A Protocol for Estimating and Mapping Global EGS Potential

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Abstract

We present a Protocol to estimate and map the Theoretical and Technical potential for Engineered Geothermal Systems (EGS) in a globally self-consistent manner compatible with current public geothermal Reporting Codes. The goal of the Protocol is to standardise the production of regional estimates and maps of EGS potential so that they are directly comparable to one another globally.

The Protocol is divided into five stages:

1. Model the temperature, heat flow and available heat of the Earth's crust to a depth of 10,000 m

2. Estimate the Theoretical Potential for EGS power in the crust 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 KML visualization and data architecture

The maps, estimates and source data underpinning the estimates and maps will be made freely available for public use and presented in the Keyhole Markup Language (KML) for Google Earth.

Keywords:

Engineered Geothermal Systems; EGS resource estimation; Global geothermal resource inventory; Google Earth; Keyhole Markup Language; KML

Introduction

Engineered Geothermal Systems

'Engineered Geothermal Systems (EGS)' is a generic term for the process whereby heat is extracted from the Earth's crust by circulating water through an artificially engineered set of permeable fractures in hot rocks (Figure 1). 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. In theory, EGS plants may be constructed anywhere that the mechanical limits of drilling and fracture engineering allow. Furthermore, geothermal systems have the second lowest land footprint of all electrical generating technologies (McDonald *et al.*, 2009). These attributes make EGS an attractive potential major contributor to world energy supplies.

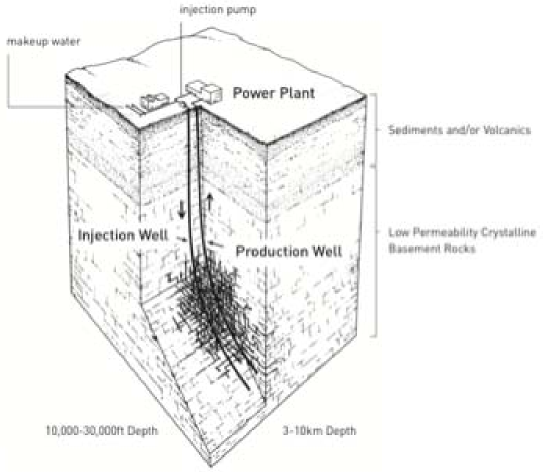


Figure 1. Conceptual EGS power plant design (from MIT, 2006)

For EGS to play a material role in the global energy mix, improving public awareness 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.

A Protocol for estimating and mapping global EGS potential

This paper summarises a Protocol to estimate and map the Theoretical Potential and Technical Potential (as defined by Rybach, 2010) for EGS in a globally self-consistent manner. 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 requires a globally consistent methodology and a globally consistent set of assumptions to fall back on when real data are not available.

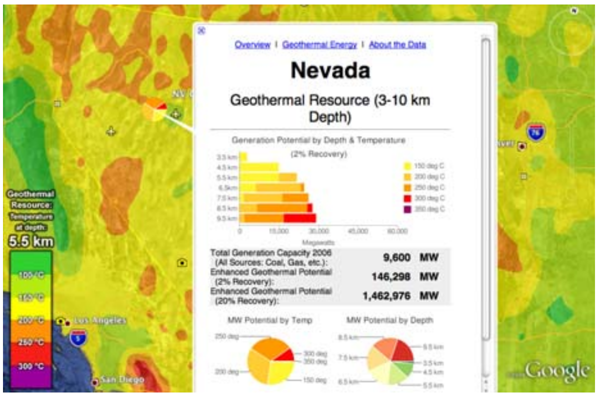
The Protocol does not seek to provide a unique picture of the magnitude and distribution of the world's EGS potential. Alternative approaches to estimating EGS potential may be more relevant in particular locations and more robust analyses will certainly be required to assess the commercial viability of EGS at specific sites. The Protocol will, however, provide consistent methodologies and assumptions that will ultimately allow a self-consistent inventory and map of EGS potential around the world.

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.

