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HIGH-POTENTIAL WORKING FLUIDS AND CYCLE CONCEPTS FOR NEXT-GENERATION BINARY ORGANIC RANKINE CYCLE FOR ENHANCED GEOTHERMAL SYSTEMS

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ABSTRACT

A Department of Energy funded study of advanced cycles and high-potential working fluids for Organic Rankine Cycles (ORC) for use in Enhanced Geothermal Systems (EGS) and their impact on cost of electricity has been conducted. The work completed to date, in coordination with AltaRock Energy, Inc., characterized the performance of advanced cycles and high-potential working fluids for EGS resource temperatures. A cash flow model to estimate the levelized cost of electricity (LCOE) is being developed. This model includes high resolution cost models for the EGS reservoir in combination with the power plant. The impact of power cycle, working fluid, and geothermal well specifications on LCOE and optimized plant configurations are evaluated. From an available list of more than 17,000 pure components, 35 working fluids were identified as high-potential. In addition to the numerous fluids that were screened from commonly available sources, additional fluids were screened from vendors that are less common or even not on the market yet. An additional 3 working fluids were included for comparison to the current state-of-the-art. The performance of the working fluids was evaluated in a subcritical ORC, supercritical ORC, and trilateral flash cycle and compared to the performance in baseline subcritical ORCs. The primary advantage of the supercritical cycle or trilateral flash cycle over the subcritical cycle is a better match between resource cooling curve and working fluid heating curve. The lack of constant temperature evaporation allows the heat source to be cooled to a lower temperature despite a similar pinch point as in a comparable subcritical cycle leading to greater utilization of the geothermal resource. The supercritical cycle offers significant improvement in net power output compared to a baseline subcritical cycle. The topics that will be presented include the modeling efforts for the supercritical, subcritical and trilateral flash cycles, the cost & economic modeling of EGS plants and results of the comparison with baseline subcritical cycles resulting in a 30-50% increase in net power output and optimized LCOE calculations.

INTRODUCTION

Enhanced or Engineered Geothermal Systems (EGS) have the potential to become a significant sustainable power source for the future [1]. Unlike classic geothermal applications, EGS is not limited to specific geologies with hot, high porosity geology and water. Significant research and production plants are under construction or operation to take advantage of this abundant renewable energy opportunity (Figure 1). These efforts vary significantly in size, technology and purpose.

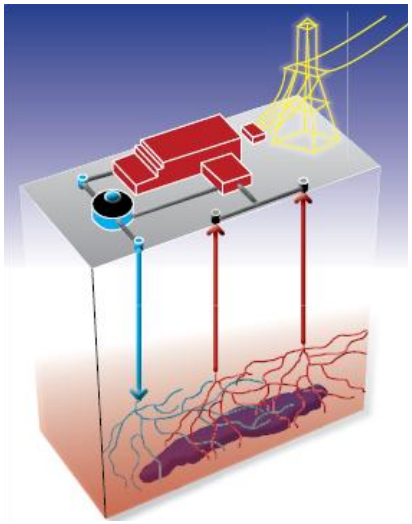

Figure 1: Typical EGS Setup

EGS is a key green technology to deliver zero emission energy to millions of US households. Improvement in energy conversion technology is highlighted as one of the key requirements for increased acceptance and successful development of EGS [1]. Successful development of advanced fluids and energy conversion technology under this program will aid in enhancement of the U.S. lead in geothermal science and technology. The design capability for optimal energy conversion efficiency at the plant can be combined with drilling cost models to find an optimal design point between drilling depth

and energy conversion plant investment. In addition, such models allow for the evaluation of system performance under a range of boundary conditions.

If geothermal source temperature variation over time can be predicted, the energy conversion system can be designed to have optimal efficiency over a range of source temperatures. A similar analysis can also be used to improve output performance under heat sink night and day temperature variation. By providing for optimization over the lifetime of the complete EGS system, it is expected that further economic and output performance benefits can be realized.

