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Advanced Binary Cycles: Optimum Working Fluids

September 20-23, 1998
Geothermal Resources Council 1998
Annual Meeting, San Diego, California

Prepared by:
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ABSTRACT

A computer model (Cycle Analysis Simulation Tool, CAST) and a methodology have been developed to perform value analysis for small, low- to moderate-temperature binary geothermal power plants. The value analysis method allows for incremental changes in the levelized electricity cost (LEC) to be determined between a baseline plant and a modified plant. Thermodynamic cycle analyses and component sizing are carried out in the model followed by economic analysis which provides LEC results. The emphasis of the present work is on evaluating the effect of mixed working fluids instead of pure fluids on the LEC of a geothermal binary plant that uses a simple Organic Rankine Cycle. Four resources were studied spanning the range of 265ºF to 375ºF. A variety of isobutane and propane based mixtures, in addition to pure fluids, were used as working fluids. This study shows that the use of propane mixtures at a 265°F resource can reduce the LEC by 24% when compared to a base case value that utilizes commercial isobutane as its working fluid. The cost savings drop to 6% for a 375°F resource, where an isobutane mixture is favored. Supercritical cycles were found to have the lowest cost at all resources.

INTRODUCTION

An effective means to improve the performance of binary cycle power plants designed for low- to moderate-temperature, liquid dominated resources is to use mixed hydrocarbon working fluids rather than pure hydrocarbons. The value of using mixed working fluids, which typically consist of two main components and are termed *binary*, has been shown in earlier work by Demuth (1981). Demuth found that the most promising binary mixture for a 280°F temperature resource was a 90% propane and 10% isopentane mixture. The Next Generation Geothermal Power Plants (NGGPP) study (Brugman et al., 1996) also identified mixed working fluids as an attractive and low risk modification. Mixtures of non-adjacent components that have a mass fraction of the light component greater than 85% tend to be the most effective in increasing geofluid effectiveness and reducing the LEC of the plant. The performance increase is a result of the thermodynamic behavior of the binary mixtures. The mixed working fluids change phase in the boiling, for the case of a non-supercritical cycle, and condensing processes over a temperature range, rather than at a fixed temperature as for a pure fluid. This property of mixed working fluids has the effect of reducing irreversibilities in the cycle and improving plant performance (Bliem et al., 1988).

In this study, a computer simulation tool and economic analysis spreadsheet are used to find the optimum binary working fluid, based on the lowest LEC, for a 50 MWe plant with air cooled condensation situated at four typical resources. The performance results of this study are compared to the base case results that used a similar cycle with commercial isobutane as presented in the NGGPP study. The computer simulation tool and economic spreadsheet were initially written by Bliem (1995) and further developed and modified at the National Renewable Energy Laboratory (NREL). CE Holt Company provided the economic information used for the base cases in the NGGPP study and this data was used in the LEC calculations.

This paper presents the results and preliminary analysis. Much remains to be explored in the results and more thorough analysis will be presented in future papers.

GENERAL APPROACH

For each resource a variety of binary fluids were used to determine design cycle performance in terms of geofluid effectiveness, second law efficiency (the ratio of the net work extracted from the cycle to the availability of the geofluid based on its reinjection temperature limit, which, as the lowest temperature allowed for the geofluid, represents the state of lowest availability), and LEC. For each fluid studied at a resource the heater pressure, heater pinch point, and condenser bubble point temperature were varied until the plant with minimum LEC was found. The plants optimized with different working fluids were then compared to find the plant at the particular resource with the lowest overall LEC. This plant's performance was then compared to the base case plant using commercial isobutane to gauge the improvement possible with the optimum binary fluid.

The resource temperatures considered in this work were 265°F (similar to the Thermo Hot Springs resource in Utah which will be referred to as RE-1), 300°F (similar to the Raft River resource in Idaho, RE-2), 330°F (similar to the Vale resource in Oregon, RE-3), and 375°F(similar to the Surprise Valley resource in California, RE-4). Reinjection temperature limits for these resources were 66°F for RE-1, 98°F for RE-2, 125°F for RE-3, and 156°F for RE-4. These values were determined by Bliem from the information on the resources provided by EPRI in the NGGPP study. Actual conditions at the resources may be different from the information given in the NGGPP study. The resources may be considered to be typical low- to moderate- temperature, liquid dominated resources. The geofluid reinjection temperature was not allowed to go below the temperature limit in the cycle analyses. The geofluid reinjection temperature became a significant limitation for the two hottest resources. Design environmental air temperature was 50°F at all resources. CE Holt's design air temperatures ranged from 47°F to 51°F with an average of 49°F.

