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Economic Development of Geothermal Resources:

Property Rights and Policy

Sam Malafeh

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Economics

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Auckland, New Zealand

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Abstract

Questions on where, and how efficiently, the world’s energy consumption is sourced are becoming increasingly important. Secure electricity production is essential for economic growth. Increasing fuel costs and recent international initiatives to tackle carbon emissions encourage the use of renewable resources like wind, solar, hydro, and geothermal energy for electricity generation. Geothermal resources have the potential to contribute significantly towards electricity generation and economic growth. There has been rapid increase in the use of geothermal resources for electricity production in the last three decades.

Geothermal resources are often described as ‘renewable’. However, this needs qualification. At low levels of exploitation of a geothermal field, the energy resource can last indefinitely and any associated natural features may not be noticeably affected, depending on the proximity of wells to the features. However, large-scale developments effectively mine heat from the resource, and the amount of heat available to the development and any natural features associated with the field will decline over time. If all production is stopped, the energy resource will usually recover over a long period, but is likely to suffer some permanent changes. Well-defined and enforced property rights can encourage sustainable growth and keep actors accountable for their actions. The objectives of this thesis are to analyse current New Zealand policy related to development of geothermal resources, identify areas for improvement, and suggest economic instruments that may contribute towards reducing depletion rates while allowing firms to operate at profitable levels.

Although there is a body of literature on the sustainability of geothermal resources, there is little focusing on access policies, especially in the case of multiple landowners with limited access to the same geothermal reservoir. This thesis
analyses the property rights of geothermal resources and the issues that arise in a multiple access scenario. It uses specific examples to answer some of the critical questions around access policy. The first question is whether current property rights arrangements lead to lower depletion rates while allowing for higher net present value of profit from geothermal resource development. Addressing this question includes identifying the components of property rights, and then determining whether policy allows rights holders to optimise benefits by exercising their rights. The second question is whether multiple-access policy leads to higher net present value of profit and lower depletion rates when the solution is left to the free market. The third question is whether there is an economic policy that can encourage sustainable use of resources while allowing firms to operate at profitable levels.

The New Zealand system allows for multiple access to and development of geothermal reservoirs. Chapter 2 analyses the New Zealand system and its impact on the development of geothermal resources through a number of case studies. The outcomes show that in the absence of exclusive rights and guarantee for the duration of rights, a shorter-term operation is more desirable for firms, and consequently overly intensive extraction may take place. In the current New Zealand situation, where firms face uncertainty about future use of geothermal resources, there is less incentive for longer-term investment, which lowers the net present value of profit from development of the resources. Therefore, a multiple access policy can lead to lower net present value of profit gain from the resource. Further results from chapter 3 demonstrate that, in a fragmented land ownership system with multiple access to resources, lack of available space leads to faster depletion of resources and lower economic benefits for all rights holders when they do not agree to work together. Firms enter a non-cooperative game that leads to undesirable outcomes.

The results from chapter 4 show that when the market fails to control the depletion rate of geothermal resources, the introduction of royalty charges on revenue can
keep the market under control and restrict development size. The findings show that investments become more restricted as the royalty rate increases, which leads to a lower depletion rate. They also show that a variable ad valorem royalty that is linked to temperature drop may be the best option to encourage better planning, development of more efficient technologies, and compensation for depletion. The variable ad valorem royalty penalises those who depreciate resources and rewards those who take steps to reduce the depletion rate.
Acknowledgements

My sincere thanks to my supervisor Professor Basil Sharp for his support, patience, encouragement, enthusiasm and understanding.

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Special thanks to my wife, Asefeh, and my daughter, Tara, for supporting and encouraging me to pursue higher study, and coping with the hardship of this for the last few years. I apologise for not spending much time with you during my study and I promise to make it up.

Thanks to my father, who is no longer with us, and my mother, my brothers, relatives and friends for their encouragement and support during my study.

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Chapter 1

Introduction
Chapter 1

Introduction

1.1. Background

Energy is an essential element of any contemporary society and economy. Questions on where, and how efficiently, the available energy is being used are becoming increasingly important. Electricity is a significant component of energy consumption within societies. Electricity plays a vital role in today’s modern lifestyle, commerce and industries. Both electricity shortage and excessive supply may have negative effects on the economy (Covarrubias, 1979). A short power cut causes significant disruption and delays to almost every single activity in the society. It is almost impossible to calculate the cost of a one-minute power cut. Standards of living are related to per capita electricity consumption in the domestic sector. Hence, maintaining a secure and reliable supply of electricity is essential for economies.

Energy may be in primary or secondary form. Primary energy is taken directly from a natural source and is not subjected to any transformation or conversion other than separation and cleaning. Secondary energy refers to energy that is obtained from a primary energy source. Oil, natural gas, solar power and geothermal energy are examples of primary energy, and electricity and oil products are examples of secondary energy. Energy resources can be divided into two categories: renewable and non-renewable. Renewable sources are the primary resources that are constantly replenished and available, for example, solar and wind. “The non-renewable source of energy is one where the primary energy comes from a finite stock of resources” (Bhattacharyya, 2011, p. 10).
Currently, reliability and lower capital costs are advantages of conventional or non-renewable fuel electricity generators. The system operator can count on their availability, except in the case of unforeseen mechanical faults. In most cases, per megawatt capital cost of installing a conventional fuel generator is generally lower than the capital cost of most renewable fuel generators (Denne, 2007). However, running costs are higher for non-renewable electricity generators, and generally increase with rises in fuel prices. Although the efficient use of non-renewable resources may contribute to economic growth and society’s well-being, the scarcity and the price of those resources are major concerns for economies. In addition, greenhouse gas emissions produced by these generators are unavoidable.

Hydro, geothermal and wind are major commercial sources of renewable energy resources for electricity generation in New Zealand. Technological improvement may also create opportunities for greater use of solar and marine energy sources. “New Zealand has an abundant supply of renewable, low emission resources – wind, water and geothermal – that can be harnessed to reduce energy sector emissions” (NZWEA, 2009). The Ministry of Business, Innovation and Employment states that in 2011, more than 80 percent of electricity generation in New Zealand was from renewable sources (MBIE, 2011). Using renewable resources complies with government policy for 90% of New Zealand’s electricity supply to be from renewable sources, and also international protocols/commitments (Parker, 2008).

Governments around the world are encouraging the use of renewable resources. In some countries, for example the USA, subsidies have been introduced to encourage the use of renewable energy resources. Investment in renewable energy generators will first, diversify the sources of electricity supply and increase security of supply; secondly, increase the certainty in electricity prices (as the fuel cost is almost zero); and third, reduce reliance on constrained supply of exhaustible fuels (NZWEA, 2009). Some renewable resources have distinct characteristics that make them unique in comparison to other resources around the world. For example, geothermal resources can be used as a base-load for electricity generation.
Geothermal resources located in the central North Island of New Zealand are valuable resources that can be used for large-scale electricity generation, in addition to other uses such as medical purposes, tourist attractions, and farming. Most of New Zealand’s geothermal resources are located on land owned by Maori.

Investment in geothermal electricity generation has national economic benefits as well as contributing to Maori communities (through access fees collected by Landowners) and regional development. It can contribute towards national and regional economic growth. The regional socioeconomic impact of electricity generators depend on the size and location of the generators. New electricity generators lead to an increase in the employment rate and contractual opportunities, community budgets, local school budgets, and regional income sources. The immediate impact of electricity generators is the creation of jobs for construction, operation and maintenance works. The construction period generally has the highest positive impact on the local economy. Developers require construction labour, vehicles and equipment. Temporary and permanent workers spend money in the area for their daily living. Labour and contractor workers require temporary or permanent accommodation. On average, construction takes around two years. Operational and maintenance labour can be supplied by local communities. Table 1.1 demonstrates some of the benefits gained from the development of Rotokawa II in Taupo (Reeve, 2007).
<table>
<thead>
<tr>
<th><strong>Type of expenditure</strong></th>
<th><strong>Benefits</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capital cost of the project</td>
<td>NZ$430 million</td>
</tr>
<tr>
<td>Salaries during construction</td>
<td>NZ$15 million</td>
</tr>
<tr>
<td>Operations and maintenance costs (O&amp;M)</td>
<td>NZ$16.5 million/year</td>
</tr>
<tr>
<td>Local salaries as part of O&amp;M</td>
<td>NZ$1.3 million/year</td>
</tr>
<tr>
<td>Total locally spent from O&amp;M</td>
<td>NZ$10.5 million/year (64% of total O&amp;M)</td>
</tr>
<tr>
<td>Total nationally spent from O&amp;M</td>
<td>NZ$4 million/year (24% of total O&amp;M)</td>
</tr>
</tbody>
</table>

**Employment**

<table>
<thead>
<tr>
<th><strong>Activity</strong></th>
<th><strong>Number of people employed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>150 local</td>
</tr>
<tr>
<td>Permanent</td>
<td>15 local and 9 national</td>
</tr>
</tbody>
</table>

**Table 1.1.** Financial benefits from Rotokawa II development (Nga Awa Purua), (Reeve, 2007)

In addition to the mentioned economic benefits, road development may be required to facilitate equipment transfer to the site. This can be a permanent infrastructure change that may have a positive impact on the local economy. Changes can include road widening and paving, which make roads safer to travel on in the future.

Despite the economic benefits of geothermal development, there are issues around property rights attached to geothermal resources, and policies designed to address
development of geothermal resources located on land with multiple owners. Property rights of natural resources are more complicated when the resource, as with geothermal, is migratory and can be accessed by multiple parties. Property rights play an important role in shaping production possibilities, economic growth and income/wealth distribution within societies.

Resource ownership and attendant rights are a major concern for Maori in New Zealand, and need to be addressed before Maori agree to provide access to geothermal resources located on their land. Transaction costs associated with access and development increase when multiple parties are involved in resource development. Despite the importance of property rights, they are mostly assumed as given in the studies of economic growth. Ill-defined property rights reduce the realised value of a resource, which depends on the rights attached to it. The objectives of this thesis are to analyse current New Zealand policy related to development of geothermal resources, identify areas for improvement, and suggest economic instruments that may contribute towards reducing depletion rates while allowing firms to operate at profitable levels.

Although there is a body of literature on the sustainability of geothermal resources, there is little focusing on access policies, especially in the case of multiple landowners with limited access to the same geothermal reservoir. This thesis analyses the property rights of geothermal resources and the issues that arise in a multiple access scenario. It uses specific examples to answer some of the critical questions around access policy. The first question is whether current property rights arrangements lead to lower depletion rates while allowing for higher net present value of profit from geothermal resource development. Addressing this question includes identifying the components of property rights, and then determining whether policy allows rights holders to optimise benefits by exercising their rights. The second question is whether multiple-access policy leads to higher net present value of profit and lower depletion rate when the solution is left to the
free market. The third question is whether there is an economic policy\textsuperscript{1} that can encourage sustainable use of resources while allowing firms to operate at profitable levels.

This chapter contains an overview of geothermal resource characteristics, use, availability, externalities and sustainability. Section 1.4 discusses implications for Maori and geothermal resources located on Maori land. Section 1.6 examines New Zealand access policy. Section 1.7 reviews the literature around the economics of natural resources, as a foundation for the economic models used in the following chapters. The final part describes the structure of this thesis.

1.2. Introduction to geothermal resources

Geothermal is a Greek word meaning “internal heat of the earth”. It is a combination of ‘geo’ (earth) and ‘therme’ (heat). Geothermal energy comes from the heat in earth’s core and radioactive decay within its mantle. The New Zealand Geothermal Association (2009) describes [the hydrothermal] geothermal resources as follows:

At high temperatures and pressures within the mantle, melting of mantle rock forms magma which rises towards the surface carrying the heat from below. In some regions where the earth’s crust is thin or fractured, or where magma bodies are close to the surface, there are high temperature gradients. Deep faults, rock fractures and pores allow groundwater to percolate towards the heat source and become heated to high temperatures. Some of this hot geothermal water travels back to the surface through buoyancy

\textsuperscript{1}Economic policy is actions a government takes to influence the economy. A policy that considers rules, regulations, resource utilisation, access, taxation, rights and etc. that can lead to course of actions implemented by government units aiming at optimising the use and utilisation of resources.
effects to appear as hot springs, mud pools, geysers, or fumaroles. If the ascending hot water meets an extensively fractured or permeable rock zone, the heated water will fill pores and fractures and form a geothermal reservoir. These reservoirs are much hotter than surface hot springs, reaching temperatures of more than 350°C, and are potentially an accessible source of energy. Geothermal areas are commonly close to the edges of continental plates, and New Zealand's location on an active plate boundary (between the Indo-Australian and Pacific Plates) has resulted in the development of numerous geothermal systems and a world-class geothermal energy resource. The characteristics of geothermal systems vary widely, but three components are essential: first, a subsurface heat source that may be igneous magma bodies or heat stored in other rocks; second, fluid to transport the heat; third, faults, fractures or permeability within sub-surface rocks that allow the heated fluid to flow from the heat source to the surface or near-surface (NZGA, 2009).

Geothermal fluid fall into three categories: first, high temperature, which has a temperature of 200 to 350°C at economically drillable depths; secondly, moderate to low temperature resources, with a maximum temperature of 140°C at drillable depth; and third, very low temperature resources, which are widespread but close to ambient temperature (NZGA, 2009). High temperature resources are usually magmatic-related resources, with limited occurrence, in areas less than 50 square kilometres. Moderate to low temperature resources are usually of non-magmatic origin. The difference between moderate to low and high temperature resources is not very clear, as the outflow of hotter resources can cool, and fall into the moderate to low temperature range. Geothermal resources with temperatures of 140 to 220°C can be used for drying, process heat and binary electrical plants. Geothermal resources with temperatures higher than 220°C can be used in steam turbine, binary electricity, or process steam plants. Thermo-culture, bathing, space and water heating and drying are other uses of geothermal resources with temperatures lower
than 140°C. The following chapter of this thesis provides more information on geothermal resources.

### 1.2.1. Historical use of geothermal resources

Predominant customary uses of geothermal resources were heating and cultural and spiritual purposes, through withdrawing the fluid and extracting its heat content. Today, geothermal resources are also used for science, tourism, recreation, therapeutic and medicinal uses, food processing, pulp and paper industry, mineral production, energy production for heating and electricity generation (WRC, 1992). The Lindal Diagram shown in figure 1.1 can be used to identify various uses of geothermal resources at different temperatures. Where the water in these reservoirs has a temperature of at least 150°C, enough of it will flash to steam to run turbines that generate electricity. It can be used for refrigeration and food processing at temperatures above 100°C. Where the fluid is not as hot, above 50°C but below 100°C, it can still be used for residential and industrial heating, as is done in China, Italy, Iceland, New Zealand, and Japan. A resource with 20 to 50°C can be used for green houses and fish farms. The right-hand-side of figure 1.1 shows how the heat extracted from a reservoir can be used for different purposes before the fluid is reinjected to the ground or discharged into the environment.
1.2.2. Electricity generation

A geothermal power plant usually consists of geothermal extraction wells, pipelines carrying geothermal fluids, a generator (utilisation plant), and injection/reinjection wells. The utilisation plant may include: turbine/s, separators, flashers, condensers, non-condensable gas removal system, pumps, piping and valves, station electrical equipment, instrumentations and controls. Efficiency of electricity generation depends intrinsically on the temperature, or more specifically, enthalpy of the fluid (Clotworthy et al., 2010). Power station life span is designed around the economic return on investment over 35 years. Wells may last for that long but require significant renovation after on average around 15 years. There is a high capital cost associated to wells and pipelines. In addition, some wells become less productive and need replacement. Therefore, it is economically efficient to integrate other

Figure 1.1. (left) Lindal Diagram showing the utilisation of geothermal fluid – (right) cascade use of geothermal energy (Dickson & Fanelli, 2004)
systems that use geothermal fluid to spread the cost. Such systems may include an electricity generator, greenhouse heating, residential/commercial heating, and farming. However, there are some economic disadvantages associated with the involvement of multiple parties including temperature and pressure drop, chemical composition, and purity. There are also costs associated with multi-part relationship management.

