A Protocol for Estimating and Mapping Global EGS Potential

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Keywords

Engineered Geothermal Systems. Enhanced Geothermal Systems. EGS resource estimation, global geothermal resource inventory, Google Earth, Keyhole Markup Language, KML

ABSTRACT

This paper establishes a Protocol to estimate and map the Theoretical and Technical potential for Engineered (or Enhanced) Geothermal Systems (EGS) in a globally self-consistent manner compatible with current geothermal public Reporting Codes. The Protocol, derived and modified from that designed by the team lead by Professor David Blackwell at Southern Methodist University (Dallas, Texas), is divided into five stages:

- Model the temperature, heat flow and available heat of the Earth's crust down to a depth of 10,000 m
- Estimate the Theoretical Potential for EGS power in the crust down to a depth of 10,000 m
- Estimate the Technical Potential that can be realized with current technology, and considering geographic, ecologic, legal and regulatory restrictions
- Define a level of confidence in the estimated Technical Potential at each location, consistent with public Reporting Codes
- Present results using common visualization and data architecture

The goal of the Protocol is the production of regional estimates and maps of EGS potential that are directly comparable to one another globally. The maps, estimates and source data will be made freely available for public use and presented in common data formats such as the Keyhole Markup Language (KML) for Google Earth.

1. Introduction

1.1. A Protocol for Estimating and Mapping Global EGS Potential

This paper sets out the framework for a Protocol to estimate and map the Theoretical Potential and Technical Potential (as defined by Rybach, 2010) for Enhanced/Engineered Geothermal Systems (EGS; see Section 1.2 below) in a globally self-consistent manner. Estimates and maps of EGS potential for different regions may only be directly compared against each other, or aggregated into estimates of total potential, if the methods and nature of the datasets underlying each estimate and map are the same, and if a consistent set of assumptions is used when real data are not available. Any estimate or map of EGS potential in a region involves a number of inputs about geology, thermal properties, recovery factors, power conversion efficiencies, ambient temperatures and so on. It follows that an inventory of the global EGS potential will require a globally consistent methodology and set of assumptions.

The purpose of this Protocol is to provide consistent methodologies and assumptions for estimating EGS potential over broad geographic regions such that the results can be directly compared. It does *not* seek to provide a unique answer to the magnitude and distribution of the EGS potential in any particular locality. Alternative approaches to

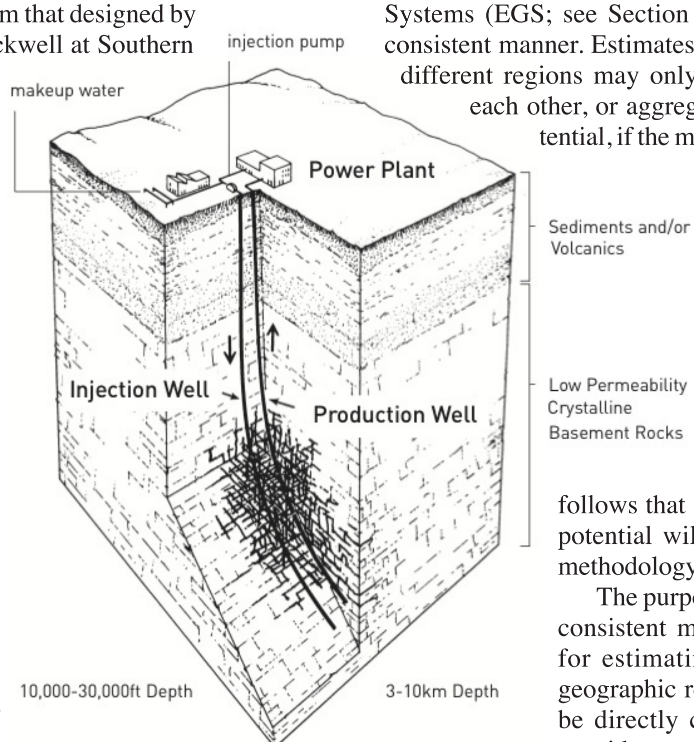

Figure 1. Conceptual EGS Power Plant Design (from MIT, 2006).

estimating or mapping EGS potential using other sets of assumptions may provide equal or greater accuracy in particular locations. More robust analyses will be required to assess the commercial viability of EGS at specific sites. This Protocol will, however, allow global EGS potential to be assessed following the same general process as described by MIT (2006) and Blackwell *et al*. (2007) to derive regional values for contained heat and potential electrical power generation.

This Protocol suggests distinguishing 'Theoretical' versus 'Technical' potential based on the state of geophysical data and EGS technology. As these will change over time, assumptions such as available heat, depth limits, recovery factor and net thermal efficiency will adjust, changing Theoretical and Technical estimates.

The Protocol will provide utility for academia, policy makers and commercial entities by standardizing technical language, improving understanding of EGS generation potential, providing a consistent visualization platform, and facilitating international commercialization efforts.

1.2. Enhanced/Engineered Geothermal Systems (EGS)

The heat stored within and fluxing through the Earth's crust is a ubiquitous source of energy that can potentially be tapped and exploited at virtually any location. 'Enhanced/Engineered Geothermal Systems (EGS)' is a generic term to describe a process whereby heat is extracted from the Earth's crust by circulating water through an artificially engineered system of fractures in hot rocks. In its most basic form, an EGS development can be thought of as a production well extracting hot fluid from the ground and passing it through a power conversion plant (electricity and/or heat) before re-injecting the cooled fluid back underground (Figure 1) where it is reheated by the rock in a continuous cycle.

Although significant engineering and financial hurdles remain, EGS plants hold the promise of nearly ubiquitous, low to zero CO_2 emission, secure, base-load power for millennia to come. So long as appropriately hot rocks can be drilled and fractured, the heat within those rocks can be extracted and utilized. In theory, EGS plants are locationally constrained only by the mechanical limits of drilling and fracture engineering. Furthermore, geothermal systems have the second lowest land-intensity of major electrical generating technologies (McDonald *et al*., 2009). These attributes make EGS an attractive potential significant contributor to world energy supplies.

EGS is currently economically competitive in a few select locations. Since its conception in the 1970's, successive EGS projects have achieved consistent increases in fracture reservoir volume, flow rates per well, accuracy of micro-seismic monitoring and mapping, hard rock drilling performance, and understanding of the critical geo-mechanical interactions that underpin the EGS concept. The current portfolio of projects under development is set to continue this positive trend. Advents in high-temperature submersible pumps, high-temperature/pressure hard rock drilling, hydro-fracturing, and sedimentary EGS could provide further cost reductions. As EGS technology improves and reduces in cost, ever-larger resources will become commercially viable for development.

EGS's characteristics warrant aggressive research, development and demonstration concurrent with the ongoing commercialization efforts of companies around the world. The current state of knowledge of global EGS potential remains limited, both in technical and public awareness terms. For EGS to play a material role in the global energy mix, improving and dispersing knowledge of the global potential and its regional distribution is a vital precursor to informed R&D, energy policy making, and broad-scale commercial deployment.

1.3. Theoretical and Technical Potential

The aim of this Protocol is to produce a living document describing a framework that may be easily modified as technology advances. Distinguishing between 'Theoretical' and 'Technical' potential is important to accurately represent the current resource potential for EGS and to allow the benefits of new technology to be easily quantified and communicated.

Following the terminology proposed by Rybach (2010), this Protocol suggests an initial estimate of the 'Theoretical Potential' for EGS across a region. This is an estimate of "the physically usable energy supply over a certain time span in a given region. It is defined solely by the physical limits of use and thus marks the upper limit of the theoretically realizable energy supply contribution." Only a portion of the Theoretical Potential will be accessible and extractable and represent a Geothermal Resource as defined by public Reporting Codes (see Section 1.6 below).