Review of available Concepts/Technology:

The focus of this project is cost efficient power generation from Engineered or Enhanced Geothermal System (EGS) resources. EGS, like most geothermal projects, is characterized by a substantial amount of the project cost (50-80%) being bound in the well field. Significant effort is underway to reduce the cost per kW installed by technology development, one of the ideas being improvements in the energy conversion system. Classical higher temperature hydrothermal plants use flash steam systems. In newer, lower temperature plants Organic Rankine Cycles (ORC) are a common energy conversion system. ORC's use organic liquids as working fluids that relative to water have lower critical pressure and temperature allowing the cycle to run more efficiently at low temperatures and at reasonable pressure levels. A fluid is chosen depending on the application with the most common ones being hydrocarbons like n-Pentane, iso-Butane or refrigerants like R134a or R245fa.

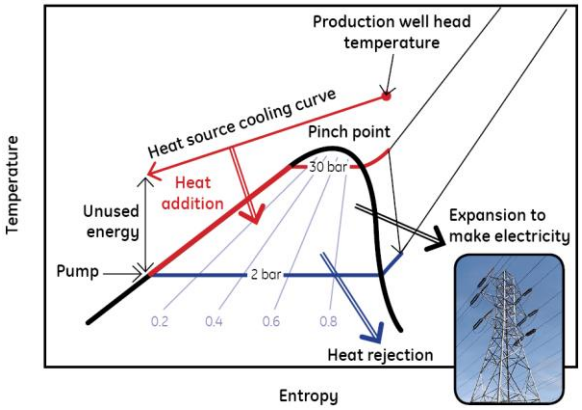

Figure 2: Subcritical Rankine Cycle

The approach to improve the energy conversion side of EGS systems is focused on evaluating advanced cycles relative to the subcritical Rankine cycle, namely the supercritical and the trilateral flash cycle. An example of all three cycles is shown in Figure 2,3, and 4. Another cycle of interest uses fluid mixtures to take advantage of a gliding boiling point; however, previous GE studies have shown this technology not being cost effective, due to heat exchanger design considerations to avoid de-mixing of the fluid mixture and the lower heat transfer coefficients.

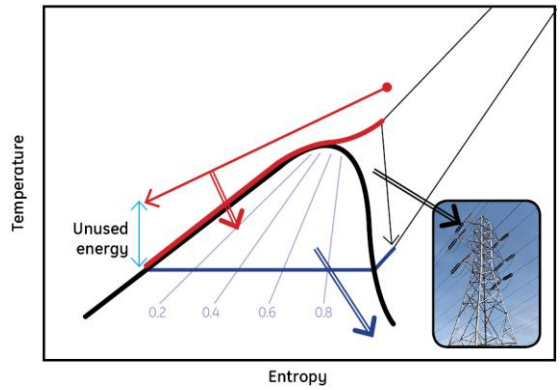

Figure 3: Supercritical Rankine Cycle

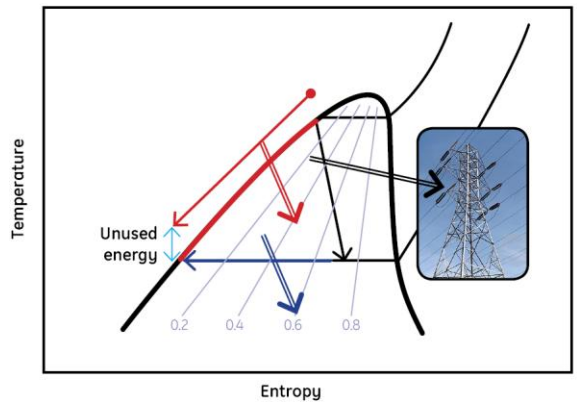

Figure 4: Trilateral Flash Cycle

The ideal energy conversion system has: 1. greater than atmospheric condenser pressure at low temperatures, 2. optimal heat source utilization where heat source curve and working fluid boiling curve are parallel with minimal temperature difference (pinch point) and 3. manageable working fluid pressure at maximum source temperature. For a given resource temperature each cycle has a preferable fluid and pressure levels to work with/at. The subcritical and the supercritical cycles are the most mature systems with the supercritical cycle likely operating at higher pressure levels (higher cost and more pump power required) and need for additional engineering on the supercritical heat exchangers and special attention paid to the pressure ratio limits on the expander. The trilateral flash cycle with its flash expansion would require a higher mass flow rate for a similar power output, thereby requiring more pump power compared to a subcritical cycle. In addition a two-phase expander is currently commercially not available and R&D effort would be necessary for development.