A typical geothermal plant development for electricity might start with seeking and obtaining land and access to the resource. Pre-drilling exploration and drilling permits for exploration drilling are then required. Firms can use the exploratory findings to apply for a plant permit and start operation when the plant is ready. Developers usually start negotiating power purchase agreements and also transmission and interconnection work during the plant permit work. The economics of the development must be carefully considered, as geothermal developments have large upfront spending with uncertainty around the final outcome. The economic development plan should consider the capital cost (including interest payments and financing costs), operations and maintenance costs (O&M), resource characteristics (well productivity and rate of decline), make-up well-drilling costs, development and operational options (installed plant capacity, number of years of make-up well drilling, and project life), and macro economics climate (interest and inflation rate) (Sanyal, 2004). Figure 1.2 shows a suggested algorithm for economic considerations of a geothermal plant development.
Figure 1.2. Economic Model for geothermal power systems (Bloomster, 1975)

Well productivity is important as well as how it declines with time as it can affect power cost in two ways. First, fewer wells are needed in a higher well productivity situation. Secondly, more make-up well drilling will be required when there is a higher rate of decline in well productivity (Sanyal, 2004). In most cases, temperature decline rate increases as installed capacity increases. Exploration and drilling costs are unpredictable in geothermal development. Although geothermal resource exploration costs can vary, operating costs are generally constant if the inflation effect is removed.

In general, the per-megawatt-hour cost of geothermal power generation is lower than other sources of electricity generation such as wind, hydro, gas and coal. Table 1.2 compares the electricity production and investment cost for different resources. It is also important to mention that there are constant economies of scale in
geothermal power plant expansion. New production and injection/reinjection wells are needed to increase production capacity. Each well has a certain limit, and for extra production the plant will require new wells, piping and other fittings for transmission. Therefore, the cost of capital increases as the capacity increase.

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Fixed cost NZD/MWh</th>
<th>Fuel cost NZD/MWh</th>
<th>Variable O&amp;M Cost NZD/MWh</th>
<th>Total Cost (NZD/MWh) 10% Discount rate</th>
<th>Total Cost (NZD/MWh) 5% Discount rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Coal</td>
<td>4.16</td>
<td>37.89</td>
<td>3.1</td>
<td>77</td>
<td>66</td>
</tr>
<tr>
<td>CCGT</td>
<td>1.78</td>
<td>46.67</td>
<td>3.1</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>OCGT</td>
<td>6.85</td>
<td>68.11</td>
<td>3.1</td>
<td>123</td>
<td>107</td>
</tr>
<tr>
<td>Wind</td>
<td>8.56</td>
<td>0</td>
<td>7.3</td>
<td>75</td>
<td>56</td>
</tr>
<tr>
<td>Hydro</td>
<td>3.11</td>
<td>0</td>
<td>6.3</td>
<td>78</td>
<td>53</td>
</tr>
<tr>
<td>Geothermal</td>
<td>3.81</td>
<td>0</td>
<td>6</td>
<td>52</td>
<td>37</td>
</tr>
</tbody>
</table>

**Table 1.2.** Electricity generation cost in New Zealand (Denne, 2007)

Italy, New Zealand, and the USA were the first three countries to develop geothermal resources for commercial power production. Iceland, which initially used geothermal only for district heating, commissioned its first power plant, with a capacity of 3MW, in 1969 (Armstead, 1983). In 1904, the first geothermal development for power generation was undertaken in Larderello in Southern Tuscany, Italy. The first generator worked with direct use of steam from the field
and had a short life due to the impact of chemicals in the steam. Later, heat exchange technology was used, which helped to produce clean steam for generation. In 1913, the first power station, with a capacity of 250 KW, was started in Larderello, and by the early 1920s, the capacity increased to 3.5 MW. Further development in Boraciferous region increased Italy’s installed geothermal power capacity to 132 MW by the end of 1943. Larderello and other plants in Boraciferoud region were totally destroyed in 1944 during the Second World War (Lund, 2004). The plants were up and running again in 1950 and they are running today at more than 500 MWe capacity.

New Zealand’s first geothermal generator was commissioned at Wairakei in 1958. It was the second large-scale commercial operation geothermal plant in the world and the first one to exploit a wet (rather than dry) geothermal resource. The Wairakei development started around 1950 as a joint project between the New Zealand and United Kingdom governments. The project was intended to produce 47MW of electricity and heavy water. The price of heavy water fell during construction and the whole project was changed to a large-scale power plant. The first part of the plant was commissioned in 1958 and the entire project was completed by 1963. In 1960, the world’s next commercial geothermal power plant was started in The Geysers Geothermal Field in San Francisco, California, with a 12 MW capacity. It was further developed to 14 MW in 1963. The installed generational capacity at the Geysers Geothermal Field peaked at 2,000 MW in 1989 (Sanyal & Enedy, 2011). However, the level of production declined in the following years, as discussed in the following chapters.
1.2.3. Availability of geothermal resources

Most of the world’s commercially viable geothermal resources are located on plate boundaries. Large takes of geothermal fluid are mainly used for heating and electricity. There is great potential around the world to increase the electricity produced by geothermal resources. World’s main known geothermal resources are located in Russia, Japan, Eastern China, the Himalayas, the Philippines, Indonesia, New Zealand, Canada, the United States of America, Mexico, the Central American Volcanic Belt, the Andean Volcanic Belt, the Caribbean, Iceland, Northern Europe, Eastern Europe, Italy, the Eastern and Southern Mediterranean, and the East Africa Rift System (Dickson & Fanelli, 2004). Figure 1.3 shows the existing significant geothermal resources around the world.

Figure 1.3. Significant geothermal resources around the world (Dickson & Fanelli, 2004)
Chevron is the largest producer of geothermal energy in the world. It started in the 1960s by developing The Geysers in California and later expanded its geothermal development to the Philippines and Indonesia. Chevron’s production capacity in the Philippines and Indonesia is 1,273 megawatts (Chevron, 2010). As of 2010, the USA, the Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland, Japan, El Salvador and Kenya were the top ten countries in the world with the highest installed capacity of geothermal power generation (Holm et al., 2010). Kenya is planning to produce 490 MW by 2012 and increase it to 4,000 MW by 2030. Germany expects to have over 280 MW online by 2020. Turkey has a goal to reach 550 MW by 2013. Argentina, Canada, Chile, Greece, Honduras, Hungary, Nevis, Romania, Spain, Slovakia and the Netherlands are also expected to have initial geothermal capacity by 2015. Algeria, Armenia, Belarus, Bolivia, Comoros Islands, Croatia, Czech Republic, Dominica, Denmark, Djibouti, Fiji, Georgia, Guadeloupe, India, Iran, Ireland, Latvia, Madagascar, Montserrat, Nepal, Norway, Peru, Poland, Rwanda, Saba, Samoa, Serbia, South Africa, Switzerland, Tunisia, United Kingdom, Vanuatu, Yemen and Zambia have also identified projects under consideration as of 2010 (Holm et al., 2010). Table 1.3 shows the 2010 level of capacity of installed geothermal power plants in different countries around the world.
<table>
<thead>
<tr>
<th>Country</th>
<th>2010 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 USA</td>
<td>3086</td>
</tr>
<tr>
<td>2 Philippines</td>
<td>1904</td>
</tr>
<tr>
<td>3 Indonesia</td>
<td>1197</td>
</tr>
<tr>
<td>4 Mexico</td>
<td>958</td>
</tr>
<tr>
<td>5 Italy</td>
<td>843</td>
</tr>
<tr>
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**Table 1.3.** Installed geothermal capacity with ranking (Holm et al., 2010)
Geothermal power plants generate 18% of the total electricity produced in the Philippines. Geothermal plants provide 26% of the electricity generated in El Salvador and around 25% in Iceland. Ninety percent of Iceland's heating is from geothermal resources (Holm et al., 2010). “From an economical perspective, [in Iceland,] the present value of the estimated savings of house heating with geothermal instead of oil between 1970 and 2008, using 2% real interest rate over the cost price index, is estimated at 880,000 million ISK (127 ISK/US$)” (Ketilsson et al., 2010b).

“New Zealand lies in the Southwest corner of the Pacific ‘ring of fire’ chain of volcanic activity and has extensive high-pressure geothermal resources. The main geothermal area is centred near the towns of Taupo and Rotorua” (Power-technology.com, 2010). New Zealand has high-quality geothermal resources, mainly located in the central North Island. Currently, around 14% of New Zealand electricity supply is from geothermal energy (MED, 2012). Many of the existing geothermal generators are located in the Taupo Volcanic Zone. Figure 1.4 and 1.5 illustrates the location of geothermal resources in New Zealand and Waikato Region located in central North Island of New Zealand. New Zealand’s geothermal installed capacity increased by 50% from 421 MW in 2003 to 628 MW in 2010. There are opportunities to increase the level of electricity generation. Mokai, in Taupo, is the largest privately developed geothermal project in New Zealand owned by the indigenous Maori. Most of New Zealand’s geothermal resources are located on land owned by Maori tribes. In most cases there are multiple owners with access to different parts of a hydraulically connected resource. Kawerau, in the Bay of Plenty region of New Zealand, is an example of a geothermal development with multiple access to the reservoir (Boast, 1989). Issues around multiple access to geothermal reservoirs are discussed in the following chapters.
Figure 1.4. Major geothermal areas in New Zealand
Figure 1.5. Geothermal resources of the Waikato Region (Luketina, 2012)
1.2.4. Environmental and sustainability issues

Although geothermal resources are widely considered to be ‘clean’ and renewable there are environmental and social issues associated with development of geothermal systems for electricity production. Environmental issues include surface disturbances, physical effects on the resource and the surrounding environment, noise, thermal effects, chemical pollution and impact on local biology and natural features (Bromley et al., 2006). Environmental effects can be summarised as (Axelsson, 2008):

- Surface disturbances such as those due to drilling, road construction, pipelines and power plants as well as general untidiness. The local scenery also needs attention and often protection. In some instances landslides are liable to occur, if care is not exercised.
- Physical effects of fluid withdrawal and reinjection such as changes in surface manifestation, i.e. fading of hot springs and geysers or increased steam discharge from fumaroles, land subsidence, lowering of ground-water tables and induced seismicity.
- Noise such as that associated with drilling, discharging of wells and power plant operation.
- Thermal effects of excess energy contained in wastewater and steam discharge.
- Chemical pollution in the water phase, particularly from arsenic (As) and mercury (Hg), and through the discharge of geothermal gases such as carbon dioxide (CO₂) and hydrogen sulphide (H₂S).
- Impact on local biology, i.e. fauna and flora
- Protection of natural features that are of scientific or historical interest as well as being tourist attractions.
Reinjection is proposed as a solution to some of the above issues by sending the pollution back to the reservoir and also maintaining the reservoir’s pressure (Axelsson, 2008). However, reinjection does not maintain the temperature of the reservoir and therefore the biology of the surrounding environment. A power plant reduces the life of the reservoir when the heat regeneration rate is lower than the heat extraction rate. “When we exploit a geothermal field, we are tapping a capital store of energy that has been gradually built up over thousands of years. The energy, except for a small fraction, is not strictly ‘renewable’ unlike hydro-power which is seasonally, or at least periodically, replenished” (Armstead, 1983, p. 280).

Successful geothermal system management controls energy extracted from the system to maximise the resulting benefits. Our knowledge about reservoirs is never perfect, particularly before actual drilling. In addition, human activity in one part of the reservoir can have an impact on other parts of the same system. Complexity and incomplete scientific information leads to a situation in which decisions have to be made with uncertainty. Careful monitoring is required to better understand geothermal systems. Geothermal systems have different characteristics and therefore monitoring systems have to be adapted to meet the requirements of each system (Axelsson, 2008). Geothermal resources may be monitored through direct or indirect observation. Axelsson (2008) cites the below list as the basic observations that should be included in a conventional geothermal monitoring programme:

- Mass discharge histories of production wells (pumping for low-temperature wells).
- Temperature or enthalpy (if two-phase) of fluid produced.
- Water level or wellhead pressure (reflecting reservoir pressure) of production wells.
- Chemical content of water (and steam) produced.
- Injection rate histories of injection wells.
- Temperature of injected water.
- Wellhead pressure (water level) for injection wells.
• Reservoir pressure (water level) in observation wells.
• Reservoir temperature through temperature logs in observation wells.
• Well status through diameter monitoring (calliper logs), injectivity tests and other methods.

Surface observation can be used as a means of indirect monitoring of the in-depth geothermal system. Indirect monitoring methods are mainly used in high-temperature fields and must be repeated regularly to understand changes in the characteristics of the reservoir. The following methods are used for indirect observation (Axelsson & Gunnlaugsson, 2000):

• Topographic measurement.
• Micro-gravity surveys.
• Electrical resistivity surveys.
• Ground temperature and heat-flow measurements.
• Micro-seismic monitoring.
• Water level monitoring in ground water systems.
• Self-potential surveys.

It is important to manage geothermal developments in a sustainable way to secure the expected life of the reservoir and maintain its associated features. Geothermal development may be perceived as sustainable if it can maintain the geothermal features and productivity for 100 to 300 years (Axelsson et al., 2005). Lack of monitoring may lead to unexpected changes. A centralised monitoring and management is required in managing a geothermal system with a large surface area and several developers. “Overexploitation mostly occurs because of lack of monitoring and/or when many users utilise the same resource without common management” (Axelsson, 2008).
Constant production below the sustainable limit, stepwise increases in production, excessive intermittent production, and excessive production followed by an excessive period of low production are the four methods of developing a geothermal resource suggested by Axelsson (2012) and Ketilsson et al (2010a). Availability of information on the reservoir’s behaviour is the key point for any of the above methods. As illustrated in figure 1.5, Axelsson (2008) describes the four principle methods of sustainable geothermal utilisation as follows:

1. Constant production (aside from variations due to temporary demand such as annual variations) for 100-300 years. This is hardly a realistic option because the sustainable production capacity of geothermal systems is unknown beforehand.

2. Production increased in a few steps until the sustainable potential has been assessed and the sustainable limit attained.

3. Excessive production (not sustainable) for a few decades (about 30-50 years) with total breaks in between (about 30-50 years), wherein a geothermal system is able to recover almost fully.