From the Theoretical Potential, the Protocol provides guidelines to estimate the 'Technical Potential', or "the fraction of the theoretical potential that can be used under the existing technical restrictions…structural and ecologic restrictions as well as legal and regulatory allowances" (Rybach, 2010). These restrictions will necessarily vary greatly with geology, location and time, providing some limited qualitative and quantitative flexibility to estimate and modify Technical Potential based on local conditions.

1.4. The EGS Potential of the USA

A seminal project by a multidisciplinary team lead by Professor Jefferson Tester of the Massachusetts Institute of Technology concluded in 2006 that EGS could provide 100,000 MW_e of electrical generating capacity to the United States by 2050 (MIT, 2006). A critical component of that study was a review of the available heat resource within the top 10,000 m of the earth's crust beneath the continental United States by Professor David Blackwell and his team at Southern Methodist University (SMU) in Dallas, Texas. Blackwell *et al*. (2007) documented the process.

The SMU team developed a set of broad approximations to characterize the thermal state of the upper crust. Fundamental to the process was the assumption that conduction is the primary heat transfer mechanism in the crust. Beyond that, the upper crust was broadly divided into sections of 'sediment' and 'basement', each with its own physical properties of thermal conductivity and internal heat generation.

A key outcome from Blackwell *et al*. (2007) was a series of tables illustrating the distribution and magnitude of the heat resource beneath different states of the USA at different depth/temperature intervals in the crust. Blackwell *et al*. (2007) used different terminology, but these tables effectively provide the Theoretical Potential of EGS for the USA, relative to mean surface temperature. MIT (2006) applied a set of assumptions to these results to derive a first estimate of the Technical Potential of EGS in the USA in terms of electrical generation capacity (although MIT also used different terminology). In 2008, the SMU team and Google.org converted the data into KML format for visualization on the Google Earth platform (Figure 2). The layers are available for free download and viewing from www.google.org/egs/.

1.5. A Global EGS Inventory

This Protocol will ultimately allow a self-consistent inventory and map of EGS potential around the world. There are a number of reasons to collate such an inventory, if even in a relative sense.

Firstly, understanding the magnitude, distribution, and characteristics of geothermal potential provides valuable foundational knowledge for strategic R&D, commercialization, and public policy.

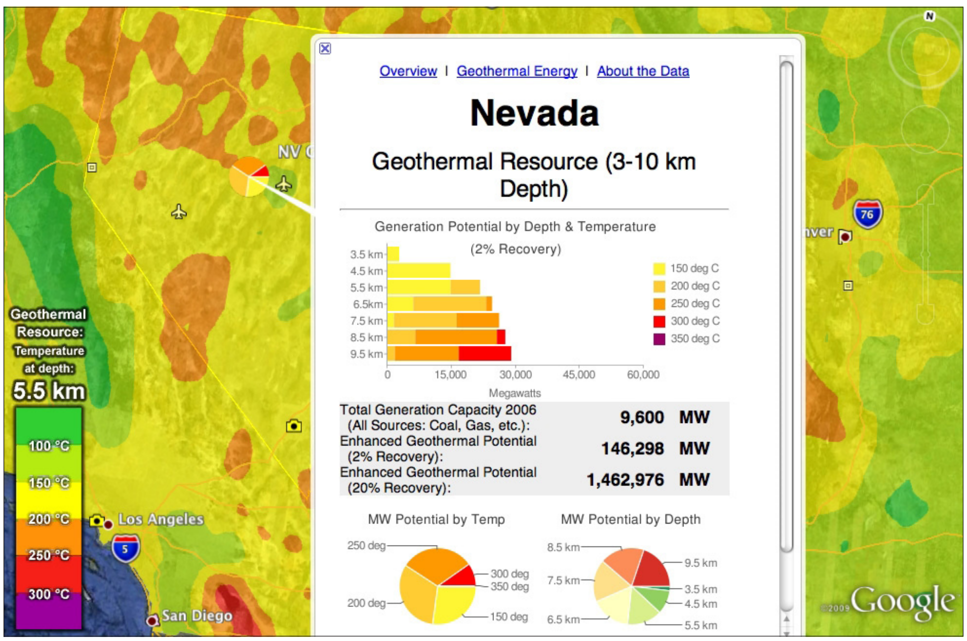

Figure 2. Screen capture of a Google Earth layer depicting the predicted temperature at 5.5 km and the EGS Potential base for Nevada, USA.

Secondly, current estimates of EGS potential for different parts of the world remain non-interchangeable. They utilize different sets of assumptions (especially recovery factor and conversion efficiency), represent different values (heat flow vs. temperature at depth vs. stored heat), are presented in different formats (GIS vs. JPG vs. KML) and therefore cannot easily be directly compared against each other or in aggregate.

Thirdly, national governments and international NGO's cannot factor EGS into future energy scenarios without meaningful estimates of the distribution and magnitude of the potential. Nations such as China and India, who's energy future is of critical importance to global climate and energy concerns, have limited, if any, EGS potential maps or estimates available to the general public. Much of Africa, South America, the Middle East, and Asia also lack coverage. Currently, regions active in EGS (primarily Western Europe, North America and Australia) present data in different formats.

Fourthly, commercial entities interested in developing or investing in EGS technology do not have a standardized and interchangeable language for representing relative EGS energy potential, geographic market potential, and booked reserve values. A standardized language relevant to the technical and business communities could facilitate and accelerate EGS commercialization.

Lastly, public awareness of the potential for EGS could be increased via widely accessible, engaging, and globally consistent tables and maps. Google Earth is a free and universally accessible software program for geospatial data visualization with hundreds of millions of users worldwide. KML layers can be viewed simultaneously with other layers, presenting different interactive geospatial information. Because of these attributes, it is recommended that estimates and maps be compatible with Google Earth.

A global Protocol is required.

1.6. Geothermal Resource Reporting Codes

There is presently a push within several investment regulatory jurisdictions around the globe for standardized protocols for the reporting of Geothermal Resource estimates. Australia and Canada represent two such jurisdictions. The Australian Geothermal Energy Association and the Australian Geothermal Energy Group released the first edition of the 'Australian Code for Reporting of Exploration Results, Geothermal Resources and Geothermal Reserves' in August 2008. At the time of writing, the second edition is close to release. The Canadian Geothermal Energy Association released a closely aligned 'Canadian Geothermal Code for Public Reporting' in January 2010 (Toohey *et al*., 2010).

The Protocol proposed in this document aims to be consistent with those reporting Codes in so far as respecting their underlying principles of 'transparency', 'materiality' and 'competence'. These principles will be honored through the inclusion of all relevant information (generally as metadata) with each set of maps and tables produced, and by including the personal endorsement of one or more 'Competent' or 'Qualified' Persons. The following minimum level of information is proposed to comply with these principles:

1. A statement that the data should not be relied on to inform commercial investment decisions
2. Sources of all data utilized for the estimates of EGS potential
3. A brief description of the modeling technique
4. Assumed ambient temperatures, recovery factors, and conversion efficiencies
5. Assumed lifespan of power generation
6. Statement of relative accuracy / confidence
7. The name(s) of the Competent or Qualified Person(s) who accept(s) responsibility for the Resource estimate

In the terminology of the Canadian Reporting Code and second edition of the Australian Reporting Code, estimates of EGS potential derived from this Protocol will mostly fall into the category of either 'Exploration Results' or 'Inferred Geothermal Resources'—"that part of a Geothermal Resource for which recoverable thermal energy can be estimated only with a low level of confidence."

