June 16, 2025

Utah FORGE Geothermal Resource Assessment Based on Stored Heat

Stuart F Simmons & Ben Barker
EGI, University of Utah

Background

Geothermal resources and their energy production potential are generally assessed using datasets derived from a range of different types of measurements, including geoscientific surveys, temperature logs, and fluid production well tests (e.g., Grant and Bixley, 2011). A simple first order method for determining the available thermal energy (Q) involves a stored heat calculation;

(1) $$Q = V\,(1 - \phi)\,\rho\,C\,(\Delta T)$$

which is based on the reservoir volume (V), porosity (ϕ), rock density (ρ, kg/m^3), specific heat of rock (C, kJ/kg°K), and the difference between the reservoir temperature and a cutoff temperature (ΔT°C; Muffler and Cataldi, 1978). Although application of this type of assessment to reservoirs hosted in convective hydrothermal systems has been problematic (e.g., Hochstein, 1988; Grant, 2018), the stored heat calculation is ideally suited for hot dry rock EGS reservoirs where thermal energy originates locally from host rocks penetrated by a pair of closely spaced wells wherein one is used for injection of cold water and the other the production of hot water (e.g. Tester et al., 2006).

EGS energy transfer and production relies on a process often referred to as heat sweep, in which injected cold water infiltrates the reservoir and heats up along fluid flow paths confined to series of roughly, parallel and planar stimulated fractures (i.e., ones that have been created or reopened via injection of pressurized water). Once steady state fluid flow is achieved, the narrow zones of hot rock situated directly adjacent to the margins of flowing factures are the prime source of extractable energy. At fine scale for a single fracture, the period of useful energy production is dictated by the interplay between high rate of advective heat transfer to the cold water and the slow rate of replacement by conductive heat flow through the rock. Conductive heat transfer is passive and thus causes rock cooling to become concentrated along the facture margin. Consequently, the even distribution of temperature across the hot rock in its initial reservoir state becomes transected by highly localized corridors of cooling along fractures that facilitate fluid flow. To optimize the extraction of thermal energy at a continuous rate from an EGS reservoir, a number of close-spaced factures are stimulated to penetrate the reservoir uniformly and create a very large surface area so that energy can be collected along multiple fluid flow paths. For resource management, forecasts of energy production and reservoir drawdown rely on numerical models that capture and quantify the fine scale dynamical complexity of heat transfer processes occurring in the reservoir. Notably, once thermal energy is extracted, a considerable length of time will be required to reheat the rock as heat transfer via conduction is exceedingly slow. In this respect, the amount of energy that can be produced from a hot dry rock reservoir is effectively finite, and the volumetric stored heat calculation provides a first order upper limit on the total amount of energy that can be economically produced.

Describing the dynamics of reservoir heat transfer is simplified by designating a variable called the recovery factor (r). The recovery factor represents the aggregated fraction of the heat that can be recovered over the productive life of the reservoir. As there are too few examples to draw on, the determination of recovery factor in EGS operations is poorly constrained and estimates range widely from <2 to >20% (Tester et al., 2006; Grant and Garg, 2012; Grant, 2018; Ciriaco et al., 2020). The recovery factor represents a source of significant uncertainty in making resource assessments. Nonetheless, it helps to focus attention on the importance of optimizing heat transfer across the reservoir as a key goal of energy production. To convert the fraction of producible stored heat into thermal power output (MW_{th}), the total amount (Q) is multiplied by r and divided by the period of production. To convert to electrical power output (MW_e), the thermal power output is multiplied by the power plant conversion efficiency (η), which reportedly ranges between 5 and 15% (e.g., DiPippo, 2004; Ciriaco et al., 2020); i.e.,

(2) $$MW_e = \eta \, r \, Q \quad .$$

With equations (1) and (2), a parametric evaluation of stored heat can be undertaken based on specified volumes of stimulated hot rock which form the EGS reservoir as is shown below.

