further, an example of cash flow distribution is presented. Note that a variation of the plant life or interest rate would alter the discounted incomes and O.& M. cost, while leaving the investment cost unchanged, giving different results for ***NPV*** and IRR.

3.4 Analysis of the selected configurations

The results of conducted calculations, summarized by IRR and power, are presented in fig. **4** for case A, variable steam quality, and fig. **5.** for case **B,** variable noncondensables content.

- flash cycles:

  the general configuration considered includes two flashes, however, the optimized pressure values show that: i) the first flash pressure is very close to the well head pressure, so the flash chamber can be simplified as a simple liquid-steam separator; ii) the second flash pressure increases with steam quality, **fiom** about 2 bar up to **5** bar, while changing less than 1 bar over the range of noncondensables content; iii) the optimum condensation pressure is very low for pure steam and increases continuously, both with steam quality (0.1 - **0.4** bar) and noncondensables (0.06 - 0.3 bar).

- binary cycles:

  the curves shown for the ORC cycle represent the best solution among the three possible feed conditions: liquid phase, gaseous phase, and both phases. Both phases are used until the steam quality reaches about ***0.5,*** after which better performance is obtained using only the gaseous hction. ***An*** air condenser is needed when steam quality exceeds 0.6.

  As a consequence, the optimum parameter **mix** is continuously modified.

  Increasing noncondensable content reduces the brine temperature slightly, so the optimum cycle moves towards lower temperatures. Cycle efficiency varies only slightly as a result, but heat input is lower, giving a lower output. Moreover, the heat transfer coefficients become lower, giving a negligible reduction in investment cost: as a result IRR drops sensibly.

- mixed cycles:

  when focusing on the cost of the ORC section the most remarkable result is that the specific cost **($/kW)** increases, at constant well head conditions, if the last flash pressure is decreased. This is primarily due to a size effect, since ORC mass flow is reduced, but is also a result of decreased inlet temperature. The choice of second flash pressure is then a compromise between the requirements of the steam cycle, where lower pressure gives more steam, and the ORC cycle, where very low pressures are unacceptable.

  As a result, mixed cycles have a first flash pressure which is still very close to well head pressure, while the second flash pressure is somewhat higher than usual for a flash cycle. Typically, the second flash occurs in the range 6 - **8** bar, with even higher values when condenser water is in short supply (steam qualities greater than ***0.5).*** By definition, the mixed cycle makes use of separated water, so it must cease to exist when x=l and no liquid is available. However, for all practical purposes the mixed cycle effectively "disappears" when the steam quality exceeds 0.6. Power fiom the ORC section is negligible compared to total power at this point and above x=0.7 the mass flow is so *small* than no positive NPV can be obtained ficm the ORC section.

- combined cycles:

  the adoption of a high condensation pressure (1.05 bar) raises the second flash pressure to between 3.5-4.5 bar, while the **first** flash pressure values are the same as for other steam cycles. The steam section produces **55-73%** of the total power over the adopted range of 0.2-1.0 steam quality. Note that an identical range of values is obtained with variable noncondensables. In the combined cycle an increase in steam quality is beneficial to both the steam and the ORC sections. The ORC cycle receives increased mass flow at constant temperature, so power and IRR increase steadily. Introducing noncondensables to the brine causes the fraction of power produced by the steam turbine to increase gradually. In contrast, the heat source of the ORC cycle shows a slightly decreasing initial temperature and sharply decreasing temperature profile. As a consequence, the ORC optimum evaporation and condensation temperatures and efficiency drop, while progressively lower pinch point differences are used in the heat exchangers. Decreasing electrical power for the ORC section results, which is only partly offset by the increased power in the steam section.

- complex combined cycles:
  in this arrangement the evaporation temperature compromise is constrained by the pinch point between the liquid brine and the working fluid. The advantage of the additional ORC section disappears as steam quality increases, with performance similar to that of pure combined cycles being obtained Moreover, when steam quality exceeds 0.7 the low liquid flow makes heat exchanger sizing troublesome.

4. CONCLUSIONS

In the context of the economic constraints and brine conditions assumed, the various plant configurations exhibit similar IRR (except the binary plant). All the plant schemes benefit from higher steam qualities, giving higher IRR, while the inclusion of noncondensables always reduces plant performance.