2. Methodology

The Protocol described in this paper has been derived and modified from the methodologies designed by the teams lead by Professor David Blackwell at SMU (Blackwell *et al*., 2007) and by Professor Jefferson Tester at MIT (MIT, 2006).

The principle assumption underlying this Protocol for estimating EGS potential is that heat transport through the crust is dominated by pure vertical conduction. The process further assumes that a simple two-layer ('sediment' overlying 'basement') geological model can be used to approximate the geology of the top 10,000 m of crust in all continental areas. After dividing a region into a grid-work of 'cells', the simple two-layer model is used to estimate the local thermal structure in each cell using a 1D heat conduction model. The EGS Theoretical Potential (relative to a defined 'base temperature') is then tallied over different depth/volume intervals by assuming density and specific heat values for the rocks in question, and assuming a uniform heat–electricity conversion pathway. The total EGS potential within the region is estimated by summing together the discrete estimates of each cell.

The Protocol is designed to apply over broad geographical regions. It is divided into five stages:

1. Model the temperature, heat flow and available heat of the Earth's crust down to a depth of 10,000 m
2. Estimate the Theoretical Potential of EGS power in the crust down to a depth of 10,000 m
3. Estimate the Technical Potential that can be realized with current technology, and considering geographic, ecologic, legal and regulatory restrictions
4. Define a level of confidence in the estimated Technical Potential at each location, consistent with public Reporting Codes
5. Present results using common visualization and data architecture

2.1. Model the Temperature, Heat Flow, and Available Heat in the Earth's Crust Down to a Depth of 10,000 m

The temperature profile of the crust can be estimated using a 'top down' approach, where surface heat flow (Q_0) is assumed to extend downwards into the crust, gradually decreasing with increasing depth due to the distribution of heat generation in the rocks. Average thermal gradient can be estimated over any depth interval from the heat flow and thermal properties of the rocks. A 'bottom up' approach is similar, except that mantle heat flow (Q_M) is assumed to extend upwards, gradually increasing towards the surface as crustal rocks generate additional heat.

The SMU approach (Blackwell *et al*., 2007) was to derive temperature in the sediment section using a 'top down' approach, and temperature in the basement using a 'bottom up' approach. This requires explicit estimates of both Q_0 and Q_M. In this Protocol we propose to estimate the temperature profile through the entire top 10,000 m of crust using a 'top down' approach. Figure 3 provides flow chart of the recommended process for estimating the temperature profile of the top 10,000 m of crust in any location.

2.1.1. Grid Geographic Region into 5'×5' Cells

The region under investigation is first divided into a regular grid. 5'×5' graticules are recommended as the basic 'cell' size. Note that this equates to different physical surface areas at different latitudes—about 83 km^2 (9.13 km×9.13 km) at the equator and about 59 km^2 (9.13 km×6.45 km) at a latitude of 45°. To assess a region such as Australia (7.6 million square kilometers at an average latitude of around 25°S), approximately 100,000 cells are required.

While a constant-area approach might have advantages, the 5'×5' cell size is adopted for consistency with Blackwell *et al*. (2007).

2.1.2. Create Sediment Thickness (Depth to Basement) map

The initial step to estimate EGS potential is to chart the average thickness of 'sediment' overlying 'basement' in each 5'×5'

1. Grid geographic region into 5' x 5' cells.	Each cell becomes a node in the regional resource estimate. A temperature vs depth profile to 10 km depth will be derived for each cell.
2. Create sediment thickness (depth to basement) map.	From well–basement intersections, seismic interpretations, potential field inversions etc.
3. Populate sediment thermal properties	Thermal conductivity (K_S) and heat generation (A_S). Include depth variation if known. From measurements if available. Else, estimate from lithological mixing and age if possible. Else, estimate from age and basin setting. Else, global averages.
4. Populate basement thermal properties	Thermal conductivity (K_B) and heat generation (A_B). From measurements and geochemical data if available. Else, estimate from lithology. Else, global averages.
5. Create surface temperature map.	Mean average annual surface air temperature
6. Create surface heat flow map.	Average real data in 5' x 5' cell where available. Else, for Q_0 use BHTs and average conductivity if available. Else, assign by tectonic age. Else, use $Q_0 = 0.032 + b \times A_B + S \times A_S$.
7a. Derive temperature and heat flow at sediment–basement interface (S < 4,000 m)	$T_S = T_0 + [(Q_0 \times S) / K_s] - A_s (S^2 / 2.K_s)$; $Q_S = Q_0 - S \times A_S$
7b. Derive temperature and heat flow at sediment–basement interface (S > 4,000 m)	$T_S = T_{4km} + [(Q_0 - 4000.A_s) \times (S-4000) / K_B] - A_s \times (S-4000)^2 / 2.K_B$; $Q_S = Q_0 - S \times A_S$
8. Derive T at depth X, between 3,000 m – 10,000 m.	$T_X = T_S + (Q_S \times (X-S) / K_B] - A_B \times ((X-S)^2 / 2.K_B)$

Figure 3. General process for estimating the temperature profile of the crust to 10,000 m depth.

cell—in effect, develop a 'depth to basement' map for the region of interest.

Sediment thickness models are generally based on a combination of borehole intercept data, seismic reflection interpretations, potential fields modeling, or interpretation of other geophysical datasets (e.g. magnetotellurics). If such data are readily available, then it might be cost-effective to develop new 'depth to basement' models for the purpose of this EGS assessment process. It is unlikely to be cost-effective to collect new geophysical or borehole data specifically for this process.

In some parts of the world, sediment thickness data might already be in the public domain and easily adapted to this process. For example, the SEEBASE[1] database of Australia (http://www.frogtech.com.au/products_content.html) can be freely downloaded over the Internet and provides a first pass estimate of the thickness of Phanerozoic basins across the continent (Figure 4). Canada also has existing databases compiled from petroleum exploration. In other regions, state geosciences agencies or petroleum exploration companies might have developed sediment thickness models and access to those models might be secured through negotiation.

In 'green fields' areas with no existing 'depth to basement' data, estimates of sediment thickness might be based on analogy with basins of similar age in similar tectonic settings. Such situations should be treated on a case-by-case basis, taking care to identify appropriate analogues. But even with appropriate analogies, uncertainty will remain relatively high and confidence in the results will be relatively low.

2.1.3. Populate Sediment Thermal Properties

The premise underlying this Protocol is that conduction is the dominant heat transfer mechanism throughout continental crust. Upon accepting this assumption, temperature can be predicted at any arbitrary depth for a given surface heat flow (Q_0), thermal conductivity (K) and heat generation (A) structure. In the general sense, average thermal gradient is equal to the surface heat flow divided by the average vertical thermal conductivity. However, the gradient trend is modified with depth through the influence of internal generation of heat in the sediment and the basement.

To maintain consistency with Blackwell *et al*. (2007), this Protocol assumes that the thermal conductivity of sediment deeper than 4,000 m is the same as the basement (see Section 2.1.4 below).

The temperature prediction process within the sediment section requires single values of vertical thermal conductivity and heat generation to characterize the bulk properties of the entire sediment section. These bulk values are usually derived from the properties of individual formations. Thermal properties of formations ordinarily vary with lithology, compaction and temperature through the sediment sequence. The general stratigraphic and lithological framework of each basin in question must, therefore, be understood or presumed. The average vertical thermal conductivity of an entire sedimentary section (K_S) is the thickness-weighted (and temperature-corrected) *harmonic* mean of all the formations that make up the sedimentary section. The average heat generation of an entire sedimentary section (A_S) is the thickness-weighted *arithmetic* mean of all the formations.