Stored Heat at Utah FORGE

The hot dry rock reservoir is hosted by fractured granite and gneiss having a temperature that is bracketed by the 175° and 225°C isotherms (Figure 1). With the high confining stress at reservoir depth, the fractures are closed and impermeable until stimulated with pressurized water and propped open. Proppants are a subject of Utah FORGE testing, the most common being fine quartz sand (e.g., England et al., 2024). For the stored heat calculation, the reservoir volume is defined simply by a cylinder centered on the deviated legs of wells 16A(78)-32 and 16B(78)-32 (Figure 2). The 500 m radius represents the extent of detected microseismicity during fracture stimulation (Niemz et al., 2024), and the cylinder length of 1200 m (~4000 ft) covers the full distance of the deviated legs. This provides a reasonable upper limit for the reservoir volume of close to 1 km^3, having a porosity that is effectively nil (<1%). The ΔT is calculated using a midpoint reservoir temperature of 210°C between 2-3 km depth and a cutoff temperature of 120°C, below which commercially viable power generation is marginal. Based on measured values, the rock density is 2700±100 kg/m^3 and the specific heat is 1.0±0.1 kJ/kg°K (Whittington et al., 2009; Gwynn et al., 2019), the calculated stored heat is 2.43×10^{14} kJ/km^3 (Table 1). For a production period of 25 years and recovery factors ranging from 100 to 1%, the thermal power outputs range from 308 to 3.1 MW_{th} (Table 2). Shortening the production period to 10 years increases the thermal power outputs, which range from 771 to 7.7 MW_{th} (Table 2).

The Utah FORGE footprint for operation is restricted to about 2 km^2, and the concept of developing deeper reservoirs is illustrated in Figure 3. The additional stored thermal energy gained is presented in Tables 1 and 2, with the total stored heat being 1.3×10^{15} kJ, which is over five times the amount in the 2 to 3 km depth interval alone. Total power outputs over a 25-year period range between 1336 to 13 MW_{th} for recovery factors of 100 to 1% (Table 2). Using reasonably conservative estimates for recovery factors in the range of 10-20%, the 25-year power output is between 134 and 267 MW_{th}.

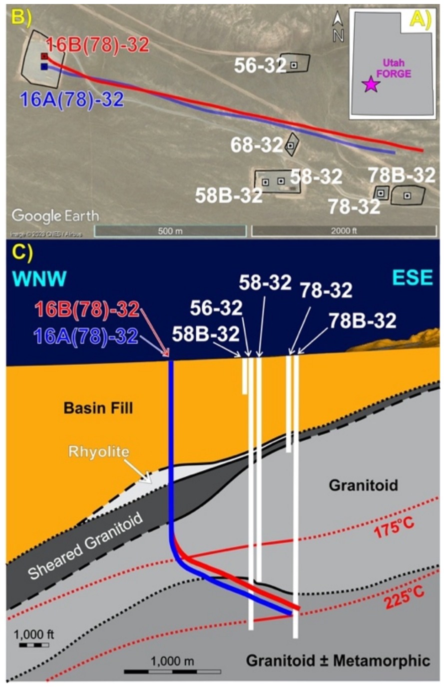

Figure 1. Map (A), plan (B) and cross section (C) views of the location of the Utah FORGE site, wellfield layout and the underlying geology hosting the EGS reservoir, respectively. The reservoir rocks comprise granitoids and gneiss, which are composed mainly of coarsely crystalline alumino-silicate minerals and quartz (Jones et al., 2024).

Table 1. Calculated values of volumetric stored heat at Utah FORGE for depth intervals between 2-3, 3-4 and 4-5 km below the surface.

depth (km)	reservoir T °C	To		stored heat kJ/m³	stored heat kJ/km³
2 to 3	210	120		243000	2.43E+14
3 to 4	280	120		432000	4.32E+14
4 to 5	350	120		621000	6.21E+14
				1.3E+06	**1.3E+15**
Q = (1-Φ)ρ Cr (Tz-To)					
ρ=2700 kg/m³; Cr=1.0 kJ/kg*K; Φ=0					
Temperature gradient 70°C/km					
2000 m depth temperature 175°C					
120°C cutoff temperature (T_o)					

Table 2. thermal power outputs (MW_{th}) based on stored heat and for 25 and 10 years of production on a per km³ basis.