Depending on the specific customer requirements there are several cycle design options that may help the system economics. A recuperator can be

employed to use some of the superheat available after the expansion process (e.g. when using R245fa) to preheat the working fluids after the pump before it enters the preheater. Even though this piece of equipment increases the cycle efficiency, it does not necessarily increase the net power output of the plant, depending on the change in heat utilization. From an economics point of view the heat transferred does not have to be rejected in the air cooled condenser and therefore required a smaller air cooled condenser. In case that a lot of solubles are in the brine and a minimum temperature is required to prevent scaling in the heat exchangers, a recuperator can raise the reinjection temperature to prevent precipitation or the use of chemicals to prevent scaling.

One key component of the cycle is the expander. The ideal expander provides high conversion efficiency at the design point and at the same time maintains the high efficiency in off-design operation. Unlike industrial waste heat recovery applications with very predictable operating conditions, geothermal applications always carry the risk of the unknown resource. Sufficient information on the resource is available when the actual flow test is performed, relatively late in the overall project. Even then the resource will decline over time and cause a change in the operating conditions. For smaller applications expanders like scroll, screw or piston expanders may be applicable. However, the required flow rate for EGS applications are pushing into the area of radial and axial expanders. Radial expanders provide the advantage of relatively high efficiency under part load conditions, while axial expanders shine with very high design efficiency; they also have a significant efficiency loss for any off-design case.

Fluid Selection Process:

A review of similar undertakings in the literature has identified several groups of fluids that best fit the needs of the ORC application. Fluids were gathered from literature [2,3,4,5,6,7] commercial software such as Engineering Equation Solver (EES), Aspen HYSYS, Aspen Properties, DIPPR database, NIST RefProp, and from internal GE sources. The full list of available fluids contained more than 17,000 pure components. Fluids considered suitable for the current application were hydrocarbons, which can be categorized into saturated, unsaturated, cyclic/heterocyclic, aromatic, and halogenated8. The halogenated hydrocarbons are also classified as refrigerants. Alcohols, perfluorocarbons, a variety of refrigerants and siloxanes were also considered. It is essential to note that by classifying the fluids into chemically similar groups, the fluids used in cycle analyses will be reduced by assuming chemically similar fluids to exhibit similar cycle behavior [6].

In addition to the numerous fluids that were screened from commonly available sources, additional fluids were screened from vendors that are less common or even not on the market yet. In doing so, fluid vendors have been identified and contacts were made with several vendors.

The selection of working fluids for Organic Rankine Cycle was based on fluid properties that affect (i) cycle feasibility, (ii) environmental considerations, and (iii) cycle performance. The operation of ORC between the available resource temperature (T_R) and ambient temperature (T_o) put a bound on the fluid melting point, critical temperature, and the boiling point for certain thermodynamic cycles to be used with air cooled condensers. Additionally, environmental considerations like the ozone depleting potential (ODP), global warming potential (GWP), and toxicity were also taken into account. These parameters were therefore treated as elimination criteria for the working fluids. Fluid properties like density, molecular weight, thermal conductivity, availability, etc. that directly affect the cycle performance and cost but do not restrict the application, were therefore used to tabulate the expected relative fluid performance. These criteria were used to rank the fluids according to their suitability to various cycles against industrial standards like Iso-Pentane, R123, and, n-Butane. The initial list of about 150 fluids short-listed as possible working fluids for ORC were evaluated based on a target site for the pilot plant operation. Each of these factors is discussed in detail in this section.

- The melting point (T_m) of the working fluid should be lower than the lowest ambient operating temperature at the pilot site in order to ensure that the fluid will remain in the liquid phase. This criteria enables the use of air cooled condensers and plant reliability in extreme weather conditions.
- The critical temperature (T_c) should be higher than the average ambient temperature at the pilot plant site to enable feasibility of various cycles considered in this study.
- The boiling point (T_b) should be lower than the maximum cycle operating temperature for certain cycles considered in this study.
- The global warming potential (GWP) is an index that determines the potential contribution of a chemical substance to global warming. The current European standard for an industrial fluid of GWP less than 150 (equivalent of carbon dioxide over 100 years) is used for working fluids screening in this study [8].
- Toxicity of the working fluids was tabulated in terms of NFPA health hazard rating from 0 to 4, with 0 being non-toxic to 4 being deadly. Toxicity rating of 2 or lower was determined to be the criteria for fluid selection.

