

HOT ROCKS IN AUSTRALIA – NATIONAL OUTLOOK

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ABSTRACT

Australia's hot rock and hydrothermal resources have the potential to fuel competitively-priced, emission free, renewable baseload power for centuries to come. This potential and the risks posed by climate change are stimulating geothermal energy exploration projects in Australia. Extracting just 1 percent of the estimated energy from rocks hotter than 150°C and shallower than 5,000m would yield ~190 million PJ or about 26,000 times Australia's primary power usage in 2005. This figure neither takes account of the renewable characteristics of hot rock, nor the resource below 5,000m.

To year-end 2007, thirty-three companies have joined the hunt for geothermal energy resources in 277 licence application areas covering more than 219,000 km² in Australia. Companies are targeting resources that fall into two categories: (1) hydrothermal resources in relatively hot sedimentary basins; and (2) hot rocks. Most exploration efforts are currently focused on hot rocks to develop Enhanced Geothermal Systems (EGS) to fuel binary power plants. Roughly 80 percent of these projects are located in South Australia. The basic geologic factors that limit the extent of hot rock plays can be generalised as:

- source rocks in the form of high heat producing basement rocks;
- traps defined by favourable juxtaposition of low (thermal) conductivity insulating rocks to radiogenic heat producing basement rocks;
- heat-exchange reservoirs under favourable stress conditions within insulating and basement rocks; and
- a practical depth-range limited by drilling and completion technologies (defining a base) and necessary heat exchange efficiency (defining a top).

A considerable investment (US\$200+ million) is required to prove a sustainable hot rock play, and demonstrate the reliability, scalability and efficiency of EGS power production. The proof-of-concept phase entails the drilling of at least two deep (>3,500m) hot holes (one producer and one injector),

fracture stimulation, geofluid flow and reinjection and heat exchange for power generation. Compelling demonstration projects will entail up-scaling, including smooth operations while drilling and completing additional Hot Rock production and injection wells and sustained power production, most probably from binary geothermal power plants.

Australian government grants have focused on reducing critical, sector-wide uncertainties and equate to roughly 25% of the cost of the private sector's field efforts to date.

A national hot rock resource assessment and a road-map for the commercialisation of Australian hot rock plays will be published in 2008 by the Australia federal government.

Play and portfolio assessment methods currently used to manage the uncertainties in petroleum exploration can usefully be adapted to underpin decision-making by companies and governments seeking to respectively push and pull hot rock energy supplies into markets. This paper describes the geology, challenges, investment risk assessment and promising future for hot rock geothermal energy projects in Australia.

INTRODUCTION

Australia's vast geothermal resources (Fig. 1) fall into two broad categories: hydrothermal (from relatively hot groundwater) and hot rock resources (Fig.2). Where geothermal reservoir quality can be 'engineered', the results are called Enhanced Geothermal Systems (EGS). The majority of current geothermal exploration, proof-of-concept and demonstration projects in Australia are focused on EGS, although some companies are also exploring for hydrothermal resources in the Great Artesian, Gippsland, Perth and Otway Basins.

In 2007 Geoscience Australia (the Australian Federal Government geoscience agency) produced an estimate of total contained crustal energy for that portion of the Australian continental crust which is shallower than 5km and hotter than 150°C. Totalling 190 million PJ, just 1% of this value (which ignores the renewable characteristics of EGS) is equivalent to around 26,000 years of Australia's primary power

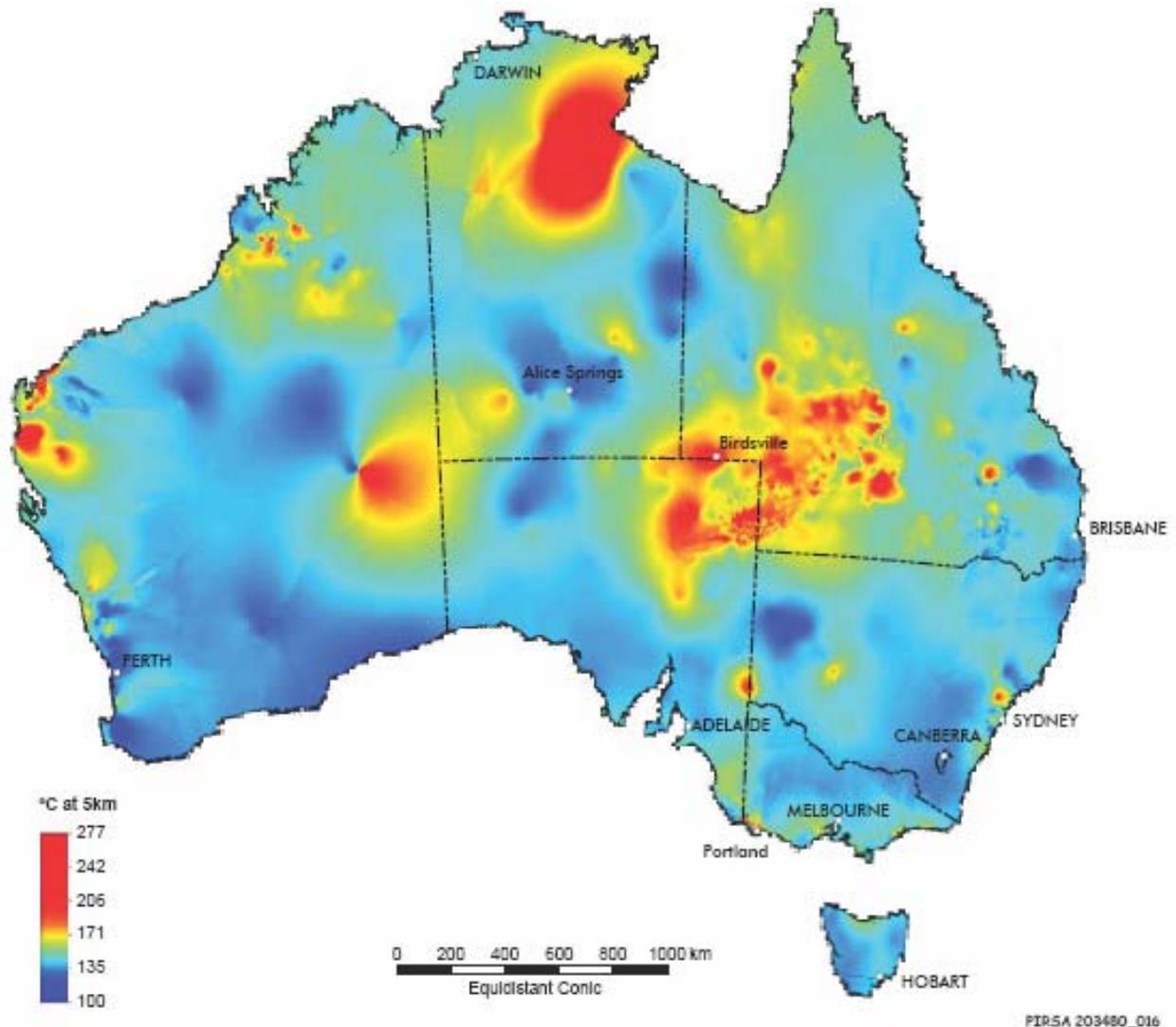


Figure 1: Map of estimated crustal temperature at 5 km derived from the Austerm database of Chopra & Holgate (2005). Image is ©2007; Dr Prame Chopra, Earthinsite.com Pty Ltd Note: map is based on available (in places sparse) data and it is likely additional areas of relatively high temperature (> 200° Celsius above 5 km) will be identified in areas not yet depicted.

usage in 2005. It is expected that this estimate will be further refined by Geoscience Australia in 2008 with the addition of both new and existing geothermal data.