	Thermal power production period: 25 years						Thermal power production period: 10 years					
depth (km)	100% MW	50% MW	20% MW	10% MW	1% MW		100% MW	50% MW	20% MW	10% MW	1% MW	Recovery factor
2 to 3	308	154	62	31	3.1		771	385	154	77	7.7	
3 to 4	548	274	110	55	5.5		1370	685	274	137	14	
4 to 5	788	394	158	79	7.9		1969	985	394	197	20	
	1336	**668**	**267**	**134**	**13**		**4110**	**2055**	**822**	**411**	**41**	***Total***

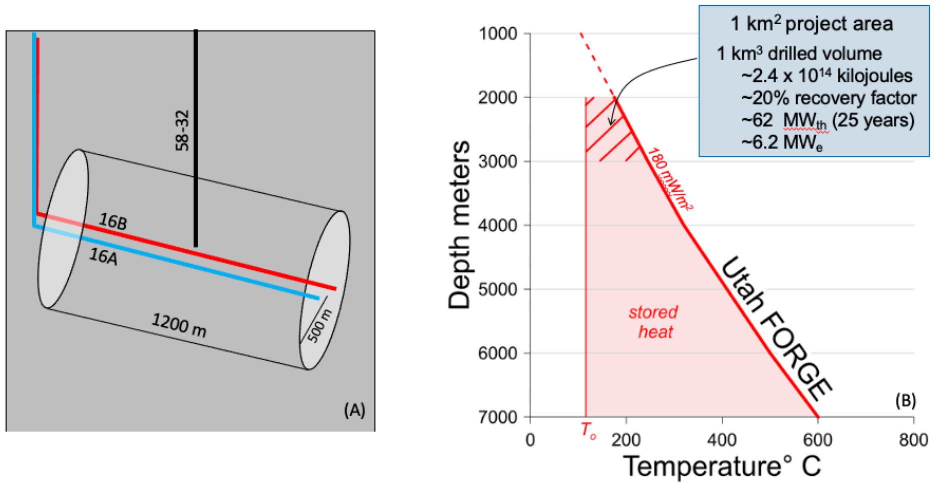

Figure 2: A) Schematic of the reservoir volume; B) representation of the depth interval (2-3 km, hachured zone) for the stored heat calculation and power outputs ($\eta = 10\%$), with the Utah FORGE thermal gradient from Allis et al. (2019).

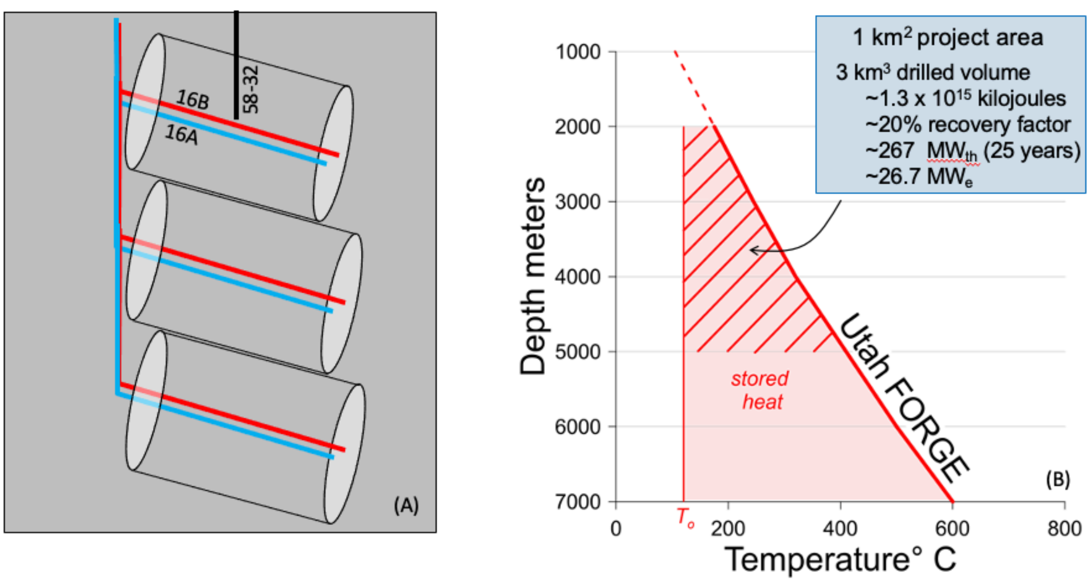

Figure 3: A) Schematic of stacked reservoir volumes (3 km^3 total); B) representation of the depth intervals (2-5 km, hachured zone) for the stored heat calculation.

Power Production During Circulation Test at Utah FORGE

For comparison, the energy produced during the 27-day circulation test (8 August to 4 September, 2024) are examined. During this trial, cold water was injected into 16A(78)-32 at 2800 to 3000 psig and 10 bpm (420 gpm, 26.5 l/s), and hot water was produced from 16B(78)-32 at 200 psig, 365° to 385°F (185° to 196°C), and 9 bpm (378 gpm, 23.9 l/s). Two separate calculations are shown below: 1) produced thermal energy based on a 25°C cutoff, relevant to ambient temperature during the test; 2) produced thermal energy based on a 65°C cutoff, relevant to one that is being considered for future testing involving cooling and small power generating units.