The total number of working fluids was down selected to about 35 fluids based on the elimination criteria above. These 35 fluids were ranked based on their relative properties with industry standards. The

properties used for this ranking are discussed further below.

- The density (ρ) of the working fluid must be high either in the liquid or vapor phase. High liquid or vapor density results to increased mass flow rate and equipment of reduced size. In this study we consider the liquid fluid density at 20°C at 1 atmosphere or at boiling point when the fluid was in gas phase at the standard condition [9].
- The thermal conductivity (k) must be high in order to achieve high heat transfer coefficients in both the employed condensers and vaporizers.
- Higher molecular weight working fluids are ranked higher due to their better performance in a low temperature thermodynamic cycle [10].
- The number of atoms per molecule in the fluid determines the phase of a particular fluid during the expander section of the cycle. Molecules with 3 atoms or less are rated as 1 and wetting fluids with more than 6 atoms per molecule on the other hand are rated as higher with a score of 3 [11].

A ranking of shortlisted fluids was based on the above criteria with weights decided based on thorough literature research and experience.

NET POWER PRODUCTION:

A modeling effort has been performed in order to evaluate the impact of high-potential working fluids in advanced binary cycles for EGS applications. The cycles of interest are the subcritical Organic Rankine Cycle (baseline), the supercritical Organic Rankine Cycle, and the Trilateral Flash Cycle using organic fluids. In this first phase of the study the main focus was on the technical cycle model with the net power output being the key parameter to evaluate the cycle performance.

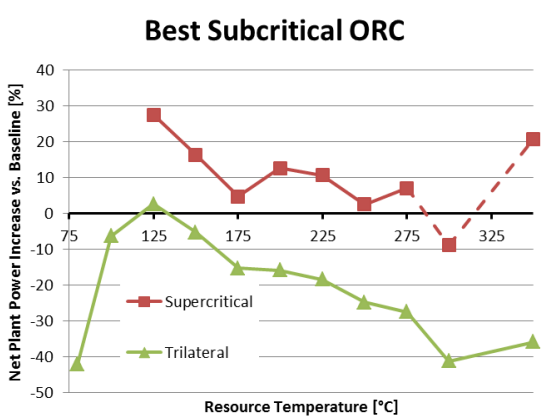

Figure 5: Relative plant net power output increase compared to best subcritical cycle

Depending on the source temperature, each cycle has a set of different fluids that lead to maximum net power output. Figure 5 shows the in- or decrease in net power output of the best performing fluids for each cycle relative to the best performing fluid for the subcritical cycle. It is obvious that at the lower temperatures the supercritical cycle outperforms the subcritical cycle, while at the higher temperatures both the cycles are comparable. The trilateral flash cycle underperforms across the resource temperature range investigated. The main focus of this activity is to find combinations of advanced cycles and high potential working fluids that increase the net power output of the system relative to currently employed hydrocarbons and refrigerants in subcritical ORC applications. Figure 6 shows the change in net power output for the different cycles and their best performing fluids relative to the baseline n-Butane subcritical Rankine cycle.

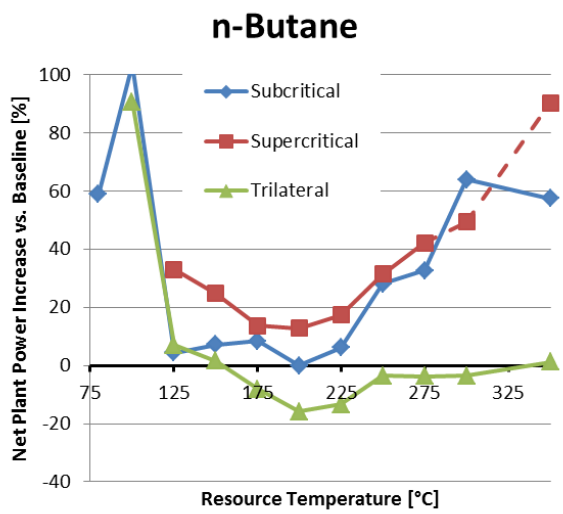

Figure 6: Relative plant net power increase compared to baseline fluid (n-Butane).