Thermal properties of formations are best measured on actual samples, and corrected for *in situ* conditions. If thermal conductivity and heat generation data are already published for a region, those data should be adopted. New measurements are unlikely to be cost effective for the purpose of this estimation process, but results can be updated if new data subsequently become available.

In the absence of specific data for formations, thermal conductivity can be estimated from collations of published data for rocks of similar lithology, age and burial depth. Schön (1996) published one such compilation. If no specific stratigraphic and lithological data are available, mean conductivity values might be assumed based on global compilations of measured sedimentary data. For example, Clauser (2006) found that the conductivity of over 4,000 samples of clastic sediments measured at an ambient temperature of 25°C had a distribution of 2.65 ± 1.08 W/mK, while over 1,500 samples of chemical sediments had a distribution of 2.80 ± 1.19 W/mK (Figure 5). When corrected for *in situ* temperature of (say) 75°C (using the temperature-correction algorithm of Vosteen and Schellschmidt, 2003), these values suggest a global mean *in situ* sediment thermal conductivity of about 2.50 W/mK.

Heat generation is a by-product of radioactive decay of isotopes of (primarily) uranium, thorium and potassium in rocks. Heat generation of a rock can be estimated if the density of the rock and the concentrations of these elements are known. In most cases, though, elemental abundances are not known and values must be estimated from other evidence.

Heat generation in sediments is closely tied to the clay content of the sediment, because the lattices of clay minerals tend to host the heat generating elements. There

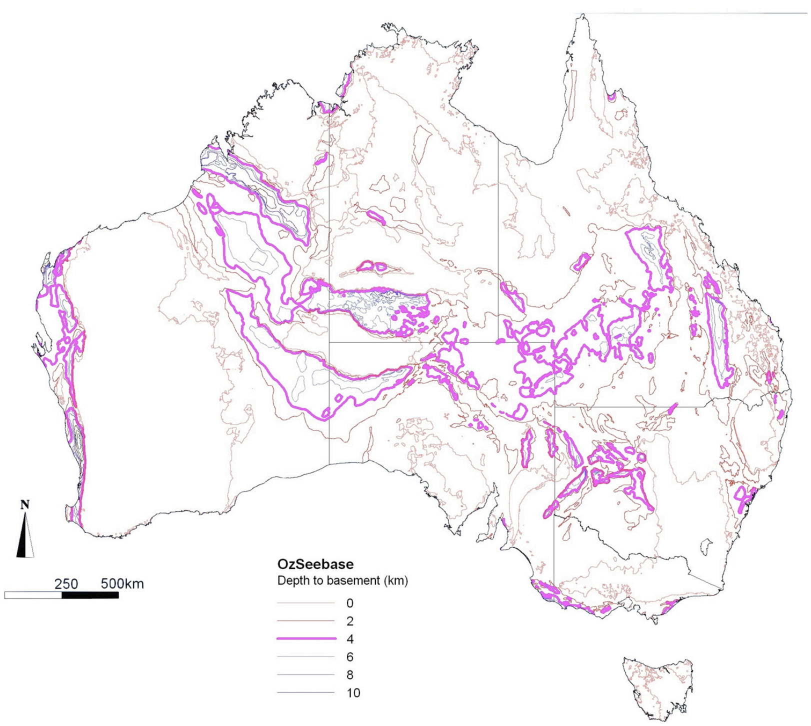

Figure 4. A visualization of the SEEBASE^{TM}[1] database. www.frogtech.com.au/products_content.html.

Rock Type		N	N_{total}	μ	σ	Q1	M	Q3
Sedimentary rocks	physical, marine (φ > 80 %)	648	6416	0,94	0,21	0,80	0,94	1,06
	physical, terrestrial (φ < 30 %)	4204		2,65	1,08	1,93	2,57	3,09
	chemical	1564		2,80	1,19	2,15	2,64	3,61
Volcanic rocks	high porosity	115	4450	1,75	0,64	1,31	1,66	2,10
	low porosity	4335		3,08	0,73	2,63	3,07	3,55
Plutonic rocks	rich in feldspar	805	6893	2,70	0,50	2,37	2,73	3,02
	poor in feldspar	6088		2,86	0,63	2,38	2,79	3,28
Metamorphic rocks	rich in quartz	514	13476	4,71	1,10	3,98	4,63	5,48
	poor in quartz	12962		2,70	0,82	2,20	2,54	3,00

Figure 5. Statistics of thermal conductivity data. N = number of measurements; μ = mean; σ = standard deviation. From Clauser (2006).

is a relationship between heat generation and the response of a gamma ray (GR) log. For example, Bücker and Rybach (1996) suggested the relationship:

$$A_S = 0.0158 \times (GR - 0.8) \qquad \text{Eq 1}$$

Eq 1 yields A_S in units of $\mu W/m^3$ when GR is in API units.

A small number of measurements published by McKenna and Sharp (1998) suggest that mudstone/shale generates heat at a rate of about $1.6x10^{-6}$ W/m³, sandstone about $1.0x10^{-6}$ W/m³ and limestone about $0.4x10^{-6}$ W/m³. Where the exact sedimentary composition is unknown, a value of $1.0x10^{-6}$ W/m³ might be adopted.

The confidence in the values of thermal conductivity and heat generation assumed for a particular basin will be directly related to the method relied upon to estimate the values. Confidence will be highest where actual measured data are applied to constrained formation types and thicknesses, and lowest where gross global average thicknesses and values are assumed.

2.1.4. Populate Basement Thermal Properties

The Protocol also requires that single values of thermal conductivity and heat generation be estimated for the basement. Unless there is evidence to the contrary, basement is assumed to comprise a single lithology. If the lithology of the basement is known, then its mean thermal conductivity (K_B) and heat generation (A_B) can be estimated from existing measurements or from collations of published data for rocks of similar lithology and age around the world.

If no specific lithological data are available for the basement, global compilations might provide appropriate values. Clauser (2006) found that almost 7,000 samples of plutonic rocks measured at an ambient temperature of 25°C had a mean conductivity of 2.84 W/mK, while the mean conductivity of almost 13,000 samples of quartz-poor metamorphic rocks was 2.70 W/mK (Figure 5) and over 500 samples of quartzite had a mean conductivity of 4.71 W/mK. When corrected for *in situ* temperature of (say) 175°C (using the algorithm of Vosteen and Schellschmidt, 2003), these values suggest a global mean *in situ* conductivity for plutonic or quartz-poor basement of about 2.14 W/mK, or 3.45 W/mK for quartzite basement.

Heat generation within basement rocks is more influenced by lithology. Where specific data are not available, a granitic composition might be assumed. Cermák *et al*. (1990) published a small set of data from granite and granodiorite samples that displayed a mean heat generation of $2.65x10^{-6}$ W/m³.

The confidence in the values of thermal conductivity and heat generation assumed for a section of basement will be directly related to the method relied upon to estimate the values. Confidence will be highest where actual measured data are applied, and lowest where gross global average compositions are assumed.

2.1.5. Create Surface Temperature Map

Mean surface temperature, T_0, is an important boundary condition for models of underground temperature and for estimates of EGS potential. Climatic records of a region may include long-term mean surface air temperature (e.g. Figure 6). For any given location, air temperature may be several degrees warmer or cooler than surface rock temperature, depending on the interplay between surface evaporation and insolation. However, for the purpose of this Protocol, the two are considered to be approximately equal.