CYCLE ANALYSIS SOFTWARE TOOL (CAST)

The cycle analysis software tool (CAST) developed at NREL sizes plant components and estimates plant performance using established typical heat transfer coefficients in the heat exchangers and isentropic efficiencies of the turbine, gearbox, generator, and feed pump from the NGGPP study. The CAST program uses simplified methods that speed computation; for example, no frictional losses are considered in the plant piping. The simplified methods do not deliver large inaccuracies in the results—comparisons between the CAST program results and CE Holt's base case results show good agreement considering the simplifications. Since the program is used to provide comparative cycle performance results, the relative ranking of the plants with different fluids is valid.

In this work, the CAST program was modified to calculate the plant equipment sizes and plant performance over a range of heater pressures, heater pinch points, and condenser bubble point temperatures. The results were written to a text file that was then imported into the economic analysis spreadsheet. Heater pressures ranged from 200 psia to 630 psia for RE-1, RE-2, and RE-3. Heater pressures ranged from 200 psia to 850 psia for RE-4. The heater pressures were limited to 630 psia for resources RE-1 through RE-3 because the economic information from CE Holt was for plants at those three resources with pressures of 235 psia, 325 psia, and 610 psia, respectively. It was thought that the economic information for a 235 psia plant, in the case of RE-1, could be used up to approximately 600 psia without significant problems due to a change in rating of the high pressure fittings. For RE-4, the economic information was for 850 psia, so the cycle analysis was allowed to go up to that pressure. Heater pinch points ranged from 2°F to 14°F. Condenser bubble point temperatures ranged from 60°F to 150°F. The condenser pinch point was calculated using an NTU-effectiveness method given the inlet and outlet working fluid state points and entering air temperature. In all cases, the turbine expansion was outside the saturation dome. The turbine inlet state point was determined from the minimum entropy value required for a dry expansion to the condenser pressure.

The fluids studied were binary mixtures of propane and isopentane, and isobutane and hexane. These were identified in earlier studies as the most promising mixtures. The mass fraction concentration of the heavy component was allowed to vary from 2% to 15%. Pure propane, isobutane, and isopentane were also analyzed. Property information on the mixtures and pure fluids was obtained from the NIST14 database. The NIST14 source code was modified to generate the property data files required by the CAST program.

The economics spreadsheet used the value analysis technique developed by Demuth and Whitbeck (1982) and described by Bliem et al.(1996). This technique determines the incremental change in LEC due to changes in the component sizes and power production of a modified plant compared to a base case plant for which equipment sizes, flow rates, and costs are available. CE Holt provided the detailed equipment sizes, flow rates, and costs for their base cases in the NGGPP study. CE Holt used commercial grade isobutane, a mixture of approximately 96.6% isobutane, 1.8% n-butane, and 1.6% propane, in their base case cycles. This information was put into the economics spreadsheet. The economics spreadsheet determined the LEC for each case at a given heater pressure, heater pinch point, and condenser bubble point temperature. The plants were then ranked according to LEC and the lowest value found for each fluid. The values for each fluid were then ranked to determine the overall lowest LEC and best fluid for the resource.

RESULTS

Resource Temperature of 265°F (RE-1)

The geothermal resource at 265°F temperature (Thermo Hot Springs, RE-1) showed the greatest potential for LEC reduction. The base case plant used a heater pressure of 235 psia, heater pinch of 10°F, and condenser bubble point temperature of 83°F. The geofluid effectiveness was 2.44 $W/\dot{m}_{geo}$, second law efficiency, 23.3%, and LEC, 0.1022 \$/kWhr. The base case was first optimized which resulted in an LEC of 0.0828 \$/kWhr, 19% lower than the base case value. Note that both the base case and the optimized base case use commercial isobutane as working fluids. Then the CAST program was used to study the effect of a series of mixed working fluids on the LEC. The CAST study showed that the best mixed working fluid for this resource was 98% propane and 2% isopentane, which when used in a plant designed for it delivered a geofluid effectiveness of 3.62 $W/\dot{m}_{geo}$, second law efficiency of 34.6%, and LEC of 0.0776 \$/kWhr, a 24% reduction from the base case. This plant had a heater pressure of 620 psia, heater pinch of 6°F, and condenser bubble point of 80°F. The plant with the next higher LEC, 0.0778 \$/kWhr, used a mixture of 95% propane and 5% isopentane. The results for the LEC study are summarized in Figure 1. The mixtures are designated "M" followed by the light and heavy fluid names and the percentage composition of the heavy fluid. The optimized base case is designated by "Comm iC4." Propane mixtures have lower LECs than isobutane mixtures at this resource. All of the plants had a brine outlet temperature that was higher than the reinjection limit of 66°F.

