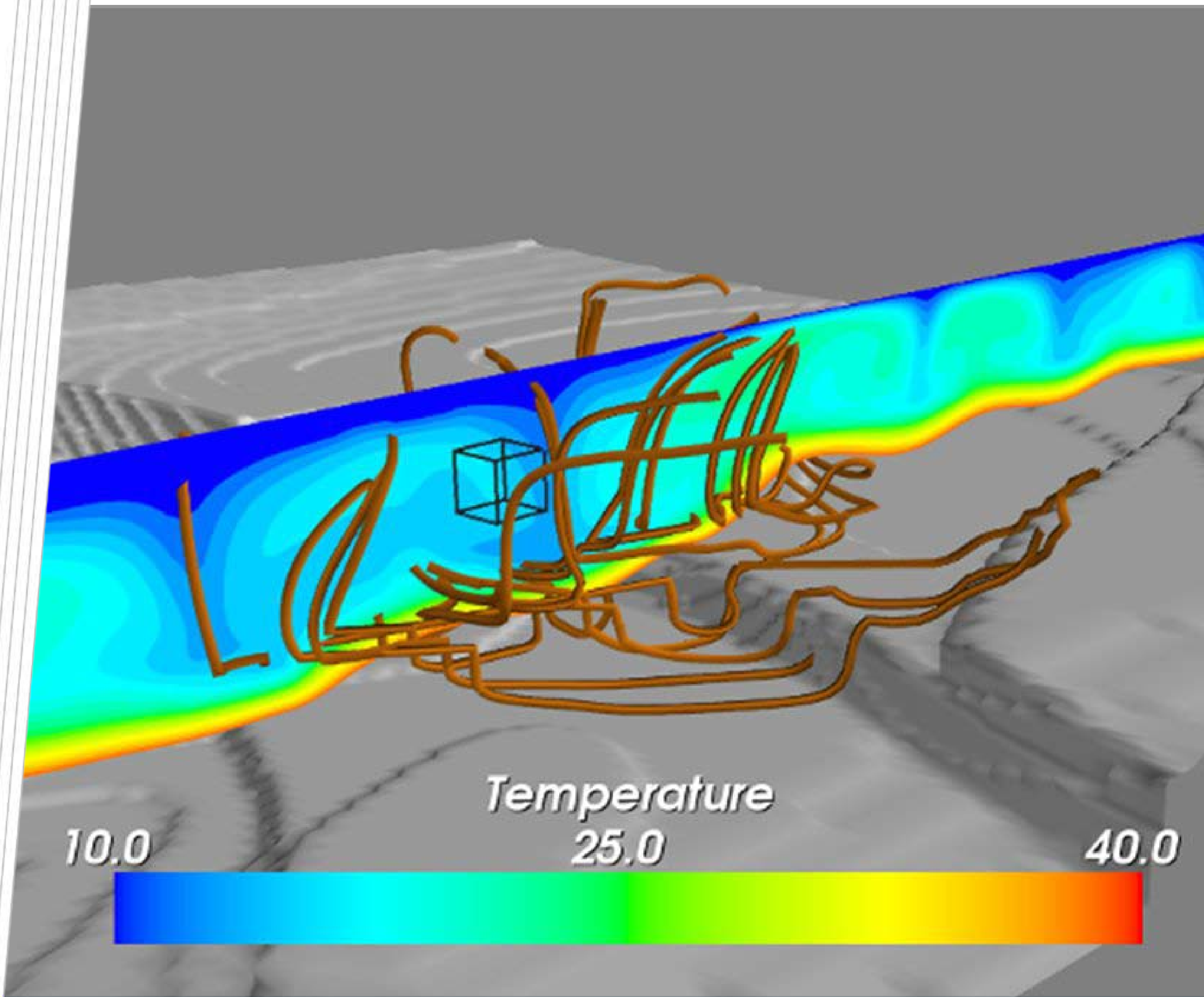

The potential of geothermal energy

Cameron Huddlestone-Holmes and Jenny Hayward

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Enquiries should be addressed to:
Cameron Huddlestone-Holmes
PO BOX 883
KENMORE QLD 4069
Australia
Ph: 61 7 3327 4672
E-mail: Cameron.Hh@csiro.au

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1. EXECUTIVE SUMMARY

Geothermal energy is heat extracted from the earth. This heat is extracted by circulating a fluid through the reservoir to bring the heat to the surface where it can be used to generate electricity or as heat in direct use applications. The most commonly-exploited geothermal resource used for power generation globally are convective hydrothermal systems that are found in high heat flow and volcanic regions associated with tectonic plate boundaries (e.g. west coast of the USA, New Zealand, Indonesia). These resources have high geothermal gradients (high temperatures at relatively shallow depths) and have significant volumes of fluid (steam and hot water) that can be extracted from the reservoir, bringing heat to the surface. These resources are not found in Australia’s intraplate tectonic setting, and the Australian geothermal industry is targeting two new concepts of geothermal reservoirs.

The first are enhanced geothermal systems (EGS), which uses resources that are deeper in the crust. These resources are in crystalline rocks, heated by radioactive decay with this heat trapped in the reservoir by insulating sediments. The rocks need to be fractured to allow a working fluid to be circulated from the surface, through the reservoir where it is heated, and back to the surface where the heat can be used. The second are hot sedimentary aquifers (HSA). These consist of hot water in highly-permeable rocks, typically in sedimentary basins. Australia has substantial EGS and HSA resources, but these technologies are in the development phase.

The key ingredients for geothermal energy production can be summarised by this equation:

$$MW \approx c_p \times F \times \Delta T \times \eta - P$$

where c_p is the specific heat of the working fluid; F is the flow rate from the production well; ΔT is the sensible heat that can be extracted from the fluid produced by the production hole ($T_{reservoir} - T_{rejection}$); η is the efficiency with which the heat energy can be used, and P is the parasitic losses. The goal in geothermal systems development is to optimise as many of these parameters as possible to increase electrical output relative to the capital costs of developing the geothermal energy resource and surface plant. This approach improves the economics, since the capital cost is by far the largest component to the levelised cost of electricity (LCOE) of geothermal systems.

In EGS systems, by drilling deeper wells ΔT increases. However, the cost of drilling can be as much as 80% of the capital cost of a plant, and this cost increases with depth. In addition, P for pumping increases in deeper wells and it is more difficult to achieve a high flow-rate (F); therefore, tradeoffs need to be evaluated. In HSA systems ΔT tends to be lower. Therefore, targets for increasing the output and lowering the cost are increasing the flow-rate, reducing parasitic losses and improving the efficiency of energy conversion.

Research targets for technical and economic development of these technologies are improved exploration and resource/reservoir characterisation, lower-cost drilling techniques, reservoir engineering (obtaining the required fluid flow) and more efficient power conversion. Currently, fluid flow in the reservoir is the biggest technical challenge facing EGS developers.

Other issues can also impact the development of geothermal in Australia, such as social and environmental risks, surrounding groundwater use and induced seismic events from drilling; competing use of resources as geothermal resources can be located near coal seam gas, groundwater and sites for CO_2 sequestration; and financial risks given the large scale, relatively high capital costs and high number of uncertainties.

