Geothermal Power Concept for Singapore

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We need a feasibility study costing SG$ 2m
Singapore has world class heat flow

Singapore = 110-130 mW/m²

Geothermal Power for Singapore?

- Secure, base-load renewable energy
- Electric power, district cooling, process heating, desalination
- Predictable costs, probably cheaper than natural gas
- Close to market
- Contributes to renewable energy targets

Engineered Geothermal System (EGS), Hot Sedimentary Aquifer (HSA), Binary Cycle (BC)

One cubic km of buried granite at 200°C has the stored energy equivalent to 10 MW for 20 years.
Unconventional Geothermal: EGS and HSA in plate interiors

Conventional Geothermal: hot, wet volcanic rocks near active tectonic boundaries

Geothermal Power Plants
Provide 9700 MW for 60 m people
Number of EGS projects 1970-2010

Stafford (2010)
Recent EGS/HSA/DC geothermal exploration

- Germany, France, Australia, USA have commercial and demonstration EGS and HSA plants: use binary cycle generation

- Works programs in Australia (2002-13) worth US$903m


- 2009 Petratherm (HSA US$63m) + Geodynamics (EGS US$90m)

- 2010 Perth District Cooling (HSA/DC) (Green Rock En US$12.4m)

- 2010 Greenfire Energy $2m DoE Grant for CO2-based geothermal EGS, Arizona

- 2011 (April) Brady EGS (ORMAT) Seismicity during the EGS Injection (Mag < 0.58)

- 2011 (Oct) Pertratherm Paralana main fracture simulation 900 m (Mag < 2.6)
Heat flow map of SE Asia
data from oil and gas wells, Hall & Morley (2003)
Fig. 3: Contoured heat flow map of part of SE Asia.

- Singapore
- Sumatra
- Malay Basin

**Average geothermal gradient:**
- Singapore is twice the average gradient.
- Singapore: 32 – 40 °C/km
- Up to 80 °C/km

**Geothermal characteristics:**
- Williams & Eubank (1995)
- 100 km

**Legend:**
- Average continent
- Singapore is twice the average

**Scale:**
- mW/m²
Heat flow data points
Hall, pers. comm (2010)

Blue triangle = volcano.
Red = NGDC data.
Green = IPA/SEAPEX data
Distribution of >60 thermal springs from Chong (2010)
The distribution of temperature and flow rate of hot springs in the Malay Peninsula
Heat source is the subducted Wharton Spreading Ridge?

Whittaker et al. (2007)
Compare heat flow with USA

Desert Peak EGS 50 MW

Continental average 60 mW/m²

Singapore 110-130 mW/m²
Compare heat flow with Australia

Singapore
110-130 mW/m²

Europe: Temperatures at 5 km depth

Singapore = 205 - 230°C

Geology Map of Singapore with hot and cold springs

Lineament trend (35°E) from geology maps and satellite images. SI = Sentosa Island. UWC = United World College. PP = Punggol Point. MF = Mt Faber
Sembawang Hot Spring, Singapore

Discovered in 1909

In ~100 m bore holes the max $T$ of the water was 70.2°C. Estimated yield of approx 150 L/m. Pumped at 400 L/m.

$T = 70^\circ C$

Zhao et al (2002)
Results of chemical geothermometers
Temperature in the reservoir

- SiO$_2$ quartz, Fournier (1973) 125 °C
- SiO$_2$ Swanberg and Morgan (1979) 126 °C
- SiO$_2$ Carmicheal (1989) 125° C
- Na/K/Ca Fournier and Truesdell (1973) 166 ° C
- Na/K Fournier and Truesdell (1973) 169 ° C
- Na/K Fournier (1979) 162 ° C
- Na/K Truesdell (1976) 166 ° C
- Na/K Santoyo and Diaz-Gonzalez (2010) 163 ° C

Analyses listed in Lee & Zhou (2009)
Temperatures in springs on Bukit Temah

Jungle Fall Valley Spring 24°C at 120 m

Wallace Walk Spring 26°C at ~60 m

Temp incr 2°C in 60m = 3.33°C/100m
Geothermal gradient = 33.3°C/km

Compare with previous estimate of 35°C/km
Where is the heat in Singapore?
Geological Cross Section

Younger Alluvium (Recent)
Older Alluvium (<1.8 M yr)

Jurong Formation (210 M yr)
Gombak Gabbro (253 M yr)
Singapore Bukit Timah Granites (245-230 M yr)
Bukit Timah Granite
U = 6 +/- 1 ppm,
Th = 15 +/- 2 ppm
K2O = 4.00 +/- 0.1 wt %

Heat production from 10 km thickness of upper crustal granite gives a heat flow of 69 mWm^-2
cf actual ~120 mWm^-2

4 km?
Five Geothermal Prospects

- **Jurong Is**
  - Hot Sed Aquifer
  - Engineered Geothermal System
  - Boreholes 3 – 4 km

- **Punggol & Changi**
  - EGS in Hot Granite Rock

- **P. Tekong**
  - EGS/HGR
  - High heat flow from the mantle

**SW**

**NE**
Jurong Island HSA/EGS

Semakau: Unconfined Hot Sedimentary Aquifer?

