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What Technical Performance Measures are Critical to Evaluate Geothermal Developments?

Josephine Varney, Nigel Bean and Betina Bendall

School of Mathematical Sciences, The University of Adelaide, Adelaide, South Australia, 5005

josephine.varney@adelaide.edu.au

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ABSTRACT

When geologists, geophysicists and engineers study geothermal developments, each group has their own set of technical performance measures. While these performance measures tell each group something important about the geothermal development, there is often difficulty in translating these technical performance measures into financial performance measures for investors. In this paper, we argue that *brine effectiveness* is the best, simple financial performance measure for a geothermal investor. This is because it is a good, yet simple indicator of ROI (return on investment); and importantly, links well production to power plant production, hence describes the geothermal development in a holistic sense.

1. INTRODUCTION

Geothermal resources can most easily be divided into two different types: conventional and unconventional. Conventional geothermal resources are hydrothermal volcanogenic systems, and unconventional geothermal resources are non-hydrothermal, non-volcanogenic resources. The degree of `engineering intervention' to access conventional resources is small, in that, wells are relatively easy to drill, and complete, and once they are drilled, hot geothermal fluid flows to the surface (so, no well stimulation is required). In contrast, in order to access unconventional geothermal resources much more `engineering intervention' is required. That is, the difficulty involved in creating a geothermal system: drilling production and re-injection wells, completing wells, and well stimulation, is much greater than in a conventional geothermal resource. Unconventional geothermal resources have been given many different names in order to describe what they are, and the differences between themselves (i.e.\ enhanced or engineered geothermal systems (EGS), hot sedimentary aquifer (HSA), hot dry rocks (HDR)). However, it is more accurate to think of unconventional geothermal resources as a continuum, requiring increasing amounts of engineering intervention to access the resource. Thus, it is simplest to think of all geothermal developments on a continuum of increasing engineering intervention, with conventional geothermal at the low end, and unconventional geothermal going from the medium to high end.

In geothermal developments, as with all technologically intensive projects, it can be challenging when investors and technical staff communicate. Technical staff have lots of important knowledge about their projects, but investors do not need (or necessarily want) to know all of this information. Investors are interested in the efficiency of their investment, they are interested in how their profits relate to the capital they have invested. The commonly used measure for this is called *return on investment* (ROI).

In this paper we argue that *brine effectiveness* is the most important performance measure for an investor considering geothermal developments because it is a good, yet simple, indicator of ROI for these systems. In simple terms, brine effectiveness is power produced per unit of flowrate of geothermal fluid (Mines, 2000), and is a parameter applied by technical specialists when characterising a geothermal system[1]. The advantage of brine effectiveness is that it directly links production from the wells with production from the plant, hence, describing the geothermal development in a holistic sense. Thus it can act as a common term bridging the gap between the technical and the commercial viewpoints. Finally, brine effectiveness is especially useful in dealing with the significant uncertainty around geothermal fluid flowrate; because it can easily be adjusted for different geothermal fluid flowrates, to determine the impact of such changes.

2. RETURN ON INVESTMENT

ROI is defined as revenue over cost. For power plants, it is clear that revenue is equal to the net electricity generated (W_{net}) multiplied by the cost of electricity. Cost, however, is a lot more complicated.

In this paper, we follow the cost analysis used by the International Energy Agency (IEA) in 2005 (Nuclear Energy Agency and International Energy Agency, 2005) and the National Renewable Energy Laboratory (NREL) in 2010 (Ridbull et al., 2010) for determining the cost of electricity. In this method, cost is divided into three categories: capital cost, operations and maintenance (O&M) cost, and fuel cost.

Geothermal developments are more capitally intensive than traditional steam fired power stations (see Table 1). However, they make up for their increased capital intensiveness by not having to pay for fuel (i.e. coal or gas), which traditional steam power plants must do. It is worth noting here, that in some types of cost analysis, fuel costs are considered part of the O&M costs (Energy Information Administration (US), 2013), hence, results from this type of analysis show geothermal power stations to have much lower O&M costs in comparison to traditional steam power plants. Both types of analysis work from the same raw data, it is simply a different decision about where to allocate fuel costs. Here, we consider fuel costs as a separate, individual cost (i.e. they are not

[1] Moya and DiPippo (2007) also refer to ‘specific brine consumption’ which is the inverse of brine effectiveness.

considered to be part of O&M costs) because this clarifies the major difference between geothermal and conventional steam power plants.