EGS energy needs hot basement rocks to generate heat and insulating cover rocks to trap heat. Australia is endowed with anomalously radioactive Proterozoic granitoids, the best known examples being those associated with the South Australian Heat Flow Anomaly (Fig. 3) where the mean heat flow is estimated to be $92 \pm 10 \mu\text{Wm}^{-2}$ compared to $51\text{--}54 \mu\text{Wm}^{-2}$ for continental crust.

Elsewhere in Australia, radiogenic iron oxides, hydrothermal systems, high-heat producing granites and hot depocentres associated with recent volcanic activity in the Otway Basin constitute other targets for geothermal energy exploration.

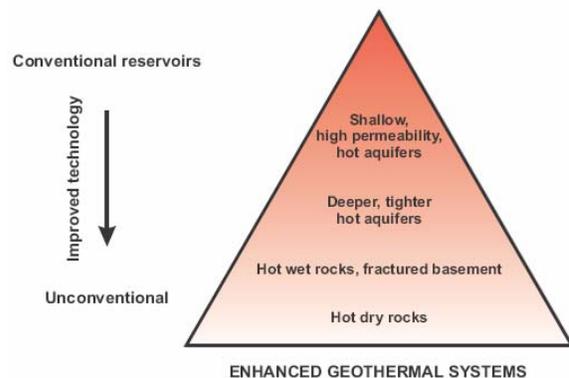


Figure 2: Geothermal resource pyramid demonstrating the continuum from shallow, permeable hydrothermal systems to deep hot dry rock with reduced permeability. After Hillis et al, 2004.

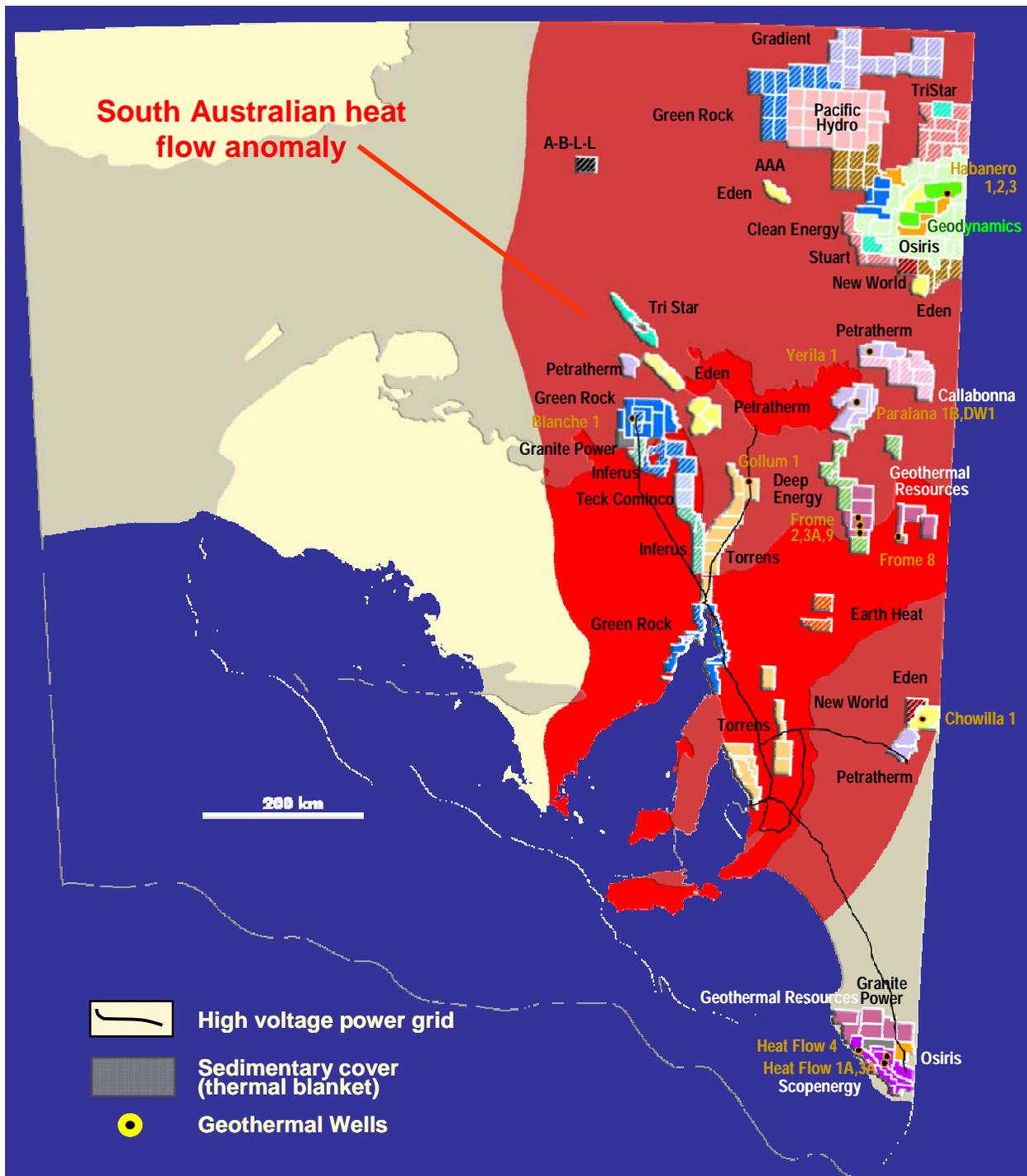


Figure 3: Hot rock play delineation in South Australia. The juxtaposition of the insulating sedimentary cover and the South Australian Heat Flow Anomaly has attracted Geothermal Licence applications. Prospective hot rock plays have also been identified outside these areas, including trends in the Otway Basin in SE South Australia

CURRENT USE

The only geothermal power currently being generated in Australia emanates from a small binary power station located in Birdsville, Queensland (Fig. 4). This development draws from hot (98°C) hydrothermal waters at relatively shallow depths in the Great Artesian (also referred to as the Eromanga)

Basin. The gross capacity of the plant, which is run by Ergon Energy, is 120 kW, and the plant has 40kW of parasitic losses. Total power generation at Birdsville in 2006 was 2,034,615 kWh of which 715,182 kWh was provided by the geothermal power plant with the remainder provided by auxiliary diesel powered generators. Ergon Energy has commenced a

feasibility study into whether it can provide Birdsville's entire power requirements and relegate the existing LPG and diesel-fuelled generators to peaking.

STATUS OF GEOTHERMAL EXPLORATION

Since the grant of the first Geothermal Exploration Licence (GEL) in Australia in 2001 through to end December 2007, thirty-three companies have joined the hunt for renewable and emissions-free geothermal energy resources in 277 licence application areas covering ~219,000 km² across Australia (Fig. 4). Supportive investment frameworks and quality geothermal resources have combined to result in some 80% of geothermal licence applications and forecast national expenditure being located in the state of South Australia. New geothermal legislation, calls for licence applications and licence applications announced in 2007 are expected to attract considerable additional investment in geothermal projects in coming years in all Australian states and the Northern Territory.

Since the drilling of Habanero 1 by Geodynamics Limited in 2003 through to end December 2007, six companies (Geodynamics Limited, Petrathern Limited, Green Rock Energy Limited, Geothermal Resources Limited, Scopenergy-Panax and Torrens Energy Limited) have drilled a total of fourteen wells to establish the extent of hot rock resources in

Australia. A summary of these drilling operations, all of which were undertaken in South Australia, is provided below. Further geothermal exploration drilling and appraisal operations are scheduled by Geodynamics, Petrathern, Torrens Energy and Eden Energy in 2008, all in South Australia.