Similarly, a detailed analysis was performed for a combination of advanced power cycles and high-potential working fluids for a range of different resource temperatures. For each cycle a set of different working fluids has been found that maximizes the cycle power output for a given resource temperature. Overall the proper cycle/fluid combination shows the promise of a net power output increase of 30-50% and above.

Looking at Figure 5 it is obvious that at lower temperatures the supercritical cycle have an advantage over the subcritical and the trilateral flash cycle. At higher temperatures the subcritical and supercritical cycle are comparable to each other. The trilateral flash cycle clearly loses ground at the higher temperatures.

THERMO-ECONOMIC MODELLING:

The analysis above was solely focused on the technical aspects of geothermal power generation

with special attention paid to fluid selection, fluid validation, different cycles (subcritical, supercritical, and trilateral flash). A lot of assumptions in the models, like pinch points or efficiencies, were taken as constants across all models, even though in reality these numbers will vary depending on an economic analysis.

This part is focused on expanding the current thermodynamic model capabilities by adding an economic piece that predicts Levelized Cost of Electricity (LCOE) and $/kW installed. This enhanced model will then be used to find for every resource temperature, cycle and fluid combination the optimum (minimum) LCOE point. In order to evaluate the economic benefits of advanced working fluids and cycles for geothermal applications, a comprehensive levelized cost of electricity model for the whole geothermal site has been developed and integrated with the thermodynamic model for the power cycle.

Levelized cost of electricity calculation:

The levelized cost of electricity (LCOE) of the geothermal project is calculated from the capital expenditures of the power unit and the well field, the operational expenses, the power production and several financial parameters. The calculation of the power unit and well field capital expenditures using cost functions is not detailed in this section, and considered an input for the presented LCOE model. The levelized cost of electricity is estimated via a cash flow analysis taking into account effects specific to geothermal binary power plants.

The capital expenditures are calculated by summing up the well field, power unit and transmission line cost. The well field cost model includes cost functions for a selection of production and reinjection wells appropriate for enhanced geothermal systems. Choosing among a pre-selection of geothermal locations estimates a depth temperature gradient. By providing the desired brine flow rate and temperature, the well field cost model selects the appropriate number and design of producers and injector wells to estimate the well field cost. Well field parameters impacting the power production, such as the well and reservoir pressure drops, are estimated during this step. The power unit cost model is based on the major components (expander, heat exchangers, condenser, and pumps) cost functions. These major costs are summed up, and multiplied by a fixed coefficient to account for the installation cost (including freight, sales tax, building materials and labor). The transmission line cost is estimated following a method used in the GETEM [12] cost model for geothermal power plants taking into account the geography, population density, voltage and distance to the grid.

The operating cost is calculated by summing up the equipment maintenance cost and the labor cost. The equipment maintenance cost is taken as a fraction of the capital expenditure for the power unit. For the well field, operating costs account for the well field pumps maintenance and the re-stimulation cost at given time intervals. The labor cost is estimated based on a method used in the GETEM [12] cost model.

The financial model includes an array of parameters usually encountered in cost of electricity model such as the inflation, tax rate, contingency, land leasing royalties and depreciation. Moreover, the model accounts for the major impact of timing on a geothermal power project. Delays in the power production from the initial investments are considered. As the well field development and power unit construction phases can take up to two years each, the power production and therefore revenues can begin only several years following the initial investment. Moreover, the geothermal project debt structure can change over time, accounting for important financing differences at different times of a geothermal project life. Debt will indeed be more expensive and more difficult to secure during the early exploration and confirmation phases of a geothermal project [13]. As a consequence, the earliest phases of a geothermal project are typically dominated by a large share of equity financing. As the project moves forward, and the risk decreases, the equity share of financing can be decreased along with the cost of the debt. An overall project discount rate is calculated from individual discount rates at each project phase, weighted by the discounted capital expenditure for each phase.