4. Excessive production for 30-50 years followed by a steady, but much reduced production for the next 150-170 years. The production following the excessive period would thus be much less than the sustainable potential at constant production.
Figure 1.6. A schematic diagram showing examples of possible different methods of sustainable geothermal system utilisation. The numbers refer to the production methods discussed above. (Axelsson, 2008)

Although the pressure can be partially controlled by injecting/reinjecting the brine back to the reservoir, the temperature may be almost out of human control (Gringarten, 1978). Temperature depends on the conductivity and permeability of the hot rocks connected to the reservoir. Overdevelopment may not be an appropriate approach as it might put too much pressure on the resource and deplete or damage it. The reservoir might need years of no extraction to recover from the damage. In some cases it might never reach the original status (Boast, 1989). The issues around depletion of geothermal resources will be discussed further in the following chapters.
1.3. Maori and geothermal resources

Maori are the indigenous people of New Zealand with a population of around 560,000. They own large tracts of land that contain many natural resources including wind, water, and geothermal. Renewable energy resource development will help Maori to maximise their current well-being, while keeping resources for their future use (Treasury, 2008). Much of New Zealand’s geothermal resources are located on land in Maori ownership. These geothermal resources can be utilised for electricity generation if the property rights around the resources are well defined.

Maori had a traditional practice of communal control over their resources. Tribal – Iwi – and sub-tribal – hapu – control continued until the arrival of Europeans in New Zealand and the introduction of Treaty of Waitangi. Soon after European arrival the traditional communal ownership changed to the individual land ownership system. Issues around property rights of geothermal resources and Maori ownership are discussed in chapter 2. Figure 1.6 illustrates the geothermal resources located in Taupo Volcanic Zone and the links to Iwi.
Figure 1.7. Geothermal areas in the Rotorua-Taupo volcanic zone of North Island, New Zealand (tribal areas indicated by large lettering) - Source: (Tutua-Nathan, 1992, p. 195)

1.4. Access policy in New Zealand

“New Zealand was the first country in the world to adopt a scheme of environmental management based on sustainability” (Luketina, 2011). However, “under New
Zealand law, the owner of land has no automatic right of ownership to any underlying geothermal resource. Land owners above a geothermal system can control surface access to the system” (WRC, 1992, p. 12). Multiple landowners having access to the same geothermal reservoirs is characteristic of most of New Zealand geothermal resources. Managing access and finding an integrated way of developing resources has been an ongoing issue for New Zealand. New Zealand has been through a series of changes on access to geothermal resources to identify a sustainable way of developing geothermal resources. The two latest developments are known as single tapper policy and multiple access policy.

Single tapper policy, or single operator policy, tried to address the common pool problem by limiting resource access to the first developer - single operator can have multiple shareholders. The single operator had accountability for the sustainability of the resource. Single tapper policy was intended to avoid fragmented development of a system and eliminate any conflict and interference that could arise with multiple developers. “The system would allow for responsible staged development of a resource based on data collected and interpreted during the development” (Decision No. A047/2006 2006, p. 90).

In 2007, New Zealand’s Environment Court ruled out the single tapper policy in favour of multiple access policy, subject to a few conditions. The new policy allows for multiple operations on a reservoir. Any new development should include a reservoir modelling that justifies the efficiency and beneficial use of the resource, has a mechanism for conflict resolution, has a system for research and monitoring, and identifies the parties accountable for any adverse effects. Developers must also include processes for operation and an adaptive management plan in their system management plan (Decision No. A047/2006 2006). Chapter 2 discusses the different aspects of the current New Zealand policy on geothermal development and analyses their impact on investment.
1.5. **Economics of natural resources**

Sustainable management is recognising the current need to use resources while not degrading the environment to unacceptable levels. Two criteria for recognising unacceptable levels are: “where the life-supporting capacity of the resources are endangered and where the needs of future generations will be compromised” (WRC, 1992, p. 2). Economic instruments can assist to find the optimal level of extraction or harvesting when dealing with natural resources. The concept of finding the optimal rate of extraction for a natural resource was first explored by Hoteling in 1931. Firms are assumed to be profit maximisers and to maximise the net present value of the harvesting. A schedule or ‘time path’ indicating the optimal amount to be harvested in each period will be the solution to the optimisation model (Conrad, 1999). The following parameters are used in the optimisation model:

\[ X_t: \text{Initial stock of the resource (size or amount)} \]

\[ F(X_t): \text{Growth function for the resource} \]

\[ Y_t: \text{the rate of harvest} \]

(assume that the net growth function has continuous first – and second – order derivatives)

Then, change in the resource stock is as below:

\[ X_{t+1} - X_t = F(X_t) - Y_t \quad (1.1) \]
A negative answer to the above equation means that the rate of harvesting is faster than growth (replacement). This will damage the resource in the long term and slow the rate of renewability. However, a positive answer shows a harvesting rate that is lower than growth. Zero is an optimal answer to the above equation (Conrad, 1999). The optimal rates of harvest should also take into consideration the reduction in amenity values. This is the reduction of the value of other benefits that the public are receiving from the resource. It should also consider the discount rate and the net present value of future extractions. The discount rate leads to realisation of the best timing for the investment and extraction ($\delta$: discount rate - $\rho$: discount factor $\rho = 1/(1+\delta)$). The discount rate is important “in the way the current generation weights the welfare and options of future generations” (Conrad, 1999, p. 6). Higher discount rates usually lead to rapid depletion of resources. They make environmental protection policies less attractive. The exponential nature of the discount rate adds heavy weight to the current, when there is a high discount rate, and therefore reduces willingness for sustainable development. “Such a situation could lead the current generation to throw one long, extravagant, resource-depleting party that left subsequent generations with an impoverished inventory of natural resources, a polluted environment, and very few options to change their economic destiny” (Conrad, 1999, p. 7). Time is shown by $t$ and the return from the project is shown as $\Pi$, or $\Pi_t$ for the return at year $t$.

$$\Pi = \sum_{t=0}^{T} \rho^t \Pi_t$$

(total return) \hspace{1cm} (1.2)

$\Pi_0 = 0$ payment for the first year

t: time = 0, 1, ..., $T$ (0 = current year, $T$ = last year)
The needs and wants of future generations are unknown. While technological progress may change future generations’ requirements, this is not certain. The optimisation model should balance the recovery and extraction rates to sustain a long-term business and maintain the renewability of the resource. The model maximises the net benefits for firms while controlling for the renewability constraints. The net present value of profit over the horizon time of \( t \) (= 0, 1, 2, ... T) can be calculated by using the below equation:

\[
\pi = \sum_{t=0}^{T} \rho^t \pi(X_t,Y_t)
\]  

\( \pi_t \) is the net benefit from resource abundance and harvest in period \( t \), assumed to have continuous first and second order derivatives. Different harvest strategies \( (Y_1/Y_2) \) may result in different benefits and these are usually compared to find the best strategy. Different harvest strategies will also result in different time-paths for the resource stock, \( X_t \). It is assumed that \( Y_{1,t} \) results in \( X_{1,t} \) and \( Y_{2,t} \) results in \( X_{2,t} \). The optimisation model can be finalised by adding the renewability constraint to the profit function as follows:

Maximise: \( \pi = \sum_{t=0}^{T} \rho^t \pi(X_t,Y_t) \)  

Subject to:

\[
X_{t+1} - X_t = F(X_t) - Y_t
\]

\( X_0 \) given
The best strategy will lead to sustainable extraction that can last for an infinite number of years, \( T = \infty \). It may not possible to find an effort level for every renewable resource than can lead to an infinite number of years. In some renewable resources the level of stock may initially go down to a certain level. It will then reach a steady state that can be maintained for a number of years. This may depend on the recovery speed or growth rate of the resource. The optimisation model may help to find the best possible extraction rate. The optimisation model can be solved using the Lagrangian model.

\[
L = \sum_{t=0}^T \rho^t \pi(X_t, Y_t) + \rho \lambda_{t+1} [X_t + F(X_t) - Y_t - X_{t+1}]
\]  

(1.6)

\( \lambda_t \) is the shadow price or the marginal value of an incremental increase in \( X_t \) in period \( t \). \( \lambda_{t+1} \) is the value of an additional (marginal) unit of \( X_{t+1} \) in period \( t+1 \). This value is discounted on period, by \( \rho \), to put it on the same present-value basis as the net benefits in period \( t \). thus, the expression in the [brackets] is the sum of net benefits in period \( t \) and the discounted value of the resource stock in period \( t+1 \). This sum is then discounted back to the present by \( \rho^t \) and similar expressions are summed over all periods" (Conrad, 1999, p. 11). First order necessary conditions (FOC) are written as:

\[
\frac{\partial L}{\partial Y_t} = \rho^t \left[ \frac{\partial \pi(X_t)}{\partial Y_t} - \rho \lambda_{t+1} \right] = 0
\]  

(1.7)

\[
\frac{\partial L}{\partial X_t} = \rho^t \left[ \frac{\partial \pi(X_t)}{\partial X_t} + \rho \lambda_{t+1} \left[ 1 + F'(X_t) \right] \right] - \rho^t \lambda_t = 0
\]  

(1.8)
\[
\frac{\partial L}{\partial (\rho \lambda_{t+1})} = \rho^t \left[ X_t + F(X_t) - Y_t - X_{t+1} \right] = 0 \tag{1.9}
\]

Assumptions:

\( X_0 = A \) - a known positive constant

\( \lambda_{t+1} \): Marginal value of one more unit of \( X_{t+1} \)

\( \lambda_{t+1} = B \geq 0 \)

FOC can be re-written as below:

I: \( \frac{\partial \pi(\bullet)}{\partial Y_t} = \rho \lambda_{t+1} \tag{1.10} \)

II: \( \lambda_t = \frac{\partial \pi(\bullet)}{\partial X_t} + \rho \lambda_{t+1} [1+F'(\bullet)] \tag{1.11} \)

III: \( X_{t+1} = X_t + F(X_t) - Y_t \tag{1.12} \)

Equation I demonstrates the marginal net benefit of an additional unit of the resource harvested in period \( t \). “For a harvest strategy to be optimal this marginal net benefit must equal the opportunity cost, also called ‘user cost’. User cost is
represented by the term $\rho \lambda_{t+1}$, equal to the discounted value of an additional unit of the resource in period $t+1$. In some problems we may see this condition written $p = \frac{\partial C(\cdot)}{\partial Y_t} + \rho \lambda_{t+1}$, implying that price today should equal marginal cost $\left(\frac{\partial C(\cdot)}{\partial Y_t}\right)$ plus user cost, $\rho \lambda_{t+1}$" (Conrad, 1999, pp. 12, 13). Equation II shows $\lambda_t$ as the value of an additional unit of the resource in period $t$. When the resource exploitation is optimised, the value of an additional unit of the resource in period $t$ equals the marginal net benefit of the current period, $\frac{\partial \pi(\cdot)}{\partial X_t}$, plus the marginal benefit from the next period of harvesting, $\rho \lambda_{t+1} [1+F'(\cdot)]$ (Conrad, 1999).

As the exploitation continues at a certain rate, the ratio of the extraction and recovery may reach a steady state, $X_{t+1} = X_t = X^*$, $Y_{t+1} = Y_t = Y^*$, and $\lambda_{t+1} = \lambda_t = \lambda^*$. The triple $[X^*, Y^*, \lambda^*]$ is called a steady-state optimum. $X_t, Y_t,$ and $\lambda_t$ are unchanged at the steady state and therefore equations I, II, and III can be re-written as follow:

I: \[ \frac{\partial \pi(\cdot)}{\partial Y} = \rho \lambda \] (1.13)

II: \[ \rho \lambda [1+F'(\cdot) + (1+\delta)] = -\frac{\partial \pi(\cdot)}{\partial X} \quad (\rho = 1/(1+\delta)) \] (1.14)

III: \[ Y = F(X) \] (1.15)

Substituting I into II will result in:

\[ F'(X) + \frac{\partial \pi(\cdot)/\partial X}{\partial \pi(\cdot)/\partial Y} = \delta \] (1.16)
The above equation is the ‘fundamental equation’ for sustainable harvesting of renewable resources. X* and Y* can be found using the final fundamental equation and equation III from above. The level of sustainability depends on the objectives defined for the project and the current willingness to save the resource for future generations. The left hand side of the equation may economically be interpreted as the resource’s rate of return (Conrad, 1999, p. 15). Therefore, the equation shows a rate of return equal to the discount rate. It is, in general, not straightforward to say whether all renewable resource investments can have a rate of return equal to the discount rate.

Geothermal resources are in general described as renewable. However, this requires qualification. Extraction rates higher than the recovery rate changes the resource stock/temperature and changes the steady-state equilibrium. To keep the resource sustainable, harvest/extraction must equal net growth. According to the ‘fundamental equation’ an optimal level of extraction depends on the marginal net growth rate, the marginal value of the stock relative to the marginal value of harvest/extract and the discount rate. In theory the ‘fundamental equation’ can be used to find the ‘bio-economic optimum’, the level of extraction that keeps the resource sustainable while considering the economic costs. Appropriately designed policy mechanisms – such as, taxes and tradable rights – control or encourage extraction at the ‘bio-economic optimum’ level. Chapter 2 develops a geothermal development model that considers the profit maximising firm’s reaction to different policy instruments to facilitate sustainable use of the resource.
1.6. Structure of thesis

As stated earlier, the objectives of this thesis are to analyse current New Zealand policy related to development of geothermal resources, identify areas for improvement, and suggest economic instruments that can contribute towards reducing the depletion rate while allowing firms to operate at profitable levels. With increasing demand for cleaner and more renewable sources of energy, stronger institutional arrangements are required to control the use of geothermal resources. In the rapidly growing geothermal industry, property rights have an important impact on incentives for investment, distribution of wealth, and the economic benefits that can be derived from the flow of services provided by resources. Chapter 2 examines whether the current New Zealand property rights arrangements around geothermal resources will lead to longer-term planning with a conservative approach, or a race to extract resources. It reviews property rights and the efficient market allocation system, including property rights concepts, regimes and the application of those regimes in the New Zealand context. The chapter considers the situation where developers have to make decisions in an ill-defined property rights system. An investment optimisation model is used to review firms’ behaviour and the impact of property rights arrangements on investment.

Chapter 3 analyses the impact of multiple access to geothermal resources in a fragmented land ownership system, literature around reinjection options and issues related to sustainability of resources. It considers a situation where developers do not have access to the entire reservoir and cannot reinject in the optimal location. The optimisation model is used to estimate the consequences of restricted access and the impact on return on investment and sustainability of a reservoir accessed and utilised by multiple developers.
Chapter 4 examines a range of economic instruments that can contribute towards lowering the depletion rate of geothermal resource while allowing the firm to operate at a profitable level. First, it discusses the issues around sustainability of geothermal resources and the economic efficiency of developments. Chapter 4 then investigates different forms of royalties that can be applied to geothermal developments for electricity generation. It analyses the costs and benefits of royalties and reviews the application of royalties in different countries. Chapter continues to analyse the impact of a variable ad valorem royalty as the ratio of the current temperature to the original temperature on firm’s behaviour and the impact on depletion of geothermal resources.
Chapter 2:

Property rights and the geothermal resources of New Zealand
Chapter 2:

Property rights and the geothermal resources of New Zealand

2.1. Introduction

Questions on where, and how efficiently, the world’s energy consumption is sourced are becoming increasingly important. Secure electricity production is essential for economic growth. Increasing fuel costs and recent international initiatives to tackle carbon emissions encourage the use of renewable resources like wind, solar, hydro, and geothermal energy for electricity generation. Geothermal resources are often described as ‘renewable’. However, this needs qualification. At low levels of exploitation of a geothermal field, the energy resource can last indefinitely and any associated natural features may not be noticeably affected, depending on the proximity of wells to the features. However, large-scale developments effectively mine heat from the resource, and the amount of heat available to the development and any natural features associated with the field will decline over time. If all production is stopped, the energy resource should recover over a long period, but is likely to suffer some permanent changes (Boast, 1989).