Table 1: Cost breakdown (Results are presented as a percentage of the Levelized Cost of Electricity and based on NREL data (Ridbull et al., 2010)).

	Coal	Conventional Geothermal
Capital (%)	45-50	70-80
O&M (%)	16-18	20-30
Fuel (%)	30-35	0

In 2009, the cost of plant for traditional coal fired power stations (US$3,000 to US$5,000 per kilowatt (kW) (Hassler and Rosenquist, 2009)) is over double the cost of plant for geothermal power stations (US$1,200 to US$2,400 per kilowatt (kW) (International Energy Agency, 2010; Cross and Freeman, 2009)). However, in addition to power plant costs, geothermal developments have the following additional capital costs: resource identification, resource evaluation, test well drilling and production well drilling[2]. In *conventional* geothermal developments, these costs correspond to <1%, 8%, 5% and 38% of total capital costs (respectively), which increases the total capital cost to US$3,000 to US$4,000 per kilowatt (kW) (Cross and Freeman, 2009). As the degree of engineering intervention increases, the cost of drilling each well increases. Based on four hypothetical *unconventional* geothermal development scenarios in Australia in 2010, it was predicted that the cost of drilling would range from 48% to 62% of total capital costs (Cooper et al., 2010).

3. A KPI FOR ROI

3.1 Coal Fired Power Stations

In traditional coal fired power plants, thermal efficiency (η_{th}) is the most well known key performance indicator (KPI). Thermal efficiency, for a coal fired power station, is defined as

$$\eta_{th} = \frac{W_{net}}{Q_{in}}, \qquad (1)$$

where Q_{in} is the heat added to the power plant to produce a net amount of *work*, W_{net} ,(or more easily, net amount of electricity). Thermal efficiency originates from plant engineers, and is a technical term they use to describe the efficiency of coal fired power plants. However, in addition, thermal efficiency has become a useful KPI for investors because it is a good indicator of ROI for these developments.

In order to show how thermal efficiency is related to ROI in traditional coal fired power plants, we need to relate: revenue to electricity, and cost to heat added to the plant. Relating revenue to electricity is straight forward, since

$$\text{revenue} = k_1 \times W_{net},$$

where k_1 is the price of electricity.

Relating cost to heat added is slightly more complicated. As shown in Table 1, cost is equal to roughly three times the fuel costs (i.e. the cost of coal), to allow for generalisation we write this as

$$\text{cost} = k_2 \times \text{cost of fuel},$$

where k_2 represents the ratio of cost to cost of fuel. Further, since, coal is burnt in order to heat to the plant, we can also say,

$$\text{cost of fuel} = k_3 \times Q_{in},$$

where k_3 is the ratio of cost of fuel to the amount of heat added to the plant.

So now, we can say, for traditional coal fired power stations,

$$\frac{\text{revenue}}{\text{cost}} = \frac{k_1}{k_2 k_3} \times \frac{W_{net}}{Q_{in}},$$

$$\text{ROI} = \text{K} \times \eta_{th}, \qquad (2)$$

[2] In this paper, we define drilling to include drilling and completing the production and re-injection wells, and production well stimulation, when required.

where K equals k_1 over k_2k_3. Hence, thermal efficiency is related to ROI by a constant K, and hence can be used as an indicator of ROI.