The model allows levelized cost of electricity calculations including several incentives, including feed-in tariffs, investment and production tax credits and capacity based incentives. Feed-in tariff and the production tax credit help decrease the levelized cost of electricity by generating some value based on the actual amount of power produced by the power plant every year. On the other hand, the investment tax credit represents a significant source of income at the beginning of the project. On top of that, a fraction of the investment tax credit may still be depreciated. Similarly, capacity based incentives offer a source of value for the project at the beginning of its life, depending on the power plant electrical capacity.

These contributions to the levelized cost of electricity are grouped as capital cost, operational and maintenance cost, tax benefits and incentives. The contingency and royalties are taken as a fraction of the sum of these previous contributions. The sum gives the total levelized cost of electricity.

Component Cost:

A detailed exercise was conducted to obtain the component costs for various equipment and processes that are part of an engineered geothermal (EGS) power plant. The aim of this exercise is to optimize the thermo-economic model described above. To achieve this goal, the cost of these components and processes is to be obtained as a function of thermodynamic variables to be optimized. Each of these is explored in further detail in this section.

Well Field Cost and Optimization:

The well field cost for EGS system was obtained from Altarock Inc. as a function of source temperature and the well field depth which is a function of temperature gradient at a particular location. Further, the well field type including the down-hole diameter, number of casings required, flow rate, and pressure drop are optimized to achieve the lowest cost of electricity.

Turbo-Machinery Cost:

The radial expander design practice from GE Rotoflow has directly been incorporated in the thermo-economic model. For a given thermodynamic conditions, the expander machine type, frame size, and diameter are automatically computed. This model then predicts the efficiency and cost of the machine including the control system and gearbox, if required.

Heat Exchanger Cost:

Shell and tube heat exchangers are a common choice for preheaters, boilers and superheaters in binary geothermal power plants. The design of a shell and tube exchanger is critical to its cost and performance. Due to the quality of the geothermal resource, exchanger cleaning is required quite frequently and the AME type of TEMA shell and tube exchanger is therefore considered. The AME type of shell and tube exchanger has channel and removable front cover and fixed rear cover with one tube sheet. The dirty stream, i.e. the geothermal brine is put on the tube side for easy cleaning and the organic fluid is put on the shell side with low fins on the tube outer diameter to enhance the heat transfer. Due to corrosion concerns caused by the geothermal resource, Ni/Cr/Mo steel is used for the tubes, while carbon steel is used for the shell for cost considerations.

Heat exchanger cost increases strongly with the shell diameter and the number of tubes because of shell thickness and tube-sheet fixing. However, the cost increases little with tube length. Hence, cost effective designs are usually found with long thin exchangers. Cost optimized shell and tube heat exchangers are designed using AspenTech's EDR (Exchanger Design and Rating) tool. In EDR, the design starts with the longest tubes, and shortens to get feasible cases. Shell and tube exchanger EDR Mechanical simulates the fabrication of the equipment, including all relevant shop operations (cutting, shearing, welding, drilling, beveling, etc.) per equipment part (tubesheets, flanges, nozzles, etc.) and assembly, testing and other miscellaneous shop functions. Hence, the cost estimates are reasonably accurate for this stage of the study. A total of 44 heat exchangers were designed and their cost has been estimated using EDR.

Results of this design exercise were used in part to generate the predictive cost function based on the required heat exchange area. A curve fit based on vendor quotes and optimized EDR designs allows generating the cost function based on total required heat exchange area, including the low fins.

The heat exchange area is not directly available from thermodynamic cycle simulations. The UA value, given by the ratio of the total heat exchanger duty by the log mean temperature difference over the heat exchanger, can however be easily calculated. Dividing this UA value by the overall heat transfer coefficient for the heat exchanger gives the required heat exchange area required in the cost function. An additional function has been developed to estimate the overall U-value. This function depends on the fluid considered (alcohol, hydrocarbon, ring or ketone), the operational regime (liquid heating, evaporation, supercritical heating), the maximum allowable pressure drop and takes into account an estimated fouling rate. The heat exchanger cost function developed therefore depends the desired parameters including pressure drop and heat exchange required in order to obtain a satisfactory degree of accuracy.