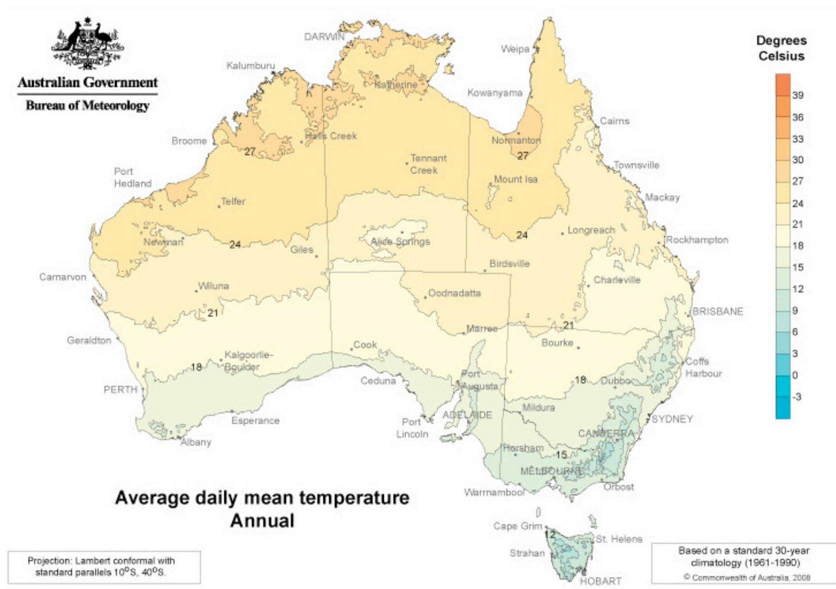

Figure 6. Average daily mean temperature across Australia 1961–1990. From the Australian Bureau of Meteorology (www.bom.gov.au).

Maps of surface air temperature should be acquired if available. Otherwise, new maps might be generated from point 'mean air temperature' data. If available, mean surface rock temperature extrapolated from borehole temperature logs might also be included in the database.

If specific air or rock temperature data are not available for a particular region, then published global climate models might be used.

2.1.6. Create Surface Heat Flow Map

In a conductive heat flow setting, surface heat flow (Q_0) is the sum of mantle heat flow (Q_M) plus heat generated within

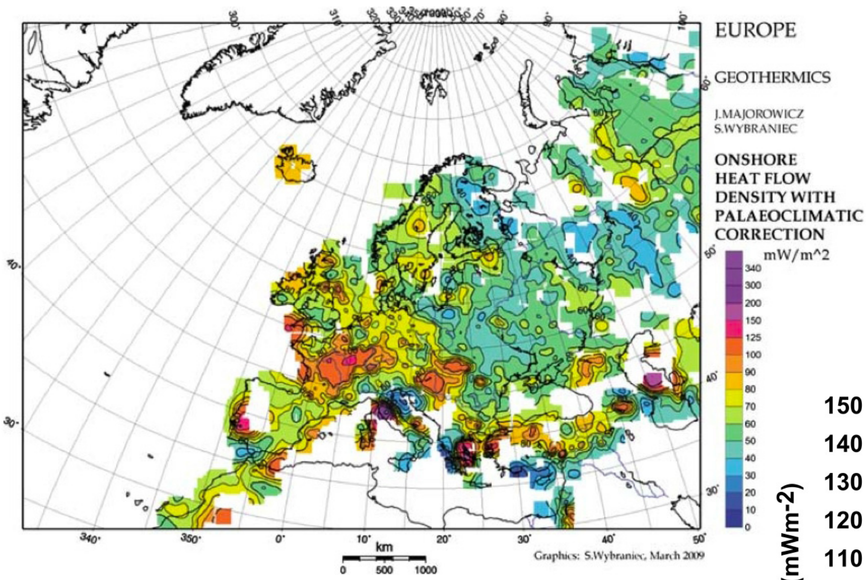

Figure 7. Surface heat flow across Europe, corrected for paleoclimate. From Majorowicz and Wybraniec (2010).

the crust. Surface heat flow maps already exist for some parts of the globe. For example, Majorowicz and Wybraniec (2010) recently published an updated surface heat flow map of Europe (Figure 7).

Surface heat flow is affected by factors including long-term changes in surface temperature (i.e. climate change), topography, and erosion/sedimentation rates. This Protocol assumes that competent and experienced heat flow practitioners have taken all such factors into account, and that the values adopted are appropriate to characterize the crust down to 10,000 m depth.

All published estimates of surface heat flow should be collated for the region of interest. Where data exist, surface heat flow for each 5'×5' cell should be determined as a distance-weighted mean of all heat flow data within a 30 km radius of the center of the cell. In other areas, surface temperature and reliable temperature data (BHT's) from wells deeper than 1000 m might be used to estimate heat flow by first calculating average thermal gradient and then multiplying by the mean thermal conductivity values derived in Sections 2.1.3 and 2.1.4 above.

Q_0 might also be derived from previous studies of heat flow provinces (regions of constant Q_M), where:

$$Q_0 = Q_M + b \times A_B + S \times A_S \qquad \text{Eq 2}$$

The parameter, b, is the thickness of heat generating basement. The value of b is determined according to the thickness of sediment, S (m):

$$\text{If } S < 3{,}000 \text{ m}, b = 10{,}000 \text{ m} \qquad \text{Eq 3a}$$

$$\text{If } S > 3{,}000 \text{ m}, b = (13{,}000 - S) \text{ m} \qquad \text{Eq 3b}$$

Note that the inclusion of sedimentary heat generation in Eq 2 is a departure from 'classical' heat flow province studies as defined by Roy *et al*. (1968).

It is likely that the majority of cells will remain unfilled after the above procedure. Surface heat flow (Q_0, W/m^2) should be estimated for these cells from basement and sediment heat generation (A_B and A_S, W/m^3) added to a mantle heat flow of 0.032 W/m^2, a mean value derived from a number of studies around the world (Figure 8):

$$Q_0 = 0.032 + b \times A_B \qquad \text{Eq 4}$$

2.1.7. Derive Temperature and Heat Flow at Sediment–Basement Interface

Temperature-at-depth estimates are determined for the mid-point of each 1,000 m depth interval from 3,000 m, and at the base of the model: X = 3,500 m, 4,500 m, 5,500 m, 6,500 m, 7,500 m, 8,500 m, 9,500 m and 10,000 m.

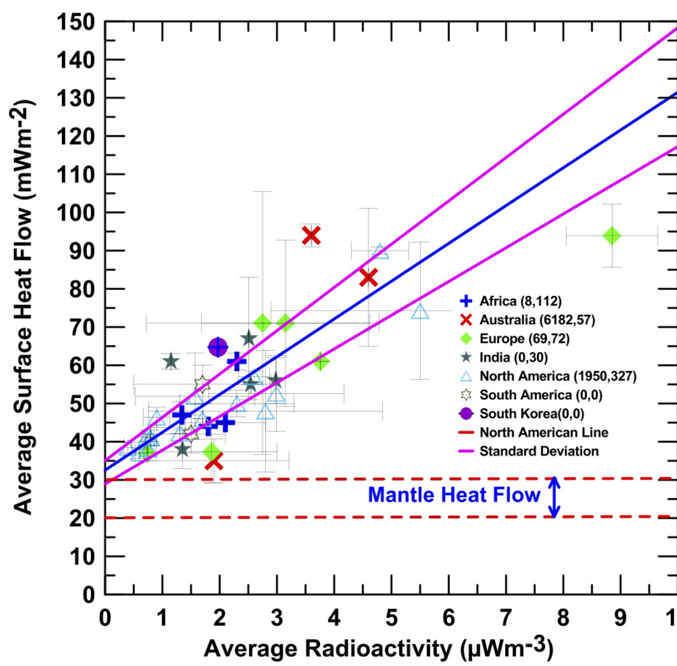

Figure 8. Summary of heat flow–heat production relationships around the world. Linear fit to the data gives Q_M = 32 ± 3 mW/m^2 (Pers. Comm., David Blackwell, 2009).