DRILLING TO YEAR-END 2007

Geodynamics Limited

The most significant advancement in terms of demonstrating the potential of Hot Fractured Rock (HFR) energy in Australia is Geodynamics' drilling, fracture stimulation and flow testing of two wells that are 500 m apart near Innamincka in the Cooper Basin (Fig. 3) in northeast South Australia: Habanero 1 (Total Depth: 4,421m), Habanero 2 (total depth: 4,357m and Habanero 3 (drilling ahead at 4,058m on 10 January 2008. The Habanero Project was the first and remains the most advanced Hot Rock 'proof of concept' project in Australia. Flow of geothermally heated formation waters (20,000 ppm Total Dissolved Solids) at a maximum rate of 25 litres/second to surface at (up to) 210°C was achieved in 2005. The geothermal reservoir is a water-saturated, naturally fractured basement granite (250°C at 4,300 m as reported by Geodynamics) with permeability that was effectively enhanced by fracture stimulation.

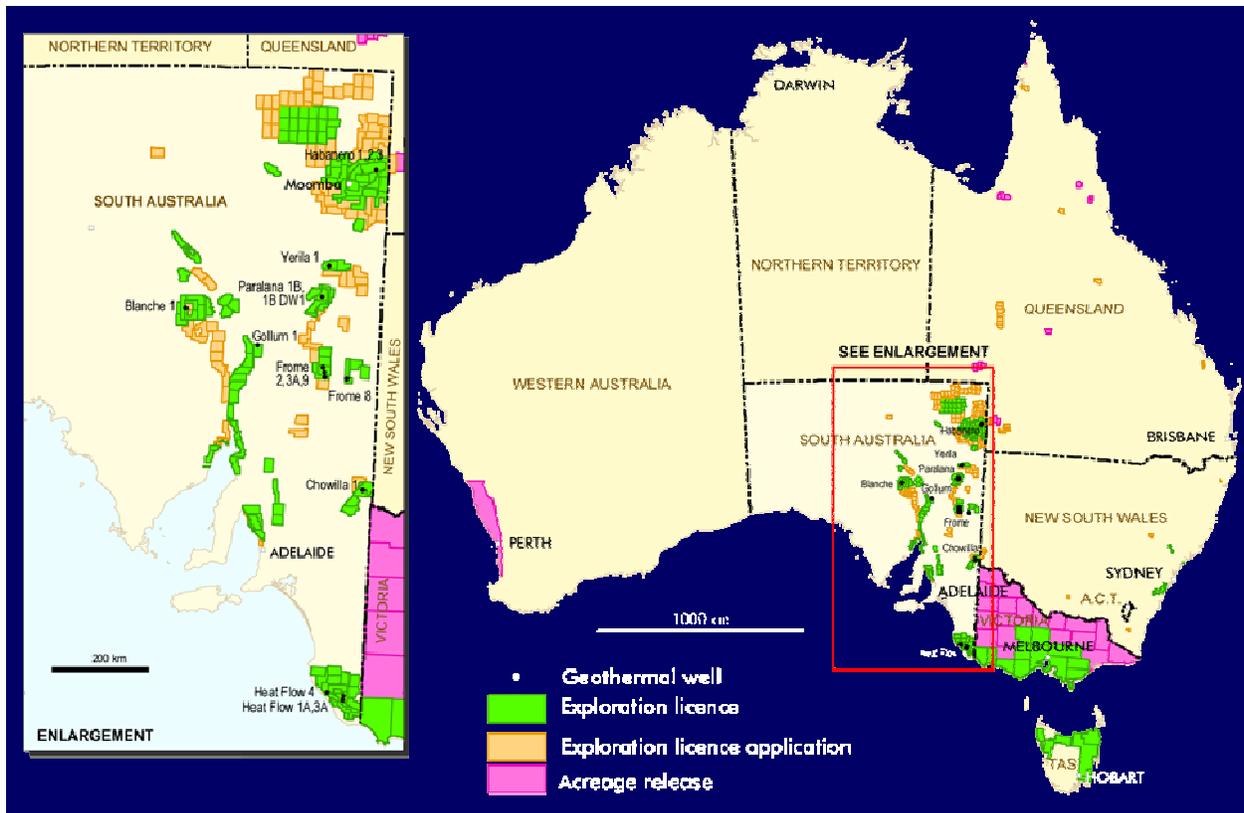


Figure 4: Geothermal licences, applications and bid blocks

Two fractured reservoir zones are present in the Habanero wells: an upper less permeable zone at 4,200 m; and a lower more permeable zone below 4,300 m. An obstruction in Habanero 2 (the intended production well) interfered with a planned flow test of the main fractured reservoir below 4,300 m while the less-productive upper fractured reservoir zone at 4,200 m remained accessible. To conclude a circulation test of the main fracture zone, Geodynamics drilled a sidetrack borehole around the blockage in Habanero 2. The sidetrack progressed to a depth 100 m above the target reservoir when the drill bit became stuck. Attempts to conclude drilling operations in the Habanero 2 sidetrack were abandoned in June 2006. Geodynamics is now drilling Habanero 3, which will have an 8 ½ inch hole through its HFR reservoirs (compared to 6 inch through reservoirs in Habanero 2). Following the drilling of Habanero 3, a flow test with tracer injection between Habanero 1 (the intended injection well) and Habanero 3 (the intended production well) is planned as a further step towards demonstrating commercial viability. Geodynamics' current fourth (planned) well in the Cooper Basin region (Jolokia 1, named after what is now named the hottest chili pepper in the Guinness Book or World Records) will be located 9 km north from Habanero 1, and beyond the extent of the fracture network drilled with its first three wells, as defined during seismic monitoring during the stimulation of Habanero 1 and 2.

The horizontal extension of stimulated reservoirs at the Cooper Basin site lends itself to multi-well developments. Geodynamics' HOTROCK 50 project entails a proposed 9-well, 50 MWe power station. The 9 wells will be drilled 1km apart at 4km depth. This will entail 4 injection wells and 5 production wells forecast to yield 10MW net per well from flows of 120 kg/sec/well. This will be an important milestone for the demonstration of EGS from HFR in Australia and a stepping stone towards commercialising vast renewable and emissions-free geothermal energy supplies to meet Australia's future baseload energy requirements. Geodynamics believes that a successful flow test between Habanero 1 and 3 will lead to large-scale development of an extensive area of more than 1,000 km² where rock temperatures, stress conditions and rock properties are extensive and favorable for geothermal energy production. Two Australian Stock Exchange (ASX) listed companies with extensive upstream petroleum interests (Origin Energy and Woodside Limited) are cornerstone investors in Geodynamics. In November 2007, Origin agreed to take a 30% equity in the Cooper Basin geothermal licences operated by Geodynamics, while it also retains roughly 10% ownership of Geodynamics. Origin Energy's forecast expenditure in Geodynamics' Cooper Basin project is expected to be about A\$100 million (~US\$88 million).

Petratherm Limited

Petratherm has drilled two wells to establish thermal gradients down to about 600 m above exceptionally high heat producing granites in South Australia. Results from both wells were encouraging, with the Callabonna and Paralana sites (Fig. 3) respectively exhibiting 68 and 81°C/ km thermal gradients. In June 2006, the phase-2 drilling program at Paralana was successfully completed with the geothermal test well being extended to 1,807 m. Temperature logging of the well suggests a world class thermal resource is located at Paralana, with extrapolations indicating 200°C can be expected at a depth of 3,600 m within insulating sedimentary rocks that are predicted to be susceptible to fracture stimulation. Petratherm refers to this play concept as Heat Exchange Within Insulator (HEWI). High heat producing basement rocks are a prerequisite for high quality HEWI plays.

Petratherm plans to create a HEWI system with the circulation of water between the two Paralana project wells to demonstrate hot rock EGS energy production from an initial small scale power plant that will supply up to 7.5 MW to a growing electricity market 10 km away at the Beverley Uranium Mine. This plan is the subject of a Memorandum of Understanding between Petratherm and the owners of the Beverley Mine, Heathgate Resources. An ASX-listed upstream oil and gas company (Beach Petroleum) has taken an equity position in the Paralana project. In November 2007, Petratherm signed a Letter of Intent for Ensign International Energy Services to secure a suitable rig and drill a Paralana well to 4,000 metres in the last half of 2008. Stimulation, flow testing and the drilling of a second well would follow, pending results of the first deep Paralana well.

