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Reply to the Letter to the Editor

Response to the Comments by Ronald DiPippo on "Efficiency of geothermal power plants: A world-wide review"

1. Introduction

We would like to thank R. DiPippo for his comments. We will provide our rebuttal on all the points he raised.

This work uses public domain data from existing and established geothermal power developments around the world, with references given for every data point used. The methodology used is conventional. It has been used for a long time, particularly when the efficiency of energy utilization is related to the geothermal reservoir temperature; please refer to Figure 2 of our paper and also Ogena and Freeston (1988). At the same time, having the efficiency a function of the resource enthalpy is also not new and has been reported in the 2010 Australian Geothermal Reporting Code, AGEA (2010). Our work shows that simple data fitting gives a good match (see our Figure 6).

The focus of the work was made clear at more than one point in the paper. This work is to serve as a high level benchmark for geothermal resource assessment which requires an efficiency of conversion to electrical power based on total available thermal power (from the stored heat/volumetric method). This is also the case when calculating the power potential of new wells during discharge/output testing, where the average efficiency of 10% is commonly used (IEA, 2007; Barbier, 2002).

We are surprised by R. DiPippo's response in regards to the conversion efficiency based on the total available thermal power. It is commonly used for resource assessment studies. We recommend some references such as Grant and Bixley (2011); Hochstein and Crosetti (2011); AGEA (2010); Ogena and Freeston (1988); Watson and Maunder (1982) where this method was used.

We do agree that geothermal energy is *sui generis*, but this does not mean we can only understand it through *exergy*. It also does not mean we cannot compare geothermal power plants with other thermal plants in terms of the input thermal power and electrical power output.

Given that not every geothermal resource assessment study will lead to a power station, this method is easy and simple to use for high level evaluation studies. It can also be used for benchmarking new plants against existing geothermal plants, and it simplifies the comparison of geothermal with other types of thermal power plants.

2. Point 1

We disagree with R. DiPippo, and refer to our response in the introduction. For simplicity, we use the term 'heat' to mean thermal power (in kW_{th} or MW_{th}). We do not mean heat transfer. There are a few points in the paper where we refer to heat transfer or heat loss explicitly.

Eq. (1) is thermodynamically correct as it follows the second law of thermodynamics, while accounting for all those losses discussed in the paper. It is similar to the alternative Eq. (1) given by R. DiPippo. The difference is that it uses total thermal power produced from the reservoir (with reference to the triple point of water) rather than exergy which refers to the surroundings or the "dead state".

3. Point 2

In our opinion, calculating conversion efficiency should not be limited to using just the "utilization efficiency" involving exergy. Using exergy just because it gives a higher and perhaps more "*respectable*" value than the conversion efficiency discussed in our work, is not, in our view, a justifiable approach.

R. DiPippo states that Eq. (1) given in our work is "*thermodynamically incorrect*". Then later (in point 3 of his commentary he stated that "*it is rather problematic, unconventional and at worst unjustifiable*". However, he provides an example using the same method. This implies that the methodology is not "incorrect", but simply an alternative approach. Applying the simpler enthalpy-based method, a calculated conversion efficiency of 14.1% is obtained for the example given from the Geysers. We find that the conversion efficiency for geothermal steam turbines has not improved much from that of 1964; it has possibly increased by another 5–6% at the most if new plant equipment are used.

We understand that it is the relatively small value of conversion efficiency, compared to that of utilization efficiency from the exergy analysis that R. DiPippo is not comfortable with, as it "*puts geothermal power plants in a bad light*". We would like to point out that the net electrical power (MWe) produced by the power plant will not actually be much affected whichever method is used.

Geothermal power plants can be considered *closed cycles* if the reservoir is included, which is what we have done in this work. In this way, conversion efficiency can be compared with other thermal power plants by simply dividing the net MW_e produced by the input thermal power MW_{th} from the geothermal reservoir.

R. DiPippo repeatedly criticizes the terminology used in our paper (heat, heat rate, heat input). We do agree that this can be a cause of some confusion. However, we would like to point out that simple dimensional analysis shows that there is nothing fundamentally wrong with our work. At the same time, local preferences to the terminology used can vary, depending on what is considered normal. However, it is a point that we have taken on board.

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4. Point 3

Most of the commentary has been addressed in the previous points. Again, this method is conventional and more widely used than the utilization efficiency of geothermal plant described by R. DiPippo in his Eq. (1).

Most of the available reported public-domain data did not provide the ambient temperature of the surroundings, i.e. the "dead state". This "dead state" also changes with the seasons throughout the year. The simple method discussed in our work uses the total thermal power produced from the geothermal reservoir. This is the product of the mass flow rate (kg/s) and the enthalpy (kJ/kg), with the reference being the zero enthalpy of liquid water at the triple point of water.

