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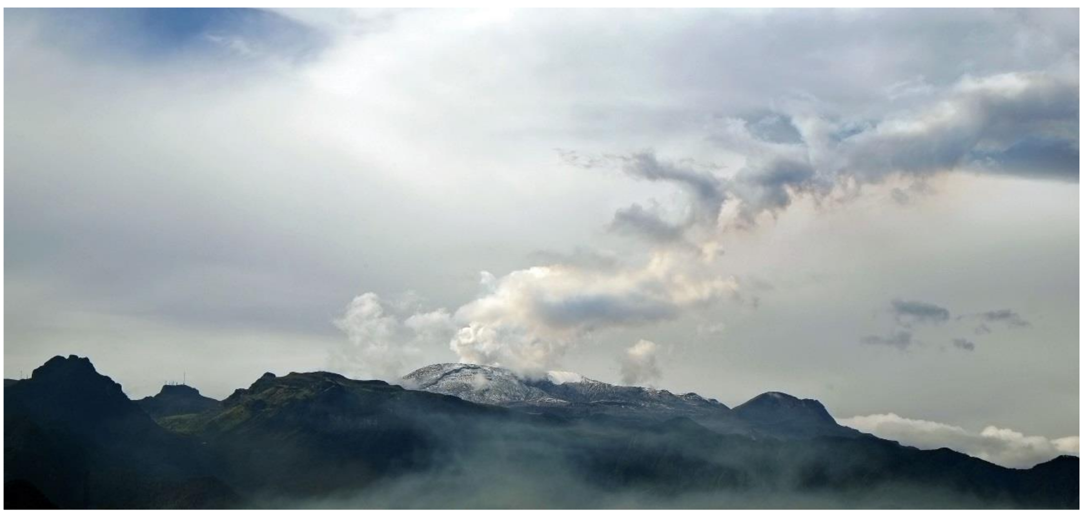
Developing the Methodology for Calculation of the Firm Energy of a Geothermal Power Plant



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Introduction

Objective

The purpose of this study is to provide a methodology for calculating estimated annual electrical energy output for a geothermal plant, given a set of design parameters and availability assumptions.

Report Content

This study is organized into three general sections: background, methodology and discussion.

The *Background* section will discuss generating power from geothermal resources, beginning with reservoir characteristics and gathering systems. The discussion will then move above ground to discuss the different types of geothermal power plant cycles that will be analyzed in this report: binary (air cooled), and flash (water cooled).

The *Methodology* section will be broken into two subsections: design point output and off-design operation. The purpose of the design point output section is to discuss the development and use of the various plant cycle tools; both binary and flash models. The off-design operation section will discuss how variations in ambient temperature affect the output of the power plant. The theory and use of capacity factors (as they relate to plant outages) and correction factors will be discussed here as well.

The *Discussion* section will include a description of the calculation of firm energy, which will be presented as the annual specific energy output as a function of resource temperature. We will compare our findings with historical data and literature references, describe uncertainties, and discuss statistical methods used in project development to define appropriate project sizes and sensitivities.

Background

The typical levelized cost of electricity from fossil plants (coal-fired, gas turbine, diesel etc.) is a strong function of the cost of fuel. In contrast, the generally higher capital costs per kW for a geothermal project are essentially buying the 'fuel supply' up front, by drilling wells and developing the reservoir. It should be noted that depending on the specific geothermal reservoir there may be on-going costs for added makeup production wells and well maintenance. In areas with good potential, geothermal power can displace costly fossil fuel generation, reduce emissions, and operate reliably for decades.

Geothermal plants also have the advantage that they are less sensitive to diurnal or annual variations in the 'fuel' supply, unlike other renewables such as solar, wind, or hydropower. Geothermal plants as a result usually operate with very high capacity factors (>90%), and thus provide valuable baseload power to add to grid stability.

There are three major components to a geothermal project: the reservoir and associated wells, the gathering system that conveys fluid from the wells to the plant, and the power plant. In this section we describe the basic characteristics of each, before proceeding to the estimates of annual energy output from the power plant.

Reservoir Characteristics

Permeability, Enthalpy, and Temperature

There are two key aspects to a geothermal reservoir: the permeability and temperature. The permeability is related to the amount of fluid that can be produced from a well; if the rock is impermeable, little flow can be produced. The higher the temperature of the fluid in the reservoir, the more energy that can be produced from each kg of geofluid. Geothermal explorers often speak in terms of temperature gradients (˚C/km); if gradients are high, higher temperature fluids may be found at shallower and more economical well depths.

Figure 1 is a general classification of geothermal resources as a function of these two parameters. Reservoirs with low permeability produce little fluid unless stimulated, and the goal of research into Enhanced Geothermal Systems (EGS) is to engineer improvements to the permeability of these reservoirs. Hydrothermal resources possess sufficient porosity to produce fluids, of either lower or higher temperature. 'High Grade' resources can produce steam to drive a steam turbine; these are often called 'flash' resources as the geofluid flashes to a mixture of steam and water. The 'Low Grade' resources, unable to generate large amounts of steam, can still generate power with binary technology, albeit at a lower thermal efficiency.

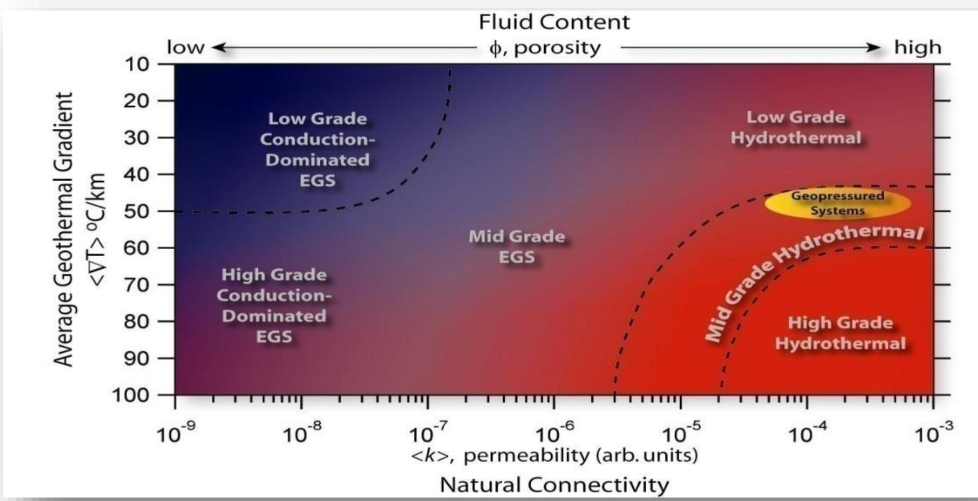

Figure 1 - The continuum of geothermal resources as a function of average temperature gradient and natural connectivity (Thorsteinsson et al, 2008).

Solids

Due to the high costs of geothermal well drilling, developers are generally motivated to extract as much energy as possible from the geofluid. However, concentrating solids by flashing, or reducing the temperature of the geofluid, can tend to precipitate solids. These solids can scale on equipment, piping, and injection wells. The primary culprit in injection scaling is silica, and a more complete treatment of the mechanics of equilibrium and precipitation can be found in DiPippo (2008).

In some locations, complicated solid separation equipment or chemical treatment of the geofluid are used. For the purposes of this study, we will assume that modest lower temperature limits on the reinjection temperatures will be sufficient for estimation purposes.

Gathering Systems

Geofluid from the production wells is conveyed to the power plant, and (in the case of a flash plant) separated into the steam and liquid phases in a separation station. The size of the gathering system depends on the well spacing and plant size, but can extend over many square kilometers. Spent brine from the plant is usually pumped or gravity flowed into injection wells, where the water can return to the reservoir and be slowly reheated. Injection of brine and/or condensate is a key factor in extending the life of the geothermal reservoir. Careful planning of an injection strategy provides pressure support to the system and minimizes the overall mass extraction.

Power Plant Cycle Types

Three types of power plant designs are discussed below: binary (air cooled), binary (water cooled) and flash plants. For our analysis, only air cooled binary and water cooled flash plants were analyzed to estimate achievable annual energy output, since water cooled binary plants or air cooled flash plants are far less common.

Binary (Air Cooled)

Binary cycles are used throughout the world to exploit lower temperature (less than ~150°C) geothermal resources. They may also be used for higher temperature resources, although economics generally lead developers in that case to flash plants. The geofluid is passed through a heat exchanger (vaporizer, or evaporator) where it heats and boils a more volatile working fluid that has a lower boiling point than the geofluid. Typical working fluids include hydrocarbons (butane, pentane), refrigerants (R134a, R254fa) and other mixtures. The choice of working fluid is dependent on the geofluid temperature, working fluid cost, supplier preference, and overall compatibility with the design conditions at a particular geothermal power plant site.

Once the working fluid is vaporized, it is expanded through a working fluid turbine to generate power. The geofluid is then condensed in either an air-cooled condenser or water-cooled condenser, and pumped back to the vaporizer. We will discuss water-cooled binary plants in the next section.

A majority of binary power plants utilize air-cooled condensers due to the lack of suitable quality makeup water available at most binary plant locations. In an air cooled condenser (ACC), the working fluid is cooled by air drawn across tubes in a heat exchanger. Air is drawn through the ACC using fans. When ambient temperature rises, the ACC pressure (and turbine backpressure) rises, reducing plant output. Summer output for an air-cooled binary unit can be significantly less than winter output, and this will be discussed later when capacity factors are presented. Binary plants do have the advantage of returning nearly 100% of the geofluid to the reservoir, thus potentially reducing the overall decline of the resource. Figure 2 shows the ACC at a binary plant in Nevada.

Figure 2 - Air-cooled condensers, binary power plant.

Once the working fluid has cooled and condensed, it is ready to be pumped back through the preheaters and vaporizers. The working fluid is never exposed to the atmosphere in this closed loop Rankine cycle, thus making the process fairly clean and safe. Figure 3 shows an overall schematic of a typical binary cycle.