Geothermal resources have the potential to contribute significantly towards electricity generation and economic growth. In 2009, NZ$0.35 billion worth of electricity was generated from geothermal energy in New Zealand and this is expected to increase to NZ$1 billion per annum by 2025 (MED, 2010). In 2010, the United States of America (USA), the Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland, Japan, El Salvador, and Kenya were the top ten countries in the world with the highest installed capacity of geothermal power generation (Holm et
Italy, New Zealand and the USA were the first three countries to develop geothermal resources for commercial power production with commercial plants commissioned in 1904, 1958 and 1963 respectively. Iceland, which initially used geothermal energy for only district and community heating, commissioned its first power plant in 1969 (Armstead, 1983).

There has been rapid growth in the use of geothermal resources for electricity production in the last three decades. For instance, New Zealand’s geothermal installed capacity increased by 50% from 2003 to 2010, from 421 MW to 628 MW. Since 1958, New Zealand has utilised different models of development. These models include: state owned development, e.g. Wairakei; privately developed geothermal projects, e.g. Mokai in Taupo (developed by Maori); joint venture, e.g. Nga Awa Purua – 75% owned by Mighty River Power (a state owned enterprise) and 25% owned by Tauhara North No 2 Trust (a Maori trust); multiple access to a single field by different operators, e.g. Kawerau in the Bay of Plenty, with three independent firms, Kawerau Geothermal Limited (Mighty River Power), Ngatu Tuwaretoa Geothermal Assets Ltd, and Geothermal Developments Ltd (Boast, 1989). Well-defined and enforced institutional arrangements are essential to the successful development of geothermal resources via any of the above models.

**Pre European arrival**

In pre-European New Zealand, geothermal resources were used for cooking, heating, bathing, healing, and as waahi tapu (sacred places\(^2\)) by Maori tribes. Communal ownership was the main form of control over New Zealand resources. Traditionally, Maori tribes were responsible for the control and use of the land,

\(^2\)Sacred places (waahi tapu) may be used to hold and protect the bones of the dead. They are places that have cultural or spiritual significance.
surface, and subsurface resources. The chief and the tribe had a duty to allocate the rights of use and utilisation of the resources to individuals. The hapu³ and whanau⁴ had input into the collective decision-making process. The hapu consisted of a chief and experts⁵ who could advise the chief on different areas, e.g. fishing, carving, agricultural skills or matters of the spiritual world. Important decisions were usually made by consensus between the chief, other leaders, experts, and individuals to ensure that the chief's decisions would be acceptable to the people. Individuals in charge of a given resource had an obligation to the tribe to utilise the resource in the best way, or their rights to the resource could be taken away. Their property rights included the right to exclude others from access to the resource (Tutua-Nathan, 1992).

**Post European arrival**

The communal ownership model utilised by Maori did not fit well with the European tradition of individual ownership. Soon after European arrival the colonial government came under pressure to make tribal lands available for Pakeha⁶ settlement. The Native Lands Act 1865 was legislated to facilitate European access to Maori tribal lands. The object of the Native Lands Act 1865 was to bring the great bulk of lands of the North Island within the reach of colonisation and to detribalise the native. “The Act established the Native Land Court, which played a significant role in forcibly removing traditional Maori tribal control over land and water resources” (Tutua-Nathan, 1992, p. 193). The Native Land Court replaced communal control over land and water resources with a title system that divided land into blocks owned by individuals. The new system allowed individuals to use or

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³ Sub-tribe  
⁴ Extended family  
⁵ Experts are called ‘tohunga’ in Maori language  
⁶ Pakeha: New Zealanders who are not of Maori blood line
reallocate land without chiefs’ permission, while in the communal system chief’s permission was necessary. Consequently, individuals could own land not occupied by them and were not obliged to utilise the available resources.

Despite the allocation of land to individuals, Maori contend that the “sale of lands did not include the sale or transfer of specific resources attached to those lands which were of cultural, spiritual and economic importance to them. One example which the people of Te Arawa and Ngati Tuwharetoa of the central North Island consider never passed from their control is the geothermal resource” (Tutua-Nathan, 1992, p. 194). Maori consider themselves the guardians (Kaitiaki) of these “spiritual” resources and believe they have a cultural obligation to utilise and develop the resources while ensuring their sustainability (protection for present and future generations).

The myth around the spirituality of geothermal resources goes back to when Te Arawa and Ngati Tuwharetoa arrived in New Zealand. Ngatoro-i-rangi (priest), who travelled with the Te Arawa and Ngati Tuwharetoa tribes to Aotearoa on the Te Arawa canoe, climbed Mount Tongariro in order to claim ownership of the central North Island’s volcanic region. Tutua-Nathan (1992) states that:

On climbing the mountain, he [Ngatoro-i-rangi] claimed the land and its resources for his people. However, the weather conditions had deteriorated, and the intense cold threatened to take his life. He invoked karakia (prayer) and called to his sisters in Hawaiki to send him fire.

7 Kaitiaki: guardianship in Maori
8 New Zealand (Maori word)
9 Hawaiki: “(location) ancient homeland - the places from which Māori migrated to Aotearoa/New Zealand. According to some traditions it was Io, the supreme being, who created Hawaiki-nui, Hawaiki-roa, Hawaiki-pāmamao and Hawaiki-tapu, places inhabited by atua. It is believed that the wairua returns to these places after death, and speeches at tangihanga refer to these as the final resting place of wairua.” ("Online Maori Dictionary," 2010)
10 According to Grace 1959 he examined: ‘O Kuiwai! O Haungaroa! I am seized by the cold wind of the south. Send me fire!... heat was sent him from Hawaiki! It came underground and passed White Island, Moutohora, Okakarua, Rotoehu, Rotoiti, Tarawera, Paeroa, Orakeikorako, Taupo and Tokaanu. (Tutua-Nathan, 1992, p. 194)
The request made by Ngatoro-i-rangi resulted in the bringing of the geothermal resource to New Zealand. The Arawa, Ngati Tahu and Ngati Tuwharetoa tribal groups are the descendants of Ngatoro-i-rangi and hold the mantle of kaitiaki (guardians) over the geothermal resource within the central North Island region. In this sense, they hold the mana, authority and control over the taonga on behalf of themselves and future generations.

Electricity generation and other uses of geothermal resources, which came with European settlement and technological advancement, complicate allocation of rights when the resource is accessible by different parties. New Zealand has seen a series of changes in the way access to geothermal resources is granted. Changes to property rights arrangements can have economic consequences. For instance, a change in 2007 from a single operator policy to multiple access led to a payment of around NZ$27 million from Mighty River Power (MRP) to Contact Energy to buy the land with access to the resource that MRP was accessing (Contact, 2007).

With increasing demand for cleaner and more renewable sources of energy, stronger institutional arrangements than have existed are required to control the use of geothermal resources. In the rapidly growing geothermal industry, property rights have an important impact on the incentive for investment, the distribution of wealth, and the economic benefits that can be derived from the flow of services provided by the resource. The question is whether current property rights arrangements lead to lower depletion rates while allowing for higher net present value of profit from geothermal resource development. Addressing this question includes identifying the components of property rights, and then determining whether policy allows rights holders to optimise benefits by exercising their rights.

This chapter reviews property rights and the efficient market allocation system, including property rights concepts, regimes and the application of those regimes in the New Zealand context. Part three considers the situation where developers have
to make an investment decision in an ill-defined property rights system. An investment optimisation model is used to review firm behaviour and the impact of the property rights arrangements on investment. It examines whether the current New Zealand property rights arrangement around geothermal resources will lead to longer term planning with a conservative approach, or a race to extract resources.

2.2. Literature

Under the assumption of perfect competition, the forces of supply and demand are predicted to lead to efficient outcomes. Producers and consumers exchange goods according to their willingness to sell or pay, respectively. Critically, the value of goods depends on the bundle of rights associated with trade. Markets exist to allow producers and consumers to exchange their rights. These concepts are based on the assumption that property rights are well defined and terms of trade are clear. The model of perfect competition can fail if rights and terms of trade are not clear: like purchasing a car but not having the right to limit others from using it. Lack of exclusivity would lead to market failure, which in turn would lower values and the incentive to invest in cars. Therefore, perfect competition may only lead to efficiency if property rights are appropriately defined. The importance of property rights can be seen in the works of Ronald Coase (Nobel prize winner in economics in 1991), Gary D. Libecap, Douglass North (Nobel prize winner in economics in 1993), Oliver Williamson (Nobel prize winner in economics in 1999), Harold Demsetz, Armen A. Alchian, and Yoram Barzel. They all emphasised the role of institutional arrangements in economic decisions and performance and pointed out that economic outcomes may be diverse under different property rights regimes.
“In the Walrasian, perfectly competitive model, rights are perfectly delineated and transaction costs are zero” (Barzel, 1989, p. 8). Commodities are homogeneous, people are fully informed, and the terms of trade are always perfectly clear. The cost of adjustment is zero and the equilibrium can be immediately achieved. However, in reality, rights are not always perfectly defined and delineated, terms of trade are not always clear, and the cost of transactions are not always zero. There are a series of problems associated with the use and allocation of natural resources. First, there is the common pool problem of resources being publicly available and non-excludable. Secondly, the governing body, for example the government, can impose limits on the use of resources because of externalities. Thirdly, resource ownership may not be clear. Clear ownership and well-defined property rights are essential to ensure return and encourage investment and efficiency. Ownership and property rights are more complicated for geothermal resources as they are fluid and migratory.

**Contracts and property rights**

Property rights are the foundation of the operation and efficient working of the market mechanism (Richardson, 2002). Contracts govern the exchange of property rights (Barzel, 1989). Negotiation can take place when property rights are well defined. Ill-defined property rights lead to higher transaction costs resulting from administration, court, lawyers, and time expended by involved parties. Stronger social customs, controls, and an enforceable legal framework reduce problems associated with contracting and facilitate the development of resources.

Solutions offered for contractual agreements may have little or no value if rights are not clearly allocated (Coase, 1960). Resource ownership and attendant rights are a major concern for Maori in New Zealand, and need to be addressed before Maori
agree to access to geothermal resources located on their land. Clearly, the transaction costs associated with access and development increase when multiple parties are involved in resource development.

**Economic growth**

Property rights play an important role in shaping economic growth and income distribution within societies. Institutional arrangements affect economic behaviour and therefore the productivity of communities (Libecap, 1986). Property rights “delineate decision-making authority over economic resources, determine time horizons, specify permitted asset uses, define transferability, and direct the assignment of net benefits” (Barzel, 1989, p. 229). The reallocation of resources to higher-value uses is extremely difficult without exclusive rights being defined. “Failure to identify the range of institutional options confronting decision makers and the likely costs and benefits associated with each one, makes it difficult to evaluate the maximisation claim” (Libecap, 1989, p. 3).

Property rights define the behavioural norms for the allocation and use of resources. A historical review shows that the higher growth rates experienced by England and the Netherlands in the sixteenth and seventeenth centuries, in comparison to Spain and France, were partly due to better property rights arrangements (North & Thomas, 1973). Well-defined property rights clarify issues around ownership of resources and the allocation of rewards and penalties for the use and development of resources. They enable rights holders to fully capture the value of their resource and encourage new investments to take place. “Indeed, without explicit recognition of the role of property rights in setting the environment
for economic activities, differences in economic performance cannot be evaluated” (Libecap, 1986, p. 228).

**Wealth distribution**

“Prosperity and property rights are inextricably linked” (Jehle & Reny, 2001). Well-defined property rights create transparency in the distribution of wealth. Defining the parameters for the use of scarce resources and assigning the associated rewards and costs increase incentives for investment. This also solves distribution conflicts over likely gains from resource development. “Distributional conflicts arise when property rights are [not clear and] coercively redistributed by the state, with little or no compensation” (Libecap, 1986, p. 228). Property rights are important not only to create incentives for investment, but also to address political and equity factors. Allocation of property rights shows the real actors in the economy and identifies those who bear the rewards and costs of resource-use decisions (Libecap, 1989). When a polluting steel producer and a hotel resort share the same river, the steel producer has to pay the resort owner for polluting the river when the resort owner has the right to clean water, i.e. steel producer cannot pollute the river without the resort owner’s permission. Hence, steel producer has to pay the resort owner for polluting the river. Therefore, the steel producer faces a higher cost and part of his wealth is transferred to the resort owner. The situation is different if the steel company has the right to pollute, as the resort owner then has to pay the steel producer to reduce the level of pollution in order to keep the river clean. Therefore, the allocation of rights changes the distribution of wealth within society. In geothermal development, the allocation of rights assists in identifying actors who will receive the benefits and are responsible for the externalities.
Economic failures associated with open access

Open access to a resource occurs when there is no exclusion and agents are free to enter and use the service of the resource. “While no individual property rights exist in the resource itself, any harvest from it normally becomes the private property of those who harvest or capture it” (Tisdell, 2009, pp. 112, 113). In the presence of sufficient demand, unrestricted access will cause resources to be overexploited. There is no incentive to conserve, scarcity rent will be dissipated and the resource is more likely to be consumed wastefully, resulting in economic loss. Investors maximise their short-term gain by putting more weight on near time benefits. Under-investment happens when there is no guarantee of return at the presence of possible immediate new entries. Consequently, the open-access scenario leads to economic inefficiencies in both cases (Tisdell, 2009). Appropriately defined property rights increase the incentive to align investment with expected benefits secured by excludability. From prospective of economic efficiency, scarcity of a resource makes property rights more important. Indeed, “In the absence of scarcity efficiency is not threatened by open access” (Tietenberg, 2006, p. 72).

2.2.1. Property rights of geothermal resources

Property may simply mean any physical or virtual entity that is owned by an individual or jointly by a group of individuals. Property rights are about ownership and/or possession (Scott, 2008). They refer to the behavioural relations among economic agents and their power to consume, obtain income and alienate a resource
(Barzel, 1989). Libecap (1989) defines property rights as “the social institutions that define or delimit the range of privileges granted to individuals to specific assets, such as parcels of land or water”. Rights can be assigned to individuals, groups, or the state. A person or group’s rights to a piece of land is the power over a bundle of rights. All societies use some sort of property rights arrangements to control access to and use of valuable resources, and to avoid the economic losses that common pool problems may cause.

“Property rights reflect the conflicting economic interests and bargaining strength of those affected” (Mahoney, 2005, p. 111). Economic decision-makers are interested in making property rights specific to enable agents to take full advantage of their resources. However, decision-makers may be restricted by historical agreements that leave them with fewer options. Therefore, history matters, as previous allocations may have significant impact on the available options, i.e. path dependence.

Well-defined and enforced property rights create strong incentives for owners to add the highest value to their resource (Pejovich, 1997). Ownership of a resource is about the level of control over the bundle of rights attached to it. The value of this bundle of rights may depend significantly on the property laws around the ownership of the resource. Constraints on the rights can range from the restriction of use and transferability of the resource, to the limits imposed because of the nuisance of proposed development plans. The restriction of use and transferability of the resource explains the ability of owners to negotiate their power and incentive on investment. The restriction on nuisance describes the consequent externalities created by starting a new activity. Central or local government rules and regulations may limit the forms of economic development of the resource and thus reduce its value. The rules regarding the externalities may change over time. These changes may depend on technological advancement, scientific findings, and/or historical activities and experience. Zoning and local planning are dynamic and can change over time. For example, establishing a new wind-farm in a remote area would be
easier at the point in time when the area has no residents, compared to a point in the future when people have started living there.