Air Cooled Condenser Cost:

There were a number of steps required to obtain a cost transfer function for the Air Cooled Condenser (ACC). The initial step was to conduct a sensitivity study to determine the critical parameters that had an impact on ACC performance. Some of critical parameters investigated were mass flow rate, working fluid properties, fan power efficiency, and surface area. The sensitivity study was done using a Design for Six-Sigma (DFSS) tool. With the knowledge of significant ACC parameters, a request for quotes were sent out to ACC suppliers based on HYSYS simulation conditions in the subcritical, supercritical and trilateral flash cycle.

The quotes obtained from suppliers were assessed to understand the assumptions made, for example, number of fans in bay and types of fin tubes. Once the assumptions were determined a comparison was made to ASPEN Exchanger Design and Rating software and other available ACC Size and Costing Models. Cost functions from literature were also compared. The cost function generated was a

function of the overall heat transfer coefficient and the fin surface area.

Pump Costs:

A review of all cycles evaluated in the study showed that the operating range of required pumps fell well within the qualifications of a centrifugal pump. The type pump was selected based on the moderate volumetric flow rate and head as well as lower viscosity and available NPSHa being greater than 1.5m. A specification sheet was completed for over 20 individual pumps from 12 cycles where all parameters were listed to specify a pump that would meet the needs of the cycle. A list of over 30 vendors for centrifugal pumps was generated and pumps were paired with vendors specializing in units of the appropriate size. Price quotes were received for pumps ranging in size from 300 gallons per minute to 6500 gallons per minute with head from 5m to over 500m. It should be noted that price quotes in the higher flow, higher head range were not as numerous as those in the lower ranges. From the quotes received, it was determined that critical costing parameters included duty, pump head, discharge pressure, and efficiency. However, a singular transfer function based on these 4 parameters with the quotes received was not possible. Following the critical parameters identified in Seider, et al. [15], a sizing parameter S was developed where:

$$S = \dot{V} * head$$

with the volumetric flow rate in gallons per minute and the head in meters. Using this parameter, a power law curve fit was generated with an R^2 value of 0.9226 where cost of the pump was only a function of sizing parameter, S.

This was compared to a quadratic transfer function included the volumetric flow rate and the head. It should be noted at the power law has excellent agreement at lower S values and begins to diverge at values higher than S = 1,000,000. The quadratic formulation however predicts a negative cost in the lower range and was thus considered unacceptable for this analysis.

O&M Cost

The operating and maintenance cost of an EGS power plant has 2 important components: (a) the O&M for the ORC power plant and (b) the well field maintenance cost. The ORC power plant O&M costs were estimated based on experience in similar power plant configurations and ORC installations. This is usually a percentage of the installed cost of the power plant on a yearly basis. Further, this model for computation of O&M costs was validated with the assumptions in the GETEM model [12]. The well field O&M includes maintenance of the primary well field equipment and reservoir production temperature at desired flow rates. The maintenance of well equipment, which includes the down-hole and reinjection pumps, is specified based on pump vendor specifications and included in the LCOE model. The well field source conditions in an EGS system are proposed to be maintained using re-stimulation of the geothermal wells on a periodic basis. This periodic cost is specified by Altarock Inc. and included in the LCOE model for cost of electricity calculations.

Model integration:

As inputs are expected to come from different sources, the levelized cost of electricity model integration is important to the overall optimization performance. A typical tool for economic calculations is Microsoft Excel®, as it includes numerous economic functions useful for LCOE calculations. Moreover, very specialized tools are available for well field design and optimization. However, these models are far too complex for the scope of this project which does not include any geographically specific geological information. As a consequence, the well field design and cost models are actually implemented in Excel®. However, the power plant design and power output estimates are generated in Aspen HYSYS® [14], a commercial chemical processing simulation tool able to simulate the power cycles of interest.

These two platforms have to interact in order to perform a levelized cost of electricity optimization. As the HYSYS® in-built Hyprotech SQP optimizer is used to minimize the cost of electricity of the geothermal project, all the functions depending on optimization parameters have to be directly calculated in HYSYS®. As a consequence, the thermodynamic model, the cost of electricity model and the component cost functions are implemented in an HYSYS® spreadsheet. Excel is used as an input/output user interface linked to HYSYS® via the Aspen® Workbook.

The levelized cost of electricity optimization algorithm and integration is presented in *Figure 7*.