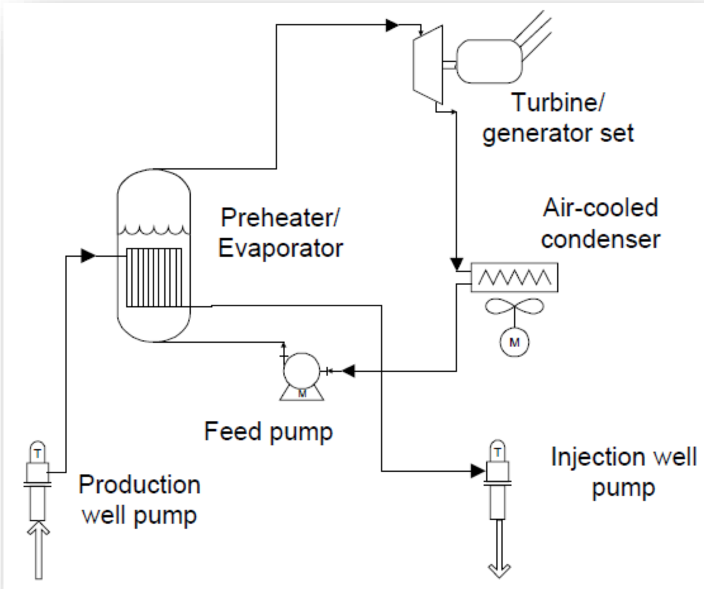

Figure 3 - Example binary cycle geothermal power plant cycle (NREL, 2010).

Binary (Water Cooled)

Where makeup water of suitable quality is readily available, water cooling can be used. In a water-cooled binary unit, the basic plant design is the same, but the air cooled condenser is replaced with a water cooled condenser. Cooling water is circulated from a wet cooling tower to the water cooled condenser by circulating pumps. The water cooled binary unit has the advantage of its output being less sensitive to ambient dry bulb temperature variations. Generally, the geofluid cannot be used as cooling tower makeup water, due to its solids concentration, and thus the majority of binary plants are air cooled. The evaporation rate for a water-cooled binary plant could be around 6 tons/hr-MW. Due to these considerations, we will focus on the air-cooled binary as the characteristic plant choice for low temperature resources.

Flash (Water Cooled)

In some cases, the fluid that comes out of the well is water hot enough on its own – roughly at 150 °C or above – to produce steam at a reasonable pressure. In these cases, the resource fluid itself can be the working fluid in a Rankine Cycle power plant. In the most exceptional cases – such as at the Geysers, Lardarello, and Darajat plants – the fluid that comes out of the wells is power-plant-quality steam that can be used directly by the turbine. This highly prized species of geothermal plant is called a “dry steam plant.”

More often, the resource produces a liquid or two-phase geofluid mixture, and as the pressure is reduced, more of the geofluid 'flashes' to produce steam. This steam may also contain some non-condensable gases. A single flash plant diagram is shown in Figure 4.

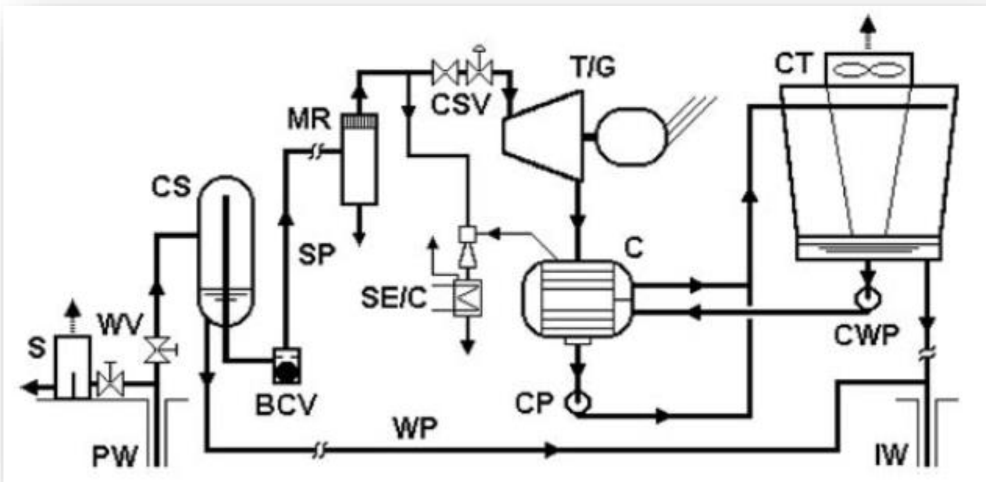

Figure 4 - Single flash process flow diagram (DiPippo, 2008).

In the simplest flash configuration, two-phase fluid flows from a production well (PW) and a steam cyclone separator (CS) produces steam that is fed to the turbine (T/G), and liquid that is injected back into the reservoir via an injection well (IW). A typical single flash plant may flash 10-30% of the incoming geofluid to steam. The exhaust from the steam turbine is condensed in the condenser (C). Cooling water to the condenser is generally supplied from a cooling tower (CT). Flash plants have an advantage in that the steam they condense can be used as makeup water for the cooling tower, thus they can be wet cooled without an external source of makeup water. Similar to binary or fossil-fired units, water cooled flash plants are not as sensitive to output variations as a function of the ambient temperature compared to air cooled units. Water cooled flash plants do lose a portion of the geofluid through the cooling tower evaporation process. Approximately 70-80% of the produced steam can be lost through evaporation. This may lead to a decline in water to be reinjected.

Phases of a Geothermal Project

Regardless of the technology employed for a geothermal project, the execution phases and decision points are similar. Table 1 describes these steps. In the initial phases of a project, little is known about the reservoir. The identification phases attempt to define the extent and quality of the reservoir, and may use exploration methods such as (DiPippo, 2008):

1. Literature surveys
2. Airborne surveys
3. Geologica studies
4. Hydrologic studies
5. Geochemical surveys
6. Geophysical surveys

If the reservoir appears promising, exploratory drilling is typically carried out, which attempts to better characterize the nature of the geofluid and the potential productivity of wells. The methodology presented in this study for the determination of energy output from a plant can be used to estimate output using a small number of major independent variables that may be estimated at this stage: anticipated geofluid temperature, flowrate, and ambient conditions. An average temperature is assumed for this methodology, characteristic of an average produced temperature (or equivalent enthalpy) of all production wells for the plant. Production well flowrates (kg/s) may be estimated from similar projects, or resource consultant experience, but in truth flowrates cannot be known until the wells have been drilled and tested. Another perspective would be to say the total flowrate required for a plant of a certain capacity can be known precisely (if within reasonable limits for the reservoir's capacity); what is unknown is the number of wells that must be drilled in order to achieve that flowrate. The uncertainty of the output predictions would be larger at this stage since the resource conditions and plant configuration is not yet finalized; this uncertainty in output might be around 20-30%. As more wells are drilled and confidence in the characterization of the reservoir improves, the output predictions would be refined.

Table 1 – Phases and decision points for typical geothermal projects (Deloitte, 2008)

Stage	Question Answered
Pre-Identification Analysis 1	How does geothermal compare with other generation options; nuclear, coal, natural gas, wind, solar, etc.?
Identification Decision 2	Does initial data research and site evaluation support further time and development? What business model serves this investment and will the project meet rate of return requirements?
Exploration Decision 3	Did the exploration drilling produce a positive resource assessment and feasibility?
Drilling Decision 4	Is the confirmation well successful and able to prove production capacity?
Production Decision 5	Do capacity, financial investment, permitting, time delays and external factors outside project control merit production?

If the exploratory drilling is promising, a decision must be made on more extensive production well drilling. Drilling usually must be funded with equity and is not without risk. Typically feasibility studies would be carried out at this stage to determine if, with the anticipated investment in wells and plant equipment, a specific power plant design can deliver an acceptable return to the investors. At this stage more detailed measurements of actual geofluid composition, enthalpy, and flow must be available. Feasibility studies typically consider several cycle types, perform an economic optimization, and assess output using a model that considers many more variables, including actual equipment performance estimates from vendor quotes, flash pressures optimized considering the actual well production curves, and limitations on reinjection temperature based on resource chemistry. As an example, for a prefeasibility study for a project in Turkey, we provided various output estimates for different plant types that varied by less than 10%. However, capital costs often have a greater impact on plant selection, and these varied by around 25%. It is difficult to determine plant costs to an accuracy of better than 20-30% without doing a significant amount of design and obtaining at least major equipment quotations. Obtaining output estimates in this stage of the project is a process that may take weeks or months.

During this exploration and confirmation phases, numerical reservoir simulations are generally developed, incorporating predictions for changes in temperature, pressure, or flowrates over time, and wellbore losses. The model is updated as more data are available, with the most valuable being actual production well long term flow testing and enthalpy measurements, among others.

Long term flow tests (weeks or months) may be preferred to better characterize wells, but permitting, water disposal, or other limitations may mean only short term tests (hours or days) are possible in the initial stages of the power plant definition. It often is preferred to carry out flow tests several months after drilling is complete, to allow the well to heat back up if it has cooled from the drilling operations. Measurement of single phase, low temperature flows are fairly straightforward, but flow and enthalpy measurements for more energetic resources often require flashing the produced geofluid in a separator and separately measuring the steam and water flows; this requires more significant investment in surface equipment, and the emissions of steam and non-condensable gases during the test. With updated data from long term tests, and using this reservoir model, the plant performance may be estimated over many years of future production.

If the results of the feasibility study and confirmation drilling are promising, then a decision can be made to proceed with the full construction of the project. The detailed design of a geothermal power plant and the calculations to determine the guaranteed net output, that might serve for a contractual target and regulatory acceptance, requires many months of effort, and relies on hundreds of items of data, many of which are only available after purchase orders for major equipment are placed and much of the detailed design is complete. These include values such as final design of the gathering and injection system, certified motor data sheets, lighting loads, HVAC loads, miscellaneous pump operating times, and many other factors. Obtaining output estimates in this stage of the project is a process that takes several years, and these often include margins, depending on the commercial penalties that may apply for not meeting performance.

After the plant is constructed and operated, variations in resource temperature, ambient conditions, and the fact that design margins (excess heat exchanger areas for future fouling, excess pump capacity to account for future wear, etc) may be present in equipment, result in the actual output inevitably varying from the design point. It is not uncommon in our experience for the actual plant to perhaps outperform the design performance by some 1-2%, or, if there are problems with the resource, output can be significantly less than design.

The plant performance at the beginning of commercial operations is generally validated with a performance test, the procedure for which is developed considering off-design performance curves in case resource conditions, reservoir conditions, etc during the test period are different than the design values. Tracking of capacity factor (or availability) over time is also generally done by the plant operator after commercial acceptance, and may be an important issue related to warranties with the equipment or plant suppliers.

Over the life of the plant, the resource may change as fluid is extracted, and output may decline. The reservoir model can be updated for operating plants using actual flow and temperature (or enthalpy) data from the wells, collected continuously or periodically. Generally, declines in well production are managed by drilling additional makeup wells. Changes in geofluid chemistry or enthalpy sometimes make modifications to plant equipment desirable after many years of operation.

In summary, the major objective of this study is to present a methodology to estimate the firm energy output of a power plant, based on a manageable set of data that likely should be available to developers or agencies at the initial stages of a project. We anticipate that in later phases, different and far more detailed calculations, and performance tests during actual plant operation, would refine these output estimates and gradually narrow the uncertainty bands.