Geothermal energy's largest contribution to the world's energy market is through direct use applications such as process heat, thermal desalination and heating and cooling (via adsorption chillers) of buildings. Direct use applications can access low temperature HSA, EGS or convective hydrothermal systems and have the advantage of not needing the very high flow rates or temperatures needed for electricity generation because of the higher efficiencies of direct use applications. Another class of direct use geothermal energy are ground source heat pumps (GSHP). GSHP are the largest single category of geothermal energy use in the world, with well developed markets in Europe, North America and China for heating and cooling of homes and commercial buildings. The resource is the thermal mass of the earth that acts as a source/sink to equilibrate temperatures. This system is different to large scale geothermal resources in that the working fluid is not in direct contact with the resource.

Geothermal energy has tremendous potential to provide Australia with reliable, base load, dispatchable and clean renewable energy for millennia. Through direct use and GSHP applications, a significant amount of generation capacity can be offset. GSHP are a well established technology available now but its uptake does suffer from a lack of awareness and critical mass relative to other technologies. Geothermal energy from EGS and HSA resources is still in the technology development stage. As a result, there is a high degree of uncertainty in the cost. There is a significant ramp up in research and development around these resources internationally. As the exploitation of EGS and HSA resources is established in Australia and internationally, it is highly likely that the costs will reduce as more effort is spent on improving the component technologies. The equivalent is also true for direct use applications.

2. INTRODUCTION

This report provides an overview of the current status of geothermal energy technology in Australia and opportunities for innovation to lead to lower costs of energy production from this resource. The report was prepared as input to the Garnaut Review Update in a relatively short time frame, and therefore is not intended to be comprehensive.

Geothermal energy is simply heat extracted from the earth. This heat can be used to generate electricity via a turbine or used directly. Geothermal energy has been utilised since the early 1900’s with a global total installed electricity generating capacity of 10,715 MWe as at end 2010 (Bertani, 2010) and direct use of 50,583 MWt as at end 2009 (Lund et al., 2010). This represents a capacity increase of 20% for electricity generation since 2005 and 60% for direct use over a similar period The vast majority of electricity generation comes from convective hydrothermal (also known as conventional) geothermal systems. These systems involve convection of heat through the crust via hot fluids and are typically found in areas of active tectonic and volcanic activity and are unlikely to occur in Australia. Geothermal energy in the Australian context will exploit enhanced geothermal systems (EGS) and hot sedimentary aquifer (HSA) style geothermal resources.

Australia’s current geothermal energy use is limited to an 80kw power plant that has been operating at Birdsville, Queensland since 1992 and a minimum of 7 MWt for direct use applications (Beardsmore and Hill, 2010). Only limited data is available for direct use of geothermal heat and many applications of this energy resource are not reported. The substantial potential of geothermal energy for Australia is highlighted in the Australian Energy Resource Assessment (Geoscience Australia and ABARE, 2010) that points out that just 1 percent of the geothermal energy resources with a minimum temperature of 150 °C and a maximum depth of 5 km could provide 190 million PJ of energy – enough to provide 25,000 times Australia’s energy usage. Geothermal energy also has the advantage of being dispatchable (available on demand).

The development of geothermal energy in Australia is at a cross-roads: there are strong indications of long-term promise; however, there has been a growing realisation of the complex underlying issues that need to be overcome to deliver heat energy to the surface.

3. GEOTHERMAL ENERGY OVERVIEW

The application of geothermal energy ranges from domestic scale ground source heat pumps used for heating and cooling of homes through to 100’s of MW scale power plants. Technically, the ground source heat pump end of the spectrum is well understood and its lack of application in Australia is mostly a market issue. The large scale power plant end of the spectrum is more technically challenging, particularly with the geothermal energy resource styles found in Australia.

3.1 Geothermal Energy Resource Types

There are three primary styles of geothermal resources exploited in the world today (Figure 1). All of these resources require anomalously high temperature gradients in the upper few kilometres of the earth's crust. These high temperature gradients can be the result of high heat flow rates from lower in the crust, advection of hot material or fluids into the upper crust, production of heat in the upper crust due to geological processes, insulating material that traps heat, or a combination of all three.

The vast majority of geothermal power plants operating (Sanyal, 2010a) around the globe access heat from convective hydrothermal systems . These systems are associated with areas of high crustal heat flow along plate boundaries and may be associated with volcanic activity. In these systems heat is moved into the upper crust by magmatic intrusions (volcanic) or convective fluid flow. Volcanic systems are generally hotter than non-volcanic systems. Convective hydrothermal systems contain large volumes of hot fluid in fractures that are tapped by wells to bring the heat energy to the surface.

The second category of geothermal resources is Enhanced Geothermal Systems (EGS) also referred to as hot rock. EGS resources are typically in crystalline rocks that are heated by the decay of radioactive potassium, uranium and thorium and buried under insulating sediments that trap the heat. For example, heat generated in the Big Lake Suite Granodiorite is trapped by the insulating carbonaceous mudstones, silts and coals of the overlying Cooper and Eromanga Basins at Geodynamics' geothermal development near Innamincka in South Australia. Anomalously high heat flows from lower in the crust may also contribute to this resource. Here, the thermal gradient exceeds 50 °C/km and the heat flow exceeds 100 mW/m^2, nearly double the average for continental crust (25–30 °C /km and 65 mW/m^2 respectively). The model for extraction of heat from EGS resources involves engineering the reservoir by fracturing the reservoir rocks to enhance their natural permeability. A working fluid is pumped through the reservoir, where it is heated by the rock, and back to the surface where the heat can be used.

The third category of geothermal resources is Hot Sedimentary Aquifers (HSA), or conductive sedimentary systems. Conduction is the main form of heat transport in these systems, similar to EGS, although convection is likely to be important contributor. HSA are simply reservoirs that contain hot water and high permeabilities. The concept for HSA use is that these volumes of water and permeabilities are sufficient to extract fluid at the high flow rates required. The heat source may be the same as for HR, or advected heat from deeper in the crust.

As Australia is on a stable continental plate far from plate boundaries, convective hydrothermal systems will not be an important geothermal resource. The geothermal resources in Australia fall in the EGS and HSA categories.