The basis for the Protocol

The Protocol closely follows the methods underpinning a report by the Massachusetts Institute of Technology, which concluded in 2006 that EGS could provide 100,000 MW of electrical generating capacity to the United States by 2050 (MIT, 2006). An integral component of that study was a review of the heat resource within the top 10,000 m of the crust by Professor David Blackwell and his team at Southern Methodist University (SMU; Blackwell *et al*., 2007). SMU assumed that conduction is the primary heat transfer mechanism in the crust, and that the upper crust can be broadly divided into sections of ‘sediment’ and ‘basement’, each with its own physical properties of thermal conductivity and internal heat generation.

In 2008, the SMU team and Google.org converted the MIT findings 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/.



Total Generation Capacity 2006 (All Sources: Coal, Gas, etc.): 9,600 MW
Enhanced Geothermal Potential (2% Recovery): 146,298 MW
Enhanced Geothermal Potential (20% Recovery): 1,462,976 MW

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.

Theoretical and Technical Potential

The Protocol calls for an initial estimate of the ‘Theoretical Potential’ for EGS across a region, following the terminology of Rybach (2010). Theoretical Potential is “defined solely by the physical limits of use and thus marks the upper limit of the theoretically realizable energy supply contribution.” 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 vary greatly with geology, location and time, providing some flexibility to modify Technical Potential based on current local conditions.

Geothermal Resource reporting codes

Codes for the reporting of Geothermal Resource estimates exist for Australia and Canada. The Protocol aims to conform to those reporting Codes in so far as respecting their underlying principles of ‘transparency’, ‘materiality’ and ‘competence’. These principles will be honoured 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 Protocol proposes the following minimum level of information 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 modelling 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.

Methodology

The Protocol assumes that pure vertical conduction dominates heat transport through the crust, and that a simple two-layer geological model (‘sediment’ on ‘basement’) approximates the top 10,000 m of crust in all continental areas. A region is divided into a grid-work of ‘cells’, and the simple two-layer model is used to estimate the local thermal structure in each cell. 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 discrete estimates of each cell may be summed to estimate the total EGS potential over the region or depth interval.

In practice, the process is divided into five stages:

1. Model temperature, heat flow and heat in 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

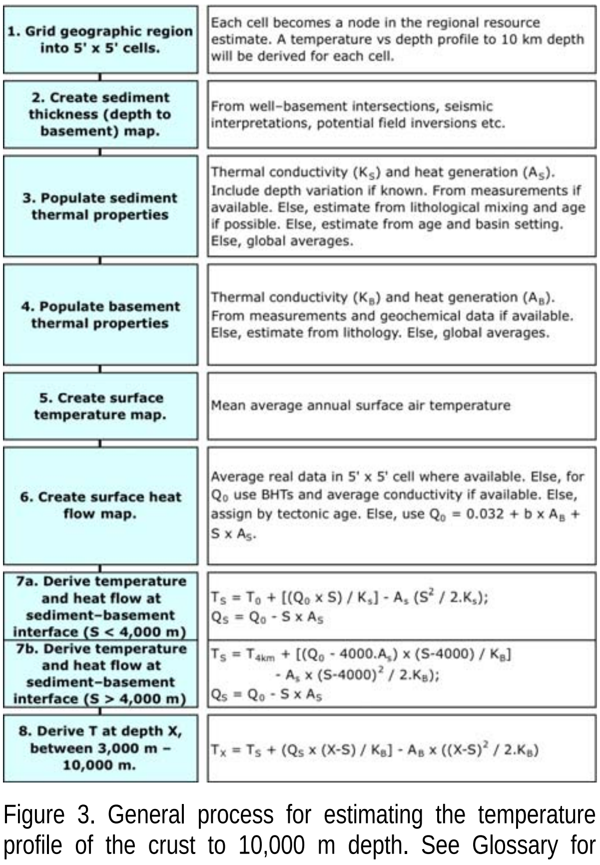
3. Estimate the Technical Potential given current technology, geographic, ecologic, legal and regulatory restrictions

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

Model temperature, heat flow and heat in the Earth's crust down to a depth of 10,000 m

The temperature in the crust can be estimated using a 'top down' approach, where surface heat flow (Q_0) is assumed to extend downwards, 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. The Protocol recommends estimating the temperature profile through the top 10,000 m of crust using a 'top down' approach. Figure 3 provides a flow chart for a process that can be applied for any location.