The literature shows separate and overlapping rights that can affect the value of resources. These rights are, in general, allowing possession, use and disposal of properties (Guerin, 2003). The taking of a property may happen when part or full bundle of rights attached to a resource is moved from one party to another (Epstein, 1999). Pejovich (1997) considers exclusivity, transferability, and constitutional guarantees for ownership as the components of the bundle of rights. Anthony Scott (2008) breaks the property rights into finer characteristics of exclusivity, duration, flexibility, transferability, divisibility, and quality of title. Property right components show the extent of rights holder’s abilities to make a decision. Ability to make a decision can have a value between 0 and 1 for each component, where 0 shows no right and 1 represents an absolute right or full control for a particular right component. The total value of the asset or resource can be calculated using the probability of decision-making for each component. Figure 2.1 shows property rights components in four main areas: exclusivity, duration, quality of title and transferability/divisibility. The value of the resource depends on the area of the circle. Reducing these components attenuates the bundle of property rights and therefore the value of the resource.
A geothermal system is a combination of a heat source, a reservoir and a fluid that transfers the heat (Dickson & Fanelli, 2004). In general, “Geothermal systems related to young igneous intrusions in the upper crust that can include magma, hot dry rock, and convective hydrothermal systems” (Kestin et al., 1980, p. 7). Geothermal resources with temperatures higher than 150°C can be used for large-scale commercial electricity generation. Property rights of geothermal resources are complex as these resources have a migratory nature and are usually accessible by more than one landowner. Ownership of the land on which the geothermal resource is located may not necessarily lead to the holding of rights to use and develop the resource, as this depends on the existing property rights arrangements. For example, in New Zealand a resource consent can be granted to a third party without the landowner’s approval, although access to the geothermal resource is not possible without landowner approval (Luketina, 2011). Careful consideration of the four components of the rights attached to a geothermal resource results in realising the value of the resource.
Exclusivity is the degree of independency to use a resource and capture the return from investment. Exclusivity enables the owner to choose to use the resource while responsible for the consequences. It internalises the costs and benefits of the decisions. In a multiple-access scenario where exclusivity is diluted, there is no guarantee of return on investment. It is also difficult to internalise the externalities and keep an agent accountable for severe consequences such as subsidence. For example, in a geothermal system with multiple land ownership and no exclusivity, each developer can contribute towards reducing the temperature of the geothermal resource that is shared by all. It is then a difficult task to keep any of the parties accountable for the damage done to the resource. In addition, an individual landowner’s gain depends heavily on the action of their competitors - neighbouring landowners with access to the same geothermal resource.

Duration refers to the period of time the owner has the right to benefit from the resource. Rights can be permanent or temporary for a leased resource. Duration could also indicate the time an owner has to develop the resource. The efficiency of electricity production relates significantly to the resource temperature (more specifically, enthalpy) and type of technology (Clotworthy et al., 2010). Efficiency may go down if a resource is overexploited over a period of time. Geothermal projects are usually given a life of 30 to 35 years, which is associated with the return on investment. In New Zealand, the Resource Management Act 1991 (RMA) aims to manage the effects of activities where the taking, use and discharge of geothermal water and energy are regulated (Luketina, 2011). Pursuant to section 123 of the RMA, geothermal developments can be granted a resource consent for up to 35 years (RMA, 1991). A new application is required to renew the consent (Luketina, 2011). In case of geothermal development, exclusivity and duration may go hand in hand. Having a competitor can reduce the life of the project as the pressure on the reservoir increases. The duration of the rights and the right of renewal are very important to create incentive for investment when the rights are not permanent.
Transferability is the next component of property rights. “The general rule today, strengthened by the insistence of the English common-law courts, has become that the holder of a freehold right has an almost unconstrained right to transfer land” (Scott, 2008, p. 9). Transferability enables an owner to divide the resource and allocate part of the rights (divisibility). Divisibility can occur in the forms of horizontal, vertical, and multiple-use (Scott, 2008). While horizontal divisibility is simply about dividing the resource into smaller parcels, vertical divisibility allows for temporary allocation of some rights for a certain amount of time. Some geothermal developments have similar arrangements where power companies are allowed to develop and use the resource for a period of time, following which they have to return the rights to use and gain income to the resource owners. This type of divisibility is usually used when the resource owner does not have access to funds, human capital and/or technology and it is more efficient to use others to develop the resource.

“In a world of uncertainty and incomplete information, transferability of ownership provides incentives for goods to be transferred from a less optimistic to a more optimistic owner” (Pejovich, 1997, p. 3). Multiple-use divisibility allows multiple parties to have rights over different parts or uses of the resource. For example, a party can use land to access a geothermal resource for electricity production while another party uses it for farming. Transferability adds to the value of the resource. It enables the owner of the rights to ask for the market value of the resource or exchange it for other resources. Restrictions on the transferability of land will reduce the incentive for investment, especially when the resource owner wants to contract rights to others.

Quality of title shows how secure a right is against others claiming the possession of the resource. It shows whether the right is absolute or proportional, compensable, and enforceable (Guerin, 2003). Geothermal resources are migratory resources under the surface that are difficult to measure, control and allocate to a single user. Geothermal development requires a large upfront investment and assurance of
return. Quality and security of title has a significant impact on investor decisions. Lower quality of title may lead to either underinvestment or investments with short-term expected return. Quality of title may depend on legitimacy, conveyance or custom, and enforceability of the title (Scott, 2008). Flexibility is “the extent to which the powers and obligations a right bestows on the holder can be adjusted without weakening title. ... Probably the most flexible kind of holding is a permit or licence to use public lands or an open-access resource; only government-imposed regulations can make such a right less flexible” (Scott, 2008, p. 7). The four components of property rights, explained above, give shape to the property rights arrangements of societies. Change in any of those elements can result in change in economic value.

2.2.2. Externalities (contemporaneous and inter-temporal)

Although exclusivity is highly significant when defining property rights, the external impact of different activities on others also needs to be considered when allocating the rights to resource owners. The act of one party may have negative or positive impacts on other parties. Externalities can be cross-sector (contemporaneous) or through time (inter-temporal). Externalities can impact on the wealth generated by others at the current time or in the future. The externality effect is more obvious when a resource is shared. Demsetz (1967) considers property rights as an economic instrument to internalise the externalities. “Property rights develop to internalise externalities when the gains of internalisation become greater than the cost of internalisation” (Mahoney, 2005, p. 127).

“Environmental problems arise when property rights are ill defined, when these rights are exchanged under something other than competitive conditions, and when
social and private discount rates diverge” (Tietenberg, 2006, p. 81). A monopoly may lead to market inefficiency with lower supply and higher prices, but it can be good for natural resources if conservative harvesting is the best way to go forward (Anderson & Hill, 1983; Conrad, 1999). Higher prices encourage research and development towards better technology and/or more efficient substitutes.

Negative externalities may lower the economic performance of society (external diseconomy) (Tietenberg, 2006). Well-defined property rights address the externality issues, when possible, by shifting the cost of the external effect to the rights owner. Demsetz (1967) calls the incentives to achieve a greater internalisation of externalities as the primary function of property rights. Not addressing externalities results in more than the socially accepted supply, lower than the socially acceptable price, and a higher than socially acceptable level of pollution or damage to the resource. Forcing agents to internalise externalities creates incentives to find better technologies to reduce pollution and not damage the resources, thus reducing both contemporaneous and inter-temporal externalities.

A large-scale geothermal power plant development may have current or future impacts on other agents. A large take geothermal electricity plant may cause change in surface geothermal activity that lead to hydrothermal eruptions, increased microseismic activity, effects on ecosystems, flora and fauna, and subsidence, and eventually damages the geothermal features around the area. It impacts on the ability to generate income from the area as a tourist attraction and reduces the welfare of others relying on those activities. Therefore, it reduces the income of others sharing the resource.

Subsidence is due to a drop in pressure level in the geothermal field. “Subsidence at Ohaaki [is] threatening to eventually inundate the Marae and other sacred sites under Lake Ohakuri unless action is taken” (NZGA, 2012). It may also reduce the possibility of the resource being used in the near future for electricity generation
and therefore reduce the possible future income. For example, electricity generation capacity at Ohaaki was reduced to 47 MW in 2010 from its originally planned 130 MW due to production constraints (Clotworthy et al., 2010; NZGA, 2012).

A conservative approach to develop geothermal resources reduces the environmental externalities while allowing for bequest benefits. It is the current generation’s responsibility to consider bequest value. Bequest value can be divided into use and non-use value for future generations. The future use value can be in further power plant development, and personal and recreational use. Although the willingness of future generations to have geothermal features is not known, history shows that the value of resources increases at the presence of scarcity and population growth. For instance, unrestricted hunting of bison was not a problem in the early days of the USA’s history. Restriction on hunting became more important as bison became scarce (Tietenberg, 2006). A similar situation was witnessed in regard to fur hunting (Demsetz, 1967).

The transaction cost of arranging and administering property rights can be higher than the benefits gained when the resource is not scarce (Demsetz, 1967). The benefits gained increase when the population grows and the resource becomes scarce (Tietenberg, 2006). Based on the economic literature, harvesting is optimised when the net benefits are maximised while the resource is sustainable. The sustainability of a renewable resource depends on the reproduction or regeneration rate of the resource. The situation is different for various resources and species, as some recover or reproduce faster than others. For instance, in a fishery, some fish species reproduce and grow as long as the resource is left untouched for a few months. The situation is different for other fish species that reproduce more slowly. A quota system aims to allow for an optimal level of harvesting in fisheries. New Zealand’s fisheries are managed through the Quota Management System (QMS), in which the quota is set for each fish species based on the historical catch and reproduction data ("Fisheries Act 1996," 1996). The optimal harvesting in forestry is different to fisheries. The net present value of a forest can be maximised by
efficient rotation, harvesting and replanting. Human beings can help the redevelopment of the forest by replanting and nurturing the forest. An interval of at least 25 years is allowed for timber forests to grow (with the specific interval varying depending on the species). Geothermal resources take a very long time to recover, and recovery time depends on the characteristics of the particular resource – although the production can resume before the resource is fully recovered. According to O’Sullivan and Mannington (2005) it may take Wairakei geothermal reservoir, in New Zealand, up-to three hundred years to recover after one hundred years of production. Time and size of the production play a vital role in the sustainability of geothermal resources (Rybach, 2003; Rybach & Mongillo, 2006).

Stock augmentation from fish hatcheries can speed the recovery or reproduction of some fish species. However, there is no technology to speed the recovery of geothermal systems. Therefore, successful geothermal system management is essential to control energy extracted from the system to maximise the resulting benefits, but it cannot change the recovery speed. Limited knowledge of geothermal resources makes it more complicated to find the optimal level of harvesting. Therefore, current optimal levels of production can impose costs on future generations and have to be carefully considered.

### 2.2.3. Government

Similar to market failure, government failure can reduce incentives for better practice. Well-defined property rights are necessary to encourage economic activity. Regulating a component of property rights may reduce the value of resources, but can help to strengthen the other components and eventually add value to the resource. For example, regulation on duration can be bundled with exclusivity to
guarantee a longer-term income for the owner and increase the net present value of the resource.

The value of a resource may depend on the degree of property rights specification and the number of interested parties, and vice versa. For example, for a low value asset, local customs and informal norms might be sufficient. Conversely, more formal governance structures and legally defined property rights are generally necessary for higher value assets and/or where there are a large number of competitors (for instance, geothermal resources). In this situation, state power is necessary to enforce constraints on access and use of resources (Libecap, 1989). Constitutional guarantees protect the economic wealth of resource owners. They encourage individuals to accumulate wealth via investment (Pejovich, 1997).

Any economic decision requires both control over goods and the ability to exchange those goods. Eggertsson (1990) notes that “the structure of the contracts depends on the legal system, social customs and the technical attributes of the resources involved in exchange” (Mahoney, 2005, p. 127). Optimal property rights regimes will depend on the characteristics of the resource, historical arrangements, enforcement power and cost, and possible ways of optimising the current and future gain from the development. Private negotiation, judicial remedies, and regulations by the legislative and executive branches of government can be used to arrange property rights and institutions.

2.2.4. Property rights regimes in New Zealand

Property rights may be held by individuals (private property rights), groups (collective rights - communal), or the state (an extended form of collective rights)
(Demsetz, 1967). Private property rights enable exclusion. Private property rights contribute to economic efficiency but the level of efficiency depends on the security of the rights. Insecure rights may cause economic inefficiency. Despite the value of private property rights, generally the state has the power to take some or all of the rights away from the resource owner. In most countries, the state has the right to seize a person’s private property when it is in the public interest. “This is described as the exercise of eminent domain in the United States, compulsory purchase in the United Kingdom, New Zealand and the Republic of Ireland, compulsory acquisition in Australia and expropriation in South Africa and Canada” (Tisdell, 2009, p. 126). Governments usually pay market value as compensation when seizing property. However, there is no compensation given when some elements of the rights are affected. For example, change in environmental regulation may limit the use of a natural resource and reduce its market value, but governments do not usually pay any compensation. Of course, one would hope that regulation results in positive net benefit to the society.

Common property is shared by individuals and governed by social rules. An example of this is shared grazing land, where all stakeholders are allowed limited numbers of stock and time to avoid overgrazing or overexploitation of the common resource (Tisdell, 2009). In common property, group members have the right to exclude non-members. “Communal ownership means that a well-defined group of people jointly hold a non-transferable asset. Ordinarily, members of the group have the right to decide how to use the asset and the right to allocate proceeds. Communal ownership in land was (and is) quite frequent in tribal communities, was known in old Rome, and is paralleled in modern times by various types of producers’ cooperatives and labour-managed firms” (Pejovich, 1997, p. 4).

Public property is owned by the nation, government controls the elements of property rights such as access and use. In open-access properties, no one has the right to exclude others. Open-access resources are also called common pool. The state can choose to change open-access properties into private, common, or public
properties. Open access may exist when the allocation and enforcement of rights costs more than the benefits gained from the allocation.

The property rights regimes governing geothermal resource access may change from communal to restricted open access or vice-versa. Communal rights are exercised when those with access to the resource agree on a joint operation or unitisation. In 2007, a change in New Zealand access policy from single tapper to a multiple access policy transformed the property rights regime towards restricted open access where all parties with access to a geothermal resource can utilise it if they meet certain requirements specified by regional/national government.

2.2.5. Land ownership in New Zealand

Ownership of a resource is about having the power to manage, dispose of, and receive income/enjoyment from the resource. Ownership is a critical consideration when developing a resource. Rules governing use of a resource in public ownership will most likely differ from those in private ownership. For example, a public owner may accept lower deals when leasing the resource and add conditions to support the environment, community and future use. Epstein (1999) uses the example of the Audubon Society in Louisiana to illustrate this. The Audubon Society owns extensive wetland properties in Louisiana and sold leases for oil and gas drilling on its properties. Despite its knowledge of the risk of pollution from drilling, the society intends to use the revenue to improve the habitat it owns and acquire additional habitat. The revenue generated is lower than similar cases in private ownership. However, to control the risk of pollution, “Audubon Society requires its lessees to take additional precautions: (i) to reduce the probability of an occurrence, and (ii) to reduce the severity of any spillage that does occur. Hence, greater care is taken in
the siting and spacing of wells and the drilling rate” (Epstein, 1999, p. 10). Therefore, society may forgo revenue in a trade-off for a better environment or other non-market benefits. Although there are some difficulties in administrating public resources, when these resources are allocated to a corporate body or a group of people that body or group can go through a normal market decision-making process to decide how to use them. This process may well undermine the interests of society, if it is not regulated.