Temperatures at these depths can now be estimated in two steps. The first step is to derive an estimate of temperature at the sediment–basement interface (T_S, °C). This is a function of the surface heat flow (Q_0, W/m^2), surface temperature (T_0, °C), sediment thickness (S, m), thermal conductivity (K_S, and maybe K_B, W/mK), and heat generation (A_S, W/m^3). T_S is derived using one or both of the following formulae, depending on whether sediment thickness is greater than or less than 4,000 m.

If S < 4,000 m:

$$T_S = T_0 + [(Q_0 \times S) / K_S] - A_S \times [S^2 / (2 \times K_S)] \qquad \text{Eq 5a}$$

If S > 4,000 m, then the conductivity of that portion of sediment deeper than 4,000 m is K_B, as described in Section 2.1.3. In this case, first calculate T_{4km} using S = 4000 in Eq 5a, then:

$$T_S = T_{4km} + [(Q_0 - 4000.A_S) \times (S - 4000) / K_B] - A_S \times [(S - 4000)^2 / (2 \times K_B)] \qquad \text{Eq 5b}$$

Heat flow at the sediment–basement interface (Q_S) becomes the 'surface heat flow' for estimation of temperature at deeper levels. Q_S is derived by subtracting the total contribution of sedimentary heat from Q_0:

$$Q_S = Q_0 - S \times A_S \qquad \text{Eq 6}$$

2.1.8. Derive T at Depth X, Between 3,000 m – 10,000 m

The second step is to use a variation of Eq 5a to estimate temperature at depth X in the basement down to 10,000 m. T_0, Q_0, K_S, A_S and S in Eq 5a are replaced by T_S, Q_S, K_B, A_B and (X–S), respectively:

$$T_X = T_S + [(Q_S \times (X - S)) / K_B] - A_B \times [(X - S)^2 / (2 \times K_B)] \qquad \text{Eq 7}$$

At the completion of this step, a mean predicted temperature profile should be available for each 5'×5' cell. Estimated temperature maps for specific depth slices, or estimated depth maps to specific isotherms should be easily constructed from these results.

2.2. Estimate the Theoretical Potential of EGS Power in the Crust Down to a Depth of 10,000 m

For consistency with existing EGS maps of the USA, EGS potential should be estimated for the midpoint of every 1,000 m thickness interval between 3,000 m and 10,000 m depth. The heat stored within a volume of rock is proportional to the temperature, heat capacity, density and volume of the rock. In addition, it can only be estimated relative to a 'base temperature'. Estimates of EGS potential, therefore, require values for each of these parameters. Figure 9 provides a flow chart of the recommended five-step process for estimating the Theoretical Potential for EGS in the top 10,000 m of crust in any location.

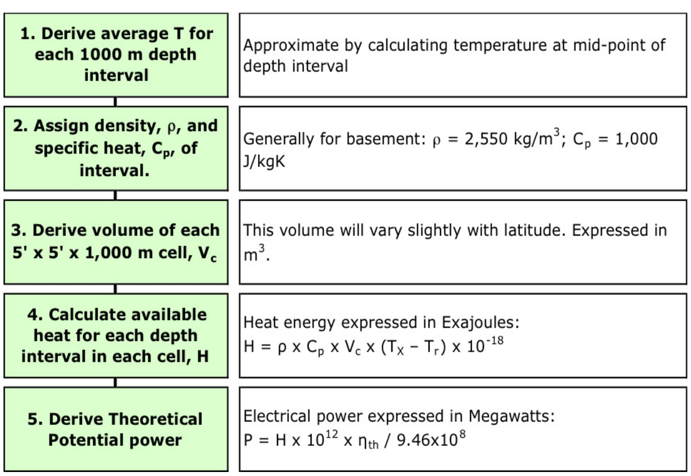

Figure 9. General Process for Estimating Stored Heat Energy and Theoretical Power Generation Potential.

2.2.1. Derive Average T for Each 1000 m Depth Interval

Crustal temperature is the key determinant of Theoretical Potential for EGS at any specific location. The temperature at the mid-point of all relevant depth intervals has already been estimated in Section 2.1.8.

2.2.2. Assign Density, ρ, and Specific Heat, C_p, of Interval

Use published density and specific heat values for the basement if available. Otherwise, for consistency with Blackwell *et al*. (2007), assume ρ = 2,550 kg/m^3 and C_p = 1,000 J/kgK.

2.2.3. Derive Volume of Each 5'×5' × 1,000 m Cell, V_c

The surface area of a 5'×5' cell varies depending on latitude, and so therefore does the volume, V_c (m^3), of a 1,000 m thick interval of crust. These volumes should be individually calculated for each cell.

2.2.4. Calculate Available Heat for Each Depth Interval in Each cell, H

Each depth interval will contain a different amount of available thermal energy. The total available heat (H, exajoules EJ) in a 1,000 m thick volume of crust is a function of the initial temperature, T_X, density, ρ, and specific heat, C_p, and a 'base temperature', T_r.

$$H = \rho \times C_p \times V_c \times (T_X - T_r) \times 10^{-18} \qquad \text{Eq 8}$$

The initial temperature is simply the average temperature (°C) of the volume of crust in question. The base temperature, T_r (°C), is the temperature to which the crust can theoretically be reduced through utilization of geothermal heat. In a recent assessment of geothermal potential in the USA, the USGS assumed a base temperature of 70°C in Alaska and 90°C in the 48 contiguous states (Williams *et al*., 2008), about 80°C above mean annual surface air temperature at each location. This Protocol proposes following the lead of the USGS by assuming $T_r = T_0 + 80$°C. Note that this is a departure from the methodology of MIT (2006) and Blackwell *et al*. (2007), who assumed a base temperature equal to the mean ambient air temperature.

2.2.5. Derive Theoretical Potential Power

Again following the lead of the USGS (Williams *et al*., 2008), Theoretical Potential power generation is derived using the following assumptions:

1. All heat (H) above the base temperature is theoretically recoverable in all locations
2. 30 years (9.46×10^8 s) life span of power generation
3. Cycle thermal efficiency, η_{th}, is a function of resource temperature as per Table 3.1 on p3-13 of MIT (2006).

Cycle thermal efficiency is location and technology dependent. The ambient air temperature and plant cooling system have a significant impact. Efficiencies are also likely to improve with time as cooling and heat regeneration technologies undergo progressive adaptations, and as plant components based on cycles other than the Rankine cycle are developed. For the purpose of this Protocol, however, a standardized estimate of thermal efficiency is required to minimize subjectivity of results.

The MIT group (MIT, 2006) calculated the net thermal efficiency for several geothermal plants, both binary and steam, for any given fluid temperature (T) and derived a relationship given by Eq 9 below. This Protocol recommends using the same relationship for estimates of thermal efficiency on a global scale.

$$\eta_{th} = 0.00052 \times T + 0.032 \quad \text{Eq 9}$$

Note that the mean fluid temperature appropriate for Eq 9 when all heat is theoretically extracted from the crust is the average of the initial rock temperature and the base temperature, where the base temperature is defined in Section 2.2.4 as (T_0 + 80°C):

$$T = (T_X + T_0 + 80°C) / 2 \quad \text{Eq 10}$$

The potential power generation, P (MW_e), from a 1,000 m thick volume of rock with available heat, H, is then:

$$P = H \times 10^{12} \times \eta_{th} / 9.46x10^8 \quad \text{Eq 11}$$

Theoretical Potential power generation is collated and tabulated for specific depth and temperature intervals.