1) Taking the difference between the enthalpies of 785 to 869 kJ/kg (IF-97 Steam tables; www.x-eng.com) for the produced fluid temperature (H_{prod}) and an enthalpy of 104.8 kJ/kg for a 25°C cutoff temperature (H_{25C}) and multiplying by the mass flow rate (W), i.e.,

   $MW_{th} = W\ (H_{prod} - H_{25C})$,

   the power outputs for 16B ranged between 14.1 and 16.0 MW_{th} (Table 3). The total energy produced is between 3.3 x 10^{10} and 3.7 x 10^{10} kJ.

Table 3. Calculated thermal power outputs (MW_{th}) for well 16B(78)-32 during flow test, using a 25°C cutoff temperature.

Inlet T° C	*Inlet H kj/kg*	*Outlet T°C*	*Outlet H kj/kg*	*Delta H*	*kg/s*	*MW_{th}*	*Total kJ*
185.0	785.3	25	104.8	680.5	20.8	14.1	3.30E+10
190.6	875.5	25	104.8	770.7	20.8	16.0	3.73E+10
196.1	869.2	25	104.8	764.4	20.8	15.9	3.70E+10

2) Taking the difference between the enthalpies of 785 to 869 kJ/kg for the produced fluid temperature (H_{prod}) and an enthalpy of 272 kJ/kg for a 65°C cutoff temperature (H_{65C}) and multiplying by the mass flow rate (W), i.e.,

   $MW_{th} = W\ (H_{prod} - H_{65C})$,

   the power outputs for 16B ranged between 10.7 and 12.5 MW_{th} (Table 4). The total energy produced is between 2.5 x 10^{10} and 2.9 x 10^{10} kJ.

Table 4. Calculated thermal power outputs (MW_{th}) for well 16B(78)-32 during flow test, using a 65°C cutoff temperature.

Inlet T° C	*Inlet H kj/kg*	*Outlet T°C*	*Outlet H kj/kg*	*Delta H*	*kg/s*	*MW_{th}*	*Total kJ*
185.0	785.3	65	272	513.3	20.8	10.7	2.49E+10
190.6	875.5	65	272	603.5	20.8	12.5	2.92E+10
196.1	869.2	65	272	597.2	20.8	12.4	2.89E+10

The preceding shows that the cutoff temperature has obvious significance in calculating power outputs as dictated by conditions of production, including the type of plant being used for energy utilization (e.g., condensing turbine vs. binary plant vs. direct use).

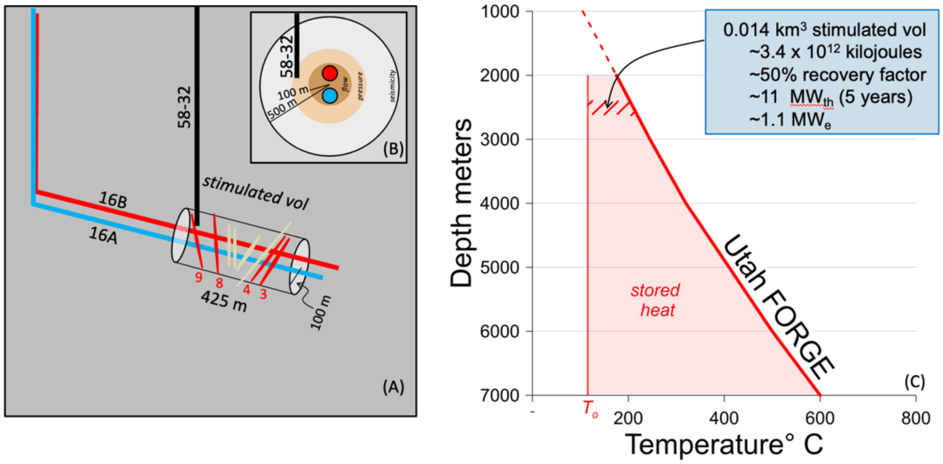

Figure 4: A) Schematic of active reservoir volume at Utah FORGE and of the factures controlling fluid flow (numbers indicate stimulation stages in 16A) during the circulation test; B) vertical profile perpendicular to (A) showing gun barrel views of 16A and 16B relative to vertical well 58-32 and fields of active flow (brown), pressure propagation and microseismicity (tan); C) the depth interval (2.4 to 2.6 km, hachured zone) for the stored heat calculation.