In New Zealand, there is no written constitution or federal structure to protect individual property rights. “Effective sovereignty is in the hands of a cabinet, and the parliament from which it is drawn” (Epstein, 1999, p. 38). Although individuals enjoy no formal constitutional protection against the legislature, landowners will be compensated if the government wants to occupy the land or take it for public use. However, the government will not pay any compensation for limiting the use of land. Although the use of resources “is regarded as equivalent to direct occupation”, section 85(3) of the RMA only “offers the property owner some limited form of judicial relief in this situation” (Epstein, 1999, p. 38). Landowners have to apply for resource consent when developing certain projects on their land. The owner of the land has to satisfy the consenting authority that their use of the resources “will not place unfair or unreasonable burden on any person having an interest in the land” (Epstein, 1999, p. 38) to receive consent.

Epstein (1999) suggests that land ownership includes the ground beneath and the area above the land. There are different ownership systems for underground resources around the world. In the American system, the owner of the land has the right to access and use the resource beneath his/her land, while in New Zealand the Crown owns most of the natural resources (Libecap, 1986). In the American system, the ownership of the geothermal resource can be separated from the land ownership and transferred to a third party for development. Geothermal resources on publicly owned lands are available for lease. Although the American system looks promising on paper in terms of protecting property rights, the final outcome of
individual cases may still be similar to the New Zealand system, as in both New Zealand and America, the government controls the size, take, use and mode of activities. Strict regulations manage the drilling, abandonment of wells, plant construction, and control of emissions. “The constitutional guarantee of property rights in America has generally turned out to be a paper tiger. It may have seemed a strong guarantee when originally included in the Constitution, but a series of judicial interpretations has systematically weakened its protection to a level similar to that prevailing in the Commonwealth countries. This convergence in outcomes suggests that the most powerful forces at work are more likely political than constitutional” (Epstein, 1999, p. 39).

In Iceland, ownership of geothermal resources is attached to land ownership. Pursuant to the Energy Act 1967, resources located on private land are privately owned and those on public land are the property of the State of Iceland (Ketilsson et al., 2010b). Exploration, utilisation and any other development of geothermal resources are subject to a licensing regime controlled by the state. Once a year, each licence holder is required to submit operation and field information such as the size of take, number of wells, current temperature and pressure. Supplied information enables the authorities to monitor the utilisation and status of the field.

In the Philippines and Indonesia the state owns, controls, and utilises the geothermal resources. Utilisation may be contracted to private operators.

In New Zealand, the ownership of minerals, water, and geothermal resources are different to land ownership, where the owner of the land may not necessarily be the owner of the resources. There are three main categories of land in New Zealand: general land; Maori land; and Crown land. General land is registered in the title and cadastral survey records administered by Land Information New Zealand (LINZ). General or private land is owned by individuals or corporations in fee simple (freehold). Fee simple ownership is the highest form of land ownership in New Zealand. It allows landowners to make changes to their property without the
consent of neighbours and without needing to change the title (PPTYLAW, 2012). Despite the benefits of fee simple ownership in New Zealand, it is limited by government taxation, police power, and the RMA’s use regulation.

Crown land is for all practical purposes government-owned land where the Crown holds the supreme or allodial title (Guerin, 2003). “Allodial title historically meant that the land was held in absolute independence, without being subject to any rent, service, or acknowledgement to a superior” (Guerin, 2003, p. 29).

Maori land is recorded with the Maori Land Court (and may also be registered with LINZ). Section 4 of Te Ture Whenua Maori Act 1993/Maori Land Act 1993 defines Maori land as either Maori customary land or Maori freehold land ("Maori Land Act 1993/Te Ture Whenua Maori Act 1993," 1993). Section 129 (subsections 1&2) of the Act provide that Maori customary land is land held by Maori in accordance with tikanga Maori and that Maori freehold land is land the beneficial ownership of which has been determined by the Maori Land Court (MLC) by freehold order. Transfer of Maori land must take the Act into account. Section 129 provides for a number of different types of land status. The status of land may only change from Maori freehold land to general land upon registration of an Order of the Maori Land Court (Guerin, 2003).

Most New Zealand geothermal systems are located on lands with fragmented ownership. Ownership may be in any of the above forms (general, Crown, or Maori). Most Maori land is held in multiple ownership, sometimes by a large number of people. Multiple ownership of land within different ownership systems adds to the complications around rights and access to geothermal resources. In the New Zealand system, there is no formal process of arbitration and no guarantee that a geothermal explorer will be the only party to extract the resource. “The current system of geothermal management under the RMA requires a developer to negotiate formal contracts with all land owners where access is required, defining what rights each party have in respect to accessing the geothermal resource” (MED,
2010). The Ministry of Economic Development’s 2010 report on geothermal energy strategy recognises land access as a key requirement to a successful geothermal development (White, 2010). It considers the lack of certainty of ownership of geothermal resources and the exclusive rights to use them as the main factor reducing incentive for investment. Developments are generally open for new entrants as soon as resource potential is identified and therefore the exploration effort by a private party can be without reward. Consequently, well-defined and enforceable property rights are required for geothermal development in New Zealand.

Section 10 of the Crown Minerals Act 1991 states that “all petroleum, gold, silver, and uranium existing in its natural condition in land (whether or not the land has been alienated from the Crown) shall be the property of the Crown”. Geothermal resources are water resources and therefore not covered by the Crown Minerals Act. In New Zealand, geothermal resources are regulated through the RMA. The RMA states that geothermal water is not always ground water. “Geothermal water is defined in the RMA as meaning water heated within the earth by natural phenomena to a temperature of 30 degrees Celsius or more; and includes all stream water, and water vapour and every mixture of all or any of them that has been heated by natural phenomena. Therefore geothermal water is not always strictly ground water in all of its states” (RPS, 2000, p. 56).

Geothermal development was first regulated through the Geothermal Energy Act 1953 and the Geothermal Energy Regulations 1961. Section 3(1) of the Act states that “the sole right to tap, take, use and apply geothermal energy on or under the land shall vest in the Crown, whether the land has been alienated from the Crown or not” ("Geothermal Energy Act 1953," 1953). Maori rights were recognised by including cooking, heating, washing and bathing, which were the main use of geothermal resources by Maori at the time of the legislation. The Geothermal Energy Regulations 1961 covered licensing and safety aspects of geothermal development ("Geothermal Energy Regulation 1961," 1961). Lack of legal control of the use of
geothermal water for domestic purposes, and limited protection of natural geothermal surface features and associated ecosystems, were evident in the Geothermal Energy Regulation 1961.

Section 354 of the RMA states that those resources vested by the Crown before the date the Act comes into force will remain under the Crown’s ownership (RMA, 1991). The rights include those allocated through the Geothermal Energy Act 1953. Most of the currently known New Zealand geothermal resources were identified between 1953 and 1991 and therefore some may conclude that the Crown owns all those existing resources. This is demonstrated by the allocation of the rights for Kawerau geothermal field, in the Bay of Plenty of New Zealand. In 2005 Mighty River Power, a state owned enterprise (SOE), paid NZ$14 million to the Crown to purchase the physical assets, commercial contracts, resource consents and intellectual property connected with the Kawerau field (Cullen, 2005). Mighty River Power then sold the Crown’s direct heat business, steam supply agreements and other geothermal assets located at Kawerau to Ngati Tuwharetoa Settlement Trust (NTST) (Teat, 2012).

Section 14(2) of the RMA prohibits take, use, dam, or diversion of any heat or energy from the material surrounding geothermal water without consent from government or regional authorities (RMA, 1991). Meanwhile, section 14(3) allows the taking and use of geothermal resources in accordance with tikanga Maori for the communal benefit of the tangata whenua when it does not have any adverse environmental effect. Therefore, according to the RMA, regardless of ownership, the government (regional or national) has control over all geothermal resources and is responsible for their sustainability. This means that the government plays a vital role in defining, allocating, and enforcing the rights attached to geothermal resources, such as exclusivity, duration, transferability, and quality of title.

Following the introduction of the RMA, the single tapper policy was proposed by Environment Waikato as the preferred form of access policy. This policy would
allow for a single unique operator for each reservoir to be responsible for take and use of the resource and accountable for the consequences of any wrongdoing. The policy in its initial form recognised that all landowners within the system boundary had rights that needed protection or recognition in the formation of the ‘single tapper’. It was proposed that a formula be constructed providing landowners with a share-holding in the ‘single tapper’. The policy was also to be required to sell fluid to existing and new users via a ‘market’. ‘Single tapper’ encourages efficiency and results in optimal rate of production, mineral recovery, and the number of wells (Decision No. A047/2006 2006). It has the potential to reduce issues with waste, creates potential for vertical integration to optimise energy use, minimises legal and litigation costs, allows for flexible adjustment to maximise net present values (NPV) continuously, and allocates clear responsibility for possible externalities and/or damage. However, the policy rewards the first comers and penalises neighbouring landowners by eliminating their access rights. It may lead to a race to develop the resources without careful consideration. Contesters may be ready to spend up to the expected rent to win the access race and gain a monopoly with the right to veto new entrants. Although in theory a monopoly may be good for natural resources in the long term, it removes competition from the market, lowers production and consequently increases the market price of the product.

The proposed single tapper policy would allow existing multiple operations to continue. The Wairakei-Tauhara geothermal system is an example of a geothermal system being developed by two different firms. Wairakei and Poihipi Road were the two power stations owned and operated by Contact Energy and Mercury Geothermal Ltd respectively. Contact Energy took possession of both and now owns and operates both geothermal plants. In 2005, Geotherm Group Ltd applied for a resource consent to construct and operate a new power station on the same reservoir. Contact Energy appealed Waikato Regional Council’s decision to give consent to Geotherm. The Environment Court heard the case, as it did not meet the requirements of the single tapper policy.
At court, Environment Waikato, Taupo District Council and Mighty River Power (MRP) supported the single tapper policy. Contact Energy and Geotherm both wanted a change in policy to allow multiple access. Contact Energy’s action was unusual, as it would allow a competitor access to the resource being used by one of its power plants, but Contact could gain benefit elsewhere. Taupo District Council supported the single tapper policy, as the council wanted a single entity to be responsible and accountable for the consequences of geothermal developments in the region, especially the effects of extraction-related subsidence and hydrothermal eruption in urban Taupo. Taupo District Council stated that multiple operators add to the complexity of identifying responsible parties. MRP also supported the single tapper policy on the basis that it could benefit investors by assuring return. However, MRP stated that single tapper is not the ‘total answer’ to the problem, but could be the best option in the current situation (Decision No. A047/2006 2006).

Following a series of hearings in Auckland and Taupo of New Zealand in 2005, the Environment Court of New Zealand ruled to change the access policy from single tapper to multiple operators under certain conditions. The court decision states that “limiting development to a single operator scenario is not the most appropriate way of providing for sustainable development of the Development Geothermal Systems” (Decision No. A047/2006 2006, p. 103). The Environment Court suggested that the likely issues related to multiple operations on a reservoir can be addressed by introducing a comprehensive system management plan that address the following issues (Decision No. A047/2006 2006, p. 104):

1. Each single Development Geothermal System needs to be managed in an integrated manner (integrated system management);  
2. Such integrated system management requires a package (regime) of objectives, policies and methods.

The key components of such an integrated system management regime for each development include (Decision No. A047/2006 2006, pp. 104, 105):
1. System management plan – including processes for preparation, amendment and review, and providing for operational flexibility and adaptive management;
2. Reservoir modelling and subsidence modelling;
3. Reinjection/injection and discharge strategy including any cascade (secondary) users
4. Multiple Operator Agreement(s) – regulatory requirement that multiple operators/consent holders coordinate and cooperate through agreements such as steamfiled management agreements and field operations protocols. These agreements need to address such matters as: efficient and beneficial use of the resource; mechanisms for conflict resolution; and accountability for adverse effects;
5. Research, monitoring and reporting;
6. Peer Review Panel;
7. Review conditions and procedures;
8. System Liaison Group/Forum;
9. Any application for large takes from Development Geothermal Systems should be classified discretionary activities.

Following the court decision, Environment Waikato’s access policy changed to allow for multiple operators. In March 2007, consent for the Geotherm application to build a power station on the Wairakei-Tauhara field that would allow Geotherm to extract 70,000 tonnes of geothermal fluid per day if wells on their property were able to produce that amount (Dowrey, 2008).

Mokai, Rotokawa, and Wairakei-Tauhara are the most likely geothermal systems in the North Island of New Zealand that could have multiple operations (Decision No. A047/2006 2006, p. 88). New Zealand’s multiple access policy does not allow for exclusive use and does not guarantee the extension at the end of consent duration. Mighty River Power (MRP) completed a successful joint power plant development in cooperation with Tuaropaki Power Company, who own the land surrounding the
Mokai geothermal system in Taupo of New Zealand. In 2000, a 55 MW geothermal power plant known as ‘Mokai I’ was commissioned. MRP has a 25% share of the development. In 2006, the total generation increased to 110 MW, which included the two phases of the project, Mokai I and II (Tuaropaki, 2010). Contact Energy owned a piece of neighbouring land that had access to the same geothermal system. However, Contact could not develop the resource under the single tapper policy. The 2006 Environment Court decision allowing for multiple tapping increased the possibility of Contact Energy starting a new plant on the same reservoir. Tuaropaki Trust decided to purchase the land from Contact energy to protect the investment they had already made. Negotiations were finalised in 2007, and the Tuaropaki Trust paid around NZ$27 million to purchase the land and the right to access. In addition, MRP agreed to allocate some of its natural gas development rights to Contact Energy (Contact, 2007). The deal shows the importance of property rights and, in particular, issues around exclusivity, duration, and quality of title, which will be discussed in section 2.3.

2.3. Case study and economic model

“The property rights approach can be understood as an attempt to formulate empirically meaningful optimisation problems by associating the utility function with the individual decision maker and then introducing specific content into the function” (Otto et al., 2006). In this way, it becomes possible to consider the behaviour of the decision-makers within the firm, government bureau, or similar collective agency.

The Environment Court’s 2006 decision led to a geothermal development policy, allowing multiple access to a geothermal resource. The policy does not give
exclusive rights to the developers and therefore reduces the likelihood of long-term planning that may allow benefit-sharing with future generations. In this section, a case study is developed to analyse the impact of the multiple access system on investment decisions and inter-temporal externalities. It is assumed that two parties, A and B, have access to a geothermal resource. The geothermal aquifer is assumed to have characteristics that allow for a maximum 140 MW plant that can be productive for 35 years. Table 2.1 shows the possible new investments.