2.3. Estimate the Technical Potential that can be Realized with Current Technology, and Considering Geographic, Ecologic, Legal and Regulatory Restrictions

It is obviously technically impossible to realize the entire Theoretical Potential for EGS power in any given location. Following the terminology of Rybach (2010), the 'Technical Potential' is that part of the Theoretical Potential that can be extracted after consideration of currently 'insurmountable' technical limitations. 'Technical' is defined in its broadest definition, including (but not limited to) factors such as land access, rock type, drilling technology, fracture density, stress orientation, regulatory framework, power conversion technology and availability of water.

While Rybach (2010) argues that "the EGS potential cannot yet be termed 'technical'", this Protocol proposes a set of assumptions for deriving an estimate of Technical Potential. The steps are illustrated in Figure 10 and explained below.

2.3.1. Exclude Parts of Cells for Which Land Access Limits EGS Potential

There are many reasons why particular geographic locations may be excluded from consideration for EGS development. It is not possible to list every possible reason here, but in different parts of the world excluded zones might include:

- National parks
- Conservation areas
- Densely populated areas
- Areas of significant topographic relief
- Large lakes and swamps
- Militarized zones
- Deserts with no available water resources

In some regions these restrictions may change through time, and should be reevaluated if economic, social or political conditions change.

The proportion of each 5'×5' cell that is accessible and available for EGS, R_{av}, is defined as a value between 0–1.

2.3.2. Limit Volume to Technically Accessible Depth

This Protocol follows the MIT (2006) approach of estimating the Theoretical Potential for EGS down to a depth of 10,000 m. All practical applications of EGS technology to date, however, and likely into the foreseeable future, have been limited to about the top 5,000 m of crust. The Protocol recommends limiting estimates of Technical Potential for EGS to the top 6,500 m. This may change if there are significant advances in hard-rock drilling technology, as are currently being pursued by a number of research groups.

2.3.3. Assign Recoverability Factor, R, According to Rock Type

Williams *et al*. (2008) provided a discussion on the predicted (modeled) and observed recovery of thermal energy from fracture-dominated geothermal systems. While they concluded that "it is not possible assign a single value, or even a narrow range, for [R] for unexploited geothermal systems", R "is estimated to range from 0.08 to 0.20, with a uniform probability over the entire range."

1. Exclude parts of cells for which land access limits EGS potential	Remove environmentally sensitive areas, major cities, major topographic features, lakes, and other land areas judged inaccessible or unavailable for EGS development. Weight each cell for proportion of 'available' area, R_{av}.
2. Limit volume to technically accessible depth	6,500 m is proposed as the current practical limit for drilling and engineering a reservoir.
3. Assign recoverability factor, R, according to rock type	Following USGS—crystalline rocks, mean R = 0.14. Proposed min–max range is 0.02–0.20. Assume the same for meta-sediments until experience dictates otherwise.
4. Assume a limit to the allowable temperature drawdown	Following MIT (2006), assume it is only technically feasible to reduce resource temperature by 10°C.
5. Calculate Technical Potential for each depth interval in each cell, P_T	Power expressed in Megawatts: $P_T = P \times R_{av} \times R \times R_{TD}$
6. Collate total Technical Potential at each location	$= \Sigma P_T$

Figure 10. General Process for Estimating Technical Potential of EGS from the Theoretical Potential.

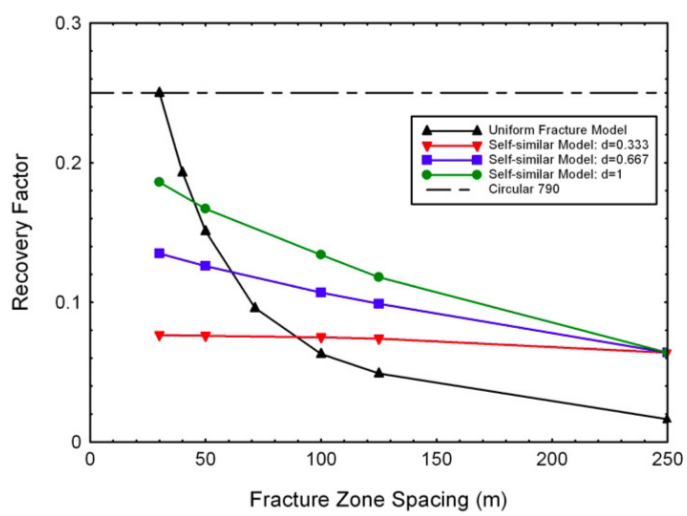

Figure 11. Predicted values of R for planar fractures with uniform flow properties (black) and fractal distributions of flow properties (green, blue and red). From Williams et al. (2008).

The main variables that influence R are the fracture spacing and the 'fractal dimension' of the distribution of flow properties within the fractures. If these are known or can be characterized with some confidence, then R can be estimated from Figure 11. In all other situations, this Protocol suggests adopting the mean value of 0.14.

As technology advances, our understanding of recoverability factors will adjust. This Protocol suggests producing estimates of potential based on a range of R values representing the expected minimum, maximum and mean values. This Protocol proposes 0.02 as a minimum value for R, following the precedent of the MIT (2006) study, and 0.20 as a maximum value for R, following the findings of Williams *et al*. (2008).

Global experience of EGS systems is dominated by projects in crystalline rocks. The behavior of mechanically softer rocks, such as meta-sediments, for EGS development is largely untested, although projects in Australia and Germany will soon start delivering data from these types of rocks. Until such time as a significant difference in thermal energy recoverability is demonstrated, this Protocol recommends using the methodology described in the previous paragraphs to estimate R, regardless of rock type.

The authors stress that the proposed recoverability factors are based on the results of numerical modeling. Practical experience of heat recovery from EGS projects is not yet sufficient to draw firm conclusions about real recoverability factors. While the proposed values of R fulfill the aim of the Protocol to provide a globally consistent set of assumptions, calculations of Technical Potential using this Protocol should only be viewed as estimates until such time as practical experience provides real data on recoverability.

2.3.4. Assume a Limit to the Allowable Temperature Drawdown

Power conversion technology is typically optimized to operate within a limited set of input parameters. Input geothermal fluid temperature is one of those critical design parameters. The efficiency of Rankine cycle power plants substantially reduces as the input temperature drops. There is, therefore, a practical limit to the temperature drawdown a power plant can withstand before it will no longer operate effectively. This Protocol recommends following the methodology of MIT (2006) by assuming a maximum allowable temperature drawdown of 10°C. This effectively introduces a 'temperature drawdown' recoverability factor, R_{TD}, defined by:

$$R_{TD} = 10 / (T_X - T_r) \qquad \text{Eq 12}$$

2.3.5. Calculate Technical Potential for Each Depth Interval in Each Cell, P_T

The Technical Potential, P_T, for EGS power for any given depth interval in a specific 5'×5' cell is that part of the Theoretical Potential that is:

- Accessible at the surface (Section 2.3.1)
- Shallower than 6,500 m (Section 2.3.2)
- Accessible via fracture networks (Section 2.3.3)
- Available with <10°C drawdown (Section 2.3.4)

That is:

$$P_T = P \times R_{av} \times R \times R_{TD} \qquad \text{Eq 13}$$

Eq 13 applies only for depths between 3,000 m and 6,500 m. Technical Potential is zero for deeper levels.