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)	$T_S = T_{4km} + [(Q_0 - 4000.A_s) \times (S\text{-}4000) / K_B] - A_s \times (S\text{-}4000)^2 / 2.K_B);$ $Q_S = Q_0 - S \times A_S$
8. Derive T at depth X, between 3,000 m – 10,000 m.	$T_X = T_S + (Q_S \times (X\text{-}S) / K_B] - A_B \times ((X\text{-}S)^2 / 2.K_B)$

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

The region under investigation is first divided into a regular grid. 5' x 5' graticules are recommended as the basic 'cell' size. A region such as Australia (7.6 million square kilometres at an average latitude of around 25°S) requires ~100,000 cells.

The next step is to chart the average thickness of 'sediment' overlying 'basement' in each 5' x 5' cell—in effect, develop a 'depth to basement' map for the region of interest. For Australia, the SEEBASE^{TM} database provides a first pass estimate of the thickness of Phanerozoic basins across the continent (Figure 4), and can be freely downloaded over the Internet. SEEBASE™ is a registered trademark of FrOG Tech Pty Limited in Australia, and stands for Structurally Enhanced view of Economic BASEment.

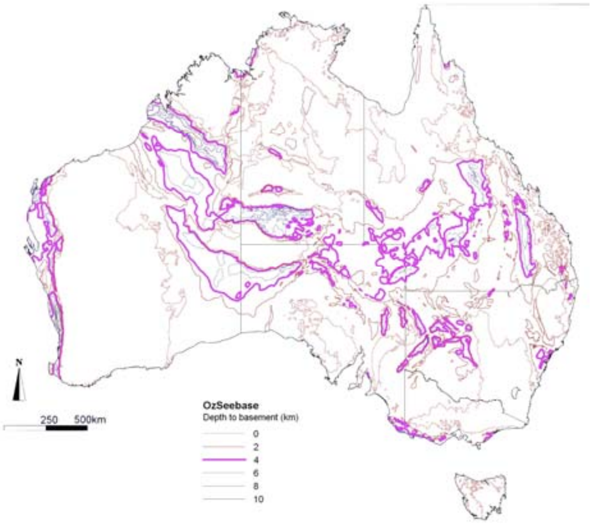


Figure 4. A visualization of the SEEBASE^{TM} database.

Temperature can be predicted at any arbitrary depth for a given surface heat flow (Q_0), thermal conductivity and heat generation (A) structure. The temperature prediction process requires that the sediment and basement sections of each cell be individually characterised with values of thermal conductivity (K_S and K_B for sediment and basement, respectively) and heat generation (A_S and A_B, respectively). To maintain consistency with Blackwell *et al*. (2007), the Protocol assumes that the thermal conductivity of sediment deeper than 4,000 m is the same as the basement (K_B).

Mean surface temperature (T_0) is an important boundary condition for models of underground temperature and for estimates of EGS potential. The Protocol assumes that mean surface rock temperature is approximately equal to mean surface air temperature.

Temperatures at depth are estimated in two steps. The first step is to estimate the temperature at the sediment–basement interface (T_S). T_S is derived using one or both of the following formulae, depending on whether sediment thickness (S) is greater than or less than 4,000 m.