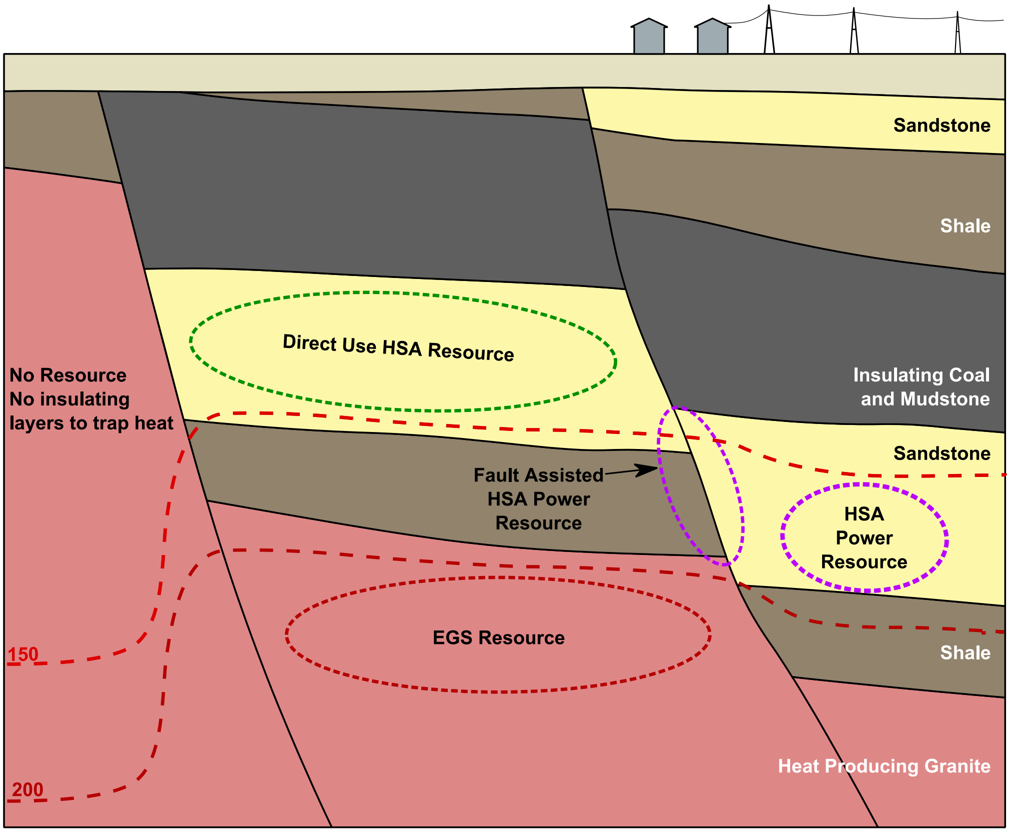

Figure 1: Schematic showing the geologic settings of the geothermal energy resource types targeted in Australia. In this figure a heat producing granite is covered by varying amounts of sediment. The red dashed line represents the depth at which a temperature of the rock reaches 150 °C, and the burgundy shows where the rock reaches 200 °C. At the far left of the image the granite extends to near the surface and the sediments above it are too thin to trap heat. In the central region the granite is buried by enough insulating sediment (coal, mudstone and shale) to trap the heat produced in the granite and from deeper in the earth. Here the geothermal gradient is at its highest, and a high temperature EGS resource is at drillable depths. The rock would have to be fractured to allow sufficient fluid flow to extract the heat. Above the EGS, is a low temperature HSA in a sandstone layer that could be used for direct use applications. To the right, the granite is too deep to reach. However, there is a moderate temperature HSA in the highly permeable sandstone layer above it. Another style of HSA target is the fault on the right side of the diagram, were fracturing of the rock increases the already high permeabilities in the surrounding sandstone.

3.2 Key ingredients of geothermal energy production

Geothermal energy can simply be described as heat extracted from the earth. The extraction of this energy relies on the transport of heat from a geothermal reservoir to the surface via a fluid (Fig. 2). This fluid is in direct contact with reservoir rocks and may naturally occur in the reservoir or may have to be introduced into the system. To understand the key ingredients for a viable geothermal system, it is useful to look at the net amount of energy produced by a single well by considering the following equation

$$MW \approx c_p \times F \times \Delta T \times \eta - P \quad \textbf{(1)}$$

where c_p is the specific heat of the working fluid; F is the flow rate from the production well; ΔT is the sensible heat that can be extracted from the fluid produced by the production hole ($T_{reservoir} - T_{rejection}$); η is the efficiency with which the heat energy can be used, and P is the parasitic losses.

Using the current global experience in power generation from convective hydrothermal resources, the minimum amount of net energy produced by a well in a geothermal power system is around 4 MW. For geothermal systems in Australia the working fluid will be water with varying degrees of salinity. The specific heat will be more or less constant for all resource types. The ΔT will be in the order of 50 °C to 150 °C, and the efficiency of current power cycles is around 10 %. Based on these numbers and ignoring parasitic losses, a well needs to flow at a minimum of 70 kg/s to be viable. This rate is orders of magnitude higher than average flows in the US oil industry, and at the upper end of production rates for water wells, particularly at the depths needed to access high temperatures. The flow problem is not as significant in convective hydrothermal resources as these typically produce steam rather than water. Although the specific heat and density of steam is lower than water, high flow rates are achieved because of steam's low viscosity and density, allowing wells to produce without pumping.

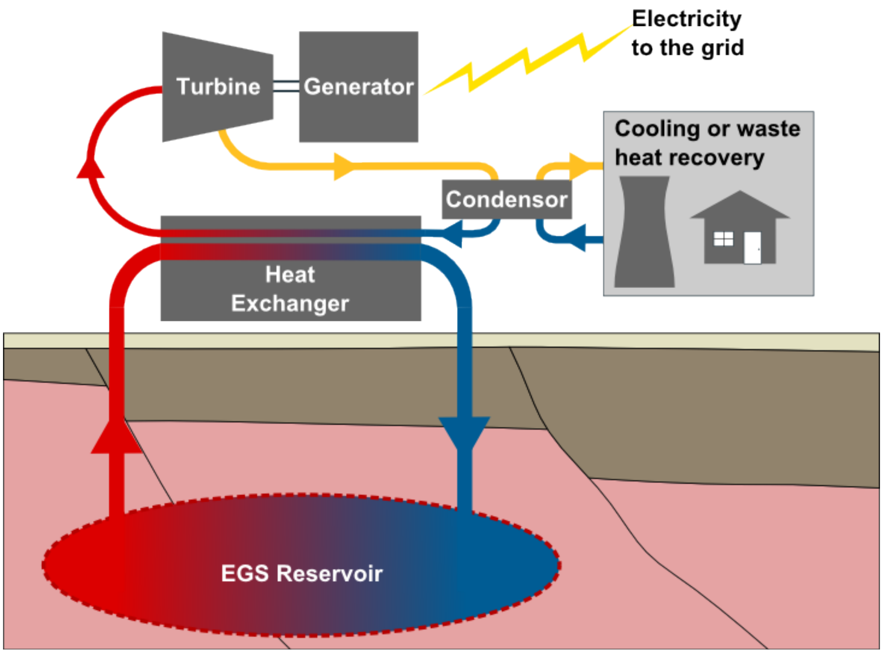

Figure 2: Schematic showing key components of a geothermal power generation system. This represents a binary generation plant where the reservoir fluid transfers heat to the turbine's working fluid via a heat exchanger. Significant cooling will be required with 5 to 10 units of heat rejected for every unit of electricity generated. This waste heat can be removed using cooling systems or recovered for direct use applications such as district heating or thermal desalination.

