FACTORS AFFECTING THE CAPITAL COST OF BINARY POWER PLANTS

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ABSTRACT

The capital cost for a representative binary plant using a hydrocarbon working fluid and rejecting heat with a cooling tower is \$1775/KW of net power output[1]. The cost of a comparable ammonia plant is \$1450/KW. If a spray pond is used instead of a cooling tower the cost is reduced to \$1250/KW. These costs do not include the wells, geofluid pumps, and piping which will add an additional \$300/KW.

INTRODUCTION

This paper will discuss some of the factors that affect the capital cost of a binary geothermal power plant. A number of factors will be considered including the plant size, resource characteristics, and the design philosophy. However, the main focus will be on how the selection of the type of working fluid and the type of heat rejection system affects the plant capital cost.

COST OF A REPRESENTATIVE BINARY PLANT

Figure 1 shows a schematic diagram of a binary geothermal power plant. This plant uses a conventional design. It uses pure isobutane as the working fluid, and rejects heat with a tube-in-shell condenser and a cooling tower. This will be the baseline design for comparing the affect of certain design options on the capital cost of the plant.

The costs of the various components along with the construction, engineering and miscellaneous costs are indicated on Figure 1. These capital costs (on a \$/KW basis) are representative for plants with the basic design as discussed above in a size range between 5-20 MW and with resource temperatures between 250-300° F. The capital cost of the plant is \$1775/KW of net power output.

This is the cost of the plant only and does not include well cost or the cost of producing, piping and re-injecting the resource. The costs associated with the resource are very site specific as they depend on well depth, productivity index, temperature, chemistry, etc. However, for a wide range of binary resources (relatively shallow wells into high permeability formations) the cost of wells, pumps and resource piping is about \$300/KW of net power output. It should be noted that for deeper wells or lower permeability formations the costs of producing and re-injecting the resource can run to \$700/KW or more.

The total project cost, combined plant and resource cost, for the baseline design is \$2075/KW. This may provide a marginal rate of return on what many investors would consider a high risk project. In order to improve the rate of return the capital cost must be reduced. The following discussion considers some of the major factors that affect the capital cost of the project and what options are available to reduce the cost.

EFFECT OF PLANT SIZE

In general the capital cost of a large plant is less than a small plant because of economy of scale. However, because of the modular nature of the design this effect is not dramatic. For example, a 2 MW plant may require two condensers that are 52 inches in diameter by 60 feet long. Since this is about the maximum size condenser that is available, a 4 MW plant would require four of these condensers. The equipment cost would double and the field installation labor would nearly double. Therefore, the savings with the larger plant would be minimal.

Since much of the equipment in a binary plant is similarly limited to a maximum size

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[1]All costs are in \$/KW of net power outut. Feed pump, well pump and condenser related parasitics have been accounted for. Well pumping is assumed to require 7% of the generated gross power output. This provides for about 300 feet of draw-down and an additional 100 psi of losses in the piping, heat exchangers and re-injection wells.

or capacity (feed pumps, brine heat exchangers, wells, etc.) the effect of economy of scale is small. For plants in the size range between 5-20 MW, the plant cost (in $/KW) will not change by more than about 10-15%.

EFFECT OF RESOURCE CHARACTERISTICS

The project capital cost will be affected by the resource characteristics. The cost of producing and re-injecting the resource will be determined by the depth and productivity index of the wells. Shallow wells with a high productivity index will reduce the cost of the project.

The chemistry of the resource will determine the scaling and corrosion tendencies of the brine. This will determine the heat exchanger sizing and material selection. Clean brines will reduce the cost of the project. For the purposes of this discussion it will be assumed that the brine is compatible with carbon steel materials and has low scaling tendencies. (Tube side fouling factors of .0005 ft^2-hr-F/BTU have been used for heat exchanger sizing).

The resource temperature will determine the efficiency of the plant. A higher temperature resource will enable a higher efficiency plant which will reduce the cost of the project.

Resource characteristics such as well depth, productivity index, and resource chemistry vary over such a wide range that it is impossible to quantify their effect on the project cost. However, the effect of temperature can be quantified. As the resource temperature goes from 250° F to 300° F, the plant cost (in $/KW) will decrease about 10%.