Methodology

Design Point Output

The first step in assessing the achievable annual energy output of a geothermal plant is to characterize the nature of the fuel source, or in this case, the reservoir temperature (enthalpy), geofluid chemistry, and flows. From that, we will proceed to examinations of how the different types of plants can convert this geofluid to energy output. Initially, we will consider the design point output at annual average conditions, and then progress to consider how this output may vary over the course of the year in order to determine the annual energy output (Off-design point operation). We will progress in this evaluation from the lower temperature resources (90 to 170 ^{o}C), where binary plants are more often used, to higher temperature resources (140 to 300 ^{o}C), where flash plants are more often used.

Resource and Environmental Design Criteria

Since this is a general methodology intended to apply to a wide range of resources, we will express net plant output and energy production in specific terms, i.e. kW or MWh per kg/s of total geofluid flow from the production wells. In this way, the results will be scalable to projects of different sizes. We assume in doing this that plant efficiency is not a strong function of plant size, which is a reasonable assumption.

The resource temperature (or produced geofluid enthalpy) will also vary between projects, so a range of estimates across the aforementioned temperature bands are provided. Increasing resource temperature helps boost plant output in two ways: the extractable energy is greater at higher temperatures, and the efficiency with which heat energy can be converted to electrical power is also higher. Thus net plant specific output is a strong function of resource temperature.

The ambient temperatures around the plant affect the size, cost, and performance of the cooling systems, and influence net output. We provide output estimates for a range of dry (for air-cooled units) and wet bulb (for water-cooled units) temperatures. Understand that simply by investing in larger and larger ACCs and cooling towers, one can increase output, but our models assume that the designers would choose a reasonable compromise between initial capital cost and plant output. We will present air-cooled binary output curves for dry bulb temperatures in the range of 15 to 25 °C, and flash plant output curves for wet bulb temperatures in the range of 10 to 20 °C.

Given that ambient temperature is an important factor in the plant design and performance, it is advisable that developers begin harvesting this data early in the process. Since the reservoir exploration and drilling is a process that may take many years, in parallel installing a weather station at the site, or verifying that there is a reliable source of historical data nearby (existing weather stations within several kilometers, perhaps) is advisable during this period. This is a low cost effort, but often overlooked, and a long data interval is preferred to make informed decisions. Ideally dry bulb, wet bulb (or relative humidity), and wind direction should be monitored.

The chemistry of the geofluid influences the lower temperature range of the geofluid that is to be injected. This is more of a limitation for binary units, rather than the single flash units under consideration, since the single flash separator operates at a relatively high temperature. We will use a constant injection temperature limit of 75 °C for the binary units; actual conditions may differ at an individual site with more or less dissolved solids. The flash process does lead to concentration of scaling materials; therefore the injection temperature at each plant site needs to be evaluated on a case by case basis.

The ambient temperature and the operating conditions of the condenser also affect the minimum injection temperature, as it is not possible to cool the brine further than below the temperature of the condensed working fluid, even if in theory the limit on precipitation of solids is lower. Operation of binary units at very low resource temperatures (<100 °C) thus may only be economic in colder climates, where the injection temperature can be lowered such that more energy can be extracted; this was the case at plants such as Husavik in Iceland and Chena Hot Springs in Alaska.

Lower Temperature Resources – Binary Plant Evaluation

To evaluate plant output at the design point conditions, we constructed a model using typical equipment sizing parameters, equipment efficiencies, and configurations for the binary cycle. These parameters include:

- Heat exchanger minimum temperature differences between the hot and cold fluid streams,

- Pressure drops in piping and equipment,
- Turbine, gearbox, and generator efficiencies,
- Heat exchanger temperature differences, and
- Pump efficiencies.

While it is possible to adjust these parameters to get more or less output to some degree, we have chosen reasonable industry standards that will result in a plant of both reasonable efficiency and capital cost.

Since different binary package suppliers use different working fluids, we compiled estimated net specific power outputs across the given temperature ranges for three commonly used working fluids: isobutane, isopentane, and the refrigerant R-245fa. Our performance estimating tool is constructed in Excel and relies on fluid property database functions from REFPROP. This software is provided by the U.S. National Institute of Standards (NIST) and provides reliable property data for a wide range of substances, including water.

In order to simplify the analysis, certain parameters were set so that the only variables we input were the brine inlet temperature and the air inlet temperature. Figure 5 shows a sample of the binary model output operating at 120 °C geofluid inlet temperature and 20 °C dry bulb temperature. For this case the working fluid is isobutane. Gross power output is 9,043 kW and total plant parasitic power to drive various pumps and fans is 2,173 kW.

Note that this power consumption value does not include any gathering system loads, such as production or injection well pumps; since the nature of the resource is not known, these cannot be determined at this time in this study. The variation in production or injection well pump loads is so great that it would be unrealistic to include them in the formulas in this study. Some production wells are artesian, flowing without requiring pumping. Some may require production well pumps, with power consumption of up to around 0.5 MW per production well. Without knowing the specific characteristics of the resource and the wells drilled, it would cloud the analysis to include it in the base case estimates.

Similarly for injection wells, there can be great variations in the injection pressure, and pumping power, required. Some injection wells operate under a vacuum, with no pumping power required. Some operate at pressures that may be as high as 50-60 bar. The injection pumps might consume somewhere between 0-5% of net power, thus including an allowance would cloud the analysis. Developers should consider modifying the net output estimates included in this study to incorporate production or injection pumps, once they have better information from their resource consultants.

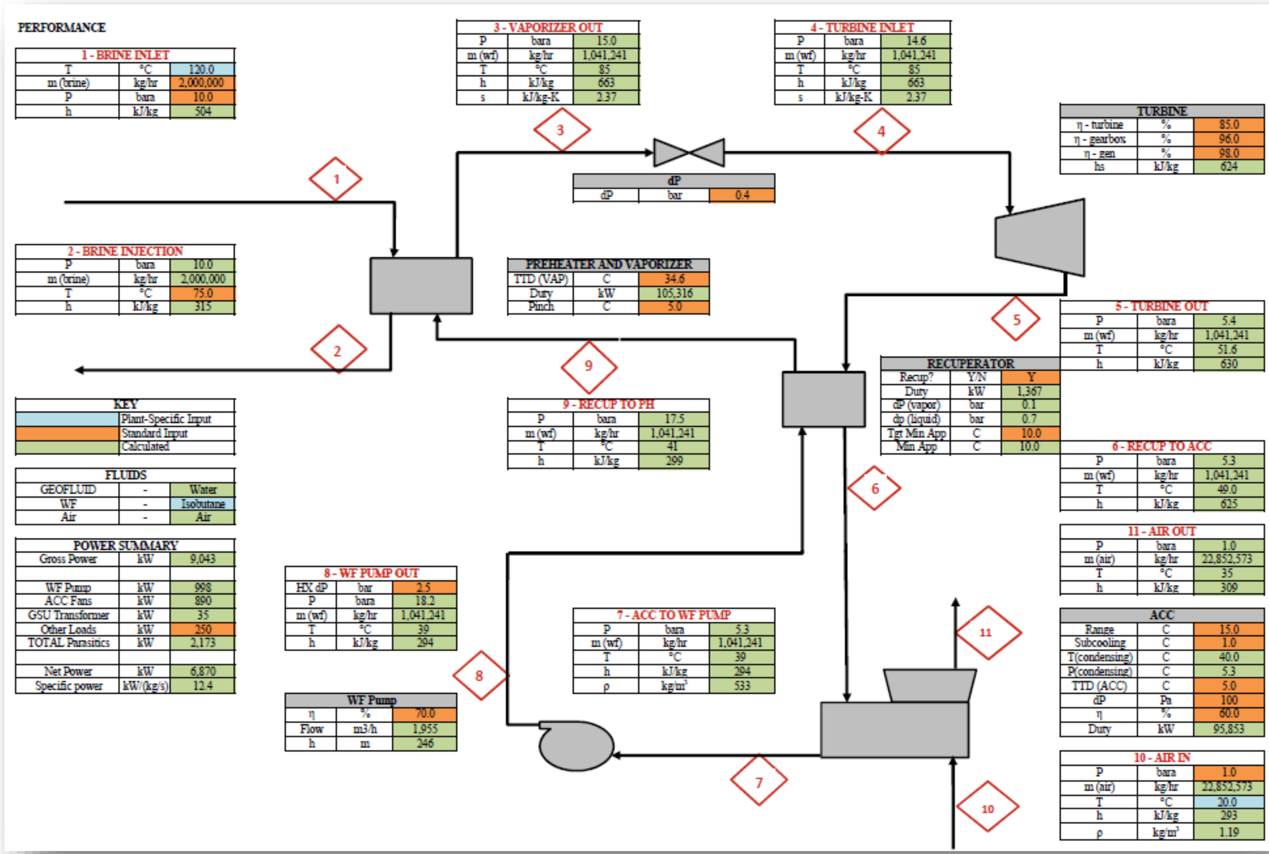

Figure 5 - Typical binary (air-cooled) model screenshot.

The geofluid releases energy in the vaporizer and preheater; with the minimum temperature approach adjusted to a reasonable value to give a balance between efficiency and economy. The vaporized working fluid passes through a turbine and is condensed in the ACC. The feed pump returns the working fluid to the preheater. The major parasitic loads are the feed pump, ACC fans, transformer losses, and an allowance for miscellaneous other loads.

The net power is divided by the total geofluid flowrate to obtain a net plant specific power output of 12.4 kW/ (kg/s) at the design point for the conditions of Figure 5. The net plant specific power consumption is plotted as a function of resource temperature.

Variations in working fluid

As stated earlier, for different resources different working fluids may be able to generate different outputs. Thus, we generated curves for isobutane, isopentane, and R-245fa. The comparison of results can be seen in Figure 6.