From a location and a desired brine temperature and mass flow rate, the well field cost model estimates the underground pressure drops and the overall well field cost. The net power output is estimated in HYSYS, taking as an input a set of fixed boundary conditions, the well field specifications and an initial guess for the optimized parameters. Thermodynamic data from the HYSYS simulation is extracted in order to lay down a preliminary design for the main components of the cycle. This preliminary design feeds the component cost functions, which allows estimating the power plant capital cost. This power plant capital cost is added to the well field cost and allows calculating the levelized cost of electricity using the assumed financial parameters. The

optimizer varies the value of several parameters, such as the heat exchangers pressure drops and minimum approach to minimize the levelized cost of electricity. The result from the optimization is finally sent back to the user in Excel in the form of optimal plant and well field configuration and the associated LCOE.

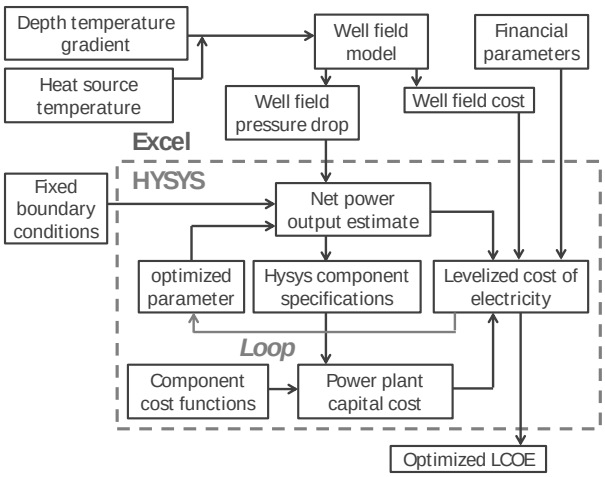

Figure 7 - Levelized cost of electricity model integration

The levelized cost of electricity calculations are primarily meant to be used on a relative basis to compare the benefits of an advanced cycle-working fluid combination to another. Uncertainties on the power unit components cost functions and on the well field design and cost estimates do not allow taking the calculated levelized cost of electricity alone as an absolute number or a measure to assess the economic viability of a geothermal project. It however offers a valuable tool for a quick, yet comprehensive, estimation of the levelized cost of electricity to assess the attractiveness of advanced working fluids.

RESULTS

For a given source condition, cycle layout and working fluid this thermo-economic model can now predict the levelized cost of electricity from an engineered geothermal system (EGS). The dependence of LCOE for subcritical ORC using Iso-butane as the working fluid is shown in figure 8. It is assumed that this power plant is located in the US west coast area to obtain the appropriate well field depth and cost. The LCOE model described above then computes the component parameters and specifications for the optimized (lowest) LCOE for a given source temperature. This tool can now be used for comparison between various organic Rankine cycles and working fluids for EGS applications. These results will be presented in the near future.

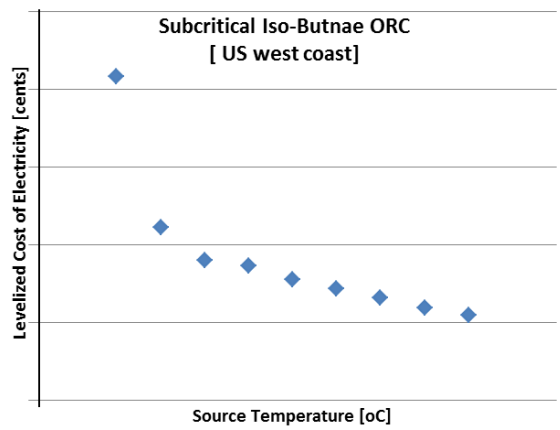

Figure 8: Levelized cost of electricity [LCOE] variation with source temperature from an EGS power plant using Iso-Butane subcritical ORC plant located on the US west coast.

CONCLUSIONS:

The LCOE model developed here enables computation of optimal engineered geothermal systems for power generation for a given set of boundary conditions. The primary input to the model includes, source conditions in terms of source temperature and thermal gradient on the well field side and organic Rankine cycle layout and working fluid on the power plant side. This gives high fidelity and resolution for the comparative study of various ORC layouts and working fluid types as discussed above.

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