Geothermal energy (heat from the Earth’s interior) is utilized for thermal energy and electrical energy production. The resource is huge but low grade; the best/hottest resources are localized, dependent on geology. Conventional hydrothermal resources have been in production for ~100 yrs; but long payback period + financial risks due to uncertainty in fluid flow systems & resource assessment. Unconventional resources EGS-type resources are difficult to develop; i.e., how do you produce energy from a large volume (100-500 km³), hot “dry” rock at 3-5 km depth? DOE FORGE represents new, big R&D support for an EGS field laboratory; new opportunity for advancing novel technologies. Utah test site is being proposed.
**Why use geothermal energy?**

**Strengths**
- Clean, renewable energy
- Base load generation
- Low cost to maintain
- Climate/weather independent
- Reliable

**Weaknesses**
- Long lead time: concept to production
- Large entry barriers
- High upfront costs/risks
- Cannot be stored/exported
- Location controlled by geology

**Commercial considerations**
- Resource information
- Managing risks & costs
- Electricity generation
- Location with respect to grid & market
- Availability of skilled personnel
- Direct use

**Efficient use of geothermal energy involves direct heating applications**

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**Diverse Nature of Geothermal Resources**

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**Total Installed Electricity Generation ~11-12 GWe**
Mokai: parallel development of high & low enthalpy resource use

111 MW power station
12 Hectares of glass house

power station
well head
glass house
tomatoes for export

Taupo Volcanic Zone, North Island, New Zealand

Power Cycles & Electricity Generation

condensing turbines  
binary plant

liquid-dominated reservoir  
vapor-dominated reservoir  
liquid-dominated reservoir

>200° C  
~240° C  
<200° C

Wairakei 2010

~235 MW capacity
1729 GWh of net generation
54.6 million tonnes geothermal fluid
60.8 petajoules thermal
>90% load factor
>50 years of production

Geothermal Power

\[ \text{MW}_{\text{th}} = m \times (H_{\text{reservoir}} - H_{75^\circ}) \]
Geothermal Systems: Stored vs Flowing

- Reservoirs < 3 km depth
- Liquid-dominated (100-300°C)
- Vapor-dominated (220-250°C)

Reservoir Heat Transfer-Idealized

- Injection
- Production
- Aquifer
- Ground surface
- Water level
- Cold water
- Hot water

Grant et al. 1982
High temperature systems occur along plate boundaries, including: 1) mid-ocean ridges and continental rifts (Olkaria, Kenya; Aluto, Ethiopia); 2) ocean island (Hawaii, Iceland) and continental hot spots (Yellowstone, USA); 3) volcanic-magmatic arcs (Taupo Volc Zone, New Zealand; Sumatra & Java, Indonesia; Philippines; S. Kyushu, Japan; Central Mexico; El Salvador, Nicaragua, Costa Rica, Lardarello, Italy).
Conventional Geothermal Resource

Reservoirs
- 220 to >300°C
- surrounded by cold rock
- hydraulically connected
- >10^{17} J/km^3 in rock
- 50-300 kg/s deep
- natural inflow

Hydrothermal System Lifespan 10,000 to >100,000 years
Energy in Fluid: Vapor versus liquid H₂O

Critical Point: 374 °C, 221 b
Enthalpy (H): 2100 kilojoules/kg

At 250 °C
- H_{water} = 1086 kJ/kg
- H_{vapor} = 2800 kJ/kg
Cyclone Separator—Early Engineering Milestone

Wells produce two-phase fluid: 25% steam & 75% water. Steam/water separation plants were a key innovation that allowed development of liquid-dominated reservoirs. This technology was proven with the development of the Wairakei resource.