Green Rock Energy

Green Rock drilled Blanche 1 (Fig. 3) to 1,935 m (718 m of sedimentary rocks and 1,216 m of homogenous hot granite) 8 km from the giant Olympic Dam mine in South Australia in 2005. The target granite is interpreted to persist to depths of 6,000 m over an area of about 400 km² and represents a potential geothermal resource in excess of 1,000 MWe. Cores and wireline logs from Blanche No 1 suggested natural fractures exist. Green Rock plans to undertake a mini-fracture stimulation program in Blanche 1 to optimize the design of a deep well stimulation.

Geothermal Resources

Geothermal Resources Limited is exploring a gravity low that could be a high heat producing granite associated with hot rock reservoirs predicted to be over 200°C at roughly 4,000m depth in its Frome project area (Fig. 3). Potential hot rock power markets for the Frome project electricity consumers connected to the National Electricity Grid, some 120 kms away (from the Frome area) at the township of Broken Hill. A number of active minerals exploration

projects that lie between the Frome Project and Broken Hill are additional, potential future power markets.

Frome 2, 3A, 5 and 9 were each drilled to depths of approximately 500m in 2007, and have provided encouragement to drill an additional three shallow holes between Frome 3 and 9 in early 2008. Pending further encouraging results from the shallow (200–300 m) drilling at Frome. 5, 10 and 11 and rig availability, Geothermal Resources will drill a Frome well to approximately 3,000m, to confirm thermal gradients consistent with the company’s geologic model.

Panax (Scopenery / Uranoz)

In the first quarter of 2006, Scopenery drilled 3 slim-hole wells near Millicent and Beachport in southeast South Australia (Fig. 3) to determine geothermal gradients and confirm several large scale heat flow anomalies previously measured in 19 petroleum exploration wells and 26 water wells in the vicinity of its tenements. In mid 2006 the company completed temperature logging of its 3 wells: Heatflow 1A, 3A and 4. Poor recovery of core samples from unconsolidated sediments and highly variable lithology affected the reliability of thermal conductivity measurements and hence, estimates of heat flow. Scopenery was acquired by Uranoz (an ASX-listed company changing its name to Panax) in

October 2007, and is now considering whether to undertake a 3D seismic program to better define drilling targets prior to drilling its first production scale hole to reservoir depth.

Torrens Energy

Torrens Energy drilled the first (Gollum 1) of a nine well program in its Lake Torrens project area in late 2007 (Fig. 3). The aim of this program is to delineate heat flow trends as a precedent to locating deep proof-of-concept wells in proximity to the National Electricity Grid and power markets.

EXPENDITURE

All Australian geothermal industry field expenditure to date is classed as research and is estimated at AUS\$33 million (US\$29 million) for the calendar year 2007. This represents a 29% increase of AUS\$7.3 million (US\$6.4 million) from the previous year. A 171% increase (to AUS\$89 million or US\$78 million) is forecast for 2008. The high level of competition for deep drilling rigs underpinned with high oil prices may be a factor in this forecast being achieved. To date, those companies which have contracted rigs capable of drilling to at least 4,000m have either bought (e.g. Geodynamics for its Cooper Basin project) or agreed to pay to refurbish a rig (e.g. the Petratherm – Beach Paralana Joint Venture) rigs. Historical, current and projected expenditure for 2008 are highlighted in Figure 4.

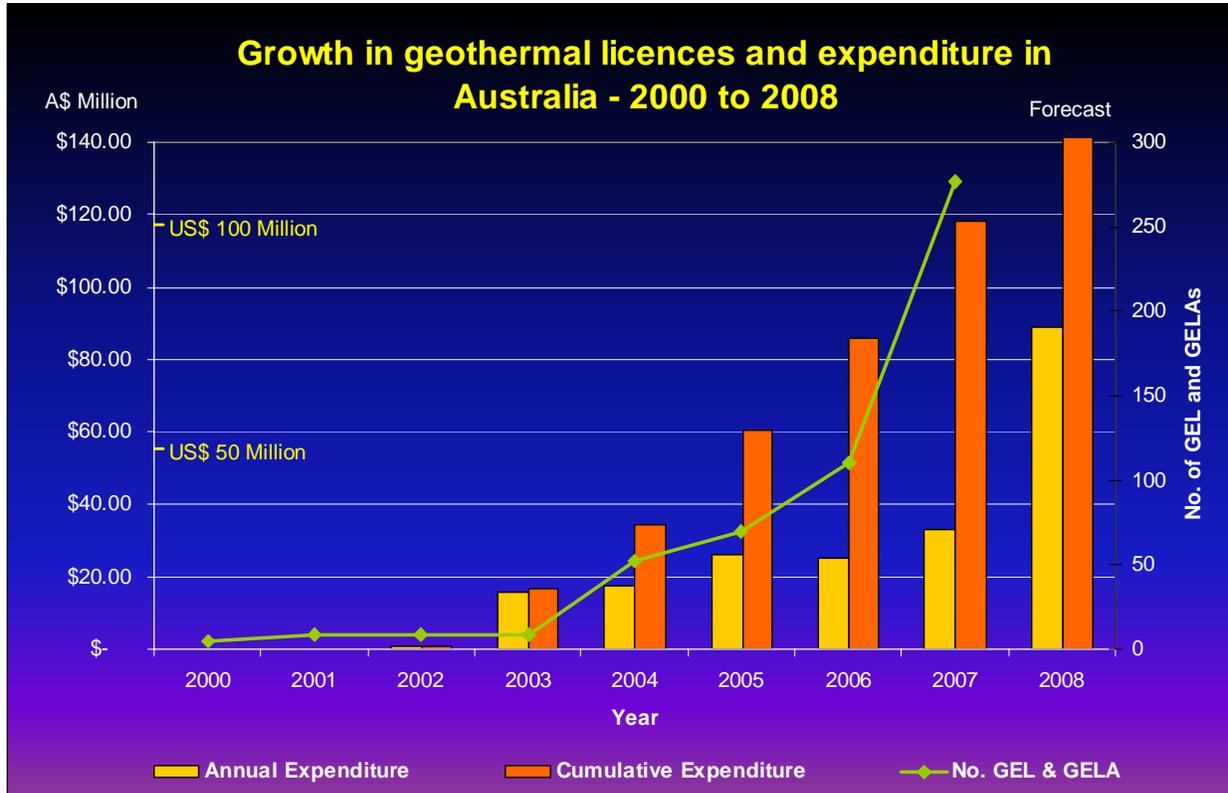


Figure 4: Geothermal Licence applications and exploration expenditure, 2000 to 2008. Source PIRSA

TRENDS IN GEOTHERMAL INVESTMENT

Assuming success in demonstration and proof of concept projects, the Electricity Supply Association of Australia concluded that 6.8% of all Australia's power could come from geothermal energy by 2030 under a "scenario that assumes no nuclear power and (CO₂) emissions reduced to 70% of 2000 levels by 2030" (ESSA, 2006). The forecast 6.8% represents 5.5 GW in generating capacity from EGS. At roughly 2% growth, Australia's power demand will grow from approximately 50 GW current generation capacity to approximately 80 GW in 2030.

The Australian Federal Government has set a target of 60,000 GWh of renewable energy consumption by 2020. That target is about 20% of the total, forecast electricity consumption in 2020. Expeditious and compelling results from Hot Rock demonstration projects in the next 5 years will be drivers for geothermal power taking up a material proportion of that target consumption.

Figure 5 illustrates the current costs of power generation from alternative fuels, including geothermal, coal, wind, gas and nuclear energy. At this point in time, coal and gas are the most competitively priced fuels for electricity generation.

In a global market with carbon pricing, geothermal energy is likely to be a significant growth industry. The anticipated cost of EGS energy in Australia has

been estimated at AUS\$50–\$60 (US\$40–\$50) per MWh (ESIPC, 2007). Without carbon pricing, many forms of conventional energy generation such as coal and natural gas are more cost effective. In May 2007, the Australian Federal Government indicated that a National Emissions Trading Scheme could be introduced from 2012.