The ΔT is dependent on the temperature of the reservoir ($T_{reservoir}$) and the rejection temperature ($T_{rejection}$) of the energy conversion system. Maximising $T_{reservoir}$ requires locating anomalously high thermal gradients, and drilling as deep as possible. Minimising $T_{rejection}$ requires cooling and minimisation of scaling in plant and pipelines due to mineral precipitation as the fluid cools.

The efficiency of energy conversion is dependent on the process used. As mentioned above, the efficiency of power generation is low for the resource temperatures under consideration in Australia. However, higher efficiencies can be gained for lower temperature resources from direct use applications of the heat in processes like adsorption chillers and thermal desalination.

Parasitic losses are due to pumping of the working fluid out of production wells and then pumping the fluid back in to the reservoir via injection wells, pumps in the power plant or direct use application, and cooling fans.

3.2.1 Ingredients of an EGS

EGS by definition require stimulation of the reservoir to increase flow. This will be done by increasing the fracture permeability of the reservoir. A key ingredient will be existing fracture systems that can be enhanced as the creation of new fractures is difficult. EGS targets will generally be deep with a relatively high $T_{reservoir}$,. The primary constraint being the depth to which construction of wells and stimulation of the reservoir is more feasible. The reservoir fluid is likely to contain a high content of dissolved minerals leading to scaling if the $T_{rejection}$ is set too low. Parasitic losses are likely to be high due to pumping and cooling requirements. EGS will most likely be applied to power generation and the efficiency of conversion of the heat energy will be constrained by the choice of power cycle.

3.2.2 Ingredients of an HSA System

HSA systems rely on the natural permeability of the reservoir. This permeability may be matrix permeability in a sandstone, or fracture permeability in a limestone or fault zone. Permeability generally decreases with depth due to confining pressure, so HSA resources will be limited in their depth extent and reservoir temperature ($T_{reservoir}$). Some enhancement of the reservoir will be required to increase near well bore permeability where the permeabilities are too low to maintain high flow. The amount of engineering that would constitute a reservoir being termed an EGS is arbitrary. The reservoir fluids for HSA are likely to contain less dissolved minerals than EGS so lower rejection temperatures ($T_{rejection}$) will be possible. The lower $T_{reservoir}$ of HSA systems will necessitate the use of power cycles with lower efficiencies than can be used in EGS with higher reservoir temperatures. Alternatively, HSA temperatures may be ideal for direct use applications, resulting in higher efficiencies.

3.3 Ground Source Heat Pumps

Ground source heat pumps (GSHP) belong to a category of systems that treat the earth as a thermal mass that acts as a heat source for heating or a heat sink for cooling. At shallow depths of several 10's of metres the earth averages out seasonal variations and maintains a constant temperature that is between the winter and summer averages. In a GSHP a heat pump is used to enhance the flow of heat from warm to cool – for example from the ground into a house during winter, or the opposite during summer. Other technologies that use this thermal mass effect include earth-air heat exchanges that work on the same principles but without a heat pump.

GSHP are the world's largest geothermal energy use with a global installed capacity of 35,236 MWt (Lund et al., 2010). While not yet popular in Australia, well established markets exist in Europe, North America and China. There is considerable potential for GSHP to offset electricity demand for space heating and cooling because of the high efficiencies of these systems. This would be similar to the effect that solar hot water systems have had on reducing the electricity demand for water heating.

The key difference between these thermal mass based systems and other forms of geothermal energy is that the heat exchange is via a closed loop, and the fluid circulated in the loop has no direct interaction with the earth. Other forms of geothermal energy use an open loop where fluids (water or brine) already in the reservoir or fluids introduced in to the reservoir are used to extract heat from the earth and bring it to the surface.

4. GEOTHERMAL ENERGY TECHNOLOGY DEVELOPMENT

EGS and HSA have not been developed on a substantial scale anywhere in the world. EGS is still in the technology development phase, and HSA is only slightly more advanced through district heating and other direct use projects, including some experience in Australia (Perth for heating of several swimming pools; district heating in Portland, Victoria; and the power plant at Birdsville in Queensland). There is a considerable level of research and development taking place globally in pursuit of the promise of EGS and HSA resources. The areas of research activity can be broken down into the broad categories of Exploration, Drilling, Reservoir Characterisation, Reservoir Engineering, and Power Conversion. There is significant overlap between these tasks.

4.1 Exploration

Exploration targets two components of Equation 1, ΔT and F. High temperatures (ΔT) are targeted by looking for areas with anomalously high thermal gradients. Flow is targeted by looking for areas with high natural permeability or with characteristics that are suitable for enhancement. The aim of the research is to reduce the risks and therefore costs of discovering a geothermal resource.

Exploration for natural resources is inherently high risk. These risks can be significantly reduced by the selection of suitable exploration targets. Targets need to be developed at all scales to enable the selection of appropriate provinces (or basins), selection of tenements within these provinces, the development of prospects within tenements and the locating exploration wells within prospects. The mineral and petroleum industries have well established approaches for exploration targeting through Mineral Systems Analysis and Petroleum Systems Analysis respectively. These approaches require an understanding of the targeted resource and the development a similar strategies for geothermal systems will require the development a deep understanding of the geology of geothermal resources.

Exploration for geothermal energy resources in Australia is a new activity. Many of the tools used for exploration come from the mineral and petroleum sectors. The geothermal industry's research and development needs are primarily focussed on adapting these technologies and skills to finding and evaluating geothermal resources. There are three broad areas of research and development need: understanding the geology of geothermal resources; development of geophysical methods for geothermal exploration; and development of pre-competitive data to assist the geothermal industry.

4.2 Drilling

Geothermal resources, by their nature, will be deep; current targets in Australia are typically at depths between 3 km and 5 km. Exploration holes drilled to these depths require a large investment before a resource can be defined. Production from these resources will require the drilling of a large number of deep holes and this drilling will make up a substantial part of the capital invested in a geothermal project. A significant reduction in the costs of drilling will greatly improve the viability of the geothermal industry, as well as opening up areas with deeper geothermal resources for exploitation.

The geothermal industry is currently relying on technologies developed in the petroleum industry, where wells are routinely drilled to depths of 4 km to 5 km. However, there are several key differences between geothermal drilling and petroleum drilling: geothermal reservoirs are hotter than the petroleum reservoirs (although the petroleum industry is working in deeper and hotter reservoirs as shallow reservoirs are depleted); the crystalline (granitic/metamorphic) formations expected in EGS geothermal wells are generally harder and more fractured that the sedimentary formations typically encountered in petroleum reservoirs; and, geothermal wells are usually completed at larger diameters than petroleum wells to allow for the required flow rates.

Improvements in drilling technologies will allow higher temperatures to be targeted by enabling deeper wells, and have the potential to increase flow.