Note that there are a host of factors affecting the conversion efficiency, as discussed in our work, and our method is simply a lumped approach that requires the least number of input parameters. We feel this should be of greatest value in the early stages of development, but it also provides a simple reference to other plants in service and during development. It is also of value when screening data; this will be demonstrated later in our response to point 6.

5. Point 4

It was acknowledged in our work that the power plants working in cold environments are more efficient than those operating in warmer ambient air conditions. Figure 9 gives a simple example using the Carnot and Triangular efficiencies for two different ambient temperatures. Zarrouk et al. (2014) also shows (from field data) that the produced MWe increases with decline in ambient air temperature.

Our work acknowledges the importance of Exergy analysis as a tool when optimizing the production from existing plants. We disagree that plant design "has to be" carried out using exergy analysis and hence our statement "*Exergy analysis is normally performed*". Most existing geothermal power plants were not designed using exergy analysis. Discussing this further was outside the scope of our paper.

Eqs. (1) and (2) given by R. DiPippo are the basis for the USGS stored heat/volumetric method of resource assessment (Williams et al., 2008; Garg and Combs, 2010).

We refer, instead, to the method described in AGEA (2010):

$$W_e = \frac{H_{th} R_f \eta_c}{L \cdot F} \quad (1)$$

where W_e is the power plant capacity in kWe; H_{th} is the theoretical available energy (kJ) in the reservoir from the volumetric method; R_f is the recovery factor; η_c is the conversion efficiency or conversion factor; F is the power plant load factor/capacity factor; L is the power plant life (converted into seconds).

This is a simple case of two different approaches to geothermal resource assessment.

The reference point (dead state) in our approach is taken to be the zero enthalpy of liquid at the triple point of water 0.01 °C and 0.00616 bar (Wagner et al., 2000; IFC, 1967). This is a consistent reference point in most recent steam tables (Watson, 2013).

Note that Williams et al. (2008) provide a plot of utilization efficiency as a function of temperature based on reported field data. This effectively serves the same purpose as our efficiency plots when carrying out resource assessment studies.

Example: A geothermal well produces 100 kg/s from a liquid dominated geothermal reservoir at 250 °C. Calculate the power potential of the well in MWe?

1. Conversion efficiency (thermal) method:

   $$\text{Power} = \eta_c \dot{m}_R h_R$$

   (a) Single flash plant

   $$\text{Power} = \frac{0.085 \times 100 \times 1085.7}{1000} = 9.2\,\text{MWe}$$

   (b) Double flash plant

   $$\text{Power} = \frac{0.094 \times 100 \times 1085.7}{1000} = 10.2\,\text{MWe}$$

2. Utilization efficiency (exergy) method:

   $$\text{Power} = \eta_u \dot{m}_R e_R \quad \text{where} \quad e = h_R - h_0 - T_0(s_R - s_0)$$

(a) For a dead state of 15 °C and using a utilization efficiency of 40% (Williams, 2008)

$$\text{Power} = \frac{0.4 \times 100 \times [1085.7 - 63 - (15 + 273.15) \times (2.793 - 0.224)]}{1000} = 11.3\,\text{MWe}$$

(b) For a dead sate of 30 °C and using a utilization efficiency of 40% (Williams, 2008)

$$\text{Power} = \frac{0.4 \times 100 \times [1085.7 - 125.7 - (30 + 273.15) \times (2.793 - 0.224)]}{1000} = 9.8\,\text{MWe}$$

Please note that: the data given by (Williams, 2008) for calculating Utilization efficiency has large variability, and at the same time it does not account for different types of plant.

We hope that this simple demonstration shows that the difference between the two methods is relatively small.

6. Point 5

As discussed in our work, there are three components of pressure loss as the geothermal reservoir fluid travels up inside the well (Watson, 2013).

$$\frac{dP}{dz} = \left(\frac{dP}{dz}\right)_{grav} + \left(\frac{dP}{dz}\right)_{accel} + \left(\frac{dP}{dz}\right)_{fric} \quad (2)$$

Commonly, wellbore simulators are used to model the flow from the reservoir to the wellhead and different combinations of correlations for flow in wells using the Eq. (2) above (see McGuinness, 2014; Watson, 2013). Our comment was not only about the heat loss (heat transfer) through the casing and cement, but also the loss of pressure in the well due to the above three components which contributes further to enthalpy loss. It is our understanding that R. DiPippo agrees with the three pressure loss components in Eq. (2) above. Generally (in liquid dominated reservoirs) this will account for about 50 to 100 kJ/kg of enthalpy loss from the bottom of the well (reservoir) to the wellhead; depending on well depth, feed zone depth, casing configuration and others.

The down-hole pump that consumes electricity to produce the geothermal fluid is simply another parasitic load (electrical power)