In all configurations considered the first flash

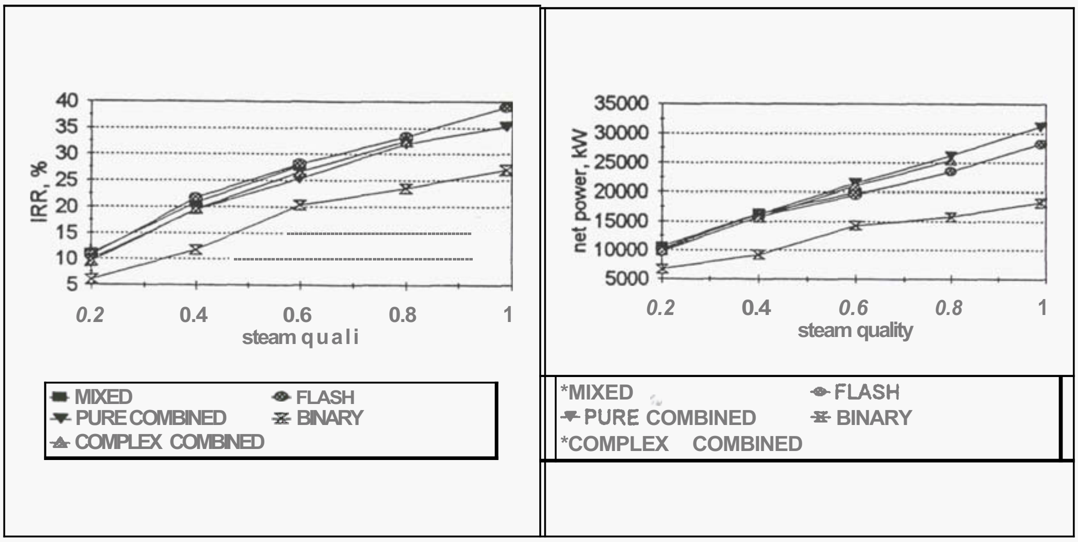

Fig. 4 IRR and net power for the selected configurations with increasing steam quality

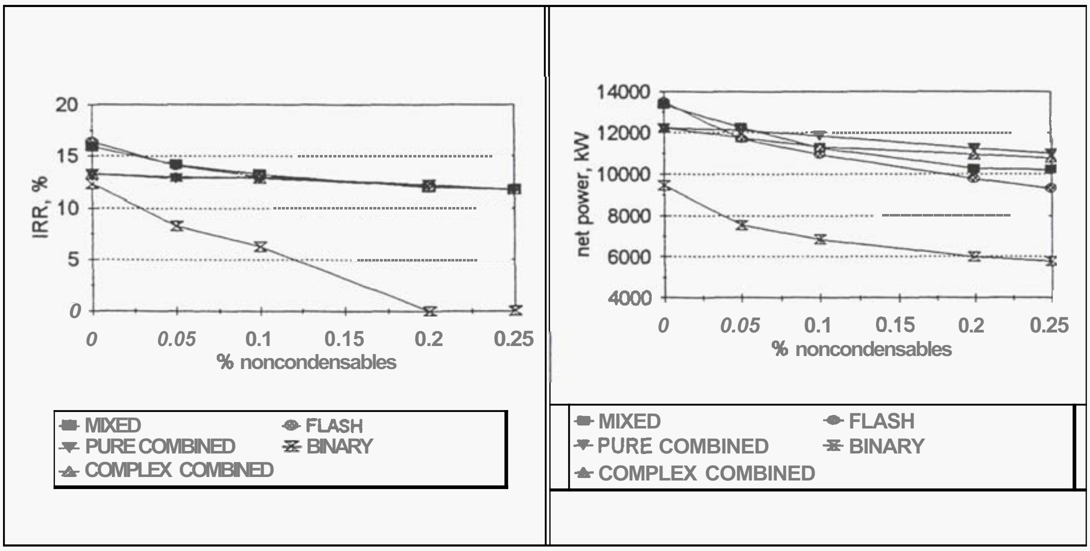

Fig. 5 IRR and net power for the selected configurations with increasing noncondensables content.

chamber operates very near the wellhead pressure and can be considered as a simple liquid-steam separator.

The greatest net power is obtained fiom either the pure combined cycle or the mixed cycle, depending on the defined steam quality and noncondensables content. This could alter the result of IRR analysis if different economic constraints were imposed. For example, they may become the most attractive option with a higher electricity price or longer plant life.

The binary cycle IRR and power are always somewhat lower than the others but several of the initial assumptions may contribute to this result. The simple cycle and maximum evaporation temperature employed are both a disadvantage to the binary cycle. In addition, if the value of assumed geothermal cost is low a further disadvantage occurs. It must also be remembered that this cycle is more effective for lower enthalpy geothermal fluids.

5. REFERENCES

GRC ***Geothemzal Research Council Database,*** **http//www.geothermal.org/grgpower.html**

Zoggia, F., (1997) ***"Technical Economic Analysis of Binary Cycles for Medium-Low Temperature Geothermal Sources Exploitation"***
Graduation Thesis, Politecnico di **Milano,** Italy (in **italian)**

Macchi, E., Bombarda, P., (1998) ***"Zero ODP fluids: Technical Economic Optimization of Conversion Cycles",*** Internal report