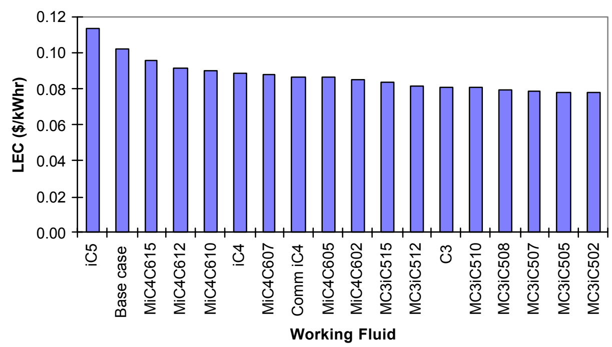

Figure 1. LEC results for RE-1.

The geofluid effectiveness results are shown in Figure 2 for a sampling of the working fluids studied. The fluids are arranged on the x-axis according to their LEC ranking. To illustrate one of the differences in performance between propane and isobutane mixtures, compare an isobutane mixture plant using 95% isobutane/5% hexane (MiC4C605) with the nearest plant, in terms of LEC, using a propane mixture. This plant uses 85% propane/15% isopentane (MC3iC515). The propane mixture has the lower LEC primarily because of the significant reduction in turbine size. The propane mixture plant has a turbine exit area of 2.11E-7 ft^2/lb of geofluid flow, but the isobutane mixture plant has a turbine exit area of 4.51E-7 ft^2/lb. Heat exchanger sizes are approximately the same for the two plants.

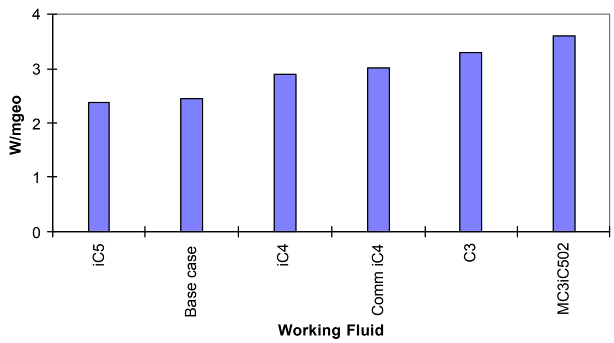

Figure 2. Effectiveness results for RE-1.

It is interesting to compare the performance of the best fluid to others to illustrate why that mixture is delivering the lowest LEC. First, compare the best fluid, 98% C3 / 2% iC5, to pure C3. There is a small component of heavy fluid in the mixture, but it is practically pure propane. In terms of cycle performance, there is greater geofluid effectiveness for the mixture because it is condensing at a slightly lower average temperature. The mixture's dew and bubble points in the condenser are at 84.5°F and 80.0°F, for an average temperature of approximately 82°F. The pure propane condenses at 84°F. The condenser pressure is also lower for the mixture than for the pure fluid: 142 psia vs. 152 psia. The lower condensing temperature and pressure increase the work output of the mixture cycle. Also, because the condenser pinch point temperature difference in the mixture cycle is about 0.5°F higher than for pure propane, the amount of cooling air flowrate is reduced, which reduces fan power requirements.

If a little bit of isopentane makes such an improvement, what happens when the fraction of isopentane is increased? The pure propane and best propane mixture allow the cycle to operate under supercritical conditions. The addition of more isopentane causes the cycle to become subcritical at the maximum pressure allowed, 620 psia. This is the case for 88% C3 / 12% iC5, which has a heater pressure of 560 psia for the cycle with lowest LEC. The subcritical cycle has significantly lower geofluid utilization. Also, as the percentage of isopentane increases, the heat transfer coefficient in the tubes of the condenser decreases, thus increasing the size of the condenser. The tube-side heat transfer coefficient for the 88% C3 mixture condenser is 34% lower than the 98% C3 mixture condenser.