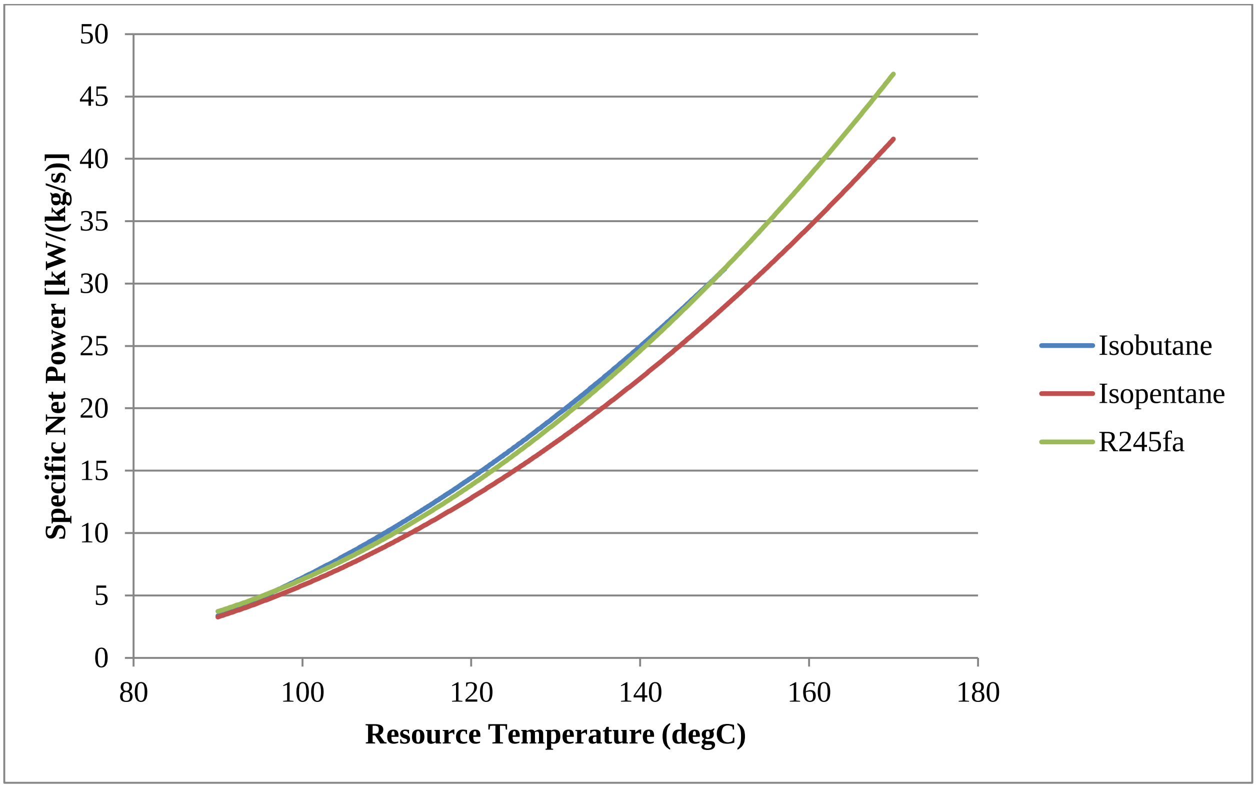

Figure 6 - Net air-cooled binary plant specific output as a function of resource temperature at 15 °C dry bulb temperature.

The working fluid that generates the highest net plant specific power is not necessarily the preferred option, as the economics of cycles based on different working fluids may also vary. There may also be non-economic considerations such as the desire by the owner to standardize on a certain working fluid for multiple plants, flammability concerns, or other factors. Overall the power generation by the different working fluids can be seen to be comparable across most of the temperature ranges. Therefore, the figures in this report are based on an average specific net power output for the three working fluids isobutane, isopentane and R245fa.

Figure 7 shows the variation of power for a binary cycle using an average of the three working fluids over a range of geofluid temperatures. It can be seen that there is a strong correlation between geofluid temperature and output; as the temperature rises, both the quantity of extractable energy increases, and also the conversion efficiency from thermal to electrical power.

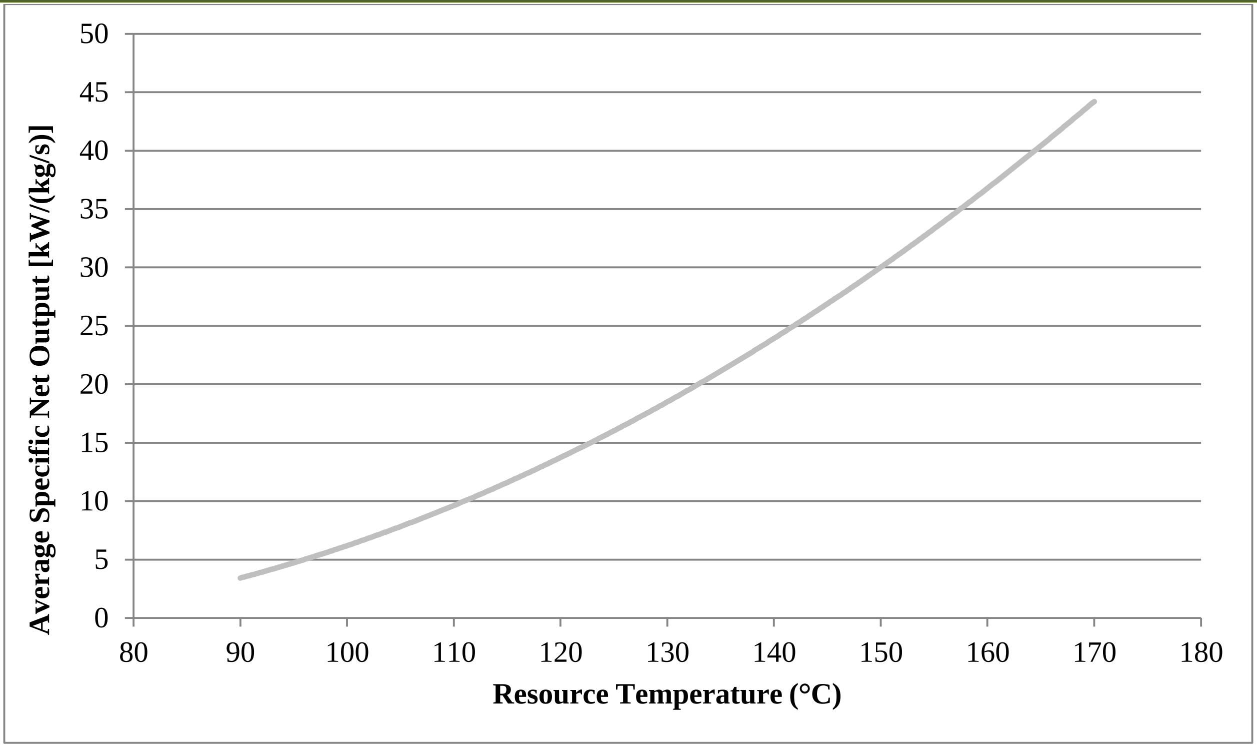

Figure 7 - Net air-cooled binary plant specific output as a function of resource temperature at 15 °C DBT.

Variations in ambient temperature

Ambient temperature has a profound impact on the performance and economics of the plant. Hance (2005) provided a curve of average output of a nominal 20 MW binary air-cooled plant as it varies month to month, shown in Figure 8. In a tropical location where annual average temperatures are high, the plant cost per installed kW is higher and net power output lower, than if it were in a colder location.

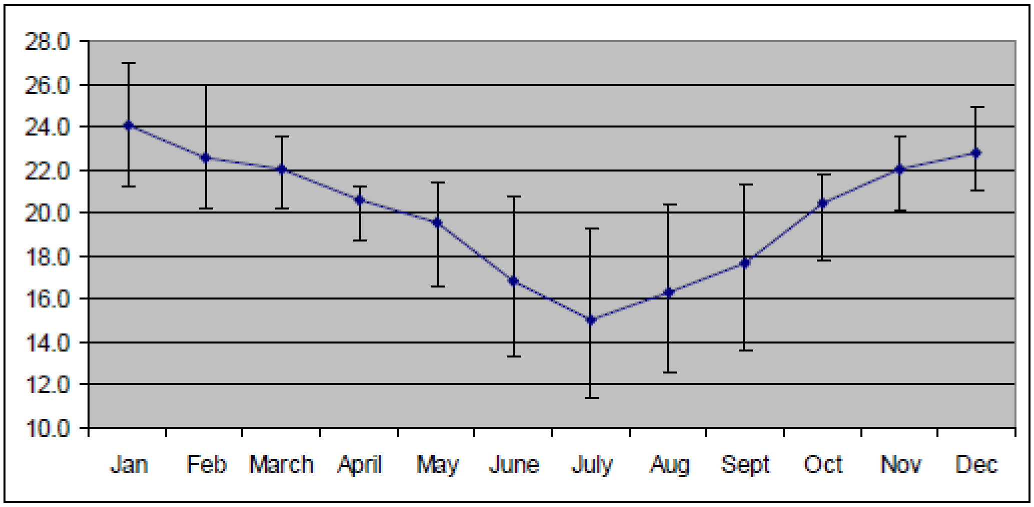

Figure 8 – Estimated power output variation of a 20 MW air-cooled binary plant (Hance 2005).

We show the effect of the design point ambient temperature on plant specific power output in Figure 9. At lower resource temperatures, the cooling systems must reject more heat, and high ambient temperatures have a more pronounced impact both on cost and performance.

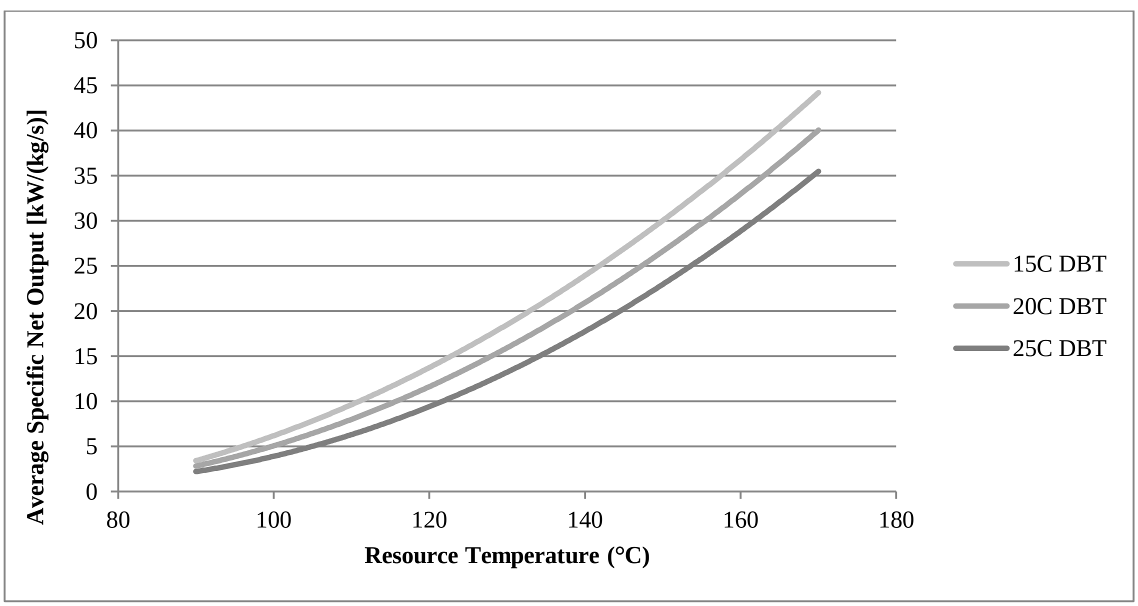

Figure 9 - Net air-cooled binary plant specific output as a function of resource temperature at Various DBT

Design point power predictions

We combine the results of the explorations of resource temperature, working fluid, and ambient temperature to develop an overall curve of net plant specific output. An equation is proposed to fit these points for an average of the three working fluids (isobutane, isopentane and R245fa):

$$z = (3.382 \ x \ 10^{-3})x^2 - (2.481 \ x \ 10^{-3})y^2 - (9.349 \ x \ 10^{-3})xy - 0.229x + 0.800y - 2.167 \quad \text{(Eqn 1)}$$

Where z is the specific net output [kW/ (kg/s)], x is the resource temperature (°C) and y is the dry bulb temperature (°C).

