Methodologies for geothermal resource assessment, with special reference to the Mutnovsky Geothermal Power Project

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  o Resource assessment concepts

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  o Numerical simulation
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The Mutnovsky Field

> Most thoroughly studied in Russia

> Largest geothermal development in Russia
  o first plant in 1999: 12 MWe
  o second plant in 2003: 55 Mwe

> Located in Kamchatka

> Comparable to other high-temperature geothermal systems on the Pacific Rim
What do we mean by “Resource Capacity”? 

> The assessment of “resource capacity” for a geothermal system can be based on a number of different criteria

> Usually we mean “the output that can be sustained for a 20-30 year project life, with a suitable contingency”

> But there are other possibilities, e.g. minimising environmental effects, maximising economic return
## Examples of various capacity estimates for a single field

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Production Level (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural throughput</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>Sustainable long term</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>No impact on surface features</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Acceptable surface changes</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>No impact on other operators</td>
<td>160</td>
</tr>
<tr>
<td>6</td>
<td>Maximum production rate</td>
<td>600 / 0</td>
</tr>
<tr>
<td>7</td>
<td>Field exhausted after 25 years</td>
<td>400 / 0</td>
</tr>
<tr>
<td>8</td>
<td>Maximum initially; rundown</td>
<td>500 / 300</td>
</tr>
<tr>
<td>9</td>
<td>Maximum for plant life</td>
<td>225 / 150</td>
</tr>
</tbody>
</table>
Depletion curves

Scen 1: natural throughput
Scen 2: sustainable long term
Scen 3: surface features unchanged
Scen 4: acceptable surface changes
Scen 5: no impact on other operators
Scen 6: maximum production and rundown
Scen 7: exhaustion at 25 years
Scen 8: maximise initially, then rundown
Scen 9: maintain capacity for plant life
For Mutnovsky

The recent resource capacity estimates for Mutnovsky are based on what is reasonably physically sustainable, at an acceptable level of drilling and piping cost, for a 25 year project life.
Preliminary assessment methods

Heat flux method

> based on estimate of natural heat flow

> gives a minimum sustainable output
  o but usually very much an underestimate of what is actually achievable

> can use a correction factor to estimate possible development size?
  o eg. Iceland; factor of 10x

> For Mutnovsky using this method
  o initial estimate of 75 MWe
  o later 105 MWe for part of field only
  o proved to be suitably conservative
Preliminary assessment methods

Areal method

> based on an empirical analogy with other fields

> assume a power density (MW/km²)
  o minimum value of 10
  o maximum value of 25
    • where there is proven high enthalpy and permeability
  o note some studies have used unrealistically high factors, eg. 40-60 MW/km²

> multiply by area
### Examples of production density

<table>
<thead>
<tr>
<th>Field</th>
<th>Installed Capacity (MWe)</th>
<th>Area (km²)</th>
<th>Extraction Rate (MWe/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Whole Field</td>
<td>Bore Field</td>
</tr>
<tr>
<td>Bulalo</td>
<td>370 (+40)</td>
<td>20</td>
<td>8.8</td>
</tr>
<tr>
<td>Tiwi</td>
<td>330</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Tongonan I</td>
<td>112.5</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>Leyte (total)</td>
<td>670</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Palinpinon</td>
<td>192</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>Bacon Manito</td>
<td>150</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Gunung Salak</td>
<td>330</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>Cerro Prieto</td>
<td>620</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Ahuachapan</td>
<td>125</td>
<td>6.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Otake &amp; Hatchobaru</td>
<td>67.5</td>
<td>12</td>
<td>0.03</td>
</tr>
<tr>
<td>Ohaaki</td>
<td>116.2</td>
<td>12</td>
<td>1.7</td>
</tr>
<tr>
<td>Wairakei</td>
<td>1998 (I)</td>
<td>184</td>
<td>25</td>
</tr>
<tr>
<td>Lardarello</td>
<td>400</td>
<td>180</td>
<td>2.2</td>
</tr>
<tr>
<td>The Geysers</td>
<td>1,000</td>
<td>78</td>
<td>13</td>
</tr>
</tbody>
</table>
Areal method at Mutnovsky

- This is the basis of the “Russian Standard Method”, which has been applied twice at Mutnovsky, giving estimates of 324-330 MWe for the whole field, divided into various levels of confidence.