To estimate the proportion of heat that was produced during the circulation test, the reservoir volume is reduced in size to more realistically represent the active volume of facture-controlled fluid flow between 16A(78)-32 and 16B(78)-32 as shown in Figure 4. In this case, the volume is represented by a cylinder having a radius of 100 m and a length of 0.425 km, comprising 0.014 km^3. The producible stored heat is 3.4 x 10^{12} kJ (Table 5). For production periods of 5 and 10 years, the power outputs range from 22 to 0.22 MW_{th} and from 11 to 0.1 MW_{th}, respectively (Table 6). Using the much smaller volume of active flow, the short-term recovery factor over the 27-day period of circulation test appears to be 50% or greater, but this is expected to decline over time as heat is extracted from the margins of flow pathways.

Table 5. Calculated volumetric stored heat for the active flow volume (0.014 km³) at Utah FORGE.

depth (km)	reservoir T °C	To		stored heat kJ/m^3	stored heat kJ/km^3	reservoir volume km^3	kJ stored heat
2 to 3	210	120		243000	2.43E+14	0.014	3.40E+12

Table 6. Calculated power outputs based on stored heat in active flow volume (0.014 km³) for 5 and 10 years of production.

Thermal power production period: 5 years						Thermal power production period: 10 years				
100% MW	50% MW	20% MW	10% MW	1% MW		100% MW	50% MW	20% MW	10% MW	1% MW
22	10.8	4.3	2.2	0.22		11	5	2	1	0.1

Having calculated the total heat loss resulting from the 27-day circulation test (3.3 x 10^{10} and 3.7 x 10^{10} kJ; Table 3) and having redefined the active volume of heat transfer as shown in Figure 4A, the fraction of produced thermal energy is ~1% of the original pre-circulation test value of stored heat. This equates to a uniform drop in reservoir temperature of ~ 1°C (i.e., from 210 to 209 °C); such a calculation is for illustration purposes, only, as the thermal drawdown of the reservoir in its current state is instead expected to be non-uniform and highly localized around stimulated fractures.

Key Points

- The foregoing analysis provides an upper limit of the amount of thermal energy that can be produced from the Utah FORGE reservoir. For a reservoir volume ~1 km^3 having a cylindrical shape shown in Figure 2A, this amounts to ~2 x 10^{14} kJ.
- Currently, the stimulated reservoir volume is much smaller ~0.014 km^3 and more closely reflects that shown in Figure 4A, with ~3.4 x 10^{12} kJ of stored heat.
- During the 27-day circulation test, between 3.3 x 10^{10} and 3.7 x 10^{10} kJ of thermal energy was produced at a power output between 14 and 16 MW_{th} (Table 3); for this period, the thermal reservoir drawdown is ~1% equating to a theoretical uniform temperature drop of ~1°C. Thermal drawdown, however, will be localized to the margins of the actively flowing fracture corridors shown in Figure 4A.
- Although relatively simple, the stored heat calculation highlights the importance of the recovery factor in maximizing power production, and it provides a basis for comparing the thermal power production during circulation tests.
- The stored heat calculations also provide an estimate of the potential producible energy from the underlying resource covering an area 1 km^2 and located between 2 and 5 km depth (i.e., 3 km^3) of ~1.3 x 10^{15} kJ, which is about four times larger than that estimated over the 2 to 3 km depth interval.
- The Utah FORGE project lies within an area, covering at least 40 km^2, that is underlain by hot dry rock (Allis et al., 2019). The total productivity of the volume of hot rock between 2 and 5 km depth over 25 years (Table 3) could attain between 500 and 1000 MWe (assumes 10-20% recovery and 10% conversion of thermal to electrical energy). Improvements in recovery or conversion factors could lead to a doubling or tripling of such estimates.

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Abbreviations

°C: temperature Celsius
°F: temperature Fahrenheit
°K: temperature Kelvin
bpm: barrels (159 liters) per minute
gpm: gallon (3.79 liters) per minute
H: enthalpy (kJ/kg)
kg: kilogram
kJ: kilojoule
l: liter
m: meter
MW_e: power in megawatts electrical energy (~10% of MW_{th})
MW_{th}: power in megawatts thermal energy
psig: pounds per square inch gauge reading