4.3 Reservoir Characterisation and Modelling

The exploration process will identify prospective geothermal resources and provide a certain level of information about those resources, primarily in regard to the resource size and its contained heat, permeability and fluid volumes. At some stage in the development cycle of a geothermal resource, the focus shifts from defining what the resource is to characterising in detail the reservoir and its properties which allows a definition of reserves. This reservoir characterisation is needed to allow for the design of the below and above ground systems that will be used to extract the resource. The distinction between exploration and reservoir characterisation is somewhat arbitrary. Reservoir modelling will be extremely important for understanding geothermal reservoirs. A small scale trial plant for a geothermal resource will still require many millions of dollars to be spent on drilling, so virtual trials and models of long term reservoir behaviour and its response to changes in temperature and chemistry with time will play a very important role in characterising reservoirs and designing geothermal operations.

4.4 Reservoir Engineering

Reservoir stimulation is the single biggest issue for EGS or enhanced geothermal systems (MIT-led panel, 2006). As described above, geothermal reservoirs will need high production rates to be economic. Research and development field projects in EGS reservoirs have only been able to sustain fluid circulation rates of 10 to 30 kgs^{-1}; these flow rates are sub-economic. Stimulation procedures that are used in the oil and gas industry need to be modified to work in the high temperatures and pressures of the EGS environment. These procedures must be able to induce pervasive permeability in the reservoir without creating short circuits. Short circuits occur when cold fluid injected into the reservoir flow through pathways that have high permeability and reach production wells before the fluids have had time to extract heat from the reservoir rock.

HSA reservoir engineering issues are more concerned with maintaining long term production from the aquifer without short circuits, sand production, or formation damage around injection wells that reduce permeability.

The high flow rates required from geothermal reservoirs will need artificial lifting systems that are able to maintain high performance levels in harsh environments. Use of down-hole production pumps may help to control reservoir pressures, reducing the risks of short circuits, fluid loss and induced seismicity. Significant improvements are needed in temperature tolerance and service life in the currently available fluid lifting systems for the hot and saline environments of geothermal wells. Current down-hole pumping technologies are restricted to line shaft pumps that are limited to working depths less than 600m and electric submersible pumps that are limited to temperatures below 200°C. Research and development is needed in high temperature electronics and motors, high temperature and pressure seals, and corrosion resistant materials. There is also a need to ensure that pumps operate as efficiently as possible to reduce parasitic pumping power.

There is some research into the use of supercritical CO_2 as a working fluid but this is very much in the experimental phase. Supercritical CO_2 has a lower viscosity than water and should be able to flow through the reservoir more easily. Some of the CO_2 is likely to be sequestered, providing an added benefit. Supercritical CO_2 also has some favourable thermodynamic properties that make it attractive.

4.5 Power Conversion – Electricity

Once geothermal heat has been extracted from the reservoir and carried to the surface by the working fluid, the heat is then converted into useful power. EGS and HSA geothermal power stations will have similar operating parameters to conventional geothermal. However, the harsh and remote locations of some of Australia's geothermal resources create some challenges A 50-MWe geothermal power plant needs to "dump" about 300MW of heat to cool its condensers. To dispose of this heat using a conventional wet cooling tower would consume water at a rate of about 100 kg/s or over 3 million tonnes per year. For geothermal generation to be a commercial reality, it needs to develop cost-effective and efficient dry cooling technologies. The most significant impact of research and development in power conversion will be in improved efficiencies that increase the amount of heat converted into useable energy. A step change in efficiency could transform the industry. The barrier of low flow may be overcome using next generation technology that will bring geothermal power conversion to the same level of maturity enjoyed by other power generation technologies.

4.6 Power Conversion – Direct Use

The high efficiencies of direct use applications of geothermal energy have great potential to expand the viability of geothermal resources where temperatures are too low for economical generation of electricity. Direct use applications include thermal desalination; dehumidification; sorption chillers for cooling and air-conditioning; heating of commercial and residential buildings and greenhouses; and, process heat in industrial applications. Research and development of these technologies is needed to build modelling tools for these systems (coupling below ground with above ground plant to create the most efficient overall systems); increasing the efficiencies of direct use applications; and, investigating the effects of scaling in surface plant used with these technologies.

There is also potential for the development of novel applications of heat from geothermal resources. For example, geothermal heat could be used to dry brown coal in the LaTrobe Valley. There is a need to identify opportunities for development of industries that can utilise direct use technologies in areas of known geothermal resources.

5. COSTS AND COST REDUCTION FOR GEOTHERMAL ENERGY

Capital costs are the biggest component of the costs of geothermal energy production. The Australian Electricity Generation Technology Costs – Reference Case 2010 (EPRI Palo Alto CA and Commonwealth of Australia, 2010) has the capital costs for HSA and EGS in the range of 83 % to 88% of the levelised cost of electricity (LCOE). A good geothermal resource will be one that achieves as high as possible installed capacity for the amount of capital invested in the project. The most significant factors in determining the capital costs per unit of installed generating capacity before connection to the grid can be summarised by a modification of Equation 1.

$$Cost / MW \approx \frac{C_{drill} + C_{BOP}}{c_p \times F \times \Delta T \times \eta - P} \quad \textbf{(2)}$$

Where C_{drill} is the cost to construct production/injection wells, including engineering the reservoir and C_{BOP} is the cost of the balance of plant, including the surface power conversion equipment (electricity generation or direct use) and equipment required for pumping the working fluid into and out of the reservoir. A significant decrease in the capital costs of either C_{drill} or C_{BOP}, or a significant increase in F, ΔT or η will have a significant effect on the cost of generation for geothermal resources. The parameters are not totally independent. Drilling costs will be related to the depth of the resource and the targeted depth will be dependent on the temperature of the reservoir, and therefore, ΔT. The efficiency of electricity generation is dependent on ΔT.

Table 1 shows the differences between these parameters for the resource styles in Australia. Quantitative data is not yet available, so the table shows how these parameters are expected to vary between resource types.

	EGS	**HSA Power**	**HSA Direct Use**
C_{drill}	High, Uncertain	Med	Low
C_{BOP}	Med - High	Med - High	Low
c_P	~ Constant	~ Constant	~ Constant
F	Low, Uncertain	High, Uncertain	High, Uncertain
ΔT	High, Uncertain	Med, Uncertain	Med, Uncertain
η	Poor	Very Poor	High
$P^{\#}$	High, Uncertain	Med, Uncertain	Med - Low

Table 1: Relative nature of inputs into the costs of geothermal energy the range of geothermal resources found in Australia. For example, this shows how the lower ΔT in HSA Power systems is offset by the lower drilling costs. It also highlights where parameters are uncertain either due to the lack of experience with Australian geothermal energy resources, or the inherent uncertainty in exploiting earth resources.

5.1.1 C_{drill}

The cost of drilling can be as much as 80% of the cost of the plant for hot fractured rocks however this can vary considerably depending on the depth of resource. Any reduction in drilling costs will have an impact on the viability of geothermal energy projects; a step change could transform the industry. The costs of drilling a well are related to the depth of the well, and therefore the size of the drill rig, the rate of penetration, bit life, casing design, cementing, and stimulation activities. To achieve cost reductions in drilling, better rock reduction methods that produce an increase in rates of penetration, reducing the time it takes to drill a well, are the most significant challenge.