2.3.6. Collate total Technical Potential at Each Location

The total Technical Potential in each 5'×5' cell is the sum of the results for the depth intervals centered at 3,500 m, 4,5×00 m, 5,500 m and 6,500 m.

2.4. Define a Level of Confidence in the Estimated Technical Potential at each Location, Consistent with Public Reporting Codes

This Protocol deliberately avoids using the terms 'Resource' or 'Reserve' to describe estimates of potential EGS heat or power. Those terms have specific meanings relating to the commerciality of the heat energy under the Australian and Canadian Geothermal Reporting Codes. This Protocol makes no claims for or against the commerciality of areas identified with EGS potential.

In areas where this Protocol derives EGS potential using real data, the resulting estimates of thermal energy might meet the definition of 'Resources' under the Codes (so long as other Code requirements are met). In areas where EGS potential is derived entirely from assumed values, or using data of low confidence, the results are best described as 'Exploration Results' in the terminology of the Reporting Codes.

The Australian and Canadian 'Geothermal Reporting Codes' do not require quantitative reporting of confidence levels for Geothermal Resource or Reserve estimates. Rather, the Codes define broad categories of Resource and Reserve based on the confidence in the underlying data. These categories are Inferred, Indicated or Measured Resource (in order of increasing confidence); and Probable or Proved Reserve. It is expected that in all but a small number of special cases, the highest confidence level for results from this Protocol will be 'Inferred Geothermal Resource.'

For each cell and depth interval, the EGS potential will be categorized according to the terminology of the Reporting Codes.

In addition to the qualitative assessment of confidence described above, the Protocol also lends itself to a robust quantitative assessment of uncertainty. All parameters in every equation in this Protocol could be assigned numerical uncertainty values, which could then be rigorously propagated through the calculations to determine the quantitative uncertainty of the estimated Potential at each cell location and depth. These values could be displayed visually, for example, by varying the transparency of the Theoretical and Technical Potential layers. Such an approach is allowable under the Reporting Codes, and could provide an additional valuable layer of information that could:

- Clearly display the fact that estimates of EGS Potential are not equally certain at all locations and depths
- Visually depict variations in data quality across regions
- Focus exploration programs on regions that require new data
- Stimulate competition across regions to decrease the uncertainty

A quantitative assessment and display of uncertainty will require addition parameters and steps in Sections 2.1, 2.2, 2.3 and 2.5 (below). These will be added to a future version of this Protocol.

2.5. Present Results Using Common Visualization and Data Architecture

Assessments of EGS potential generated as a result of this Protocol are intended to be public data, freely and conveniently accessible to all interested parties. It is recommended that source data be made publicly available, as SMU has done with its geothermal databases. All results will therefore be tabulated in a format compatible with popular data viewing and manipulation platforms such as Google Earth utilizing Keyhole Markup Language (KML). Google.org's 'U.S. Geothermal Resources (3–10 km)' layer (available at www.google.org/egs) is a reference for visualization architecture.

2.5.1. Upload T_X Data to KML Files

A three-dimensional picture of estimated temperature distribution down to 10,000 m should be complete after Stage 2.1 of this Protocol. The final step is to convert the data into a format appropriate for upload to Google Earth, and consistent with the EGS maps already available for the United States. Standard 'KML file' templates will be utilized to store and display temperature maps for depths between 3,000 m and 10,000 m.

2.5.2. Upload Theoretical Potential Estimates to KML Files

A three-dimensional picture of Theoretical Potential for EGS power down to 10,000 m should be complete after Stage 2.2 of this Protocol. The final step is to convert the data into a format appropriate for upload to Google Earth. Standard 'KML file' templates will be utilized for this Stage.

2.5.3. Upload Technical Potential Estimates to KML Files

A three-dimensional picture of the estimated Technical Potential for EGS power down to 6,500 m should be complete after Stage 2.3 of this Protocol. The final step is to convert the data into a format appropriate for upload to Google Earth. Standard 'KML file' templates will be utilized for this Stage.

2.5.4. Upload Confidence Data to KML Files

A three-dimensional representation of 'confidence' in terms consistent with the Australian and Canadian Geothermal Reporting Codes should be complete after Stage 2.4 of this Protocol. The final step is to convert the data into a format appropriate for upload to Google Earth. Standard 'KML file' templates will be utilized for this Stage.

3. Conclusion

The intention of this Protocol is to conform closely to the methodology utilized by MIT (2006) to assess the EGS potential of the United States. However, it does depart from that methodology in some key ways. Firstly, this Protocol divides the EGS potential into Theoretical Potential and Technical Potential. Each is likely to change through time, with Theoretical Potential most sensitive to new geological and geophysical data, and Technical Potential most sensitive to improvements in technology.

Secondly, this Protocol aims to conform to the tenets and terminology of public Geothermal Reporting Codes, with results at different locations and depths classified according to different confidence levels.

Thirdly, this Protocol extends the methodology described by MIT (2006) and Blackwell *et al*. (2007) to apply in areas where real data are scarce or non-existent.

Fourthly, this Protocol recommends assessing EGS potential relative to a base temperature of $T_0 + 80°C$, rather than relative to T_0. This is to conform to the requirements of the Australian and Canadian Geothermal Reporting Codes.

Estimates of EGS potential derived using this Protocol are not 'final'. They will continue to be refined as more relevant data become available. Theoretical Potential will be refined as new geological and geophysical data are progressively collected about areas to improve our understanding of the thermal structure of the crust. Refinements here are expected to be gradual. Technical Potential will be refined as technological advancements in drilling, power conversion and legal regimes allow greater amounts of the Theoretical Potential to be realized. Changes here are expected to be sudden and dramatic.

Application of the Protocol will undoubtedly reveal gaps and uncertainties that will require the Protocol itself to be refined through time. This will, therefore, be a 'living document'. It is hoped that the EGS potential of most of the world's continental surface will eventually be assessed and charted, allowing for the first time a view of the size and distribution of the 'hidden' energy stored in the rocks of the top 10,000 m of the Earth's crust.

Glossary Of Symbols

η_{th}	cycle thermal efficiency for power conversion (0–1)
ρ	density (kg/m^3)
$A_{S,B}$	heat generation: sediment, basement (W/m^3)
b	thickness of heat generating basement (m)
C_p	specific heat capacity (J/kgK)
H	total available thermal energy (EJ, exajoules)
$K_{S,B}$	thermal conductivity: sediment, basement (W/mK)
P	Theoretical Potential EGS power (MW, megawatts)
P_T	Technical Potential EGS power (MW, megawatts)
$Q_{0,S,M}$	heat flow: surface, base of sediment, mantle (W/m^2)
R	recoverability factor (0–1)
R_{av}	proportion of cell available for EGS (0–1)
S	thickness of sediment (m)
$T_{0,S,X}$	crustal temperature: surface, sediment base, X (°C)
T_r	base, rejection, or re-injection temperature (°C)
V_c	volume of section of crust (m^3)
X	arbitrary depth in crust (m)

Acknowledgements

The development of this Protocol was made possible by the financial support of Google.org through its 'Renewable Energy Cheaper than Coal' initiative (RE<C). The details of the Protocol have been widely reviewed and this resulting document is due in no small part to constructive criticism by Colin Williams (USGS),

Anthony Budd (Geoscience Australia), Susan Petty (AltaRock Inc), Christoph Clauser (RWTH Aachen University), Dan Yang (Borealis GeoPower Inc), Arner Hjartarson (Manvitt Engineering), Wendy Calvin (Great Basin Center for Geothermal Energy) and others.

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