If S < 4,000 m:

$$T_S = T_0 + [(Q_0 \times S) / K_S] - A_S \times [S^2 / (2 \times K_S)] \qquad \text{Eq 1}$$

If S > 4,000 m, the conductivity of that portion of sediment deeper than 4,000 m is K_B. In this case, first calculate T_{4km} using S = 4000 in Eq 1, then:

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

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:

$$Q_S = Q_0 - S \times A_S \qquad \text{Eq 3}$$

The second step is to estimate temperature at depth (X) in the basement (T_X):

$$T_X = T_S + [(Q_S \times (X-S)) / K_B] - A_B \times [(X-S)^2 / (2xK_B)] \qquad \text{Eq 4}$$

At the completion of this step, a mean predicted temperature profile to 10,000 m depth should be available for each 5' x 5' cell.

Estimate the Theoretical Potential of EGS power in the crust down to a depth of 10,000 m

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 5 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.

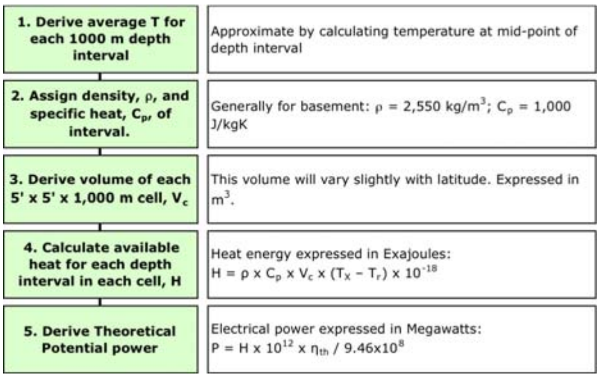


Figure 5. General process for estimating stored heat energy and theoretical power generation potential. See Glossary for symbol definitions.

Crustal temperature is the key determinant of Theoretical Potential for EGS at any specific location. Equation 4 provides this value for any specific depth. To relate temperature to heat content in a particular volume of crust, we need to assign a density (ρ) and specific heat (C_p) value for the volume of interest.

Each depth interval beneath a surface cell will contain a different amount of thermal energy. The total available heat in exajoules (H) in a volume of crust (V_c) is a function of the temperature, density, specific heat, and a 'base temperature' (T_r):

$$H = \rho \times C_p \times V_c \times (T_X - T_r) \times 10^{-18} \qquad \text{Eq 5}$$

The base temperature is the temperature to which the crust can theoretically be reduced through utilization of geothermal heat. The Protocol proposes following the lead of the USGS in a recent assessment of geothermal potential in the USA (Williams *et al.*, 2008), in which the USGS assumed approximately $T_r = T_0 + 80°C$.

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 life span of power generation
3. Cycle thermal efficiency, η_{th}, is a function of resource temperature as per MIT (2006):

$$\eta_{th} = 0.00052 \times T + 0.032 \qquad \text{Eq 6}$$

Note that the temperature appropriate for Eq 6 is the average of the initial rock temperature and the base temperature:

$$T = (T_X + T_r) / 2 \qquad \text{Eq 7}$$

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

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

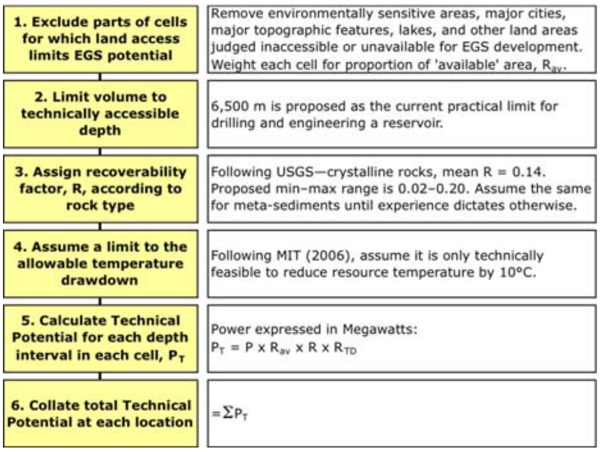
Theoretical Potential power generation can be collated and tabulated for specific depth and temperature intervals.

Estimate the Technical Potential given current technology, geographic, ecologic, legal and regulatory restrictions

It is impossible to realize the entire Theoretical Potential for EGS power in any 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 sense, including factors such as land access, rock type, drilling technology, fracture density, stress orientation, regulatory framework, power conversion technology and availability of water.