Resource Assessment: Stored Thermal Energy

T gradients in crust

Boiling point for depth (hydrostatic pressure) is the max T gradient in high T systems

Anomalous heat measured against normal gradient
\[ \Delta Q_R \text{ heat stored in rock (J/m}^3\text{)} \]
\[ \Delta Q_F \text{ heat stored in pore fluid (J/m}^3\text{)} \]

\[ \Delta Q_R = (1 - \Phi) \rho_p c_R [T_z - T_{z0}] \]
\[ \Phi \text{ porosity, } \rho_p \text{ density, } c_R \text{ specific heat, } T_z \text{ & } T_{z0} \text{ temperatures in & out} \]

\[ \Delta Q_F = (\Phi) \rho_L [h_z - h_{z0}] \]
\[ \Phi \text{ porosity, } \rho_L \text{ density, } h_z \text{ & } h_{z0} \text{ enthalpies in & out} \]

\[ \Sigma Q = \Delta Q_R + \Delta Q_F \text{ Total Stored Heat} \]

Note sources of uncertainty:
- reservoir volume (diffuse vs sharp boundary)
- reservoir temperature
- recoverable energy not considered

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### Geothermal Energy

**GEOLOGY**

**Physical:**
- Heat & mass transfer
- Temperature-pressure gradients
- Permeability-porosity
- Hydrology & fluid flow

**Chemical:**
- Fluid compositions
- Fluid-mineral equilibria
- Mineral corrosion/deposition
- Hydrothermal alteration
New Zealand Geothermal Energy

Unique tectonic setting straddling a plate boundary.

Extensional volcanic arc (10 mm/y) due to oblique subduction (North Island)

Transpressional transform fault-Alpine Fault (South Island)
Taupo Volcanic Zone Geothermal Fields

Extensional basin-volcanic arc
high heat flow volcanism,
seismicity & hydrothermal activity

Structures segmented rift NE-SW
normal faults caldera volcanoes

Hydrothermal systems (red=low
resistivity)

Compare the locations of volcanic
centers, faults, & hydrothermal
systems

Wairakei (>50 yrs)

25 km² (reservoir 10 km²)
Hot springs & geysers in
valley on northern edge
Fumaroles & steaming
ground in the south
Borefield in between surface
features.
Reservoir boundaries
unknown when first drilled
Faulted volcanic stratigraphy

Rosenberg et al. 2009 (Geothermics)
Wairakei (>50 yrs)
50/150 wells (<2.5 km)
3 km³ fluid produced
2750 Petajoules
1450 kg/s
1130 kilojoules/kg
20 bar pressure drop
No injection

*Bixley et al. 2009 (Geothermics)*

Wairakei: Next 50 Years

- 15 MW binary plant commissioned 2005
- 150 MW power station baseload operation >50 years

- Total fluid production matches estimates of total pore fluid in reservoir, but exceeds natural flow rate. Production increases 1.7x this year.
- No signs of reservoir degradation/cooling. Implies deep inflow has substantially increased as a result of production stimulation-unpredicted.
- Additional 166 MWe was just commissioned. Numerical models forecast sustainable production for next 50 years.
**USA Resource Potential**

- $14.0 \times 10^6$ EJ Stored thermal energy 3-10 km depth
- $0.28 \times 10^6$ EJ requires 2% Recovery
- 100 EJ Total consumption (2005)

$EJ=10^{18}$ joules

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**San Andreas Fault System & Great Basin**

<table>
<thead>
<tr>
<th>Project</th>
<th>MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geysers</td>
<td>850</td>
</tr>
<tr>
<td>Cerro Prieto</td>
<td>750</td>
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<tr>
<td>Salton Sea</td>
<td>410</td>
</tr>
<tr>
<td>Coso</td>
<td>302</td>
</tr>
<tr>
<td>Roosevelt</td>
<td>26</td>
</tr>
<tr>
<td>Steamboat Spgs</td>
<td>48</td>
</tr>
<tr>
<td>Mammoth</td>
<td>40</td>
</tr>
<tr>
<td>Beowawe</td>
<td>18</td>
</tr>
<tr>
<td>Dixie Valley</td>
<td>66</td>
</tr>
<tr>
<td>Raft River</td>
<td>13</td>
</tr>
</tbody>
</table>

no evidence of magmatic heat source

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*Heat Flow Map*

*Dorsey 2010*
reservoirs < 3 km depth

Geysers: Vapor-Dominated Reservoir

liquid-dominated (100-300°C) vapor-dominated (220-250°C)

enthalpy kJ/kg

Great Basin

Dixie Valley
Beowawe

First wells drilled 1959
Boiling point for depth to ~200 m
Temperature reversals at depth