3.1.1 Limitations

From equation (2), it is easy to see that using thermal efficiency as an indicator of ROI only works when the values of K, for different power stations, are comparable. K varies when k_1, k_2 or k_3 vary, so let's look at each of these in turn, providing examples of when thermal efficiency is not a good indicator of ROI.

k_1 represents the price of electricity. It is clear, if two power stations (A and B) are the same, except that Station A can sell its electricity at a higher price than Station B; then Station A has a higher ROI than Station B, even though they both have the same thermal efficiency. However, this is implicitly understood by any investor.

k_2 is the ratio of *cost* over *cost of fuel*. Hence, when the capital or O&M costs are higher, or fuel costs lower in comparison to other power stations, k_2 increases. For example, super-critical power stations are more expensive to build and have higher thermal efficiencies than basic low temperature sub-critical power stations. However, even though super-critical plants have higher thermal efficiencies than low temperature sub-critical power stations, it does not necessarily mean they have higher ROIs than low temperature sub-critical power stations, because the values of k_2 are different. This difference is quite easily managed as thermal efficiencies are most often quoted in categories along with the category of plant (i.e. super-critical, high pressure sub-critical, low pressure sub-critical).

k_3 is the ratio of the cost of fuel over the amount of heat added to the plant. The amount of heat added to coal fired power plants (as with all steam power plants) is the difference between the boiler temperature and the condenser temperature. Fuel is burnt to achieve the boiler temperature, and water (or air) is used to achieve the condenser temperature. So, for plants with the same thermal efficiency, increasing the condenser temperature decreases the heat added to the plant for a given amount of fuel, and hence, decreases the electricity generated (for that same amount of fuel). It follows, that all other things being equal, k_3 increases as the condenser temperature increases, because less heat is added to the plant for the almost the same amount of fuel burnt. This difference is not often mentioned because 99% of steam power stations in the US are built near large bodies of water for cooling (Stiegel Jr et al., 2006, p12), to ensure low, stable cooling temperatures. Hence, most steam power stations have similar condenser temperatures, hence this limitation rarely arises. However, for the 1% of cases which do not use water for cooling, this is a significant issue.

3.2 Geothermal Developments

In geothermal developments, thermal efficiency is still used by plant engineers to describe the efficiency of the geothermal power plant, but can or should thermal efficiency be used as an indicator of ROI for a geothermal development as a whole (i.e. wells and power plant)?

For geothermal developments, just like coal fired power plants, it is clear that revenue can be related to electricity by,

$$\text{revenue} = c_1 \times W_{\text{net}},$$

where c_1 is the price of electricity. We allow c_1 to be different from k_1 to allow for 'green pricing' schemes).

However, can cost be related to heat, given that fuel/heat is essentially free (in a recurrent sense) for geothermal developments? We can link cost to drilling costs, as follows,

$$\text{cost} = c_2 \times \text{drilling cost},$$

where c_2 is the ratio of cost over the cost of drilling all wells. Further, drilling cost can be related to the mass of geothermal fluid (m_{brine}), by

$$\text{drilling cost} = c_3 \times m_{\text{brine}},$$

where c_3 equals drilling cost over mass of geothermal fluid. Hence, c_3 relates to the expected geothermal flowrate per well. Finally, it is possible to relate the amount of geothermal fluid to the amount of heat added to the system, as

$$m_{\text{brine}} = c_4 \times Q_{\text{in}},$$

where c_4 equals the amount of geothermal fluid over the amount of heat added.

However, c_4 will only be constant across geothermal developments, when the difference between production and re-injection temperatures is similar, and we argue, that this rarely occurs across geothermal developments. Geothermal development production temperatures (which are used to produce power) range from 73°C in Chena, Alska (Alska Center for Energy and Power, 2012) to 320°C and above in Iceland (Bjornsson, 2010), and re-injection temperatures range from 50°C in Mutnovsky, Russia (DiPippo, 2008) to 140°C in Cerro Prieto, Mexico (DiPippo, 2008). With such a wide range of difference, we argue that the wide variation in c_4 means that thermal efficiency is not a good indicator of ROI for geothermal developments.