The drilling rigs used for geothermal plants are the same rigs used for oil and gas wells, however, there are some significant differences including:

- geothermal wells are usually completed at a larger diameter than oil and gas wells, increasing the costs;
- salty water is more corrosive than oil and gas requiring different casing materials and cementing methods;
- the effects of thermal expansion require different approaches to well completion;
- high temperatures effect bit life;
- the rock in EGS reservoirs are significantly harder than those found in oil and gas or HSA, effecting bit life and rates of penetration;
- high temperatures effect drilling muds, and these muds require cooling at the surface; and
- drilling muds can cause formation damage and need to be carefully managed.

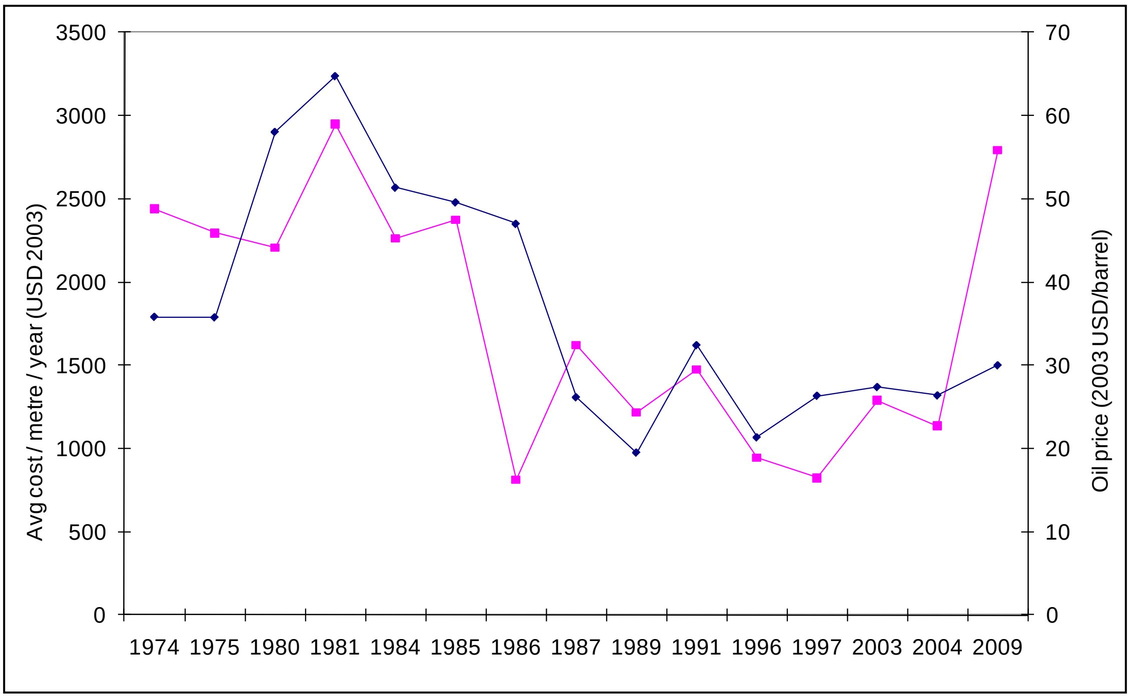

Figure 3: Geothermal well drill cost per metre (pink) and oil price (blue) over time. Note that data was not available for some years (Augustine et al., 2006, Energy Information Administration, 2009)

Another major source of variation in drilling cost is the price of oil, because the drilling rigs are used for oil and gas wells as well as geothermal plants. The effect of this on the drilling cost is shown in Figure 3, where the high degree of correlation between the average cost of drilling a geothermal well per metre and the oil price since the year 1974. Note that the data for the drilling cost are based on wells deeper than 2km as the cost per metre for drilling deeper wells is higher than for shallower wells (Chad et al., 2006). When the price of oil is high, drilling rigs for geothermal wells are scarcer as they are used to drill for oil which pushes up the rig price (Bloomfield and Laney, 2005, Cosgrove and Young, 2009).

Therefore, it is possible to form estimates of the cost of drilling an EGS based on the oil price. In addition, since various studies project the future oil price, it is also possible to determine estimates for future drilling prices. The low demand for large onshore drill rigs in Australia means that the costs for drilling in Australia are very high due to a lack of competition. If the geothermal industry drives up the demand for drilling allowing drilling contractors to base more rigs locally then this is expected to place further downward pressure on the costs of drilling.

To counterbalance the high drilling cost, a high degree of learning occurs when drilling at one site, especially when the same rig and crew are used (Williamson, 2010, Brett and Millheim, 1986, Pinto et al., 2004), and more than one well is required for any geothermal plant. Therefore, for subsequent wells drilled at any one site a learning rate can be applied to the cost of drilling. The learning rate is based on the cumulative number of wells per site. The rate is quite high – 20% and this is based on general estimates from onshore oil drilling rigs (Brett and Millheim, 1986). These learning rates may be conservative as drilling of geothermal wells in Australia is a new activity and the learning curve for a single resource will be replicated for an industry. The seven deep geothermal wells drilled in Australia up to this point in time have been drilled by large production rigs with limited mobility that were not the best suited to the task. The costs of mobilising these rigs were a significant part of the cost of the wells drilled so far and with the benefit of hindsight, cheaper smaller, and more mobile rigs may have been a better option.

There are various ways in which the cost of drilling can be reduced. There is research into some novel methods of rock reduction (e.g. Potter et al., 2010) that may significantly increase penetration rates. An Australian company, GlobeDrill (www.globedrill.com.au), has developed a new style of drilling rig that has more in common with minerals industry rather than oil field rigs. The company claims that by using air hammer drilling this rig will achieve faster penetration rates than oil field rigs while using less fuel, less operators with significantly lower mobilisation requirements. There is also work underway to optimise the performance of current technologies to EGS and HSA applications, as well as from the combination of minerals industry drilling methods with oil field rigs. If suitable alternatives for oil are found this will release many rigs and crew from drilling for oil and they can then transfer to the geothermal industry. This reduction in demand should help to drive drilling prices down.

5.1.2 C_{BOP}

The second part of the cost is the Balance of Plant, or BOP. Estimates for the BOP can be obtained from conventional geothermal plants, since the equipment is essentially the same. Learning also occurs in the BOP, where costs reduce by 8% for every doubling of cumulative capacity. The BOP will have two components, the surface plant (power generation or direct use) and pumps.

The costs of surface plant will be a significant component of the capital costs of a geothermal project. Restricting these costs while maximising the efficiency of the energy conversion is the key here. Development of more efficient energy conversion technologies will need to come without the penalty of significantly increased costs. This will not be a zero-sum game and optimisation of the whole geothermal system (flow, temperature, power plant design and efficiency) will be the goal.

A working fluid will need to be pumped out of and back in to the reservoir for most unconventional geothermal systems. This would typically involve the use of submersible pumps for lifting the fluid out of the reservoir and surface pumps for injection. These pumps will be the largest contributor to the parasitic losses on a geothermal project. They will also be directly exposed to the reservoir fluids, and submersible pumps will be working in a particularly harsh environment (hot, corrosive). Efficient pumps that have a good balance between performance, reliability and cost will be important to keeping this component of the capital costs down.