The model output can be compared to historical data from operating plants. Table 2 shows data from selected binary plants around the world in order to check the agreement between model output and actual plant data, where available in the public domain.

Table 2 – Historical plant data, adapted from DiPippo (2004).

Plant	Approximate Reservoir Temperature (°C)	Assumed Design Dry Bulb Temperature (°C)	Actual Plant Net Plant Specific Output (kW/(kg/s))
Brady	107.8	16.8	8.9
Nigorikawa	140	13	20
Stillwater	155	13	37
Heber SIGC	165	15	54.5
Binary Plant 1	135	14	22.4
Binary Plant 2	96	2	8.1
Binary Plant 3	157	74	40.2

As stated, the complexity of the cycle, investments in cycle equipment, and variations in injection temperature can result in performance that is less or more than the model predictions. Figure 10 shows the actual plant performance overlaid with predicted performance of binary plants at a constant 15 °C dry bulb temperature, including some confidential and unnamed plants. Overall the agreement is fairly good, but there can be deviations. The Heber SIGC plant, for example, is a dual pressure level cycle, which is more complex but which offers some advantages over the single pressure cycle used in the binary model. As a result, one might expect that actual plant performance may differ from the model predictions within a band of some 10-20%.

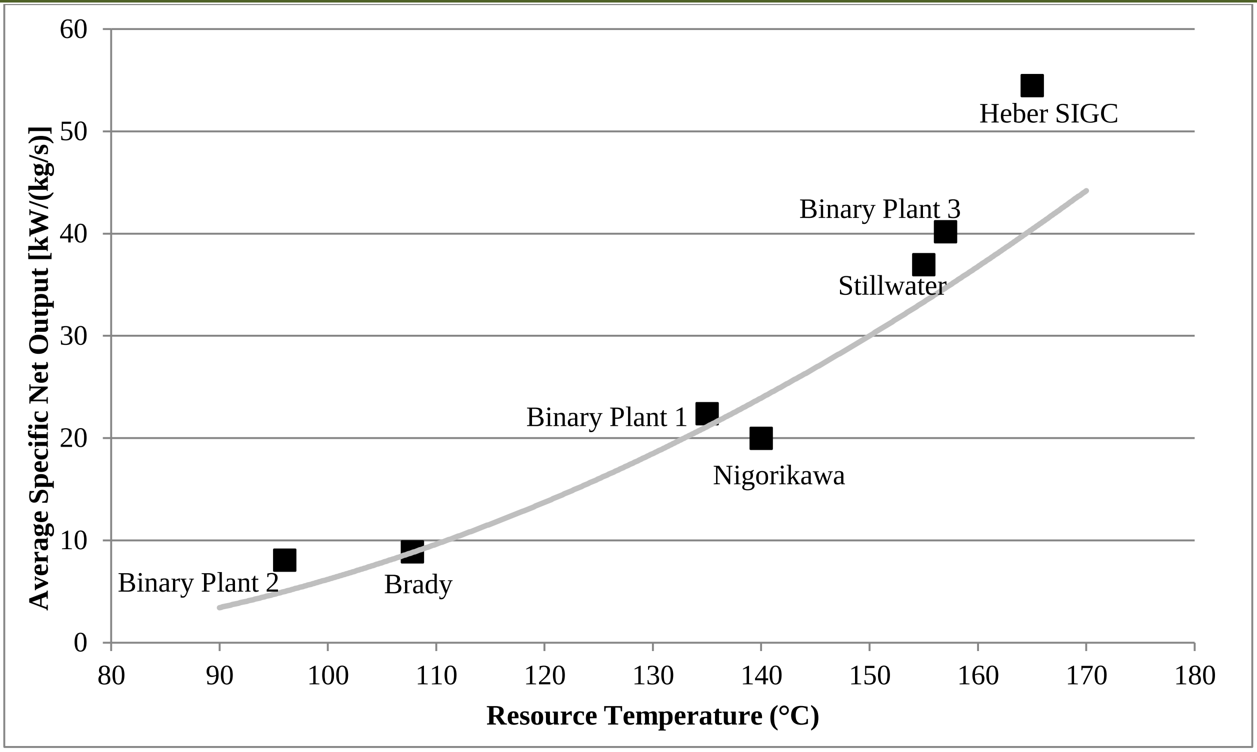

Figure 10 - Comparison of binary plant model predictions and historical plant output.

Higher Temperature Resource – Flash Plant Evaluation

As resource temperatures and enthalpies rise, flash plants become an increasingly economical option over binary plants, although they can be competitive with one another in an overlapping temperature range around 150-190 °C. Bombarda and Macchi (2000) presented an economical and technical performance comparison that covers these aspects in more detail. For the purposes of this study, we looked at resource temperatures above 140 °C.

Single flash plants generate additional steam from the brine of the first flash and are the most common flash configuration. However, double and triple flash plants exist, as well. A double flash plant might add 10% in output, but incur additional capital costs for the gathering system, separators, and turbine. The lower temperature of the lower pressure flash can also lead to scaling concerns in the low pressure brine. Since the resource chemistry is undefined, and since single flash is a common choice for developers, the single flash cycle was chosen for the base case flash model.

As for the binary cycle, we constructed a model using typical equipment sizing parameters, equipment efficiencies, and configurations for the flash cycle. These parameters, for which reasonable industry standards have been applied, include:

- Separator (flash) pressure,
- Pressure drops in piping and equipment,
- Turbine and generator efficiencies,
- Pump and fan efficiencies,
- Condenser sub-cooling, and
- Cooling tower range and approach.

The selection of the optimum separator pressure is relatively complex for a real project, as it depends on the enthalpy of the resource, deliverability of the wells, and the scaling potential of the geofluid. For this study, we use a principle described by DiPippo (2008), which is that the theoretical optimum single flash temperature is midway between the resource temperature and the condenser temperature. For the purposes of the separator temperature estimation, we assume a condenser temperature of 50 °C; this value is an economic optimization that would be developed during detailed thermodynamic design. This equal temperature split principle provides a reasonable point for power output estimation; if actual flash pressures are slightly different, they do not affect the power output estimate markedly.

Figure 11 shows sample model output from a base case flash plant, operating at 270 °C geofluid inlet temperature and 15 °C wet bulb temperature. Gross power output is 34,670 kW and total plant parasitic power to drive various pumps and fans is 2,494 kW. Note that this power consumption value does not include any gathering system loads, such as production or injection well pumps; since the nature of the resource is not known, these cannot be determined at this time.

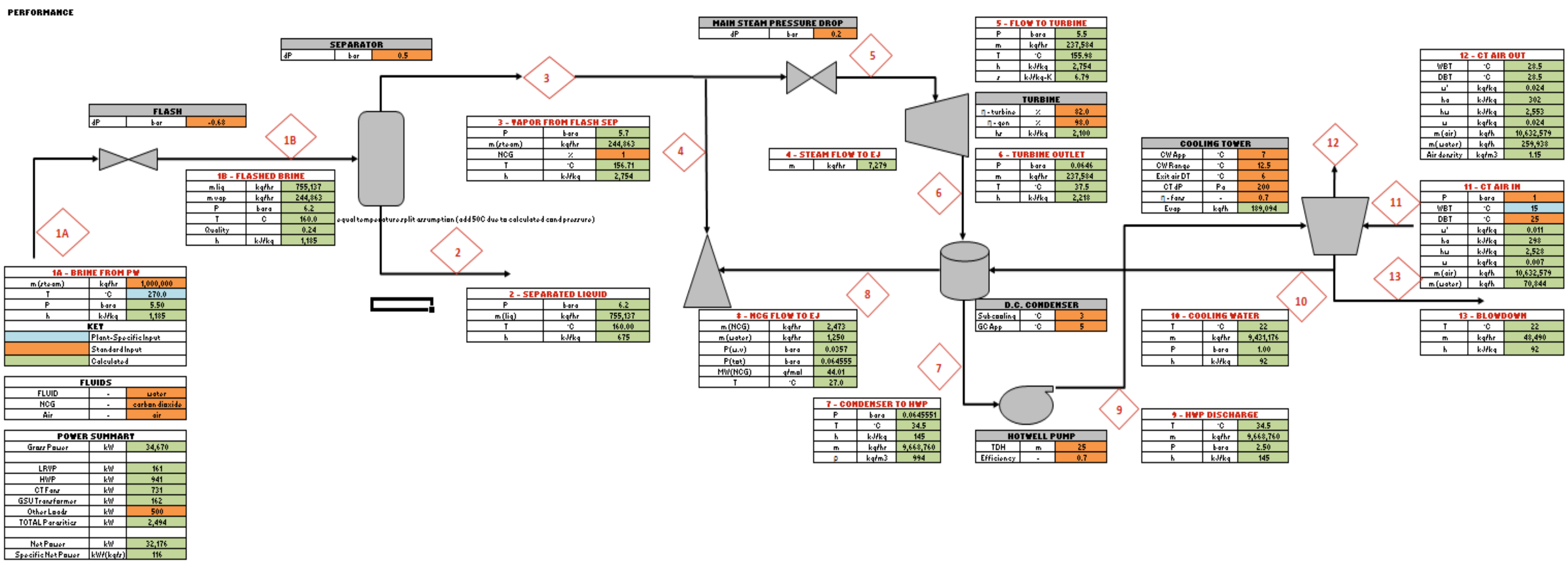

Figure 11 - Sample output from the flash plant model.