Instead, we suggest that the approximation of cost is much more accurate if it is stopped one step earlier, that is

$$\text{cost} = c_2 c_3\, m_{\text{brine}}.$$

This allows us to relate ROI to brine effectiveness η_{brine}, as follows.

$$\frac{\text{revenue}}{\text{cost}} = \frac{c_1}{c_2 c_3} \times \frac{W_{net}}{m_{brine}},$$

$$\frac{\text{revenue}}{\text{cost}} = \frac{c_1}{c_2 c_3} \times \frac{\dot{W}_{net}}{\dot{m}_{brine}},$$

$$\text{ROI} = C \times \eta_{brine}, \qquad (3)$$

where $\eta_{brine} = \frac{\dot{W}_{net}}{\dot{m}_{brine}}$,

$$C = \frac{c_1}{c_2 c_3},$$

$\dot{W}_{net}$ is power and $\dot{m}_{brine}$ is the flowrate of the geothermal fluid.

<u>3.2.1 Limitations</u>

From equation (3), it is easy to see that using brine effectiveness as an indicator of ROI only works when the values of C for different geothermal developments, are comparable. C varies when c_1, c_2 or c_3 vary, so let's look at each of these in turn, providing examples of when brine effectiveness is not a good indicator of ROI.

c_1 is the price of electricity. As for coal fired power stations, the effect of this is implicitly understood by investors.

c_2 is the ratio of cost to cost of drilling all wells. This ratio will decrease quite significantly, as the degree of engineering intervention increases. For conventional geothermal resources this is not a problem, as the degree of engineering intervention for conventional geothermal resources is quite similar. However, for unconventional geothermal resources, which have a large variation in the degree of engineering intervention required, this ratio needs to be well understood by investors.

c_3 is the ratio of drilling cost to mass of geothermal fluid. This means that c_3 will increase as average geothermal fluid flow per well decreases. Geothermal fluid flowrate per well is one of the largest unknowns in geothermal developments. Importantly, brine effectiveness allows investors to easily determine the effect on power output due to varying geothermal fluid flowrates. This is done simply, by multiplying brine effectiveness by geothermal fluid flowrate. In other words,

$$\dot{W}_{net} = \eta_{brine} \times \dot{m}_{brine}.$$

4. DISCUSSION

One of the starkest observations of the previous discussion is that neither the temperature nor the depth of the geothermal resource have been mentioned anywhere. Often, these are the first things mentioned when describing a geothermal resource, so, why aren't they mentioned above?

We believe that from the depth of a geothermal resource investors often infer the cost of drilling. However, we argue that this is not a good approximation to the cost of drilling, particularly when comparing unconventional resources with conventional resources. It is quite possible to have shallow unconventional geothermal resources; however, these resources will potentially have higher drilling costs than deep conventional resources. Or, you could have two unconventional geothermal systems at similar depths, however, one which requires complex well completion technology and/or multiple stimulation operations to achieve adequate fluid flow. Hence, the degree of engineering intervention required is a much better indicator of drilling cost than the depth of the geothermal resource.

Similarly, we believe that from the geothermal resource temperature, investors often infer the amount of power that can be generated by the resource, and hence revenue. However, again, we argue that this is not a good approximation either. The power generated by a geothermal resource is fundamentally dependent on two things: the geothermal fluid flowrate, and the *difference* in temperature between the resource and re-injection temperatures. So, the approximation of resource temperature to power generation falls down in two ways: first, it fails to take into account the geothermal fluid flowrate; and, second, it fails to consider the re-injection temperature.

The most significant issue facing the use of brine effectiveness as an indicator of ROI, is that any comparison is only valid while the ratio of cost to drilling cost is roughly the same, that is when the degree of engineering intervention is roughly the same between comparative developments. However, we believe this problem is manageable within the industry and by investors. Importantly, brine effectiveness allows investors to easily understand the effect of the two most significant resource risks in the geothermal industry: drilling cost per well and geothermal fluid flowrate per well.

5. CONCLUSION

In this paper, we have shown that brine effectiveness is the best, simple approximation of ROI. However, to use brine effectiveness accurately, it can only be compared to geothermal resources which require a similar degree of engineering intervention. Additionally, investors can use brine effectiveness to understand the effect of changes in geothermal fluid flowrate on power output, and hence, revenue.

Importantly, brine effectiveness describes geothermal developments in a holistic sense, linking power production to well production; the two halves that make a whole geothermal development.

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