- A good method for early assessment, but it now needs updating to take account of new data and greater plant efficiency.
Later assessment methods

Well outputs

> total of measured outputs

> extrapolate using wellbore simulation for future wells

> not specifically done as a method of overall resource assessment at Mutnovksy, but done informally at various stages

> reveals the need for ongoing drilling
Mutnovsky total well outputs, stage I

Mutnovsky Steam Supply Scenario

Steam Flow (kg/s)

Subtotal Existing Wells  Subtotal Spare Wells  Subtotal New Wells

Later exploration / delineation

Stored heat method

> estimate heat stored in reservoir volume
> includes both rock and fluid (steam/water)
> corrected for recovery / efficiency of conversion
> note: Mutnovsky plant more efficient than most

\[
Q = A \cdot h \cdot \left\{ C_r \cdot \rho_r \cdot (1 - \phi) \cdot (T_i - T_f) \right\} + \left[ \rho_{si} \cdot \phi \cdot (1 - S_w) \cdot (h_{si} - h_{wf}) \right] + \left[ \rho_{wi} \cdot \phi \cdot S_w \cdot (h_{wi} - h_{wf}) \right]
\]

- heat in rock
- heat in steam
- heat in water

\[
E = \left[ \frac{Q \cdot R_f \cdot \eta_c}{F \cdot L} \right]
\]
Stored heat model

Depth [m]

LAYER 0: < 240°C (NOT INCLUDED)

1,000 m

LAYER A: STEAM ZONE AT 240°C

1,500 m

LAYER B: WATER AT 260°C

2,000 m

LAYER C: WATER AT 280°C

2,500 m

500 m ADDITIONAL STORAGE BELOW DRILLED DEPTH

3,000 m
Later exploration / delineation

Monte Carlo Simulation

> refinement of stored heat method

> based on “probability ranges” for parameters rather than point values

> model generates values for stored heat parameters

> stored heat calculations repeated many times (2,000) until probability distribution for field output obtained
Probability distributions

PDF for Reservoir Thickness

Triangular Distribution
- minimum value = 500m
- most likely value = 1,000m
- maximum value = 1,250m

PDF for Reservoir Porosity

Log-normal Distribution
- mean = 0.2
- std. dev. = 0.05

Thickness [m]

Porosity
Monte Carlo simulation of resource capacity
### Input parameters for Mutnovsky

#### stored heat estimate

<table>
<thead>
<tr>
<th>Sector</th>
<th>Layer</th>
<th>Temp °C</th>
<th>Thickness m</th>
<th>Area km²</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Med</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Northern</td>
<td>1</td>
<td>180</td>
<td>220</td>
<td>230</td>
<td>300</td>
</tr>
<tr>
<td>Dachny</td>
<td>2</td>
<td>220</td>
<td>240</td>
<td>250</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.4</td>
<td>270</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td>Central</td>
<td>1</td>
<td>200</td>
<td>240</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>Dachny</td>
<td>2</td>
<td>240</td>
<td>260</td>
<td>270</td>
<td>450</td>
</tr>
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<td></td>
<td>3</td>
<td>280</td>
<td>300</td>
<td>310</td>
<td>450</td>
</tr>
<tr>
<td>Southern</td>
<td>1</td>
<td>200</td>
<td>240</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>Dachny</td>
<td>2</td>
<td>240</td>
<td>260</td>
<td>270</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>280</td>
<td>300</td>
<td>310</td>
<td>400</td>
</tr>
<tr>
<td>Vulkanny</td>
<td>1</td>
<td>180</td>
<td>230</td>
<td>240</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>230</td>
<td>260</td>
<td>270</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>240</td>
<td>280</td>
<td>290</td>
<td>300</td>
</tr>
<tr>
<td>V. Mutnovsky</td>
<td>1</td>
<td>180</td>
<td>210</td>
<td>220</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>210</td>
<td>230</td>
<td>240</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>240</td>
<td>260</td>
<td>270</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>240</td>
<td>300</td>
<td>300</td>
<td>0</td>
</tr>
</tbody>
</table>
Capacity of Central Dachny Sector based on stored heat