5.1.3 F (Flow rate)

Achieving and maintaining high flow rates will be critical for the development of EGS and HSA geothermal energy resources. Increasing flow rates may be a way of improving the economics of a geothermal system by making each well more productive. It is important that increased flows are balanced against reservoir life, avoiding short circuits between production and injection wells. Advancing stimulation and well completion technology that allow the productivity of a well to be increased through stacked stimulation zones will be important in optimizing EGS systems (Sanyal, 2010b).

5.1.4 ΔT

There are many aspects to this. One is finding and extracting the heat from the high temperature resources. Exploration technologies that allow thermal anomalies to be detected will be crucial, including an increase in the available pre-competitive data provided by governments. At the other end, allowing the rejection temperature to be decreased through more efficient cooling (air cooling, water cooling in HSA systems) will increase the amount of energy that can be extracted.

5.1.5 η (efficiency)

As discussed earlier, a step change in this area could lead to significant reductions in the cost of electricity generation from what are relatively low temperature heat sources. The focus of research in this area is on new cycle fluids for binary plants. There is significant potential for improvements in cycle efficiencies as the average efficiencies achieved in installed binary power plants. Di Pippo (2007) found that the average actual efficiency of binary plants is in the order of 55 ± 4 % of their theoretical maximum based on the ideal triaxial cycle. This shows the considerable potential for efficiency gains.

Direct use applications also provide for increased efficiency of heat conversion and development of these technologies is also important. District heating and cooling schemes may be able provide 100’s of MW of useful energy at 10 times the efficiency of electricity generation (Regenauer-Lieb, 2010).

5.1.6 Parasitic Losses

The biggest parasitic loss for a binary power station is cooling of the condensers. Cooling may reduce the net power of a geothermal plant by 15%. Research into natural draft air cooling and shallow aquifer heat rejection systems may lead to significant reductions in these parasitic losses. Pumping is the other major contributor to parasitic losses, and design of efficient pumping systems will also reduce losses.

5.2 System optimisation

All of the identified parameters - C_{drill}, C_{BOP}, F, ΔT, η and P – should not be considered independently. For example, higher ΔT could be achieved by simply drilling deeper. However, this may negatively impact on C_{drill}, and flow rate. Sanyal (2010b) gave an example of how reduced flow rates produced optimum net MW hours supplied due to better heat recovery and reduced parasitic losses over the life of a reservoir. The optimum drilling depth is one that maximises the well’s energy production relative to the cost of drilling. The overall costs of geothermal energy will come down as the industry learns how to optimise the use of its resources.

5.3 Operations and Maintenance

While capital costs will be the most significant determinant in the generation costs for geothermal systems, operations and maintenance (O&M) costs still need to be considered in the overall viability of a project. Geothermal energy will have no fuel costs. O&M costs include:

- Maintenance of pumps (seals, impellers, corrosion, scaling)
- Maintenance of power plant (seals, bearings, turbines, heat exchangers, scaling)
- Refurbishments (major overhauls of equipment)
- Well workovers and clean outs (to maintain flow)
- Electricity for start up after shut downs (for pumps etc)
- Staffing
- Government charges – taxes, royalties, permits

The O&M costs for the binary power plants that are the most suitable technology for the geothermal resources will be lower than for the flash plants commonly used in convective hydrothermal systems as the turbine is not in direct contact with the reservoir fluids. Sanyal (2010b) suggested that the LCOE for some EGS will be most sensitive to variations in O&M costs. Reducing O&M costs will be achieved through design of pumps and power plant to deal with the temperatures and fluid chemistries encountered in geothermal reservoirs. Extending the time between maintenance and refurbishment of plant will be a key goal. The need for well remediation can be reduced by improving reservoir management practices. The workover requirements for EGS and HSA systems are likely to be less than required in convective hydrothermal systems that self flow.

5.4 Uncertainty of Geothermal Energy Costs

Current projected estimates of capital costs of hot fractured rocks plants in the year 2015 are shown in Table 2. The variation in costs reflects the high level of uncertainty surrounding this emerging technology. In CSIRO’s modelling (Hayward et al., 2011) we assume for a EGS power plant 14 wells are required to produce 50MW and the drill depth is 4000m (Cosgrove and Young, 2009, Geodynamics, 2009, Di Pippo, 2008, Huddlestone-Holmes, 2010).

CSIRO (2011)	EPRI (2010)	IEA (2010)

6496	**8116**	**4791**

Table 2: Capital cost estimates for a hot fractured rocks plant in AUD 2009/kW sent out to be commissioned in the year 2015. CSIRO (2011) is from Hayward et al. (2011), EPRI (2010) is from the Australian Electricity Generation Technology Costs - Reference Case 2010 (EPRI Palo Alto CA and Commonwealth of Australia, 2010) and IEA (2010) is from the International Energy Agency's Projected costs of generating electricity (2010).

6. OTHER IMPEDIMENTS TO GEOTHERMAL ENERGY UPTAKE

6.1 Technical and Financial Risks

There is a significant investment required to prove that a geothermal resource is viable. Unlike wind and solar resources where the energy available can be measured at low cost, geothermal resources require drilling that costs 10's of millions of dollars to confirm the resource's potential. There is also uncertainty about the technical aspects of developing geothermal resources which makes this initial capital investment unpalatable. A number of demonstration plants will be required to give the investment community confidence to take on geothermal projects.

6.2 Social and Environmental Risks

Lack of awareness of geothermal energy and its potential to be a zero emissions baseload power source in Australia will need to be addressed (Dowd et al., 2010). Events around a public meeting in the Geelong area, where information was obtained from the internet and conclusions drawn and communicated in relation to pollution and safety (wellbore incident at Geodynamics) underline the requirement for a community consultation and education campaign around any geothermal development. EGS may require significant volumes of water to maintain fluid volumes in the reservoir. Competition for water may make this contentious. There may also be community concerns about interaction of geothermal reservoirs with other groundwater systems, perceptions about radioactive material associated with heat producing granites, induced seismicity, and the noise and visual amenity issues around geothermal power plant and well fields. While these issues do not appear to be technically challenging, they will require careful management by industry and regulators.

The occurrence of seismic events associated to geothermal developments, in particular during stimulation, has raised concerns in the community about the safety of geothermal developments. Recent negative publicity around hydraulic fracturing (fraccing) in unconventional gas development will add to these concerns. Reservoir stimulation either causes movement on existing fractures or development of new fractures. This movement is typically rapid, producing seismic events. The majority of these events are small with magnitudes less than M_L 1. However, larger events have occurred at several projects, including Geodynamics Cooper Basin project (M_L 3.2, Baisch et al., 2006), and the Deep Heat Mining Project in Basel, Switzerland (M_L 3.4, Ripperger et al., 2009). In the case of Basel, the events caused damage to surface structures and forced the project's abandonment. There is a need to develop procedures for managing the risk of seismic activity during stimulation and production from geothermal reservoirs. This management involves understanding the levels of induced seismicity that may occur and their effects on natural (e.g. faults and topographic) and man-made structures that may be impacted upon.