Geofluid from the resource enters the separator and is flashed at the separator pressure. A pressure drop is assigned to the steam flowing from the separator to the turbine. The steam expands through the turbine to the lower pressure of the condenser. The direct contact condenser is cooled by water from the cooling tower, drawn into the condenser by its vacuum. The combination of condensed steam and cooling water is pumped by hotwell pumps back to the cooling tower. Some non-condensable gases (NCG) which would normally be present in geothermal steam must be removed from the condenser to maintain vacuum; these are drawn out by the gas removal system. In this case, a hybrid two stage ejector/liquid ring vacuum pump (LRVP) arrangement is proposed, which is a relatively efficient arrangement. The major consumers of parasitic power in the plant are the hotwell pumps, cooling tower fans, LRVP, and main transformer losses. An allowance has been added for other minor loads such as HVAC, lighting, miscellaneous pumps, etc.

The total parasitic loads are subtracted from the gross steam turbine generator output to find the net power, and this is divided by the total inlet geofluid flow to determine the net plant specific power. In the example shown above, the specific net power is 116 kW/ (kg/s of total geofluid flow into the flash plant). Figure 12 shows flash plant power variation as a function of geofluid equivalent resource temperature.

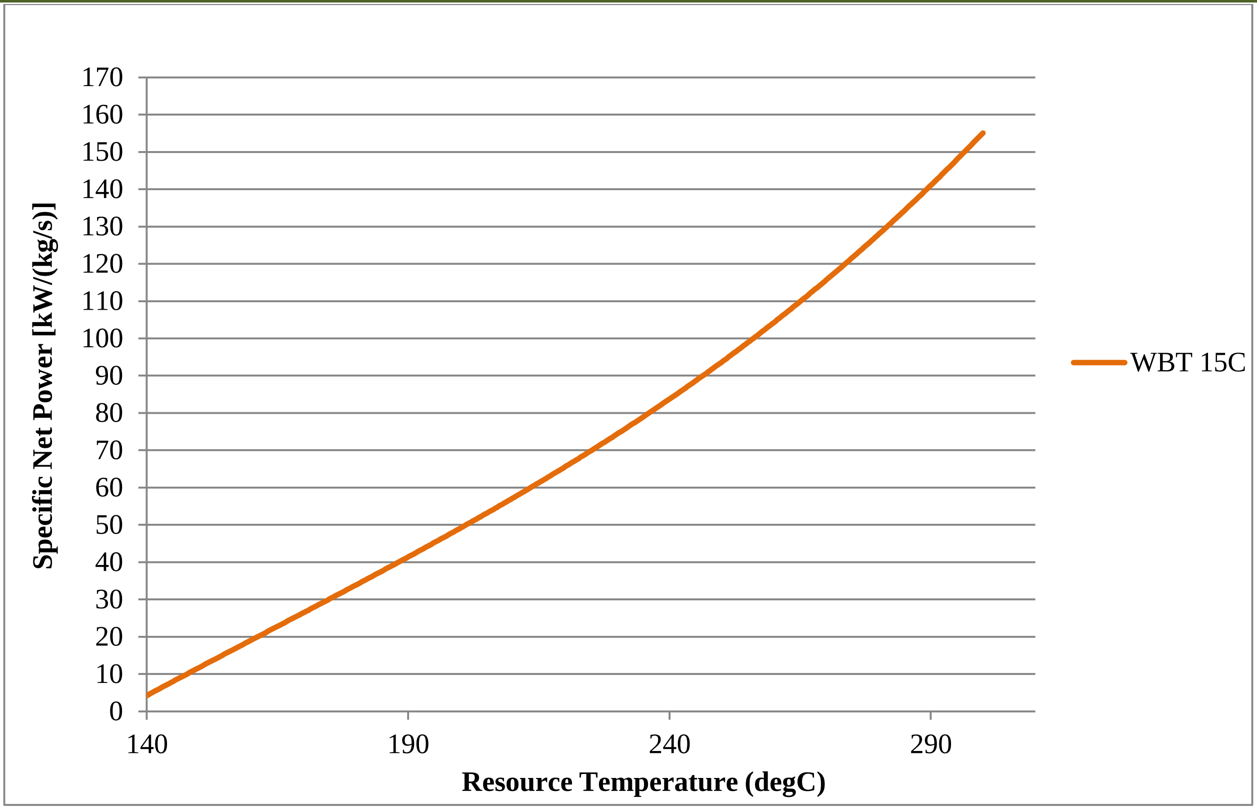

Figure 12 - Predicted flash plant output as a function of resource temperature and WBT at 15°C.

Variations in ambient temperature/WBT design point selection

The wet bulb temperature has a large impact on the sizing of the cooling tower and condenser. Lower wet bulb temperatures allow the cooling tower to produce colder water, which lowers the pressure in the condenser, which allows the turbine to generate more work. At a fixed wet bulb temperature, a larger cooling tower can also deliver lower cooling water temperature and higher performance. Plant cost is thus sensitive to these environmental and performance considerations. Power plant developers take pains during detailed design to optimize the condenser pressure and associated optimum turbine blade length; a fuller discussion of this methodology can be found in Saito (2010).

Figure 13 shows the effect of the design point wet bulb temperature on plant specific power output. At lower reservoir temperatures, the cooling systems must reject more heat and high wet bulb temperatures have a more pronounced impact both on cost and performance.

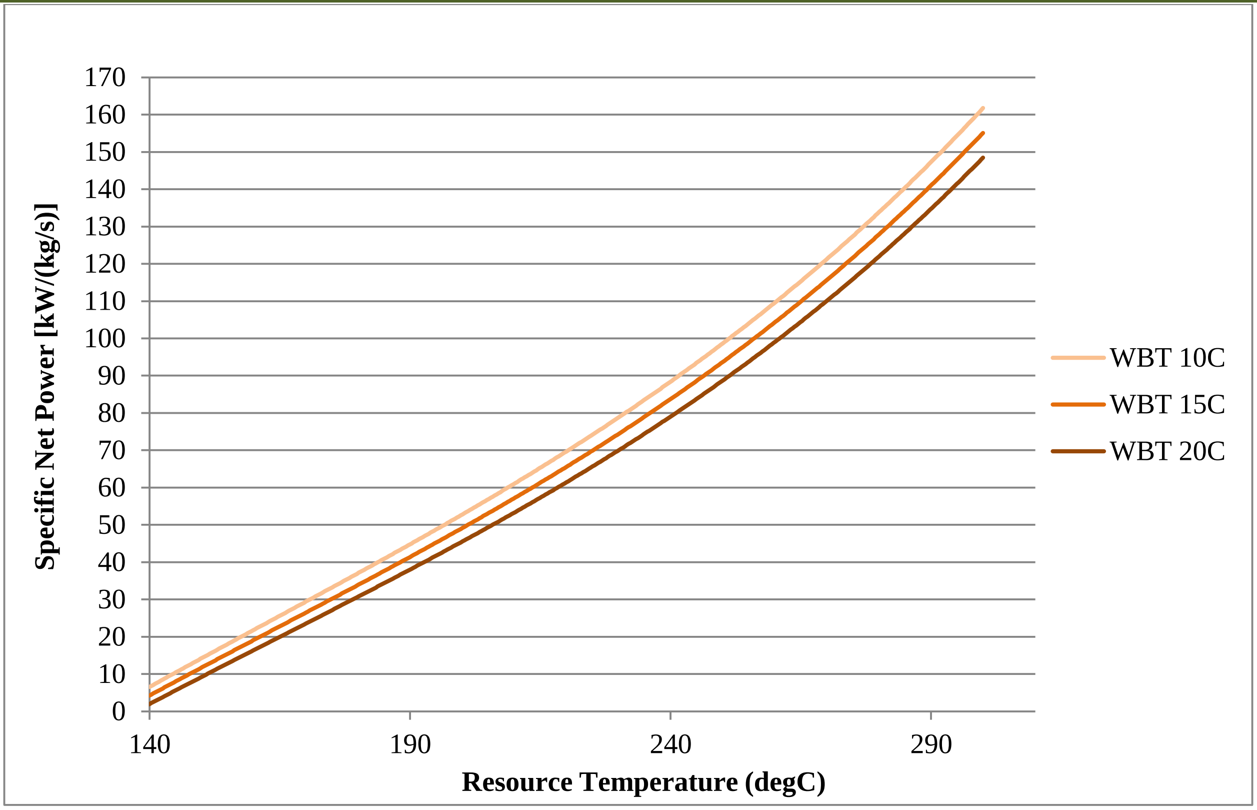

Figure 13 – Net flash plant specific output as a function of resource temperature and various WBT.

For the flash plant, the best fit curves to the data were third order. In order to simplify the equations, we split the plots into three resource temperature ranges: 140-180 C, 180-240 C and 240-300 C. For each of these temperature ranges, we developed models of operation at three different wet bulb temperatures. A surface was mapped showing output as a function of both reservoir and wet bulb temperatures, and curves fit to a two parameter equation:

<u>140 to ≤ 180°C</u>

$$z = (-2.825 \, x \, 10^{-3})x^2 - (8.524 \, x \, 10^{-4})y^2 - (4.057 \, x \, 10^{-3})xy + 1.716x + 0.132y - 174.429$$ **(Eqn 2)**

<u>>180 to ≤ 240°C</u>

$$z = (2.132 \, x \, 10^{-3})x^2 - (2.146 \, x \, 10^{-4})y^2 - (5.089 \, x \, 10^{-3})xy + (1.109 \, x \, 10^{-2})x + 0.295y - 27.835$$ **(Eqn 3)**

<u>> 240 to 300°C</u>

$$z = (2.530 \, x \, 10^{-3})x^2 + (3.262 \, x \, 10^{-3})y^2 - (6.498 \, x \, 10^{-3})xy - (8.396 \, x \, 10^{-2})x + 0.532y - 27.822$$ **(Eqn 4)**

Where z is the specific net output [kW/(kg/s)], x is the resource temperature (°C) and y is the dry bulb temperature (°C).

Design point power predictions

The equation output can be compared to historical data from operating plants. Table 3 illustrates the agreement between model output and actual plant data, where available in the public domain.

Table 3 – Comparison of model predictions and historical plant output for flash plants.

Plant	Approximate Reservoir Temperature (°C)	Assumed Design Wet Bulb Temperature (°C)	Actual Plant Net Plant Specific Output (kW/(kg/s)	Predicted Net Plant Specific Output (kW/(kg/s))	Deviation (%)
Kizildere I	200	12	39.5	51	29.1%
Miravalles III	241	22.8	77	86	11.7%
Olkaria II	270	12	111	119	7.2%
Cerro Prieto IV	320	17	174	184	5.7%
San Jacinto	260	25	117	94	19.7%

It can be seen that the general trend is towards higher specific output at the higher resource temperatures. The model may vary from actual plant performance due to more or less investment in cooling systems which increase efficiency, non-condensable gas content in the reservoir, or other factors. Kizildere I was an older plant that operates with very high non-condensable gas content (>20% of total steam flow); thus the model predicts significantly higher performance than actual. For more modern plants with more normal resource conditions, the model appears to be able to predict plant output to within 10%.