Frequency Distribution

MWtotal

Occurences
### Mutnovsky Monte Carlo stored heat estimates

<table>
<thead>
<tr>
<th>Sector</th>
<th>MWe in 25 years</th>
<th>MW/km²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5(^{\text{th}})%</td>
<td>Median</td>
</tr>
<tr>
<td>Northern Dachny</td>
<td>27</td>
<td>42</td>
</tr>
<tr>
<td>Central Dachny</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>Southern Dachny</td>
<td>33</td>
<td>46</td>
</tr>
<tr>
<td>Vulkanny</td>
<td>50</td>
<td>74</td>
</tr>
<tr>
<td>V. Mutnovsky</td>
<td>45</td>
<td>65</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>144</strong></td>
<td><strong>207</strong></td>
</tr>
</tbody>
</table>
Reservoir modelling

Covers wide range of activities for analysis of dynamic conditions and estimating fluid reserves

> Methods include:
  - Analytical Modelling
  - Decline Curve Analysis
  - Lumped Parameter Modelling
  - Numerical Simulation Modelling
Analytical modelling

> Based on same techniques as pressure transient analysis using superposition in time and space

> Used to estimate reservoir pressure changes in response to production/injection

> Proven to be useful in single phase water and steam reservoirs

> Not yet applied at Mutnovsky except for some individual wells
Decline curve analysis

> Used to determine decline in well/field flow rate with time

> Based on empirical method (matching production data to exponential or harmonic decline trends)

\[
W = \frac{W_i}{1 + D_i \Delta t} \quad \text{(harmonic decline)}
\]

\[
W = W_i \cdot e^{-D \Delta t} \quad \text{(exponential decline)}
\]
Decline curve analysis

Harmonic Decline

Exponential Decline

Time [years]

W / W_i

Di = 2%
Di = 5%
Di = 10%
Di = 20%

D = 2%
D = 5%
D = 10%
D = 20%
Decline curve analysis

> Popular in vapour dominated reservoirs (eg. The Geysers)

> Used in Cerro Prieto to make short term forecasts

> Not yet applied at Mutnovsky except for some individual wells, but it could soon be applied to the steam zone
Lumped parameter modelling

- System treated as a “tank” with average reservoir properties; may include recharge/injection

- Used to match/forecast overall field performance and changes in individual wells

- May be used as first stage of a numerical modelling study

- Not yet applied at Mutnovsky
Numerical simulation modelling

> System treated as a series of interconnected “blocks”; allows rock and fluid properties to vary through reservoir

> Calibrated by matching conceptual model and known well/field performance

> Used to forecast changes in reservoir in response to production/injection scenarios
Numerical simulation modelling

> Previously done at Mutnovsky (early 1990’s)

> Demonstrated at least 80 MW sustainable

> Now needs updating
Assessment during production

> Continued assessment required to update conceptual and numerical models

> Confidence in models and resource will increase as additional data are collected and incorporated

> Will be basis for future decisions on additional development, if justified
# Summary of Mutnovsky resource estimates

<table>
<thead>
<tr>
<th>Method</th>
<th>Resource Capacity, MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V. Mutnovsky</td>
</tr>
<tr>
<td>Stored heat</td>
<td>65</td>
</tr>
<tr>
<td>Chemistry/surface fluid flow</td>
<td>~75</td>
</tr>
<tr>
<td>Volc. Inst. (1976)</td>
<td>83</td>
</tr>
<tr>
<td>Standard Method (1987)</td>
<td>57</td>
</tr>
<tr>
<td>Reservoir Model</td>
<td>80¹</td>
</tr>
<tr>
<td>Standard Method (1990)</td>
<td>57</td>
</tr>
<tr>
<td>Fluid Upflow Rate</td>
<td>32.5</td>
</tr>
<tr>
<td>Areal Analogy</td>
<td>13-26</td>
</tr>
</tbody>
</table>
Conclusions for Mutnovsky

> The whole resource is adequate to support both the current development and probably a significant expansion.

> The current production sector at Dachny, by itself, is not sufficient to support much expansion. A bigger area will be needed.

> The next step in resource assessment for Mutnovsky is to produce an updated reservoir model.