It is also useful to compare the best propane mixture to the base case results. The performance increase is due to two effects. The first is that the propane mixture plant operates with a supercritical cycle, whereas the base case cycle is subcritical. The supercritical cycle operates with lower irreversibilities in the heater because the heating process has a lower average temperature difference. Secondly, the non-isothermal condensation behavior of mixtures reduces irreversibilities in the condenser. Commercial iC4 behaves similarly to pure iC4 in that is has a practically constant condensing temperature. Its temperature difference between bubble and dew points in the condenser is low—only 1.2°F. However, the best propane mixture shows strong non-isothermal behavior during condensation with a 4.5°F temperature difference between bubble and dew points. This behavior in the condenser increases the plant's performance in the same way as for the heater. When the economic analysis is done for these two cycles, one finds that even though the condenser and heater are smaller for the base case cycle, that cycle does not deliver a lower LEC because of its much lower power output.

Resource Temperature of 300ºF (RE-2)

The 300ºF resource (Raft River, RE-2) also showed significant potential for LEC reduction. The base case plant had a heater pressure of 325°F, heater pinch of 10°F, and condenser bubble point temperature of 87°F. Its second law efficiency was 30.6%, geofluid effectiveness, 4.04 $W/\dot{m}_{geo}$, and LEC, 0.079 $/kWhr. The results from the CAST program showed that the plant with the lowest LEC used a mixture of 93% propane/7% isopentane. This plant used a heater pressure of 620 psia, heater pinch of 12°F, and condenser bubble point temperature of 82°F. Its second law efficiency was 39.1%, geofluid effectiveness was 5.17 $W/\dot{m}_{geo}$, and LEC was 0.0700 $/kWhr, 11% lower than the base case. The LEC results are shown in Figure 3 for a sample of the fluids studied. All of the plants had a brine outlet temperature above the reinjection limit of 98°F.

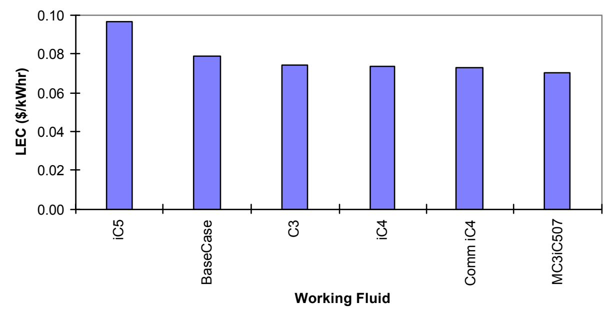

Figure 3. LEC results for RE-2.

The geofluid effectiveness results are shown in Figure 4.

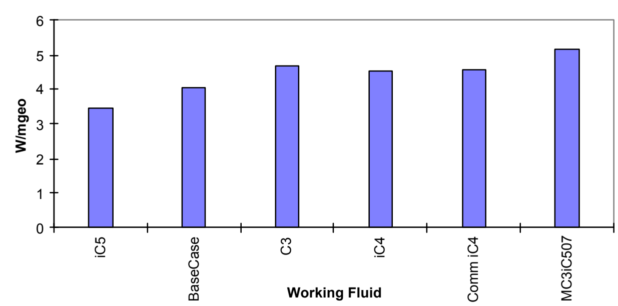

Figure 4. Effectiveness results for RE-2.

Resource Temperature of 330ºF (RE-3)

The results from the CAST program showed that if the CE Holt base case plant is optimized, the LEC is reduced from the base case value of 0.0677 $/kWhr to 0.0637 $/kWhr, a 6% reduction. No other fluid had a lower LEC than commercial isobutane. Figure 5 shows a sampling of the working fluids studied. The commercial isobutane plant (optimized base case) delivers a lower LEC than the base case because of its higher effectiveness. Optimizing the base case by lowering the heater pressure from 610 psia to 560 psia lowers the working fluid specific enthalpy difference through the turbine by 1.6%, but the working fluid flowrate can be increased 8% (because the turbine inlet temperature is lower by 6°F with the 50 psia drop in pressure, the working fluid flowrate can be increased), resulting in increased gross turbine power and higher geofluid effectiveness. The parasitic losses in the pump and condenser fan power differ for the two cases, but the differences are small enough not to have a significant impact on the net power. The heat exchangers are slightly larger for the optimized base case cycle, but this does not end up affecting the LEC significantly. Also, all of the plants that used pure propane or a propane mixture had brine outlet temperatures that were limited by the reinjection temperature limit of 125°F. All of the plants that used pure or commercial grade isobutane or isobutane mixtures had brine outlet temperatures that were above the reinjection limit.