Figure 14 shows the actual plant performance overlaid with predicted performance of flash plants. Overall the agreement is fairly good, but there can be deviations. The performance of several unnamed (due to confidentiality) plants are shown, in addition to those from Table 3.

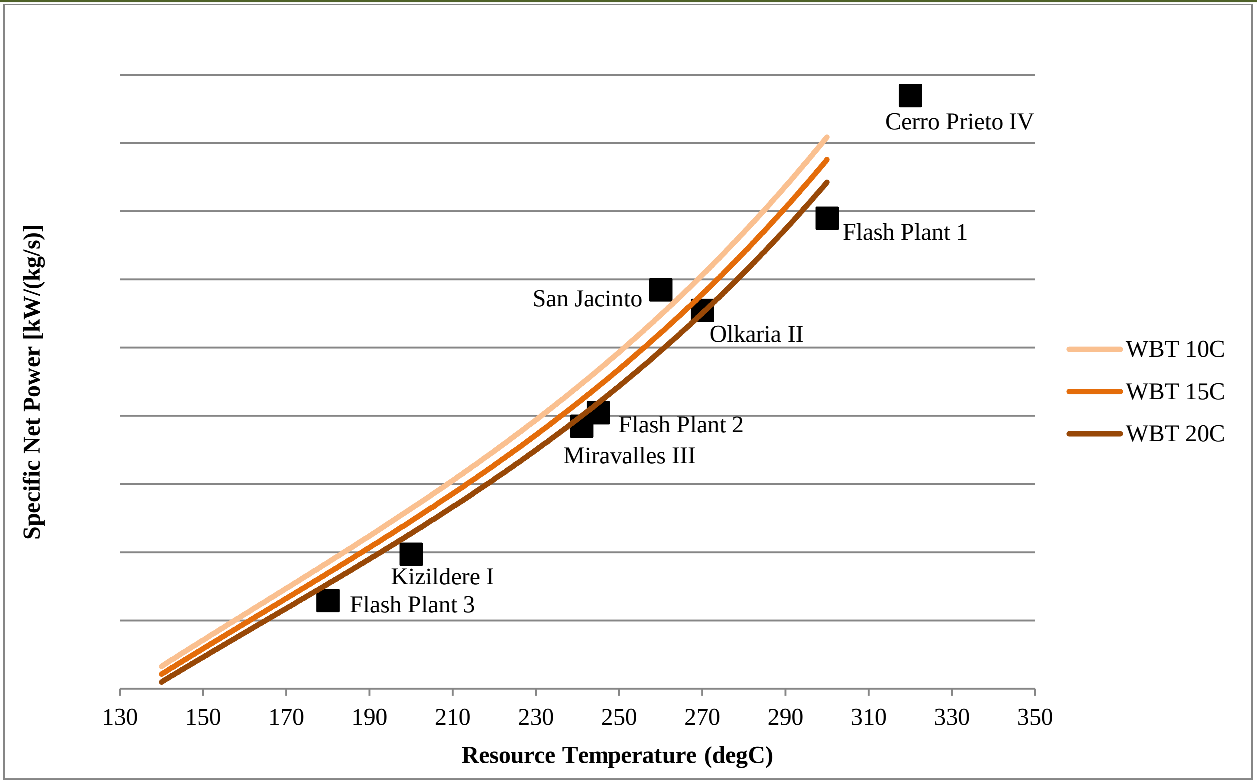

Figure 14 - Comparison of flash plant model predictions and historical plant output.

Off-Design Operation

The previous sections presented the development of a model that would predict instantaneous plant output at the design point. This output may vary over the course of a day or year. The capacity factor is defined as the actual energy output of the plant during a time period, divided by the energy output it would be capable of if it ran at the design point power. Capacity factors for other renewable sources such as wind or solar are typically less than 40%, however since geothermal plants are provided with a virtually uninterruptible fuel source, capacity factors may be well above 90%.

Two factors serve to reduce capacity factor, and we will discuss each of these in the next sections: temperature variations and outages. This analysis does not consider any impact of production well declines on output, which may typically be 1-4% per year; it is assumed that makeup well drilling is sufficient to offset these declines.

Annual temperature variations and impact

It was discussed earlier that colder temperatures allow for better cooling of the various cycles and increase design power output. After the plant is built, power output also varies as the plant experiences variations, both diurnally and seasonally. A typical plant will have a correction curve that captures the impact on net generation of variations in the dry bulb temperature (for air cooled units) or wet bulb temperature (for plants equipped with a cooling tower). A sample correction curve for an air-cooled binary unit is shown in Figure 15, using a 15 °C design point. At low ambient temperatures the turbine may or may not be sized to generate significant additional power. At high ambient temperatures the loss in generation may be substantial.

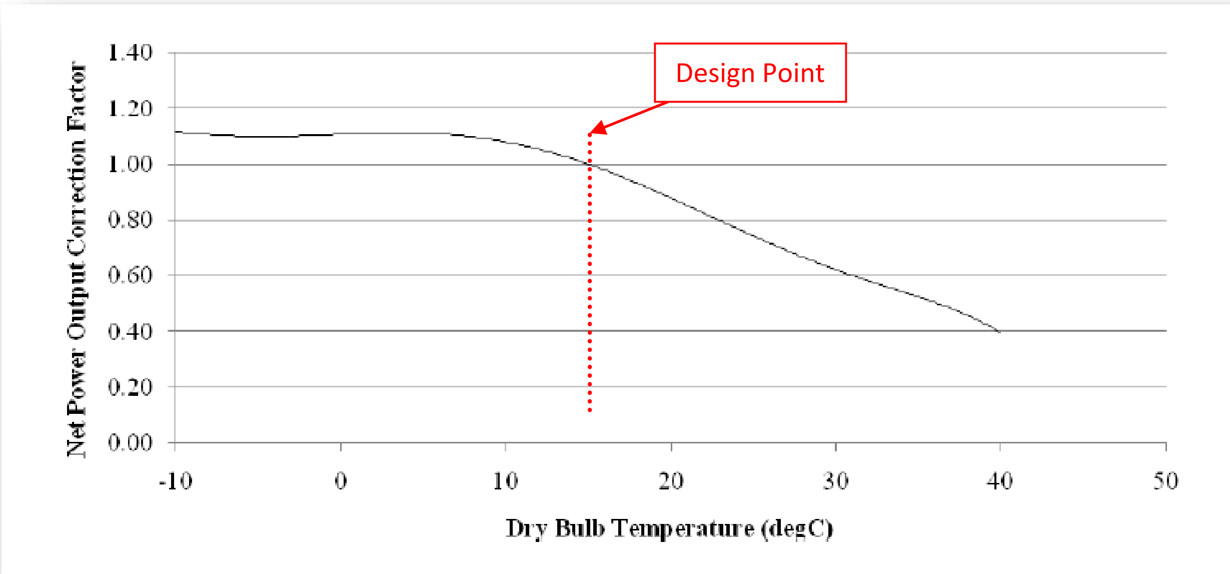

Figure 15 - Typical air-cooled binary power output correction curve versus Dry Bulb Temperature.

The average annual energy output for a plant depends on the design point selection (annual average, or a higher value), the nature of the deviations away from the design point, and the steepness of the correction curves for either higher or lower temperatures. We have found historically that if the annual average temperatures are chosen for the design point, the net effect is small (<5%), and the annual energy output can be reasonably estimated assuming design point output is achieved during the entire year, with the exception of outages.

Outages

Two types of outages may be encountered in geothermal plants: planned and unplanned. Most operators may perform planned outages for short inspection periods (1-2 days) every 6-12 months, interspersed with longer outage periods (perhaps 2-4 weeks) every 5-7 years for maintenance on major equipment. It is also not uncommon for plants to be idle unexpectedly due to intermittent grid faults or other abnormal conditions. However, historically plants are able to maintain high capacity factors despite the sum of these two effects. To some degree the outage periods are a function of the owner's investments in the operations and maintenance budgets. Table 3 shows typical capacity factors from plants around the world that reflect these combined influences of environment and outages.

Table 3 – Capacity factors by selected countries (adapted from Lund et al, 2010).

Country	Number of Units	Running Capacity Factor
United States	209	94%
Indonesia	22	92%
Iceland	25	91%
Kenya	10	98%

Typically, about 0.8% degradation in plant output per year occurs in between major equipment maintenance. About 80% of the degradation loss will be recovered during the year of the outage. The degradation loss is usually incorporated into the running capacity factor. For the purposes of this study, we will assume a constant capacity factor of 95% will apply; thus the annual firm energy output from the plant can be calculated as:

$$MWh = \frac{Design\ Point\ Net\ Plant\ Specific\ Power \left[\frac{kW}{\frac{kg}{s}}\right] x\ Geofluid\ flow \left(\frac{kg}{s}\right) x\ 0.95\ x\ 8{,}766 \frac{hours}{year}}{1000 \frac{kWh}{MWh}} \quad \text{(Eqn 5)}$$

Table 4 shows sample calculations of annual energy output for two types of resource; a lower temperature setting where a binary plant may be more economical, and a higher temperature plant for which flash might be more economical. The equations presented are used to calculate both the specific power output and the annual firm energy prediction, using assumed values for the independent variables.

Table 4 – Sample calculations of firm energy output for two resources

Parameter	Units	Resource #1	Resource #2
Reservoir temperature	°C	150	250
Cycle type assumed	-	Binary, air cooled	Flash, water cooled
Ambient temperature	°C	20 (dry bulb)	15 (wet bulb)
Design point specific power output	kW/(kg/s)	26.6	93.64
Geofluid flow	kg/s	500	1000
Plant design point output	MW	27.1	93.64
Annual firm energy output	MWh	110,656	779,828

Discussion

Output Uncertainty

Depending on the equipment supplier, cycle complexity, technology, and commercial factors, actual plants may have output more or less than these values. There are hundreds of parameters that affect the total annual output of a geothermal plant, including many economic optimization parameters. For example, the size of heat exchangers, the choice between an inexpensive but less efficient pump, the efficiency of different vendor's turbines, non-condensible gas content in the geofluid, injection pressures, and many other characteristics. These may even change over the life of the project as the resource evolves. Since very few input parameters are generally available at an initial assessment of a project, we chose those that have the greatest impact on the annual energy output, and assume reasonable values for others. Due to these factors, and in comparing the predictions with historical data, we feel that an uncertainty of ±10% in annual energy output would be a reasonable assessment to account for these variations.