Progress towards Commercialisation of Geothermal Energy

There have been a number of Federal and State Government initiatives to foster investment in geothermal energy exploration, proof-of-concept, and demonstration projects, toward the commercialisation of geothermal energy resources. These initiatives include:

- Stimulating significant exploration and proof-of-concept investment with attractive legislation, policies and programs. Since 2000, the Australian Federal and State Governments have committed more than AUS\$100 million (US\$88 million) in grants and studies for geothermal exploration and proof-of-concept projects;
- To date, Australian Federal and State Government grants have funded roughly 25% of industry's investment for Hot Rock exploration in Australia.

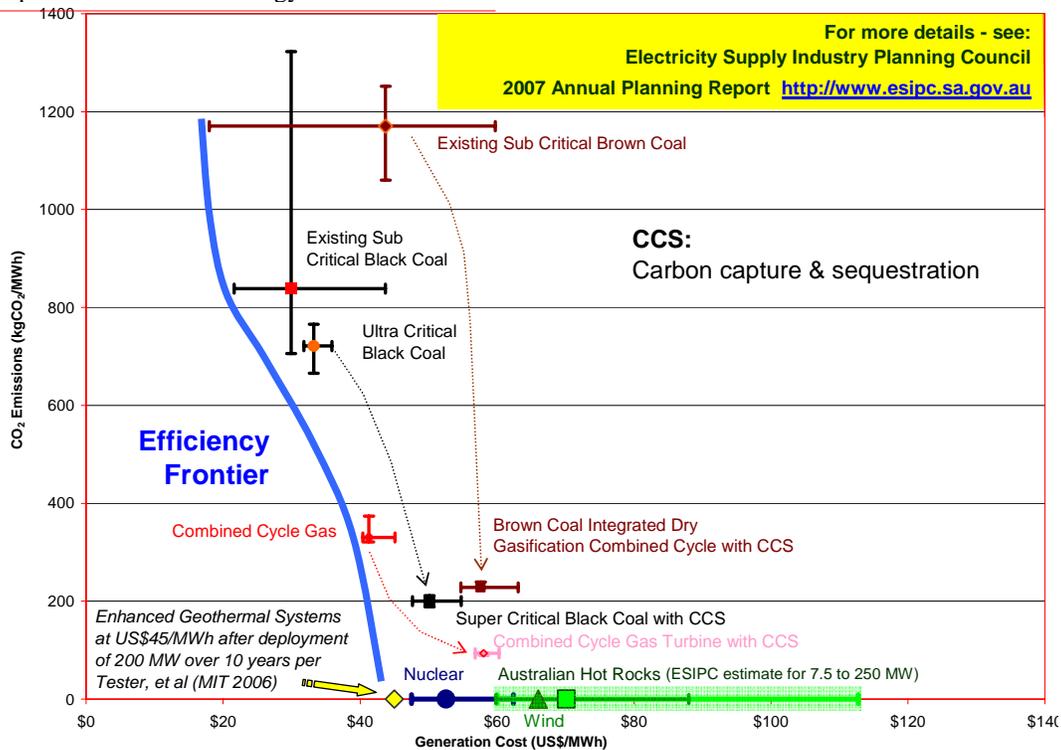


Figure 5: CO₂ emissions (Kg/MWh) on the vertical axis versus costs to generate electricity power in Australia (converted to US\$/MWh at US\$0.88/A\$) on the horizontal axis to indicate relative costs and CO₂ emissions from various fuels, with and without carbon capture and storage (geosequestration). Source: Electricity Supply Industry Planning Council 2007 Annual Planning Report.

- At least AUS\$50 million (US\$ 44 million) of Australian Federal Government's AUS\$500 million (US\$ 440 million) budget to demonstrate low emissions technologies has been reserved for the co-funding (with industry) of hot rock drilling projects.
- The direction of part of the AUS\$59 million (US\$48 million) Federal Government's Onshore Energy Security Program in 2006-2011 towards the provision of precompetitive geoscience data for the advancement of geothermal energy;
- Membership in the International Energy Agency's Geothermal Implementing Agreement (GIA) Research Cluster;
- The establishment of a whole-of-sector interest group, the Australian Geothermal Energy Group (AGEG), to provide support for Australia's membership in GIA and facilitate engagement with the international geothermal community; and
- The Australian Federal Government's Geothermal Energy Development Framework which will result in the publication of a roadmap for the development of Australia's geothermal energy resources and technologies (due April 2008).

In November 2007, corporate members of the AGEG to create a new peak geothermal industry directorate – the Australian Geothermal Energy Association (AGEA). The aim of the AGEA is to provide a unified voice to key stakeholders, notably governments, on matters of policy affecting the geothermal industry. The AGEA has stated its intentions to complement other major geothermal initiatives – notably the Australian Geothermal Energy Group (AGEG) and the Australian Geothermal Industry Development Framework.

AUSTRALIAN GEOTHERMAL ENERGY GROUP (AGEG)

The AGEG formed in late 2006. At year-end 2007, the AGEG's members include representatives from 40 companies (including all Geothermal Exploration Licence holders in Australia), the Australian Federal Government, the governments of all six Australian States and the Northern Territory, the CEO of the AGEA, and well-respected researchers from 7 academic institutions, with more likely to join in 2008. The AGEG's vision is for geothermal resources to provide the lowest cost emissions-free renewable base load energy for centuries to come.

The AGEG's terms of reference are:

1. Provide support for Australia's membership in the IEA's Geothermal Implementing Agreement (GIA) and facilitate engagement with the international geothermal community.
2. Foster the commercialisation of Australia's geothermal energy resources. Collectively:

- Cooperate in research and studies to advance geothermal exploration, proof-of-concept, demonstration and development projects;
- Cooperate to develop, collect, improve and disseminate geothermal-related information;
- Identify opportunities to advance geothermal energy projects at maximum pace and minimum cost; and
- Disseminate information on geothermal energy to decision makers, financiers, researchers and the general public (outreach).

To foster the achievement of these objectives, the AGEG has recently established Technical Interest Groups (TIGs) that are outlined in Table 1. The industry policy forum under AGEG's TIG 3 has evolved into the AGEA.

AGEG Technical Interest Groups	Purpose
1 Land Access Protocols (induced seismicity, emissions, native title, etc)	Mirrors IEA Geothermal Implementing Agreement research annex I. Management of environmental concerns and potential impacts of geothermal energy and devises protocols to avoid or minimize impacts.
2 Reserves and Resource (Definitions)	Align with similar International forums
3 Policy Issues * Industry * Whole-of-Sector	Advice to Governments.
4 Enhanced Geothermal Systems	Mirrors IEA Geothermal Implementing Agreement research annex III Investigate technologies for enhancing geothermal reservoirs for commercial heat extraction.
5 Interconnection with Markets	Transmission, distribution, network, National Electricity Market issues
6 Geothermal Power Generation	Mirrors IEA Geothermal Implementing Agreement research annex VI. Develop scenarios as a basis for comparison of cycles, plant performance and availability, economics and environmental impact and mitigation. The output would be a database and guidelines of best practice.
7 Direct Use of Geothermal Energy (including geothermal heat pumps)	Mirrors IEA Geothermal Implementing Agreement research annex VIII. This annex addresses all aspects of the technology related to geothermal energy being used directly as heat, with emphasis on improving implementation, reducing costs and enhancing use
8 Outreach (Including Website)	Create informed public through accessible information. Provide educational kits for media, all levels of schooling and university education.
9 Data management	Database design, contents and ongoing enhancements.
10 Wellbore operations	Mirrors IEA Geothermal Implementing Agreement research Annex VII. Covers drilling, casing, logging, fracture stimulation, testing, etc

Table 1. The AGEG's Technical Interest Groups

RESEARCH ACTIVITIES

The principal focus topics of Australian research relate to:

- Identification and targeting of locations with high potential for the development of Enhanced Geothermal Systems;
- Reserve and resource definitions;
- Assessment of technologies (including power systems and numerical simulation techniques) with high potential to minimize costs and maximize efficiencies in the development of EGS; and
- Environmental impacts of developing EGS, including potential induced seismicity that can be associated with the fracture stimulation of geothermal reservoirs.