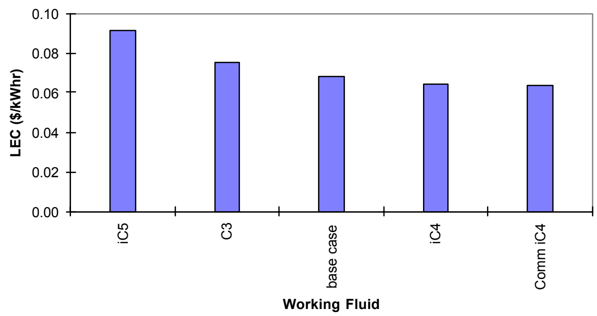

Figure 5. LEC results for RE-3.

The geofluid effectiveness values are shown in Figure 6. The base case value is 6.0 Whr/lb and the optimized base case is at 6.6 Whr/lb.

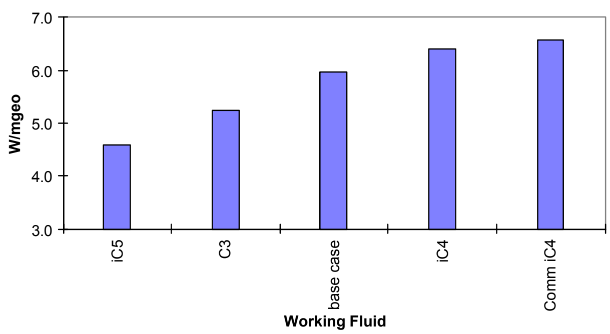

Figure 6. Effectiveness results at RE-3.

<u>Resource Temperature of 375ºF (RE-4)</u>

The CAST program results showed that a plant using a mixture of 93% isobutane / 7% hexane had an LEC of 0.0597 $/kWhr, 6% less than the CE Holt base case value of 0.0633 $/kWhr. The LEC results are shown in Figure 7 for some of the fluids studied. The base case and the optimized plant using the isobutane mixture both used a heater pressure of 850 psia. A geofluid outlet temperature limit of 156°F was imposed on the optimization studies, even though the base case had a brine outlet temperature of 150°F, and most of the plants in this study had brine outlet temperatures that were limited by the reinjection temperature limit. Bliem performed a study of the EPRI-supplied resource conditions and determined that 156°F was a more suitable temperature limit. It should be noted that if the reinjection temperature limit is allowed to be 150°F, the LEC for the plant that used the 93% isobutane / 7% hexane mixture became 0.0590 $/kWhr, 7% lower than the base case. The best case from this study has a higher geofluid effectiveness and higher efficiency than the base case even with the limitation to a reinjection temperature of 156°F. The reduction in cost is due to higher net work output from this cycle and somewhat to savings in equipment cost. The heat exchanger area in the heater/vaporizer unit is about half the size of the base case unit. There are also savings in turbine cost: the best case has a turbine 18% smaller than the base case unit. The air-cooled condenser area is about 20% higher for the best case versus the base case, but the savings in the other components more than offset its higher cost.

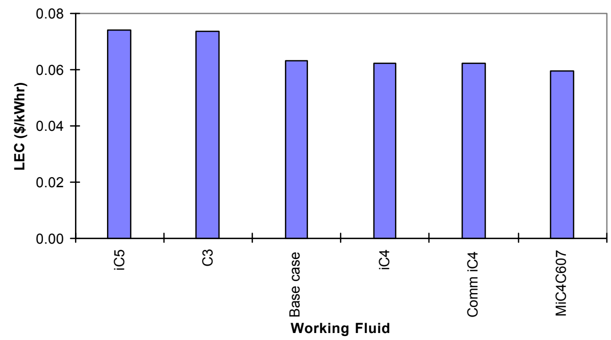

Figure 7. LEC results for RE-4.

The geofluid effectiveness results are shown in Figure 8. The effectiveness for the base case is 8.49 Whr/lb and that for the best fluid is 8.66 Whr/lb.