6.3 Competing use of resources

The reservoirs that are targeted for geothermal resources are often coincident with other earth resources including coal, coal seam gas, conventional oil and gas, groundwater, and possible sites for carbon geo-sequestration. The relationships between these different resource uses will need to be understood for the best decisions around resource use to be made,

7. CONCLUSION

Geothermal energy has tremendous potential to provide Australia with reliable, base load, dispatchable and clean renewable energy for millennia. Through direct use and ground source heat pump applications, a significant amount of generation capacity can be offset. Ground source heat pumps are a well established technology with a proven track record internationally and could be applied in many parts of Australia. Geothermal energy from EGS and HSA resources is still in the technology development stage. As a result, there is a high degree of uncertainty in levelised cost of electricity estimates. There is a significant ramp up in research and development around these resources internationally to ensure that their potential can be realised. As the exploitation of EGS and HSA resources is established in Australia and internationally, it is highly likely that the costs will reduce as more effort is spent on improving the component technologies.

The equivalent is also true for direct use applications. Lower temperature resources can be harnessed that can reduce electricity demand in applications that require heat. These include space heating and cooling, industrial process heat, and desalination.

REFERENCES

AUGUSTINE, C., TESTER, J. W., ANDERSON, B., PETTY, S. & LIVESAY, B. (2006) A comparison of geothermal with oil and gas well drilling costs. *Thirty-first workshop on geothermal reservoir engineering.* Stanford University, Stanford, CA, USA.

BAISCH, S., WEIDLER, R., VOROS, R., WYBORN, D. & DE GRAAF, L. (2006) Induced seismicity during the stimulation of a geothermal HFR reservoir in the Cooper Basin, Australia. *Bulletin of the Seismological Society of America,* 96**,** 2242-2256.

BEARDSMORE, G. R. & HILL, A. J. (2010) Australia - Country Update. *World Geothermal Conference 2010.* Bali, Indonesia.

BERTANI, R. (2010) Geothermal Power Generation in the World 2005-2010 Update Report. *World Geothermal Conference 2010.* Bali, Indonesia.

BLOOMFIELD, K. K. & LANEY, P. T. (2005) Estimating well costs for enhanced geothermal system applications. Idaho Falls, Idaho, USA, Idaho National Laboratory for the US DOE.

BRETT, J. F. & MILLHEIM, K. K. (1986) The drilling performance curve: a yardstick for judging drilling performance. *61st Annual Technical Conference and Exhibition of the Society of Petroleum Engineers.* New Orleans LA, Society of Petroleum Engineers.

CHAD, A., TESTER, J. W., ANDERSON, B. J., PETTY, S. & LIVESAY, B. (2006) A comparison of geothermal with oil and gas well drilling costs. *Thirty-first Workshop on Geothermal Reservoir Engineering, January 30-February 1.* Stanford University, Stanford, California.

COSGROVE, J. & YOUNG, J. (2009) Geothermal energy in Australia: two geothermal systems under development. Wilson HTM Investment Group.

DI PIPPO, R. (2008) *Geothermal power plants: principles, applications, case studies and environmental impact,* Oxford, Butterworth-Heinemann.

DI PIPPO, R. (2007) Ideal thermal efficiency for geothermal binary plants. *Geothermics,* 36**,** 276-285.

DOWD, A.-M., BOUGHEN, N., ASHWORTH, P., CARR-CORNISH, S. & PAXTON, G. (2010) Geothermal Technology in Australia: Investigating Social Acceptance. *GRC Transactions,* 34**,** 33-38.

ENERGY INFORMATION ADMINISTRATION (2009) Annual Energy Outlook 2009: with projections to 2030. Washington DC, United States Department of Energy.

EPRI PALO ALTO CA & COMMONWEALTH OF AUSTRALIA (2010) Australian Electricity Generation Technology Costs - Reference Case 2010. IN BOORAS, G. (Ed., Prepared for Department of Resources, Energy and Tourism.

GEODYNAMICS (2009) http://www.geodynamics.com.au.

GEOSCIENCE AUSTRALIA & ABARE (2010) Australian Energy Resource Assessment. Canberra.

HAYWARD, J. A., GRAHAM, P. W. & CAMPBELL, P. K. (2011) Projections of the future costs of electricity generation technologies: an application of CSIRO's Global and Local Learning Model (GALLM). CSIRO.

HUDDLESTONE-HOLMES, C. (2010) Hot fractured rocks. IN HAYWARD, J. (Ed.

INTERNATIONAL ENERGY AGENCY (2010) Projected costs of generating electricity. Paris, France, OECD/IEA/NEA.

LUND, J. W., FREESTON, D. H. & BOYD, T. L. (2010) Direct Utilization of Geothermal Energy 2010 Worldwide Review. *World Geothermal Conference 2010.* Bali, Indonesia.

MIT-LED PANEL (2006) The future of geothermal energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. Idaho Falls, ID, USA, Idaho National Laboratory.

PINTO, C. J., DICK, J. L., SINOR, L. A., OLDHAM, J. & STAUFFER, B. (2004) Novel PDC bit achieves ultrafast drilling in the Gulf of Thailand. *Baker Hughes In Depth,* 10**,** 20-29.

POTTER, R. M., POTTER, J. M. & WIDEMAN, T. W. (2010) Laboratory Study and Field Demonstration of Hydrothermal Spallation Drilling. *GRC Transactions,* 34**,** 249-252.

REGENAUER-LIEB, K. (2010) Working towards sustainable, zero-emission geothermal cities. IN ECCLES, J. D., GRIGOR, M. R., HOSKIN, P. W. O. & HIKUROA, D. C. H. (Eds.) *Abstract Volume GeoNZ 2010, Geoscience Society of New Zealand Miscellaneous Publication 129A.* Auckland, New Zealand.

RIPPERGER, J., KASTLI, P., FAH, D. & GIARDINI, D. (2009) Ground motion and macroseismic intensities of a seismic event related to geothermal reservoir stimulation below the city of Basel-observations and modelling. *Geophysical Journal International,* 179**,** 1757-1771.

SANYAL, S. K. (2010a) Future of Geothermal Energy. *Proceedings, Thirty-Fifth Workshop on Geothermal Reservoir Engineering.* Stanford University, Stanford, California.

SANYAL, S. K. (2010b) On Minimizing the Levelized Cost of Electric Power from Enhanced Geothermal Systems. *World Geothermal Conference 2010.* Bali, Indonesia.

WILLIAMSON, K. H. (2010) Geothermal power: the baseload renewable. IN SIOSHANSI, F. P. (Ed.) *Generating electricity in a carbon constrained world.* Burlington, MA, USA, Academic Press.

Contact Us

Phone: 1300 363 400
+61 3 9545 2176
Email: enquiries@csiro.au
Web: www.csiro.au

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