In 2005, Primary Industries and Resources South Australia (PIRSA) commissioned the Australian School of Petroleum at University of Adelaide to undertake a research study of potential induced seismicity associated with the fracture stimulation of EGS wells in the Cooper Basin. The results of this study are detailed in Hunt et al. (2006). Key conclusions are:

- The Cooper Basin in South Australia is ideally suited to EGS activities in terms of natural background seismicity levels;
- Reactivation of any basement faults in the region is unlikely in the vicinity of the Habanero Site; and
- Induced seismic events at the Habanero well site in the Cooper Basin fall below the background coefficient of ground acceleration (0.5 g) thereby not exceeding the government's current building design standards for peak ground acceleration.

The static stress damage zone would not be expected to have any impact on identified local structural features. This is due to the nearby faults being beyond the reach of the induced seismicity associated with EGS activity. PIRSA will fund similar studies in other prospective EGS provinces (in the State of South Australia) to develop trustworthy protocols for assessing the potential risks of induced seismicity.

Operators of geothermal energy projects in South Australia will then have a credible foundation to develop their own hazard management strategies to avoid negative impacts from induced seismicity. PIRSA's regulatory aim is two-fold: (1) foster robust risk-management frameworks and (2) sustain widespread, multiple-use land access for geothermal energy projects by attaining stakeholders' confidence that regulated activities undertaken by companies will deliver safe and sustainable operations.

In September 2007, the Queensland State Government committed AU\$15 million (US\$ 13.2

million) to the Queensland Geothermal Energy Centre of Excellence at the University of Queensland (UQ) for research towards exploitation of the deep geothermal reserves of South Australia and Queensland. Studies to be undertaken at UQ include: (1) resource management and optimization; (2) optimum power conversion; (3) power plant cooling systems; and (4) long-distance electricity transmission. The Centre plans to work collaboratively with other national and international research groups to address all challenges that need to be overcome before deep geothermal energy becomes a proven commercial reality. The Centre will also work with other Australian universities to introduce undergraduate and post-graduate programs to develop a local skill base.

Drivers for Commercialisation of Hot Rocks

Key steps that will drive the commercialisation of geothermal energy in Australia are:

- Geothermal exploration, proof-of-concept and demonstration projects (fostered with government grants);
- Attractive, appropriate investment frameworks in all Australian jurisdictions;
- Research and sharing lessons learnt to reduce critical uncertainties (nationally and internationally);
- A national roadmap for geothermal energy to guide the path for hot rock geothermal energy to meet a significant part of Australia's power demand by 2030; and
- Geoscience Australia's Onshore Energy Security Project – which will provide salient national maps, enabling data management tools, and a readily assessable national database for geothermal energy information.

GEOTHERMAL INDUSTRY DEVELOPMENT FRAMEWORK

The Australian Federal Government instigated the Geothermal Industry Development Framework in March 2007. The results of this work are scheduled to be published in April 2008. Eight distinct outputs are planned as follow:

1. Geothermal Technology Roadmap
2. Assessment of the training and skills development infrastructure of the geothermal sector
3. Assessment of the legislative and regulatory framework governing the geothermal sector
4. Analysis of private sector and government financing structures supporting the geothermal sector
5. Geothermal resource assessment and definitions
6. Geothermal industry communication strategy

7. Geothermal Industry Map
8. Synthesis – Geothermal Industry Development Framework

Drafts will be the subject of national and international peer review prior to publication of outputs.

GEOSCIENCE AUSTRALIA ONSHORE ENERGY SECURITY PROGRAM

The Australian Federal Government Onshore Energy Security Program (OESP) was announced in 2006 as part of a broader package of energy exploration initiatives. The AUD\$59 million, five year program will deliver pre-competitive data packages and fresh, scientifically based assessments of the potential for onshore energy resources such as oil, gas, uranium, thorium and geothermal energy. Components of this program that are of particular relevance to geothermal exploitation include:

- Compilation of existing geothermal datasets
- Collection of new heat flow data across Australia
- Construction of a new national geothermal information system to preserve and access data
- Source and trap modelling to identify potential hot rock systems
- Provision of revised National Geothermal Resource estimates in line with new data collection
- Continent-wide acquisition of new airborne radiometric data.
- A program of deep seismic data acquisition (e.g. Mt Isa-Georgetown, Qld)
- Major new AEM surveys (e.g. Paterson Province, WA)
- New gravity surveys (e.g. Cooper Basin, Qld)

GEOHERMAL PLAY CONCEPTS – ASSESSING GEOLOGIC AND ECONOMIC ADEQUACY

A large number of distinctly different geologic settings are now being explored in Australia to define ‘sweet-spots’ where deep drilling can prove the existence of conditions necessary for economically viable hot rock energy.

The portion of these exploration drilling projects that successfully identify hot rocks will then (probably) progress to flow tests, to prove locally an EGS play. Adequate flow of high temperature fluids at significant rates will be required to fulfill the objective of the proof-of-concept phase on the path to commercializing the resources.

The portion of those plays that are proved locally to have the capacity to flow at potentially economic rates can then move into a pre-competitive demonstration phase on the path to proving hot rock

(EGS) reserves, as a precedent to justify development.

Successful path-finder hot rock projects are expected to stimulate competitive investment across Australia.

Given this as background, and based on the AUS\$119 million (US\$105 million) invested in hot rock projects in Australia in the term 2002 - 2007, the Australian Geothermal Energy Group (AGEG) forecasts:

- At least 10 successful research (exploration drilling) and proof-of-concept (heat energy is recovered from fluid flows) geothermal projects by 2010-11. These will be fostered with government grants and frameworks that stimulate pre-competitive, ‘learn-while-doing’ investment to pull low emissions and renewable energy technologies through costs-curves, towards market-competitive energy supplies.
- Several geothermal power generation demonstration projects in distinctively different geologic settings in the coming years, and at least 3 by 2012, if governments provide sufficient ‘pull’ for investment in the demonstration of low emissions and renewable energy technologies, and hot rock geothermal, in particular.
- Compelling success with geothermal power generation demonstration so the investment community is convinced hot rock EGS is real by 2012, again, if governments incentives provide sufficient ‘pull’.
- Realising the vision of safe, secure, reliable, and the lowest-priced renewable and emissions-free base load power from geothermal energy for centuries to come, with at least 7% of base-load demand from hot rock power by 2030.

Standard investment management methods including the aggregation of risk-weighted (expected) net present values will inevitably be applied to steward funding for efficient and effective exploration, proof-of-concept and pre-competitive demonstration projects.

A coherent portfolio approach is posed to constructively influence corporate strategies and government policies (and programs) so as to commercialize vast EGS plays efficiently, at maximum pace and minimum cost. The methodology posed enables consistent estimates of the costs and benefits of precompetitive learning-while-doing (learning curves) through research (drilling), proof-of-concept (flow testing) and demonstration (pre-competitive power generation) phases of hot rock EGS projects.

The method is presented as a hypothetical scenario of three distinct yet-to-be proven hot rock play-trends with potential to be economically viable EGS projects. The methods are as defined by Capen

(1992) and Rose (1992) for dealing with exploration uncertainties and estimating the chance of economic success in petroleum exploration. These methods are well recognized as world's best practice for petroleum exploration, and have proven to be effective in managing geologic uncertainties in very competitive oil and gas markets.