Jurong Island Confined Hot Sedimentary Aquifer?

Sandstone Limestone Shales

Mt Faber 100m alt recharge 2.4 m rainfall

Sea water recharge

Fresh water recharge

Engineered Geothermal System

Granite

No deep geophysics
Naturally fractured Bukit Temah granite is an excellent heat reservoir.
Vertical cooling joints, horizontal exhumation joints

Dairy Farm Quarry, Singapore
Naturally fractured Jurong Formation

Naturally fractured sandstones

Jurong Formation is an excellent heat reservoir

Lokos Anticline
St John’s Island
Gyben/Herzberg model for Singapore

geothermal gradient of 35°C/km

\[ z = \frac{P_f}{P_s - P_f} \cdot h \]

Water table at 120m/24°C

Rainfall = 2.4 m / yr

Hot spring 70°C

150°C at 3.6 km
(Conduction model)

Hot spring 150°C at 2.8 km
(Convection model)

Cold sea water

Cold fresh water

Warm water

Hot water

Temperature at 4.8 km depth = 192°C
Groundwater Model

Annual Rainfall: 2000 - 2300 mm

Heat flow (110 - 130 mW/m²)
2D Model grid for Singapore
Tough 2 Software

Rainfall (cm):
- 200
- 205
- 215
- 225
- 230
- 225
- 205

4@2km
9km
3km

10.5km (Bkt Timah Granite)
5km (Bkt Timah Granite)

10km (Sea)
4.5km (Jurong F)

Singapore Strait
Reservoir
Sembawang Hot spring

Johor Strait

Residual Soil
Jurong Formation Sedimentary Rock
Bukit Timah Granite

Heat flow 130mW/m²

sw  \( k = 4-20 \text{ mD} \)

k 1.0-1.5 \text{ mD}
Simulation 1. Temperature distribution

160 mW/m²

Jurong/Semakau

150°C at 4 km

Sembawang hot spring

k 1.0-1.5 mD

190°C

170°C

150°C

130°C

110°C

100°C

80°C

60°C

30°C
Simulation 2. Temperature distribution

- Sembawang hot spring
  - Temperature: \( \geq 230^\circ C \)
  - Heat flux: \( 160 \text{ mW/m}^2 \)

- Jurong/Semakau
  - Temperature: \( 150^\circ C \) at 3km
  - Permeability: \( k \ 1.0-1.5 \text{ mD} \)
  - Includes radiogenic heat

- Bukit Temah Granite 3
  - Heat flux: \( 3 \mu \text{W/m}^3 \)

- Depth:
  - 3000 m
  - 4500 m
Simulation 3. Temperature distribution

The model is porous media. Singapore is 3D fractured granite.

- Jurong/Semakau
- Hot Spring 70°C
- 150°C at 2.2 km
- 150°C at 3.2 km
- Edge effect
- Granite $k = 0.1$ mD

Heat flow 130 mW/m². No radiogenics, very low $k$ in granite.
Simulation 2D03 – Salinity (mg/l)

- Singapore Strait
- Bukit Timah
- Sembawang hot spring
- Johor Strait
- Johor

Legend:
- 31500 - 35000
- 28000 - 31500
- 24500 - 28000
- 21000 - 24500
- 17500 - 21000
- 14000 - 17500
- 10500 - 14000
- 7000 - 10500
- 3500 - 7000
- 0 - 3500
Simulation 2D03 – Temp (°C)

2km/150°C
Model groundwater flow

Vert = horiz scale
Exploration well, Semakau

Cost of drilling using petroleum technology

= US$ 9m for 3 km

Sea Level

Drilling platform

Cold sea water in unconfined aquifer

2-3 km down to hot water at 150°C?

150°C

Stress regime?
Present day stress map of SE Asia = NE/SW open joints in Singapore?