Correlations

Equations 1-4 were plotted to one graph (Figure 16) to show the correlation between the binary and flash models. For the binary equation (Eqn 1), a dry bulb temperature of 20°C was used. For the flash equations (Eqns 2-4), a wet bulb temperature of 15°C was used.

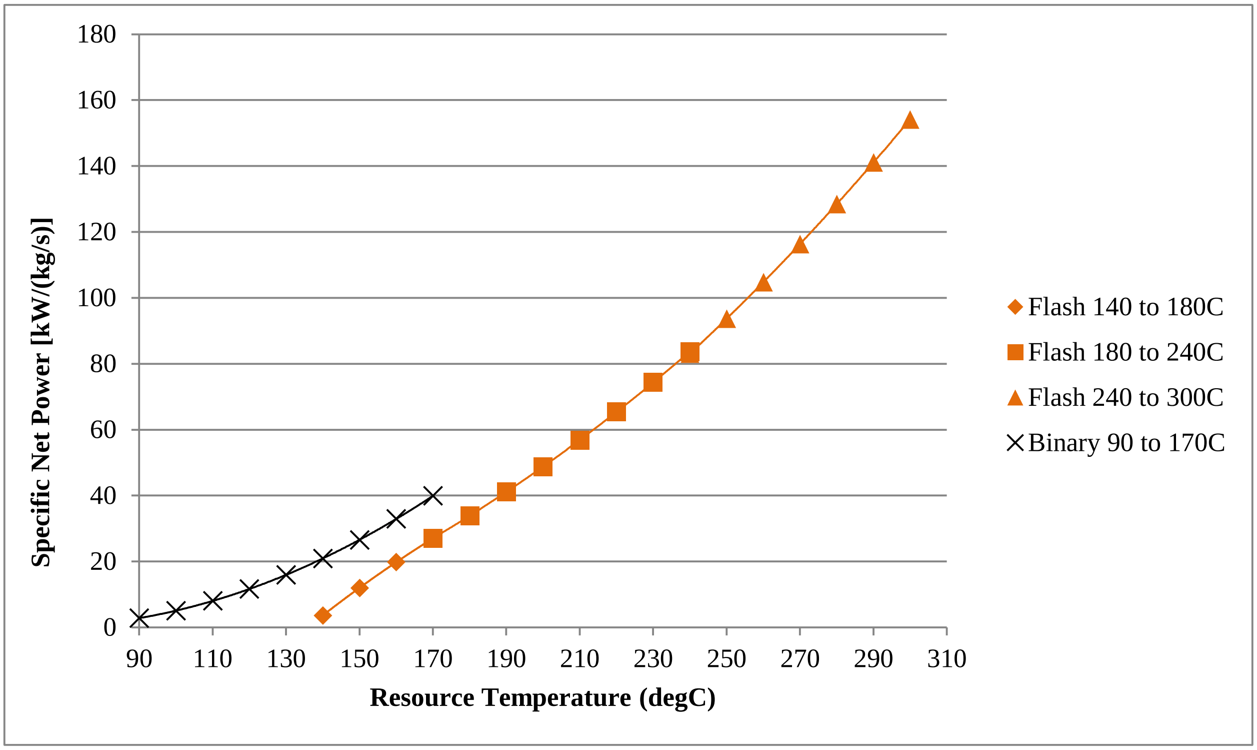

Figure 16 – Plot of flash and binary equations

The annual net energy prediction per kg/s would be incorporated into equation 5 to obtain a firm energy prediction in MWh of net plant output for a year.

It has been discussed that economic parameters may lead to the selection of a different cycle than what Figure 16 might estimate is preferred for the resource temperature. It is not uncommon for air-cooled binary plants to be used, for example, at locations where water cooling, evaporation, and net loss of fluid from the reservoir cannot be tolerated, even though the resource temperatures are high. Small modular binary units (<5 MW) may also be more appealing below a certain project size, due to their more modular nature than flash plants, even if the resource temperature is higher.

Monte Carlo Analysis

A Monte Carlo statistical analysis could be performed using these models to assess the uncertainty in annual energy output as a function of uncertainties in reservoir characteristics (flow, enthalpy/temperature, non-condensable gas content, e.g.), ambient temperatures, capacity factor, and other variables as desired.

Each component of the equations has inherent uncertainty as to what the true value will be. For instance, wells may underperform in terms of flow, assumed brine temperatures may not be representative for the long term resource, and the performance of key equipment may vary from assumed values after detailed design has finished. Each potential deviation from the assumed values of the input parameters contributes to uncertainty in the output parameters. A Monte Carlo simulation is one method of quantifying the cumulative effect of these uncertainties and reporting their impact on the uncertainty in overall plant metrics such as Specific Power or Net Plant Output.

The Monte Carlo simulation requires that the uncertainty in the input parameters be represented in the form of probability density functions (also called probability distributions). Triangular distributions as shown in Figure 17 are often employed for this purpose because they are easy to create, have clearly defined minimum and maximum boundaries, and allow skewed distributions to be utilized without significant complexity. This is in contrast to the more familiar bell shaped distributions. Triangular probably density functions are also computationally simple and allow higher numbers of simulations to be run in the same amount of computer processing time.

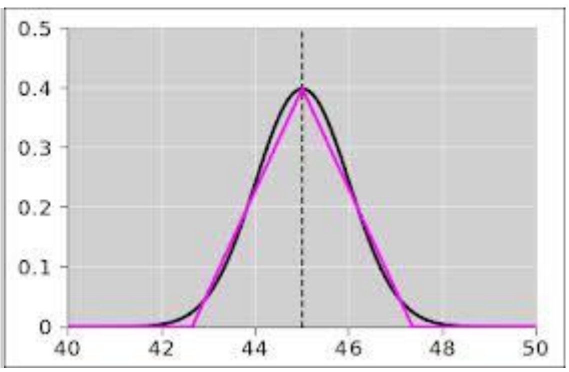

Figure 17 – Typical triangular distribution used to simulate a normal distribution (Denker, 2013)

Different parameters would have different uncertainties, and hence ‘width’ of the triangular distribution function, depending on the phase of the project. For example, annual average temperature might be known quite well at a specific location with weather station data spanning many years; the uncertainty might be +/-1 ^{o}C. However, the triangular distribution of resource temperature might be +/-5 ^{o}C, depending on the stage of exploration.

The Monte Carlo simulation method uses pseudo random numbers generated by a computer to pick values for the input parameters based on their probability density functions. The selected values represent a statistically realistic guess for each of the input parameters to be used in the calculation of plant metrics. The Monte Carlo simulation solves the plant model and estimates the key plant parameters based upon the guesses and stores these values for subsequent analysis. This is repeated many times, with simulation counts ranging from tens of thousands to tens of millions.

The number of simulations required for a Monte Carlo calculation depends on the desired accuracy and the variance in the input parameters, but 10,000 is often considered to be a minimum number to achieve reasonable accuracy. A high number of simulations will assure that the results reflect primarily uncertainty in the input parameters rather than uncertainty in the Monte Carlo simulation itself. When the number of simulations is sufficiently high, multiple Monte Carlo analyses using the same number of simulations will yield consistent results for uncertainty. Garg (2010) provides a more detailed illustration of this methodology, which can produce an estimate of probable reservoir potential, as shown in Figure 18. Figure 18 shows that for this sample reservoir, there may be a 90% probability of it having 40 MW of potential production, and a 50% probability of 80 MW.

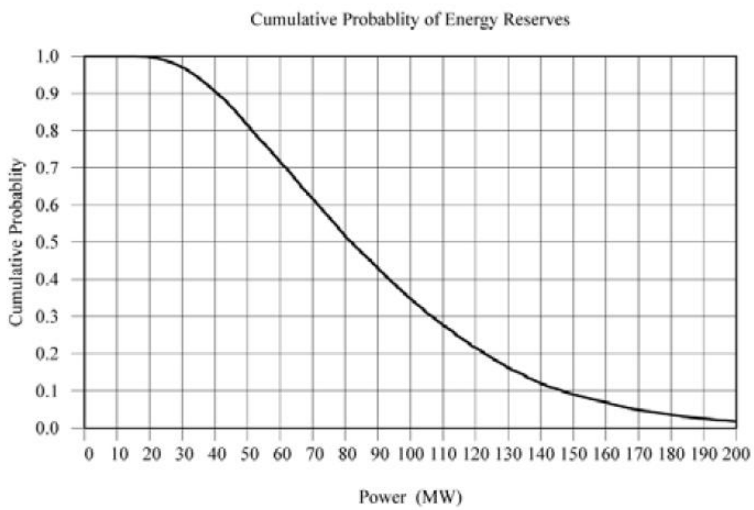

Figure 188 – Cumulative probability distribution curve of reservoir potential for a sample project (Garg, 2010)

The probability distribution functions for the input parameters used in the present study have not been defined and thus no Monte Carlo simulation has been performed on either a specific reservoir or plant output. However, future efforts to enhance a plant performance estimate may benefit from using Monte Carlo simulation to quantify the uncertainty in Specific Power and Plant Net Output. Such an improvement would allow an upper and lower bound with a particular confidence level to be provided with the calculated values of the plant metrics.

An example of the sensitivity of binary plant output to changes in the input parameters can be seen in Table 5. The working fluid used in this example is isobutane. Using a typical 150 °C resource as shown in Table 4, we vary one parameter at a time and report the variations in output (MW). Output is directly proportional to geofluid flow, somewhat sensitive to reservoir temperature, and less sensitive to ambient temperature.

Table 5 – Sample calculation showing effect of variation in parameters on output

Parameter	Units	Original Basis	Modified Geofluid Flow	Modified brine inlet temperature	Modified ambient temperature
Geofluid flow	kg/s	500	550	500	500
Brine inlet temperature	°C	150	150	151	150
Ambient temperature	°C	20 (dry bulb)	20	20	19
Resultant Output	MW	15.51	17.08	15.82	15.76

Since the probability distribution functions for the current analyses are not well defined, this uncertainty analysis was not performed; however Monte Carlo analysis to develop a range of probable plant outputs would be a path for future research or effort by developers on a specific project, one for which the resource conditions and attendant uncertainties are better known.

Conclusion

This report has provided correlations for the reasonable estimation of annual firm energy output from a geothermal plant, given as inputs a small set of assumptions such as total geofluid flow, resource temperature, and ambient temperature. Variations in technology or optimization for a specific site may result in output different from this estimation, however based on historical data it appears the uncertainty is within 10% for the majority of projects. The report provides background on the sensitivity of plant energy output as a function of many variables.

The estimation of annual firm energy output also assumes that there is sufficient reservoir capacity to maintain the design geofluid flow and temperature. Details of specific reservoir conditions may require added reduction in annual net output if there is a non-recoverable degradation in the reservoir geofluid supply condition.

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