THE METHOD

Three key geologic factors need be of at least adequate quality for the hot rock EGS plays to exist. These three factors are:

- sources of heat in the form of high heat producing basement rocks (mostly granites);
- insulating strata to provide thermal traps; and
- permeable fabrics within insulating and basement rocks that are susceptible to fracture stimulation to create geothermal reservoirs.

Paraphrasing Rose (1992), experts can assess the likelihood of key geologic factors being at least adequate within a defined area, and estimate the chance that a hot rock play exists.

This calculation does not address the size of the resource, just the likelihood that all necessary conditions that are favorable for geothermal energy to accumulate in permeable rocks (or rocks susceptible to fracture stimulation) are present in a particular location.

In a situation where all wells have found a hot rock resource, and geothermal reservoirs have been developed, the likelihood of each of these factors being adequate in the drilled area can be assessed to be 100%, and the chance of encountering at least adequate geology is also 100%.

Where insufficient information is available to have such high certainty, the chance of geologic adequacy will be less than 100%, and can be estimated from the serial product of factor adequacy assignments. For hot rock EGS plays, the serial product of the chance for at least adequate quality for three key factors (heat source, heat trap and heat reservoir) is proposed as the chance for (an at least adequate) hot rock EGS play to exist over the area where the factor adequacy assignments apply.

As defined by Rose (1992), the serial product of key geologic factor adequacy is the chance for geologic success.

Further assessment of the likelihood of economic success can take into account the minimum necessary well flow rates required to underpin a break-even (threshold economic) net present value outcome based on all forecast (scenario) costs (CAPEX and OPEX) and revenues (pre- and post tax and depreciation) for research (including exploration drilling), proof-of-concept, pre-competitive demonstration, appraisal projects to convert resources

to a proven reserve status, marketing, development, transmission, distribution and finally sales to end-users. Factors such as cost of capital and the extent of integration across the supply: demand chain will differ between companies.

On this basis, the estimated chance of attaining target heat flow rates (expressed as a threshold litres/second rate of flow to surface at a threshold initial temperature) is proposed as a fourth factor quality estimate that enables the quantification of the chance for at least a break-even economic result.

In summary, the product of the chance of geologic success and the chance for threshold economic heat flow rates is offered as an estimate of the chance for at least break-even (economic) success. This is the chance that all the factors that characterize a particular EGS play as favorable for both (1) geothermal energy to have accumulated in a particular location and (2) economic production rates.

Estimates of resource and reserve volumes to various levels of certainty for use in discounted (for time value) cash flow scenarios to express a mean (average) net present value come from other methods that are not addressed here, but will be addressed in future publications.

Taking this method another step, net present values for an average or mean full-cycle EGS production scenario, and estimates of the chance of economic success for an EGS play-trend enable estimates of expected values and a portfolio approach to investment in EGS plays. This methodology is illustrated by way of a hypothetical example.

Say, for EGS Play A, the likelihood (expressed as a probability, P) for each of the four key hot rock EGS factors are as follow:

EGS Factors	Hot Rock Play A Descriptions
$P_{\text{heat source}} = 90\%$	Very certain radiogenic granites at depth, given $\geq 210^{\circ}\text{C}$ at target depth is assumed <u>minimum</u> adequacy for heat exchange efficiency.
$P_{\text{heat trap}} = 90\%$	Insulating strata at depth very certain
$P_{\text{heat reservoir}} = 50\%$	Prevailing stress regimes favor natural fractures, but no local well control. Critical uncertainty
$P_{\text{heat flow rate}} = 50\%$	Minimum threshold flow estimated to be 75 l/s at $\geq 200^{\circ}\text{C}$ at surface

In this example:

the chance for EGS play geologic success (i.e. the probability of geological success P_g) is:

$$\begin{aligned}
 &= (P \text{ heat source} \times P \text{ heat trap} \times P \text{ heat reservoir}) \\
 &= 90\% \times 90\% \times 50\% \\
 &= 40.5\%
 \end{aligned}$$

the chance of geologic inadequacy is the complement of P_g . That is:

$$\begin{aligned}
 &= 100\% - P_g \\
 &= 100\% - 40.5\% \\
 &= 59.5\%;
 \end{aligned}$$

the chance of a technical success (i.e. a geologic success with inadequate flow rate) is thus:

$$\begin{aligned}
 &= (1 - P \text{ heat flow rate}) \times P_g \\
 &= (100\% - 50\%) \times 40.5\% \\
 &= 20.25\%;
 \end{aligned}$$

and the chance for an economic success (i.e. the probability of economic success P_s) is:

$$\begin{aligned}
 &= (P \text{ heat source} \times P \text{ heat trap} \times P \text{ heat reservoir} \times P \text{ heat flow rate}) \\
 &= 90\% \times 90\% \times 50\% \times 50\% \\
 &= 20.25\% = P_s
 \end{aligned}$$

This may be illustrated using a decision-tree format as shown in Figure 6.

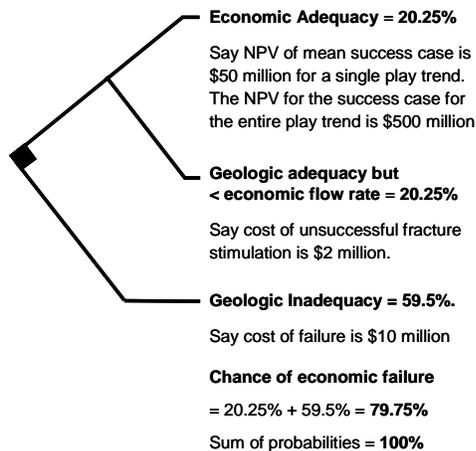


Figure 6. Decision-tree for hypothetical EGS Play A.

In this case (Fig. 6), the simplified pre-drill expected Net Present Value (NPV) to drill and fracture stimulate a well in EGS Play A is \$0.56 million and calculated as follows:

$$\begin{aligned}
 &= (P_s \text{ for Play A mean resource} \times \text{NPV of the success case}) - ((1 - P_s) \times \text{NPV of well operations with post-frac flow tests}) \\
 &= \{20.25\% \times \$50,000,000\} - \{\$12,000,000 \times 79.75\% \} \\
 &= \$560,000 \text{ Expected Net Present Value}
 \end{aligned}$$

Success on one part of a more extensive play trend has positive implications for the entire play trend. If the success scenario NPV of the entire play trend is much greater than \$50 million, the expected value of the information to be gained by drilling to test the 'play-maker' EGS Play A will be commensurately greater.

VALUE OF INFORMATION

Let us say that the unrisks NPV for the entire play that can be addressed with the drilling of one deep well is \$500 million, and if successful, the implications are:

P heat reservoir moves from 50% to 75%; and

P heat flow rate moves from 50% to 75%.

In this example:

$$\text{the chance for EGS play geologic success } (P_g) = 90\% \times 90\% \times 75\% = 60.75\%;$$

the chance of geologic inadequacy is the complement of 60.75% i.e. 39.25%.

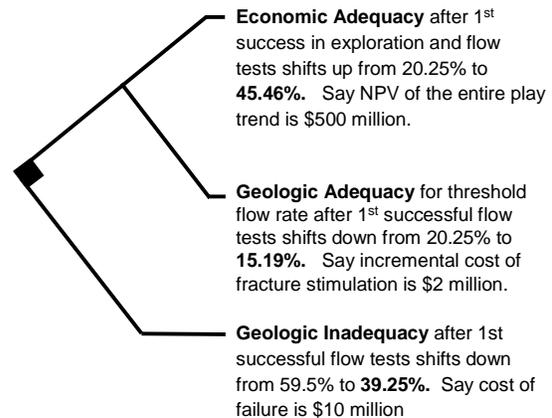
the chance of EGS technical success is

$$\begin{aligned}
 &= (P \text{ heat flow rate}) \times P_g = (100\% - 75\%) \times 60.75\% \\
 &= 15.19\%
 \end{aligned}$$

The chance for EGS economic success is

$$= P_g (60.75\%) \times P \text{ heat flow rate } (75\%) = 45.56\%$$

This is illustrated with in a decision-tree format in Figure 7.