Rybach (2010) argues that "the EGS potential cannot yet be termed 'technical'", but the Protocol proposes a set of assumptions for deriving an estimate of Technical Potential. The steps are illustrated in Figure 6.

National parks, conservation areas, densely populated areas, mountains, large lakes and swamps, militarized zones, deserts with no available water resources, and other areas may be excluded from EGS development. The proportion of each cell that is accessible and available for EGS (R_{av}) is a value between 0–1.



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 6. General process for estimating Technical Potential of EGS from the Theoretical Potential. See Glossary for symbol definitions.

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.

Recoverability factor (R) is the proportion of heat that can ultimately be recovered from a volume of rock. The Protocol suggests estimates of potential be based on a range of R values representing the expected minimum, maximum and mean values. This Protocol proposes 0.02 as the minimum R, following the precedent of MIT (2006), and 0.14 and 0.20 as the mean and maximum R, respectively, following the findings of Williams *et al*. (2008). These values are based on the results of numerical modelling. While they fulfil the aim of the Protocol to provide a globally consistent set of assumptions, estimates of Technical Potential using this Protocol should only be viewed as preliminary until such time as practical experience provides real data on recoverability.

There is 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:

$$R_{TD} = 10 / (T_X - T_r) \qquad \text{Eq 9}$$

The Technical Potential (P_T) is that part of the Theoretical Potential accessible from the surface, shallower than 6,500 m, accessible via fracture networks, and available with <10°C drawdown:

$$P_T = P \times R_{av} \times R \times R_{TD} \qquad \text{Eq 10}$$

Technical Potential power generation can be collated and tabulated for specific depth and temperature intervals.

Define a level of confidence in the estimated Technical Potential at each location, consistent with public Reporting Codes

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

In areas where the 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.

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 this Protocol could be assigned numerical uncertainty values, which could then be propagated through the calculations to determine the uncertainty of the estimated Potential at each cell location and depth. Such an approach is allowable under the Reporting Codes, and could be added to a future version of the Protocol. It would provide an additional valuable layer of information.

Present results using common visualization and data architecture

Assessments of EGS potential generated as a result of the Protocol are intended to be public data, freely and conveniently accessible to all interested parties. 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 is a reference for visualization architecture (available at www.google.org/egs).

Differences from the MIT report

The intention of the Protocol is to conform closely to the methodology utilized by MIT (2006) to assess the EGS potential of the United States. However, the Protocol departs from that methodology in some key ways.

Firstly, the Protocol explicitly differentiates between Theoretical Potential and Technical Potential.

Secondly, the 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, the 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, the Protocol recommends assessing EGS potential relative to a base temperature of T_0 + 80°C, rather than relative to T_0.

Conclusions

Estimates of EGS potential derived using the Protocol will not be 'final'. They will continue to be refined as more relevant data become available. Theoretical Potential will be refined as new geological and geophysical data 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. The Protocol will, therefore, be a 'living document'.

The authors hope that the EGS potential of most of the world's continental surface will eventually be assessed and charted following the guidelines of the Protocol, allowing for the first time a coherent 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.

Acknowledgements

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Glossary of symbols

η_{th}: 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 (10000 if S < 3000 m, else [13000 – S]) (m)

C_p: specific heat capacity (J/kgK)

H: total available thermal energy (EJ)

$K_{S,B}$: thermal conductivity: sediment, basement (W/mK)

P: Theoretical Potential EGS power (MW$_e$)

P_T: Technical Potential EGS power (MW$_e$)

$Q_{0,S}$: heat flow: surface, base of sediment (W/m^2)

R: recoverability factor (0–1)

R_{av}: proportion of cell available for EGS (0–1)

R_{TD}: 'temperature drawdown' recoverability factor (0–1)

S: thickness of sediment (m)

$T_{0,S,X}$: crustal temperature: surface, sediment base, depth 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)