<table>
<thead>
<tr>
<th>Option 1</th>
<th>Firm A</th>
<th>70 years</th>
<th>Plant size &lt; 140 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 2</td>
<td>Firm B</td>
<td>35 years</td>
<td>Plant size = 140 MW</td>
</tr>
</tbody>
</table>

Table 2.1. Options for new investment

In the absence of new entrants, firm A aims to maximise the net present value of its investment by planning for 70 years of operation, at a rate lower than 140 MW (as it has to maintain the temperature above 150°C for 70 years). Option 2 is firm B’s 35-year operation plan. For simplicity, it is assumed that only one firm (A or B) can start utilisation at year one and will have exclusive right for the duration of the resource consent. Resource consent will have duration of 35 years. Both firms (A and B) can apply for a new resource consent at year 35 to further utilise the resource. Therefore, firm A has no assurance to have the resource available for 70 years of utilisation.

The aim of this case study is to analyse whether the firm with the long-term investment plan will have an incentive to enter the market in the absence of well-defined and appropriately allocated property rights. An optimisation model is used
to compare the effect of development on the reservoir’s temperature under different policies. The characteristics of geothermal systems may vary significantly between different geothermal fields. Therefore, finding a production model that works for every individual resource may not be possible. However, all models share some general behaviour that can be used to develop a generic production model. A simple production model was adopted from Golabi and Scherer’s (1981) work to simulate the optimisation problem. The aim is to maximise the profit of individual firms, $k \in (A, B)$, by using a production function with production constraints.

The production function is subject to the availability of brine at a given temperature, $T^e$, higher than a certain level ($T^e \geq x = 150^\circ C$). It is assumed that the brine temperature must be at least $150^\circ C$ for electricity production development. The production function has a direct relationship with the quantity of extracted brine, $q_{t,k}^e$, and the temperature of the extracted brine, $T_{t,k}^e$. Electricity generation level depends on the conversion factor, $\alpha$, that is used to map electricity produced per litre of brine, as shown in equation below:

$$ Q_{k,t} = \alpha T_{t,k}^e q_{t,k}^e $$ \hspace{1cm} (2.1)

Total production from a reservoir depends on the number of years, $t$, of production and the number of firms operating on that reservoir. The total net present value of profit from development of a geothermal reservoir depends on the net present value of the revenue gained and the cost of production ($c$), including operation and fixed cost, by different operating firms. Golabi and Scherer (1981) shows a positive relationship between the extraction rate and the discount rate and a negative relationship between the extraction rate and the future energy price. Using $\delta^t$ as the
discount rate and $P_{t,k}$ as the wholesale electricity price, the profit function will be as follows:

$$\pi_{t,k} = (P_{t,k} Q_{t,k} - c q_{t,k}^e) \delta^t$$  \hspace{1cm} (2.2)

$k = A, B$ (firms)

$t = 1, 2, \ldots 35$ (T) \hspace{1cm} short term development

$t = 1, 2, \ldots 70$ (T) \hspace{1cm} long term development

Firm $k$ is assumed to maximise the present value of profit such that the production constraints are met:

$$\max_{q_{t,k}^e} \sum_{t=1}^{T} \pi_{t,k} = \sum_{t=1}^{T} (\alpha P_{t,k} T_{t,k}^e - c) q_{t,k}^e \delta^t$$  \hspace{1cm} (2.3)

s.t.

$$R_t \geq \sum_{t-d}^{T} q_{t,k}^e$$  \hspace{1cm} (2.4)

$$T_{t,k}^e \geq 150^\circ C$$  \hspace{1cm} (2.5)

$$q_{t,k}^e \geq 0$$  \hspace{1cm} (2.6)

Constraint (2.4) requires the total extracted brine to be less than the total existing brine, $R_t$, at any time. Constraint (2.5) is the limit on the brine temperature that can
be used by the generator to produce electricity. The brine temperature generally needs to be more than 150°C to enable a large geothermal electricity plant to operate. Constraint (2.6) sets the extraction at greater than or equal to zero.

The liquid and heat transfer system is assumed to be given and remain constant throughout the model. One hundred percent of the extracted brine is reinjected to the reservoir. Cold water is assumed to take three years (d=3) to reach the production wells. The amount of extractable brine depends on the original reservoir size, extracted brine, and the time that reinjected brine will take to reach the main reservoir area. It is also assumed that there is a natural recovery of temperature at the rate of $\gamma$, as illustrated in equation 2.9. Inflow is assumed to be only from the reinjection and not rainwater – rainwater may reduce the rate of recovery. In most geothermal developments pressure decline leads to decline in well output and production decline. However, in this model pressure is assumed to be constantly maintained by reinjecting 100% of the extracted brine. Therefore, temperature decline is assumed to be the only factor leading to the reduction in production. It is also assumed that firms chose a fixed level of extraction and have to keep that almost the same for the entire life of the plant. It is difficult for geothermal plants to regularly vary the production rate. Major changes in production impose higher capital and labour costs to the firm (Hotelling, 1931). Temperature change may damage pipes and other equipment attached to the system. Over time, the variation in temperature creates cracks, and it is not economical to apply such changes unless the price of electricity is so high that it can cover the cost. The high cost of labour and capital can only be recovered in extreme circumstances when there is a significant increase in price. Therefore, it is assumed that there is no change in the level of brine extraction throughout the life of the plant.

The temperature of the extracted brine is assumed to be equal to the temperature of the reservoir. The reservoir’s temperature at any time depends on the temperature of the previous period, the temperature of the reinjected brine and the time the reinjected brine took to reach the main reservoir area and the temperature recovery
factor (heat transfer from the earth). It follows the physical rule of mixing liquids with different temperatures as shown below (Golabi & Scherer, 1981):

\[
T_t^e = \frac{(T_{t-1}^e + (1 + \gamma) * R_{t-1} + T_{t-d}^e * (1 + \gamma * d) * q_{t-d})}{(R_{t-1} + q_{t-d})}
\]  \hspace{1cm} (2.9)

\begin{itemize}
    \item \(T_t^e\): Temperature of extracted brine at time \(t\) (current period)
    \item \(T_{t-1}^e\): Temperature of extracted brine at the end of previous period
    \item \(\gamma\): Temperature recovery rate
    \item \(T_{t-d}^e\): Temperature of extracted brine extracted \(d\) years ago
    \item \(d\): Lag period – number of years it takes reinjected brine to reach the production well
    \item \(q_{t-d}\): Quantity of extracted brine \(d\) years ago
    \item \(R_{t-1}\): Quantity of brine left in the reservoir at the end of previous period
\end{itemize}

The cost of wells and the initial stages of testing are embedded in the total capital cost. There is no new technological progress and the operation cost is assumed to increase by the rate of inflation during the life of the plant. Cost of renovation and reinstalment after 35 years is embedded into the calculation for firm A’s development, 70 years of operation. The level of production is limited to the available technology and installed plant. Firms can make an investment decision only at the start of the project by using the existing information on the resource.

Firms are assumed to have full access to the entire reservoir and therefore can use the optimal location for extraction and reinjection wells. There is no financial
restriction and the technology and cost functions are constant during the life of the plant. Firms are assumed to be price takers and have to accept the average prices offered by the market. This is true for the geothermal power companies in New Zealand as they offer their generated electricity for around $0 to the New Zealand wholesale auction and accept the equilibrium price that comes from the auction. New Zealand’s wholesale electricity price is on average around $60-70/MWh. The nominal electricity price is set at NZ$60/MWh and is assumed to increase by 3% per year (MED/MT, 2011). New Zealand historical data shows that the electricity price has been increasing at a rate higher than or equal to the inflation rate. According to information from the New Zealand Treasury, the discount rate for infrastructure is set to 8% per annum (NZ-Treasury, 2008). The discount rate used in the New Zealand geothermal and energy market is around 10% (Luketina, 2010). Mighty River Power, an active geothermal developer in New Zealand, uses a nominal discount rate of between 8.6% to 9.17% (Auditor-general, 2004; Macquarie, 2010).

Data related to the production function and characteristics of the reservoir are from the Rotokawa II (Nga Awa Purua) development located in the central North Island of New Zealand (Bouche, 2007). The Rotokawa reservoir is located at depths of 950m and below. It is a high-temperature geothermal field with typical chloride water at 320-330°C at depths below 1500m (MRP, 2007). The reservoir is fed by an up-flow at depth from the south of the field near Lake Rotokawa. The reservoir has a proven area of 3.3 km² and probably of 6.5km². The reservoir fluid is neutral alkali chloride water typical of high temperature fields in the Taupo Volcanic Zone, in New Zealand (Grant, 2007). This project had NZ$430 million capital cost and the operational cost is estimated to be around NZ$16.5 million per year (Grant, 2007; Reeve, 2007).

Rotokawa II (Nga Awa Purua) is a 140 MW project that uses 16,425,000 tonnes of geothermal fluid per year (average extraction rate 45,000 to 50,000 tonnes per day) to generate 1,200 GWh of electricity per year (Bouche, 2007). The extraction is limited to the mentioned yearly geothermal fluid. Considering the total yearly production, the geothermal fluid extraction per year, and the temperature of the
fluid, the conversion factor, $\alpha$, can be found to be around 0.00023 ($16,425,000$ tonnes X $320^\circ$C X $0.00023 = 1,200$ GWh). The temperature of the extracted brine is assumed to be $320^\circ$C at the outset. It is also assumed that the reservoir temperature will increase at a rate of 1% per year, will take 100 year to recover, and the returning brine’s temperature will increase by 2%. The temperature of the reinjected brine will increase as it moves through the hot rocks to reach the main part of the reservoir and the extraction well (Bromley et al., 2006). The rate of increase in the temperature of the colder reinjected brine is higher than the rate of increase in the temperature of the main reservoir. The rate of recovery is faster when the temperature is further from the main equilibrium (O'Sullivan et al., 2010; Rybach, 2003; Rybach et al., 2000). A summary of the assumptions and data can be found in Appendix A and B of this thesis.

Extraction is restricted to the amount of available brine and the capacity of the plant. The extracted brine will be reinjected to the reservoir after going through the power generation process. Revenue and extraction cost both depend on the extraction rate, breakthrough point, and the life of the project. The optimal extraction rate is found through computer programming listed in appendix E.

2.4. Findings and discussion

It is assumed that firm A aims to keep the reservoir productive for 70 years, which is longer than firm B’s 35-year operation plan. Firms maximise their gain by driving the temperature to lower than $150^\circ$C by the end of their operation, when it is not commercially viable to utilise the resource. For simplicity, it is assumed that only one firm can enter the market at the outset. Firms have to apply for a new resource consent at year 35. Therefore, year 35 is considered as a second point of entry, when
the application for consent is open to all rights holders with access to the geothermal reservoir (for simplicity it is assumed that the application is not open from year 1 to 35). The resource will not be commercially usable at year 35 if firm B starts the operation. Thus, firm B’s business model imposes external costs on other rights holders’ planning for future development as the resource will no longer be productive at year 35. Firm B effectively depletes the resource in 35 years.

This study considers 35 and 70 years as short and long terms respectively. It does not suggest 70 years is the optimal length of time to keep the geothermal reservoir available for electricity generation. The optimal length of time may depend on the discount rate, availability of future geothermal and alternative resources, future use, technology, demand, and the current right holders willingness to leave quality resources for future generations. Figure 2.2 shows the reservoir’s temperature path during two different plans.

![Temperature change for 70 years of operation (firm A) in comparison to 35 years operation (firm B)](image)

**Figure 2.2.** Temperature change for 70 years of operation (firm A) in comparison to 35 years operation (firm B)
The result shows a 100 MW plant as being the most viable option for 70 years of operation. The net present value of profit for firm A is NZ$407 million, which is slightly higher than firm B’s NZ$353 million profit when the discount rate is 8%. Therefore, in terms of the two available options, it is economically efficient to select 70 years as the best option for development as it results in higher net present value of forecasted profit. Table 2.2 shows the finding of the two investment plans.

<table>
<thead>
<tr>
<th>Project life</th>
<th>Tonnes of extracted brine/year</th>
<th>Equivalent plant size</th>
<th>Temperature in year 35</th>
<th>NPV (8% discount)</th>
<th>NPV (10% discount)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: 70 years</td>
<td>12,081,000</td>
<td>~100 MW</td>
<td>171.5°C</td>
<td>NZ$407 million</td>
<td>NZ$295.5 million</td>
</tr>
<tr>
<td>B: 35 years</td>
<td>16,161,000</td>
<td>~140 MW</td>
<td>150°C</td>
<td>NZ$353 million</td>
<td>NZ$289 million</td>
</tr>
</tbody>
</table>

**Table 2.2.** Investment decision by firms and net present value of profit

In New Zealand, around 10% is considered by energy firms to be the nominal market discount rate. Therefore, for the purposes of this study a 10% discount rate is used in calculating the net present value (NPV) of the profit gained by firms. The results are in line with the 8% discount rate, showing that the NPV of profit for a longer-term plan is higher than the NPV of profit for shorter-term investment, although the gap is smaller. Despite the higher NPV for the longer investment plan, lack of exclusive rights to use and a guarantee for 70 years’ duration opens the resource to competitors at year 35 and therefore reduces the chance of gaining the
full net present value of the profit from the resource. Indeed, the duration is limited to 35 years as the option to renew at year 35 is open for competition. Therefore, the firm with the longer-term plan would be discouraged, even though the net present value and therefore economic gains of the longer-term plan are higher. A guaranteed 70 years consent or exclusive right to extend the consent at year 35 may change the situation. Hence, both duration and exclusivity play vital role to encourage longer term planning and to achieve higher net present value of profit.

New Zealand’s multiple-access policy does not allow for the exclusive use of a geothermal resource. In a situation where the reservoir’s characteristics allow a limited capacity to be developed for electricity generation, a competitor’s entry lowers productivity and results in less income. It makes the operation inefficient. This situation is similar to constructing a dam on a river without being able to exclude others from building another dam further upstream. The flow of the stream will change and therefore the resulting benefits may not be as expected (Demsetz, 1967).

Negotiation can be a solution to prevent new entrants but this comes at a cost and therefore reduces the efficiency of the original operation. Competitors may ask for up to the expected resource rent (for the resource located under their land) in exchange for not exercising their rights. Thus the wealth of each rights holder depends on the current and future actions of the competing rights holders. This finding is in line with the New Zealand Geothermal Association’s claim that the current system does not provide certainty for geothermal exploration, as someone else can apply for resource consent after the explorer has invested in finding the quality geothermal resource. Therefore, developers have to spend considerable time negotiating exclusive access rights (NZGA, 2013). In the case study, this discourages firm A from investing in a longer-term project in the absence of exclusivity. This means that in the absence of exclusive rights, firms will choose a shorter-term operation, and consequently overly intensive extraction may take place. The results are consistent with cases in the oil industry where, in the absence of well-defined
property rights, firms with shared resources try to maximise their gain within the first few years of exploitation.

2.5. Conclusion

Although geothermal resources are often described as ‘renewable’, large-scale developments mine heat from the resource and drive the temperature down to a non-commercially usable level. Recovery can then take hundreds of years. The optimal level of extraction depends on the regeneration rate, costs of extraction and production, the discount rate, and the number of years the reservoir is utilised for electricity generation. The rights holders effectively determine the commercial life of a geothermal reservoir by selecting the size of the power plant and applying for a consent to take. A larger size power plant reduces the life of the reservoir when the heat regeneration rate is lower than the heat extraction rate.