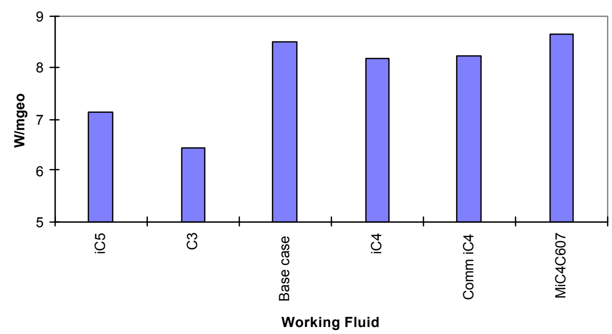

Figure 8. Effectiveness results for RE-4.

DISCUSSION

Two observations may be made about the results for the economically optimum working fluids. First, supercritical cycles are demonstraed to have lower LECs. This is shown in the results for RE-1 and RE-2. For both RE-1 and RE-2, the best fluid is a propane mixture with heating at 620 psia, which is above the critical pressure of propane. The use of propane allows supercritical cycles at these resource temperatures.

The second observation is that when all cycles are supercritical, isobutane mixtures tend to deliver lower LECs. The RE-3 resource is hot enough to allow supercritical cycles for the isobutane mixtures in addition to the propane mixtures. The best fluid at this resource is commercial isobutane at a heater pressure of 560 psia, and with an LEC 5.9% lower than the base case value. In comparison, the plants that used propane mixtures had LECs higher than the base case. The plants that used propane mixtures usually have turbines about half the size of the isobutane mixture turbines, and the heaters are somewhat smaller, but the condensers are larger. The increase in condenser area leads to higher parasitic loads in addition to capital cost. The condensers are generally larger because the propane mixture flowrates are greater, leading to higher heat rejection loads. Also, at some resource temperatures, the plants that use isobutane mixtures are often not constrained by the geofluid reinjection temperature limit, but the plants that use propane mixtures are.

At higher temperature resources, such as RE-4, where most fluids are limited by the geofluid reinjection temperature, the plants that use isobutane mixtures have lower LECs primarily because of higher effectiveness and efficiency values than the plants that use propane mixtures. The best fluid at this resource is 93% isobutane / 7% hexane, and the best propane mixture is 88% propane / 12% isopentane. The turbine in the propane mixture plant is less than half the size of the unit in the isobutane mixture plant, and the heater is 23% smaller. The condensers are about the same size. But the isobutane mixture plant's effectiveness and efficiency are 21% higher than the propane mixture plant's values and the increased plant performance has a greater effect on reducing LEC than the savings in two component sizes.

The LECs for the best plant and base case at each resource temperature are shown in Figure 9. Also shown are the LECs of three mixtures at each resource temperature. The figure shows that the highest potential for LEC reduction is at the lowest resource temperature. The propane mixture plant performs well at the lowest temperature, but poorly at higher temperatures. The 93% isobutane / 7% hexane plant has a low LEC at the highest resource temperature, but performs worse than the propane mixture and commercial isobutane plants at low temperatures. The commercial isobutane line shows the potential for LEC reduction when the base case, which used this fluid, is optimized for each resource.

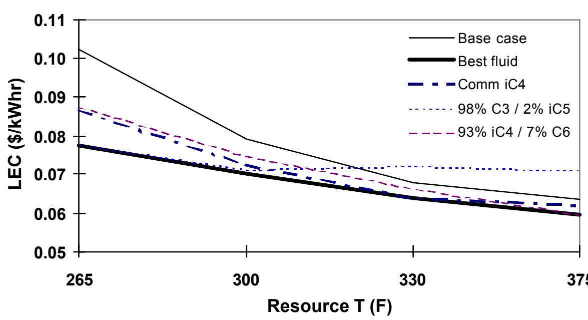

Figure 9. LEC results summary for all resources.

CONCLUSIONS

Significant savings in the cost of power production can be achieved if hydrocarbon mixtures are used in binary plants at low- to moderate-temperature geothermal resources. The amount of cost reduction increases with decrease in resource temperature. At the 265°F resource, the reduction in LEC from the base case is 24% when a propane mixture is used. At the high temperature resources studied, the amount of LEC reduction is diminished. For the 375°F temperature resource the LEC reduction was 6% when an isobutane mixture was used. Propane mixtures are favored at the low end of the range of resources studies, and isobutane mixtures at the high end. Also, the study found that the optimum fluids for a resource tend to be those that have a supercritical cycle.

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