EFFECT OF DESIGN PHILOSOPHY

There are a number of factors that affect the plant capital cost that can be grouped under the heading of design philosophy. This includes factors such as the level of complexity or flexibility that is designed into the plant or the quality of the components that are specified for the plant.

An example of this is the design of the plant control system. Binary plant controls can range from a $30,000 programmable logic controller based system to a $200,000 distributed control system. Both the programmable logic controller and the distributed control system are capable of automatically starting the plant, monitoring for faults during operation and shutting the plant down. The distributed control system has the advantages of greater flexibility and a "friendlier" user interface. The selection of the type of control system is made on the basis of a trade-off between initial cost and operating flexibility.

There are a number of other design selections that are governed by similar considerations. In making these selections it is important to consider the trade-offs. The optimum design is not the one that minimizes the initial capital cost. However, care must be taken to not design an overly elaborate plant which will increase the capital cost with unnecessary bells and whistles.

In following comparisons every effort has been made to maintain the same level of design complexity, quality of components, etc. between the different systems that are compared. The goal is to present an apples to apples comparison.

EFFECT OF WORKING FLUID

The working fluid selection affects all other aspects of the plant design. It dictates the overall system efficiency and resource utilization as well as the design requirements for all of the system components. The proper selection of the working fluid can significantly reduce the capital cost of the project.

Most current binary plants use a single component light hydrocarbon for the working fluid. For many resource conditions it appears that ammonia would be a superior selection. Table 1 summarizes the advantages and disadvantages of the two working fluids.

Brine Utilization

Both working fluids produce about the same power output for a given brine flow rate. For resource temperatures between 250°F-300°F the brine utilization of an isobutane plant (a common hydrocarbon working fluid) and ammonia are within a few percent of each other.

It should be noted that there are a number of other new working fluids that are being proposed which have brine utilization significantly better than either the single component hydrocarbon or ammonia working fluids. The most notable of these are hydrocarbon mixtures and ammonia-water mixtures. The improved utilization will tend to lower the capital cost of the project since less brine flow is required to produce the same power. However, as was mentioned above, the costs associated with the production and re-injection of the brine are typically about 15% of the total project cost. A dramatic improvement in the utilization of 25% will only reduce the total project cost by 5%.

It is possible to reduce the capital cost of the project more dramatically by selecting a working fluid that directly reduces the plant costs which account for 85% of the total binary project cost. This is where the advantages of a pure ammonia system become significant.

Heat exchanger and piping sizes

The contrast between hydrocarbon and ammonia binary plants is highlighted in Table 2. The table compares heat exchanger and pipe sizes for 6 MW plants designed for the two working fluids.

The ammonia plant has smaller heat exchangers because of its superior thermal transport properties. This is particularly evident in the condenser where the overall heat transfer coefficient for ammonia is nearly three times that of the hydrocarbon.

As is indicated by the turbine inlet and exhaust sizes, all of the piping in the ammonia plant is significantly smaller.

This is because the flow rates are much lower. The ammonia plant operates at a lower flow rate because the enthalpy drop across the turbine is much higher for the lower molecular weight ammonia. Therefore less flow rate is required to produce the same power output.

Since the ammonia requires fewer and smaller heat exchangers than the hydrocarbon plant, there is a cost savings in this portion of the capital equipment. Since the piping in the ammonia plant is smaller there is also a savings in the mechanical installation cost. (The cost reduction from the smaller size more than offsets the cost increase from the higher pressure of the ammonia system).

Turbine availability

The most significant disadvantages of ammonia are (1) there are no ammonia power plants that are currently in service and (2) ammonia turbines are not in common use.

Regarding the first concern, the plant design is not really new. The plant uses a conventional Rankine cycle power system with a single component working fluid. It is identical to all of the hydrocarbon and halocarbon binary systems that are currently in wide spread use. Unlike plants that may use working fluid mixtures, there is no concern about how to maintain integral boiling and integral condensation and there are no uncertainties regarding the design and analysis of the plant. The properties of ammonia are well known and there is extensive experience with it in the refrigeration and the chemical process industries.

Regarding the second concern, while ammonia turbines are not currently in widespread use, a conventional turbine design will work very well with ammonia. A 5-10 MW axial flow, single stage ammonia turbine would have a 14 inch diameter wheel rotating at 14,000 RPM. Sizes, speeds, and pressures are well within the range of proven bearing and seal designs.