After successful exploration and flow tests, the chance of failure shifts from:

$$\begin{aligned}
 &\{20.25\% + 59.5\%\} = 79.75\% \\
 &\text{to} \\
 &\{15.19\% + 39.25\%\} = 54.44\%
 \end{aligned}$$

Figure 7. Decision-tree for value of information associated with a hypothetical EGS Play A.

In this particular case the value of the information gained from a successful exploration (research) and flow test (proof-of-concept) result in EGS Play A is the shift in expected value, which is illustrated in Figure 7. The value of the information gained from a successful exploration and flow test result in a well that increases certainty in the prevalence of EGS Play A. A reservoirs is estimated as follows:

Pre-drill Expected NPV for Hypothetical EGS Play A

{20.25% x \$500 million unrisks NPV for EGS Play A} - {\$12 million x 79.75%) = \$91.68 million

Post drill Expected NPV for Hypothetical EGS Play A

{45.56% x \$500 million unrisks NPV for EGS Play A} - {\$12 million x 54.44%) = \$221.27 million

The value of this information is very large, and can be estimated to be the difference between the pre- and post-drill expected net present values expressed above.

Let us for a moment assume we have three independent EGS play-trends to explore with characteristic play-trend geologic factor adequacies as displayed below. We can determine the chances that these plays will be at least geologically adequate, geologically inadequate, geologically adequate but short of threshold economic heat flow rates or economically successful.

First – if assignments are made in a consistent way – this provides a tool for ranking plays.

Second – if assignments are made in a consistent way - this enables estimates of the chance that exploring all three play trends will result in at least one geologically adequate EGS play being discovered as follows:

$$1 - \{ \text{Probability}_{\text{geologic inadequacy for A}} \\ \times \text{Probability}_{\text{geologic inadequacy for B}} \\ \times \text{Probability}_{\text{geologic inadequacy for C}} \}$$

In this hypothetical example, the chance of finding at least one EGS play that will flow to economic expectations. is estimated as follows:

$$100\% - (79.75\% \times 84.81\% \times 94.38) = 36\%$$

This reflects the chance at least one success will result from drilling three plays.. Adding a fourth independent EGS play trend to the drilling program would increase the chance of demonstrating at least one economically attractive resource.

The likelihoods for success in EGS can be integrated estimates of EGS play NPVs to formulate a portfolio management system.

Play A		
Portfolio Factors	Chance of Adequacy	Chance of Inadequacy
P _{heat source}	90%	10%
P _{heat trap}	90%	10%
P _{heat reservoir}	50%	50%
P _{heat flow rate}	50%	50%
P _{geologic success} = P _g	(90% x 90% x 50%) = 40.50%	
P _{geologic failure} = 1 - P _g	(1 - 40.50%) = 59.50%	
P _{technical success}	40.50% x (1 - 50%) = 20.25%	
P _{technical failure}	(1 - 20.25%) = 79.75%	
P _{economic success} = P _s	(40.50% x 50%) = 20.25%	
P _{economic failure} = P _f	(1 - 20.25%) = 79.75%	
Play B		
Portfolio Factors	Chance of Adequacy	Chance of Inadequacy
P _{heat source}	90%	10%
P _{heat trap}	90%	10%
P _{heat reservoir}	75%	25%
P _{heat flow rate}	25%	75%
P _{geologic success} = P _g	(90% x 90% x 75%) = 60.75%	
P _{geologic failure} = 1 - P _g	(1 - 60.75%) = 39.25%	
P _{technical success}	60.75% x (1 - 25%) = 45.56%	
P _{technical failure}	(1 - 45.56%) = 54.44%	
P _{economic success} = P _s	(60.75% x 25%) = 15.19%	
P _{economic failure} = P _f	(1 - 15.19%) = 84.81%	
Play C		
Portfolio Factors	Chance of Adequacy	Chance of Inadequacy
P _{heat source}	50%	50%
P _{heat trap}	90%	25%
P _{heat reservoir}	50%	50%
P _{heat flow rate}	25%	75%
P _{geologic success} = P _g	(50% x 90% x 50%) = 22.50%	
P _{geologic failure} = 1 - P _g	(1 - 22.50%) = 77.50%	
P _{technical success}	22.50% x (1 - 25%) = 16.88%	
P _{technical failure}	(1 - 16.88%) = 84.22%	
P _{economic success} = P _s	(22.50% x 25%) = 5.63%	
P _{economic failure} = P _f	(1 - 5.63%) = 94.38%	

This form of logic is routinely applied in managing portfolios of upstream petroleum ventures, and can assist companies and governments in their process for planning multi-year budgets for the exploration and proof-of-concept and demonstrations phases of several prospective hot rock plays in Australia.

MILESTONES AHEAD ON THE ROAD TO THE VISION OF COMMERCIALISED GEOTHERMAL ENERGY

The Australian geothermal Energy Group (AGEG) has considered the future of EGS play exploration and demonstration projects in Australia and suggests it is reasonable to expect:

- At least 10 successful research (exploration) and proof-of-concept (i.e. heat energy is flowed) geothermal projects completed by 2010;
- At least 3 geothermal power generation demonstration projects in distinctively different geologic settings are achieved by 2012;
- Compelling success with geothermal power generation demonstration so the investment community is convinced that geothermal energy is reliable by 2012; and
- Safe, secure, reliable, competitively priced, renewable and emissions-free base-load power from geothermal energy for centuries to come, with at least 7% of base-load demand from hot rock power by 2030.

CONCLUSIONS

Australia's vast hydrothermal and hot rock energy resources have the potential to become a very significant source of safe, secure, competitively-priced, emission free, renewable baseload power supplies for centuries to come. This potential combined with the evidence of risks posed by climate change is stimulating growth in geothermal energy exploration, and proof-of-concept and demonstration power generation projects in Australia.

REFERENCES

Capen, E, 1992, Dealing with exploration uncertainties, in Steinmetz, R (ed.), *The Business of Petroleum Exploration: AAPG Treatise of Petroleum Geology*, Chapter 5, p. 29-62.

Chopra, P.N. and Holgate, F., 2005, A GIS analysis of temperature in the Australian Crust: Proceedings of the World Geothermal Congress, 2005, Antalya, Turkey, 24-29 April, 2005.

Electricity Supply Association of Australia, 2006, Energy and emissions study – Stage 2, Emissions Targets and Least Cost, Generation Options, Download from <http://www.esaa.com.au>

Electricity Supply Industry Planning Council, 2007, Annual Planning Report, Download from: <http://www.esipc.sa.gov.au>

Hillis, R.R., Hand, M., Mildren, S., Morton, J., Reid, P. and Reynolds, S., 2004. Hot dry rock geothermal exploration in Australia, in, Boulton, P.J., Johns, D.R. and Lang, S.C. (eds), *Eastern Australasian Basins Symposium II: Petroleum Exploration Society of Australia*, Special Publication, p. 413-421.

Hunt, S.P. and Morelli, C., 2006, Cooper Basin HDR hazard evaluation: Predictive modeling of local stress changes due to HFR geothermal energy operations in South Australia, University of Adelaide Report Book 2006/16 [Prepared by The University of Adelaide for South Australian Department of Primary Industries and Resources].

MIT, 2006, *The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century* [Prepared by an interdisciplinary panel Chaired by Dr Jefferson Tester, MIT]

Rose, P. R, 1992, Chance of success and its use in petroleum exploration, in Steinmetz, R. (ed.), *The Business of Petroleum Exploration*, AAPG Treatise of Petroleum Geology Chapter 7, p. 71-86.

LINKS

For links to Australia's geothermal sector, visit: <http://www.pir.sa.gov.au/geothermal>

For link to Electricity Supply Industry Planning Council 2006 Annual Planning Report, visit http://www.esipc.sa.gov.au/webdata/resources/files/APR_Final_for_Website.pdf