Faulder et al 1997

Resource discovery drilled 1974
215°C @ 1200 to >2000 m depth
Reservoir: Valmy Fm & Malpais fault damage zone

Faulder et al 1997
Natural heat flow 17 MWth at 230°C at 20 kg/s
Resource permeability in fracture mesh in the hanging wall
Deep thermal water-Pleistocene, dilute, bicarbonate-rich, alkaline pH
Plume rises at an angle along basin bounding fault zone

Power plant commissioned 1985; Reservoir volume <1 km³
Cool water inflow reduced production (later recovered)
Modern production history 250-260 kg/s at ~215°C sustains ~17 MWe
Total fluid production is 40% greater than reservoir resource
Deep inflow stimulation likely

Diversity of Conventional Resources

<table>
<thead>
<tr>
<th>Reservoir Type</th>
<th>Temperature Range</th>
<th>Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary Basin</td>
<td>100-300°C</td>
<td>1000-2000</td>
</tr>
<tr>
<td>Volcano-Intrusion</td>
<td>220-250°C</td>
<td>2000-3000</td>
</tr>
</tbody>
</table>
Engineered Geothermal Systems (EGS)

Deep hot rock
Induce fracture permeability
Inject fluid to advect thermal energy to surface
35 years of R&D (USA, Japan, Europe, Australia)

1.5 MWe plant Soults-sous-Forêts (France)
4 wells: 2 to 5 km depth, ~200°C
Temperature gradient: 40°C/km
Extensional tectonics: fracture connectivity restricted in granite basement (>1400 m depth)
Induced seismicity causes delays

Unconventional Resources

Enhanced/Engineered Geothermal Systems (EGS)

Fenton Hill (USA)
Rosemanowes (UK)
Hijiori-Ogachi (Japan)
Soults-sous-Forêts (France)
Basel (Switzerland)
Cooper Basin (Australia)
**EGS Cooper Basin, Australia**

Prospect area 2000 km²

Hot granite (radiogenic heat) beneath 4 km sedimentary rock

4 wells: >4 km depth, whp 350 bar, >240°C

Temperature gradient: ~60°C/km

Horizontal compression: Flat fracture system-connectivity between wells

1 MW power plant commissioned 2012

Development suspended because of insufficient funds & excess supply

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**Magmatic geothermal resources (unconventional)**

**Krafla, Iceland (50 MWe)**

volcanic eruption 1975-1984

intruded volume: 1 m wide

9 km long

7 km deep

erupted volume: 100x10⁶ m³

temperature: >1100°C
Geothermal Energy: Sedimentary Basins

Heat Transfer: Hybrid Applications

Piceance Basin

T gradient >40°C/km
>250°C at 7 km
2 x 10^{17} \text{J/km}^3
Hot rock volume >6000 km³
70 MW_{thermal}/km² for ~100 yrs
Incentive for research
High demand for cooling & heating

>300°C required

Water demand

Geothermal for preheating over long term

Time span ~100 yrs

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**DoE-FORGE**

- Frontier Observatory for Research in Geothermal Energy (FORGE)
- Funding announcement for establishing & managing field lab
- Project comprises 3 Phases, with $31 million allocated for I & II. Main objective is site selection from a starting pool of 10.
- Phase I—12 mos; Phase II—12-24 mos; Phase III—60 mos
- EGI, U Utah is leading a consortium to recommend a site in central Utah
- Ideal site: 175-225°C, 1.5 to 4 km depth, low permeability (~10^{-16} m^2), crystalline basement rocks
- Phase III includes drilling, stimulation, testing, using innovative tools, methods, & supporting science/engineering
DoE-FORGE

- Phase I funding for full scale proposal
- Phase II funding supports geoscientific & environmental investigations & proving site logistics
- Seismicity (natural/induced) are significant concerns
- Successful site selection will open new R&D opportunities for engineers & scientists
- Diverse range of physical & chemical problems related to engineering sustained heat & mass transfer for energy utilization largely involving water-rock interactions
- Differs from unconventional oil & gas development, because energy flows need to be sustained & uniform for electricity production

Summary

- Geothermal energy (heat from the Earth’s interior) is utilized for thermal energy and electrical energy production.
- The resource is huge but low grade; the best/hottest resources are localized, dependent on geology.
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