Barber-Nichols has built and operated a prototype ammonia binary power plant. The plant operating characteristics were as expected and the performance of the plant and turbine were as predicted. An ammonia plant does not have inherent risks that are any higher than other binary plant designs.

Cost comparison

A cost comparison between an isobutane and ammonia plant is shown in Table 3.

The capital cost of the ammonia plant is 20% less than the hydrocarbon plant. The main savings is in the cost of condensers, but the cooling tower, brine heat exchangers, turbine-generator, feed pump, piping and mechanical installation also contribute to the cost savings.

The real potential of an ammonia binary system must be evaluated with all of the site specific factors for a particular job in mind. However, this study has demonstrated that ammonia does have potential and should certainly be considered as a candidate working fluid in future binary plant designs.

EFFECT OF HEAT REJECTION SYSTEM

Another factor that can significantly affect the plant capital cost is the selection of the type of system that rejects heat from the cycle. The most common heat rejection systems are (1) a tube-in-shell condenser with a cooling tower, (2) a tube-in-shell condenser with a spray cooling pond, and (3) an air cooled condenser.

The selection between these systems is generally made on the basis of site specific considerations. If make-up cooling water is available then the heat is generally rejected with a tube-in-shell condenser and either a cooling tower or a spray cooling pond. If the terrain is not suitable for a spray pond then a cooling tower would have to be used. If no make-up cooling water is available then air cooled condensers must be used.

While site specific considerations may drive the selection of the heat rejection system, it is important to be aware of the effect the selection has on plant capital costs. A comparison of costs and parasitic power requirements for the three heat rejection systems for an ammonia plant is shown in Table 4.

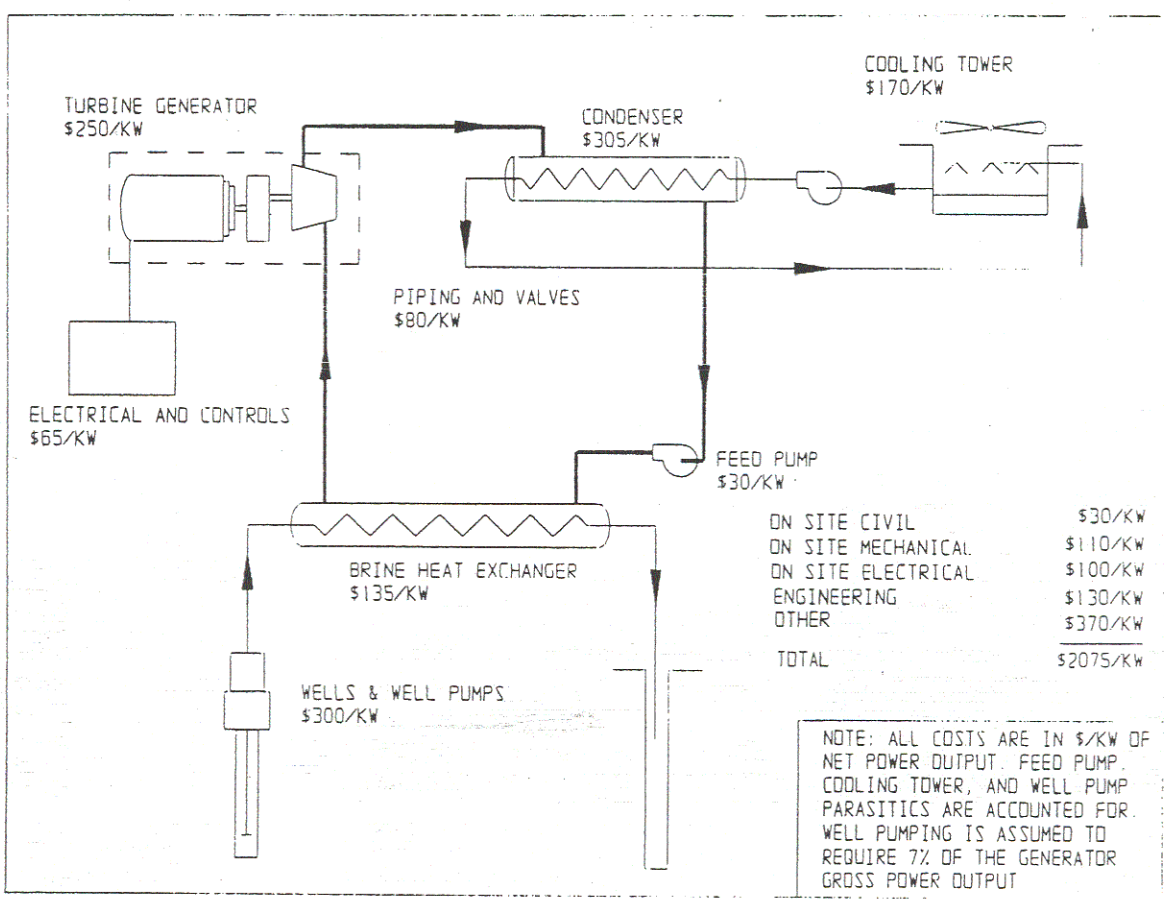
This comparison shows that by switching from a cooling tower to a spray pond, the cost of the heat rejection system can be reduced by $95/KW which is over 6% of the cost of the plant. However, the actual savings is larger than this because the condenser/spray pond also requires less parasitic power. Therefore the same plant produces more net power and the cost per KW of net power output of all of the other project costs are reduced proportionally. When this is taken into account the capital cost for an ammonia plant using a spray pond for heat rejection is $1250/KW of net power output.