Blue = Thrust F. Red = Normal F
Green = Strike Slip F, Black = Unknown
Predict that vertical joints in a NE/SW orientation will be open at \( \sim 3 \) km depth.

Brown-Hoek stress profile below 1 km, \( \sigma_2 \) is vert.

Conclude: production wells should be horizontal and orientated NW/SE.

Regional lineament trend.
Results of hydrofracturing in situ measurements in Singapore Granite

Zhao et al. (2005)

**Table 3. Summary of derived in situ stresses**

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Test No.</th>
<th>Depth (m)</th>
<th>$\sigma_v$ (MPa)</th>
<th>$\sigma_h$ (MPa)</th>
<th>$\sigma_H$ (MPa), by $T_{hf}$</th>
<th>$\sigma_H$ (MPa), by $T_{lab}$</th>
<th>Direction of $\sigma_H$</th>
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<td>BH8</td>
<td>A1</td>
<td>62</td>
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</tbody>
</table>
Exploration well (3 months)

Cost of drilling using petroleum technology

= US$ 4m for 1 km horizontal

Unconfined recharge:
cold sea water

Confined recharge:
cold fresh water from Mt Faber

Unconfined aquifer

Joint set

Hot geothermal water
150°C
from HSA
Proof of Concept: 10 MW(t) EGS
US$ 21.5m, 6 months

Proof of concept: cost of drilling = US$ 19.5m

Injection of cold water

Engineered hot granite or hot sedimentary reservoir

Acid matrix job
US$ 2.0m

3.5 km

3 km

500 m
Commercialisation: 20MW(t) EGS

Injection of recycled cold water

Production of hot water

Orientated NW/SE

3 km

1 km

500 m
Commercialisation: 50MW(t) EGS

Injection of recycled cold water

Production of hot water

3 km

1 km

500 m
Where to place geothermal power stations?

Semakau Landfill
Semakau Landfill, Singapore: 3 drilling pads?
Proof of concept: 1 doublet: 10 MWt?

~3.6 km deep with 1 km horizontals
Stacked 370 MWt Geothermal Power Station (25% efficiency = 92.5 Mwe; US$4m/MW = US$370m)
Ormat geothermal binary power plant, 57 MWe, East Mesa, California
Combined electricity generation, process heating, district cooling, desalination of sea water.
District cooling using absorption chillers

A) Conventional Chiller

- Condenser
- Compressor
- Evaporator

Marina Bay 57 MW

B) Absorption Chiller

- Condenser
- Generator
- Absorber

Uses very little electricity

Uses lots of electricity (Cost 10 cents/kWh?)

Geothermal water in at 88°C (Costs 5 cents/kWh?)
Design Parameters for District Cooling

- Housing estate will contain 6,000 homes of 120m$^2$ each (e.g. Punggol New Town)
- 80,000 residents
- Each home owner would operate their air conditioner for 8 hours a day
- Project life cycle is 30 years
- Inflation/interest rate of 3% p.a.
Desalination of sea water

61-62 °C geothermal water @ 60³m/h for desalination of sea water using multi-effect distillation: Kimolos, Greece, pilot study = 80 m³/d @ 1.6Eu/m³ operating costs (2007). Costs ‘much lower’ for a large scale plant.

Pulau Tekong?
Markets

1: Autonomous electricity generation:
+50 MW EGS neighbourhood / industrial power stations

2: Geothermal district cooling:
Either using ‘waste’ water from the EGS generators
Or 88 °C geothermal water and absorption chillers

3: Process heating:
150°C geothermal water for industrial process heating;
preheated geothermal water for coal powered stations;
preheated water for steam production

4. Desalination of sea water:
60°C geothermal water for desalination of sea water using multi-effect distillation: Kimolos, Greece, pilot study = 80 m³/d @ 1.6Eu/m³ operating costs (2007)
Singapore geothermal feasibility study = SG$1.69m (excluding project management)

- **Concept**
  - Done
  - Cost: SG$187.2k

- **Feasibility**
  - Cost: SG$1.69m
  - Duration: 15 months
  - 300m wells + model
  - Gravity Geochem: SG$275k
  - Geochem: SG$134k
  - TEM: SG$376k
  - MT: SG$700k?
  - Seismics: SG$200k

- **Exploration**
  - Duration: 6 months
  - Cost: ~SG$28m?

- **Appraisal**
  - Duration: 3 months
  - Cost: ~SG$11.5m?

- **Deep well (stress/fract)**
  - Cost: ~SG$7m?

- **Proof of concept (P o C)**
  - Duration: 15 months
  - Cost: SG$41.2m?