If make-up cooling water is not available then air-cooled condensers must be used. Switching to air-cooled condensers increases the capital cost of the plant to $1610/KW of net power output. This is the least desirable option, but if no make-up water is available then there are no alternatives.

CONCLUSION

There are a number of factors that have been discussed which affect the capital cost of a geothermal binary power plant. Two of the more important ones are the selection of the working fluid and heat rejection system.

For a typical binary plant using a hydrocarbon working fluid and a cooling tower for heat rejection, the project capital cost (plant and wells) is $2075/KW of net power output. By switching to an ammonia plant using a spray pond the total project cost is reduced to $1530/KW of net power output. This represents a savings of over 25% and provides a strong incentive to consider some alternate approaches to the common binary plant designs.



BASELINE BINARY POWER PLANT COSTS
HYDROCARBON WORKING FLUID
FIGURE 1

COMPARISON OF HYDROCARBON AND AMMONIA WORKING FLUIDS
BINARY PLANT
TABLE 1

	Hydrocarbon	Ammonia
Brine utilization	Relatively high brine utilization	Relatively high brine utilization
Heat exchanger sizing	Low heat transfer coefficients require large heat exchangers	High heat transfer coefficients reduce heat exchanger sizes
Pipe sizing	High flow rates require large pipe sizes	Low flow rates minimize pipe sizes
Flammability	Flammable	Nonflammable
Turbine availability	Turbines in common use	Requires new turbine design

COMPARISON OF ISOBUTANE AND AMMONIA
HEAT EXCHANGER AND PIPE SIZES
6 MW BINARY PLANT
TABLE 2

	Hydrocarbon	Ammonia
Preheater	2-38"X60' Shells	1-30"X40' Shell
Evaporator	2-38"X60'	1-48"X60'
Superheater	None	1-34"X40'
Condenser	6-52"X60'	2-52"X60'
Turbine inlet	20"	12"
Turbine exhaust	32"	18"

COMPARISON OF HYDROCARBON AND AMMONIA
CAPITAL PLANT COSTS
TABLE 3

	Isobutane ($/KW net power)	Ammonia ($/KW net power)
Brine heat exchangers	135	110
Condensers	305	130
Cooling tower	170	145
Turbine-generator	250	240
Feed pump	30	20
Piping and valves	80	50
Controls and control room	30	30
Electrical equipment	35	35
Engineering	130	130
Construction	240	210
Management	35	35
Bonds and insurance	55	55
Contingency	150	120
Profit	130	105
Total capital cost	1775	1415

COMPARISON OF HEAT REJECTION SYSTEMS
AMMONIA PLANT
TABLE 4

	Cost ($/KW net power)	Parasitic power (% of generator gross output)
Condenser/ Cooling tower	275	12
Condenser/ Spray pond	180	6
Air-cooled condenser	435	12