- **Work flow/costs:**
  - Costed at 2010 prices
Summary

• GOOD GEOLOGY: World class high heat flow, hot springs

• NEW TECHNOLOGY: low cost, low T binary cycle power generators, deep horizontal bore holes, absorption chillers

• MARKET: 5 m Singaporeans close to market, autonomous electrical supply, district cooling, process heating, desalination

• STRATEGIC value of a Singaporean natural energy resource

FEASIBILITY STUDY?
CONCLUSIONS
Singapore is a world class high heat flow geothermal prospect for electricity generation, district cooling and process heating.

Next, a SG$1.56m (US$ 1.22m) feasibility study
The end
Use the hot spot (120 mW/m²) to generate geothermal steam for Duri enhanced oil recovery scheme:

200°C - 24 = 176°C,
/ by 60 = 2.9 km

150°C - 24 = 126°C
/ by 60 = 2.1 km
Development costs: Singapore-type

- Development cost at 2-3 km depths, US$3.93 m / MW (av of 3 estimates)
- 50 MW power station (providing for 50k SP homes or all (or part of) the MRT) = 50 x 3.93 = US$ 197m
- Production costs at 10 cents / kWh
- Sell at discounted domestic rate of 17 cents / kWh
- Profit of 7 cents / kWh = US$70/MWh

Singapore domestic rate July 2010= SG22.98 cents/kWh = US17.3 cents/kWh
“Saves” the Singapore economy US$50 m/yr

- In 1 yr a 50 MW power station makes
  \[70 \times 50 \times 365 \times 24 = \text{US}\$30.6\text{m “profit”}\]

- Write off development = \(\frac{197}{30.6} = 6.4\text{ years}\)

- Lifespan 30 years

- 50 MW saves 0.5 m barrels / yr x US$100 / bbl = US$50 m/yr

- Carbon credits?
Comparative district cooling costs for 80,000 people over 30 years

Cost using conventional compressor technology = SG$83.2 m
Cost using 1.8 km deep doublets, 88°C, 20 MW Geothermal District Cooling = SG$48.6 m

Savings = SG$34.6 = savings of 41.6% over the study period of 30 yrs
Man-made seismicity

The oil industry routinely hydrofractures under Los Angeles, with no adverse effects.

The 3.4 $M_L$ seismic event on December 8th 2006 under Basel, Switzerland, during hydraulic stimulation of a 5 km deep EGS in an active fault zone was clearly felt in the city and was accompanied by a load bang. There was no structural damage: some stone walls were cracked and roof tiles were displaced.

3.4’s not felt more than 2 km from epicenter.

More than 100 events with a similar magnitude occur in California annually with negligible impact.

Rather than hydrofracture, use matrix acidification (HF acid)
The Packard Drill Site in Beverly Hills
Development Model – Heat Exchanger Within Insulator

- Higher Permeability
- Chemically Stable
- Lower Fracc Challenge?
- Mesoproterozoic metasediments – bedding / joint surfaces

= Cheaper Power!

HEWI Model at Paralana
The required heat exchanger is created in the insulating layers above the granite heat source. This may reduce risk, cost and time.
Key milestones for the Paralana geothermal project

Paralana JV project planned milestones

- 3rd Qtr 2011: Main fracture stimulation
- 3rd Qtr 2011: Flow test
- 1st half 2012: drilling of the Paralana 3 deep producer well
- Mid-2012: Circulation Test – Demonstration of Flows
- 2012: Commission first stage 3.75 MW power plant
Hydraulic fracture stimulation at interval 3679-3685m

Fracture stimulation, July 2011 - completed successfully

- Inject larger volume of water at higher rates, up to 27l/sec ✓
- Array capable of recording and locating micro-seismic events with very small magnitudes on the Richter scale ✓
  - Over 7000 micro-seismic events triggered
  - 98% of events below magnitude 1.0 / maximum magnitude 2.6
- Activate natural fracture network & connected to deep fractures below injection point ✓
- Succeeded to generate microseismic events beyond the target distance of 500m from the well: events detected 900m away from the well ✓
Main Fracture Stimulation greatly exceeded Target

- Over 7000 micro-seismic events triggered
- Fractured reservoir target exceeded, with micro-seismic events located 900m away from the well
- Connection to deep fractures/faults below the injection/fault point
- Reservoir will continue to grow for several weeks

interpreted outline of fracc cloud
Brady EGS, ORMAT

• Seismicity during the EGS Injection of April, 2011

• Max seismicity 2.58