In New Zealand, following the introduction of the RMA, the single tapper policy was proposed by Environment Waikato as it allowed a single unique operator for each reservoir, who would have been responsible for take and use of the resource. All landowners with the land above the system could have shares in the operation. Single tapper encourages efficiency and results in optimal rates of production, mineral recovery, and number of wells. It reduces issues with waste, creates potential for vertical integration to optimise energy use, minimises legal and litigation costs, allows for flexible adjustment to maximise NPV continuously, and allocates clear responsibility for possible externalities and/or damage. However, the policy rewards first comers and penalises neighbouring landowners by eliminating their access rights. It may lead to a race to develop resources. Contesters can be ready to spend up to the expected rent to win the access race and gain a monopoly.
Although in theory a monopoly may be good for natural resources in the long term, it removes competition from the market and lowers production, which leads to higher price.

A case study analysed investor’s reaction to New Zealand’s current multiple access policy. An optimisation model compared the effect of development on the reservoir’s temperature and lifetime under different policies.

Optimising the profit for a number of given years, the results showed a 100 MW plant is the most viable option for 70 years of operation. Using 8% (10%) as the nominal discount rate, the results show NZ$407 million (NZ$295.5 million) and NZ$353 million (NZ$289 million) as the net present value of profit gained by firms with 70 and 35 years of operation respectively. Therefore, it is economically efficient to select 70 years as the best option for development as it results in higher net present value of forecasted profit.

Higher net present value of profit should incentivise firms to select a longer-term option. However, in the absence of a long-term exclusive right and assured duration of consent, the first firm to develop has to compete with other rights holders to continue its operation after year 35. Therefore, a shorter-term operation will be more desirable for firms, and consequently overly intensive extraction may take place. This case study shows that, in the current New Zealand situation where firms are facing uncertainty about future resource use, the incentive for longer-term investment is reduced, which lowers the net present value of profit gained from development of geothermal resources. Higher net present value of profit will be gained if either longer duration is guaranteed or exclusive right is given to extend the resource consent at year 35. The results are in line with cases in the oil industry where, in the absence of well-defined property rights, firms with shared resources attempt to maximise their gain within the first few years of exploitation. Therefore, careful consideration is required when designing policies to deal with the development of geothermal resources located on land with fragmented ownership.
and multiple rights holders. A multiple access policy leads to lower net present value of profit gain from the resource.
Chapter 3

Geothermal development: Challenges in a multiple access scenario
Chapter 3

Geothermal development: Challenges in a multiple access scenario

3.1. Introduction

Secure property rights are essential for the development and sustainable use of geothermal resources for electricity production. As an illustration, the recently completed Rotokawa II (Nga Awa Purua) geothermal power station in the centre of the North Island of New Zealand cost around $430 million, of which around $60 million was invested in pre-construction activities (Bouche, 2007).

Firstly, access to the land above a potential reservoir must be negotiated with surface landowners who may or may not own the resource in situ. In New Zealand, land over active geothermal areas is typically owned by Maori. There are three broad classes of Maori land; Maori customary land, Maori freehold land, and Maori reservations. Most Maori land is held under freehold title with multiple owners. Maori freehold land ownership ranges from 10% of titles held by one owner to 10% with an average of 425 owners each (Auditor-general, 2004). Multiple ownership can create barriers to obtaining agreement for development and access to finance, and can also reduce the economic return to land/resource owners. Electricity generators, with access to technology, expertise and finance, are obvious potential partners for the development of geothermal resources underlying Maori land.

Secondly, given the significant cost of constructing a geothermal power plant, investors will require secure and, ideally, excludable rights. In New Zealand, the resource (i.e. the thermal properties of the reservoir) is owned by the Crown who, through statutory law, provides the legal foundations for regulations and policy
regarding access and sustainable use. Once a joint venture arrangement has combined the interests of developer and landowners, the rate of utilisation and future access to the resource, possibly by other parties, remains to be settled. Dilutions to excludability may arise from multiple groups of landowners spanning the reservoir and potentially opening access to their land to developers aiming to tap into the resource. To state the obvious, property rights arrangements – involving Maori, developer, and the Crown – are a significant determinant of the economic value of a geothermal resource. Further, the property arrangements determine the distribution of benefits across parties to the development, the commercial operator, landowners, and the resource owner.

Clear policies around resource ownership, access, regulation of development, taxation, incentives and risks are required to encourage the development of natural resources for energy generation (Bloomquist, 2003; Philips, 2010). Regulations on how and when to develop a geothermal resource can have a significant impact on the life of the reservoir and profitability of projects. New Zealand has gone through a series of changes in access policy aimed at optimising use of the resource while minimising externalities. In 2006, the Environment Court ruled to change the access policy from a single tapper to multiple operators under certain conditions. The ruling imposed a significant variation to geothermal access policy by allowing multiple access to a geothermal reservoir (Decision No. A047/2006 2006).

Appropriate assignment of rights can internalise externalities and may lead to sustainable business models (Kaffine & Costello, 2011). Although there is a body of literature dealing with the sustainability of geothermal resources, there is little focusing on access policies especially in the case of multiple landowners with limited access to the same geothermal reservoir.

Property rights and the efficient market allocation system, property rights concepts, regimes and the application of those regimes in the New Zealand context were analysed in chapter two. The results from chapter two show that in the absence of
long-term exclusive rights and guaranteed duration, firms will choose a shorter-term operation and consequently, overly intensive extraction takes place. New Zealand's current multiple-access policy reduces the quality of the title for each rights holder, and the value of the resource, by limiting use and creating income insecurity. Therefore, lack of certainty on both the ownership of geothermal resources and exclusive use rights reduces the incentive for longer-term investment while the net present value of the profit gained from the longer-term operation was shown to be higher in comparison to a shorter-term operation. The important issue to address is whether there is a greater benefit from firms competing to develop a geothermal resource or unitising. In this case, benefit is the gain from higher net present value and lower depletion rate.

This chapter analyses the impact of multiple access to a geothermal resource in a fragmented land ownership system, literature around reinjection options and issues related to sustainability of the resource. An investment optimisation model is introduced in section 3.3. Section 3.4 considers the situation where developers do not have access to the entire reservoir and cannot reinject in the optimal location. The optimisation model is used to estimate the consequences of restricted access and the impact on return on investment and sustainability of a reservoir accessed and utilised by multiple developers.

3.2. Literature

Property rights provide the foundation and associated incentive system that can help to shape resource allocation and efficient utilisation of scarce resources (Libecap, 1989). Property rights arrangements have a significant impact on production possibilities and economic growth (North & Thomas, 1973). Well-
defined and enforced property rights create strong incentives for owners to add the highest value to their resource (Pejovich, 1997) and create incentive for new investment (Axelsson et al., 2005). Well-defined property rights enable right holders to realise the full economic value of their resources.

Ownership of a resource is about the level of control over the bundle of rights attached to that resource. As discussed in chapter two, these rights include the right to exclude others, exclusivity, securing the period of use, duration, quality of title and transferability. Government rules and regulations impact the quality of the bundle of rights attached to the resource that, in turn, impact on the value of the resource.

“Under New Zealand law, the owner of land has no automatic right of ownership to any underlying geothermal resource” (WRC, 1992, p. 12). However, access to the resource is mostly under landowners’ control. In many cases, multiple parties, mostly Maori tribes, own the land above a geothermal reservoir. Traditional Maori society is generally not against development of resources for economic purposes as long as cultural values are respected. Maori tradition requires developers to protect resources for present and future generations, and requires control and use of resources to remain with the kaitiaki (Maori concept of guardianship for sky, water, and land).

Geothermal resources are migratory and not having exclusive rights may create significant issues. In a multiple-access scenario, there is no guarantee of return on investment. It is also difficult to internalise externalities and keep agents accountable for the economic consequences of their activities. For instance, in a geothermal system with multiple land ownership and no exclusivity, each developer’s actions can contribute towards reducing the temperature of the geothermal resource that is shared by all, which in turn reduces the productivity of the geothermal resource. Therefore, an individual rights holder’s gain depends on their competitors’ action. Kawerau in the Bay of Plenty of New Zealand is an
example of a geothermal reservoir being developed by multiple operators. Evidence shows that productivity is reducing as multiple parties extract the energy (Bloomer, 1998).

When a single landowner has access to the entire resource and can exclude others from utilisation, the case of optimal depletion is straightforward. Further, it is well established that economic efficiency follows if the resource is sold into competitive markets and there are no externalities associated with depletion (Dasgupta & Heal, 1979). Utilisation is more complicated when multiple landowners have access to a resource. Extrapolating on the example given above, development could include a joint venture of landowners and the electricity generator working according to government policy and regulation. Clearly, multiple economic interests are involved in development, and property arrangements work to influence both economic efficiency and the distribution of net benefits across the three parties; landowners, developer and government. Collective rights can mitigate open access losses, promoting efficiency. However, common property arrangements, while excluding non-group members, may not stop proximate development in the case of a migratory resource.

Using and sharing migratory resources is complicated. Since the discovery of petroleum in the United States of America in 1859, there have been serious common pool problems in the production of crude oil in some states, with different parties competing for migratory oil in subsurface reservoirs. “Under the common law rule of capture, private property rights to oil are assigned only upon extraction. ... For each of the firms on a reservoir, a strategy of dense-well drilling and rapid production allows it to drain oil from its neighbours and to take advantage of the low extraction costs that exist early in field development. In new, flush oil fields, subsurface pressures are sufficient to expel the oil without costly pumping or injection of water or natural gas into the reservoir to drive oil to the surface” (Libecap, 1989, p. 93). Rapid extraction rates, overcapitalisation, and reduced oil
recovery are the three historical characteristics of crude oil production identified by Libecap (1989).

Higher extraction rates at the early stage of exploitation are also evident from the work of Mohan and Goorha (2008). Rapid extraction by competing firms reduces the surface storage and, consequently, oil pressure. Therefore, firms have to start using pumps sooner, which in turn increases the cost of extraction. Non-cooperation between the firms eventually results in common pool losses. A high volume of extraction in the early stage of development drives the resource price down. Lower prices reduce the expected profit and hence the availability of funds for future investment. Although consumers are better off in the early stages of the extraction, future generations have to pay a higher cost to be able to use the resource, which will be limited and more expensive to extract. Therefore, everything else being equal, open access policy does not work well for consumers in the long run.

Similar to the oil industry, open access to a geothermal resource may lead to common pool problems. ‘First come first served’, ‘multiple access’ and ‘unitisation’ are three possible ways of allocating the utilisation rights when there are multiple parties with access to a geothermal resource. New Zealand pre-2006 had a ‘single tapper’ policy in place. The policy gave full access rights to a party available to develop the resource. A single tapper policy is problematic in that it creates tension between multiple landowners who have to compete to be first to develop the resource. Individuals may spend up to the expected rent to win the race and this leads to inefficiency and higher transaction costs. A single tapper policy may not allow for a timely approach that works in favour of the resource sustainability.

Post-2006, following a series of hearings in Auckland and Taupo, New Zealand, the Environment Court of New Zealand ruled against the single tapper policy, which had been proposed by regional government organisation Environment Waikato. The court decision stated that “…limiting development to a single operator scenario is not the most appropriate way of providing for sustainable development of the
Consequently, a new policy was introduced to allow all rights holders to develop a resource if they meet conditions to maintain the sustainability of the resource up to a certain level. The policy was aimed at addressing market competition issues. However, open access to a reservoir leads to a risk of overdevelopment or damage. The Environment Court suggested that issues related to multiple operations on a reservoir could be addressed by introducing a comprehensive system-management plan (SMP), or ‘integrated system management’ (Decision No. A047/2006 2006). The SMP is to include objectives, policies and methods for resource, reservoir and subsidence modelling, reinjection/injection and discharge strategy including any cascade (secondary) users, ‘multiple operator agreement(s)’, research and monitoring, a peer review panel, review conditions and procedures, and introduction of a system liaison group/forum (Decision No. A047/2006 2006). SMP relies upon effective regulation and enforcement by the regulator.

Multiple access to a resource may not ultimately be the best solution, as in theory it could lead to overdevelopment of the resource when parties try to maximise their gain. This may put too much pressure on the reservoir and deplete or damage it. The reservoir may require years of no extraction to recover from the damage done by over-utilisation. In some cases it might never reach the original temperature (Boast, 1989, p. 9).

Open access does not work well to sustain renewable resources. In a competitive situation the rent will be driven down to zero, which may be better for consumers as more output will be generated at a lower price, but this may cause faster depletion of the resource, as a higher quantity of input will be required for higher production (Conrad, 1999). Therefore, a unitisation model may work better to ensure the sustainability of the resource. Anderson and Hill (1983, p. 111) review the situation in a farming environment and comment that “…the size of the efficiency loss can be reduced, and thereby rents increased if farming effort is reduced”. Cheung (1970, as cited in Anderson & Hill, 1983, p. 111) uses a fishery example to describe the
situation, as follows: "[T]here exists incentives to fishermen to restrict the number of decision units who have access to the fishing right. That is, even if each decision unit is free to commit the amount of fishing effort, the ‘rent’ captured by each will be larger the smaller the number of decision units”. Kaffine and Costello (2011) refer to unitisation as the key answer to utilisation of a spatially linked renewable resource.

The literature around oil extraction also recommends unitisation as the solution to the common pool problem. Having one operator reduces the rate of extraction. It reduces the need for extracting pumps to be used at an early stage, which in turn reduces extraction costs. Despite the advantages of unitisation, parties involved in a single development have not always accepted it. Right holders may have concerns about the dividend share formula. Although the total production gain may be higher, the share distribution may not make all right holders better off. Those who are more productive may lose some of their advantage as the result of unitisation. Pro-rationing is an option to prevent rent dissipation by allowing for side payments through favourable quotas (Libecap, 1989). Conversely, unitisation may also lead to underinvestment when the distribution of wealth is not well defined (Mohan & Goorha, 2008). However, difficulties of contractual arrangements in the case of unitisation are not the focus of this thesis. It is assumed that the transaction cost for the contractual arrangements is zero.

Renewability of geothermal resources

Geothermal resources are considered renewable. “A renewable resource must display a significant rate of growth or renewal on a relevant economic time scale. An economic time scale is a time interval for which planning and management are meaningful” (Conrad, 1999, p. 1). Geothermal resources are different from oil
because the resource is “continually being replenished by an on-going flow of heat from depth by conduction or by convection of water” (Clotworthy et al., 2010).

While geothermal resources are generally considered to be renewable, they deplete, and the quality of the resource goes down, when a large commercial power plant operates on the reservoir. A geothermal resource is renewable when the heat extraction rate is less than or equal to the natural heat transfer and recovery of the geothermal system. The natural heat transfer rate varies for individual reservoirs. However, the temperature of a geothermal system will not be maintained if the rate of extraction is greater than the heat recovery (Axelsson & Stefansson, 2003; Ketilsson et al., 2010a; Rybach et al., 2000). In general, the renewability of geothermal resources depends on the timing and size of the exploitation (Rybach & Mongillo, 2006). A sustainable development plan for geothermal resources can maintain temperature and pressure into the future. Developers may not necessarily pay attention to the renewability of the resource if the short-term return of the project is high. As shown in chapter 2, lack of exclusivity and guaranteed duration may lead to shorter-term projects being preferred despite the possibility of higher net present value of a longer-term plan.

The renewability level of a geothermal resource and the factors that impact on this are important when comparing the development policies (Axelsson, 2008; O’Sullivan & Mannington, 2005). Limited information about geothermal resources makes the decision-making process more complicated (Sutherland, 1996). The generating capacity of geothermal systems is often poorly known and they can respond unexpectedly to long-term energy extraction (Axelsson & Stefansson, 2003). Therefore, a carefully designed and effectively implemented geothermal management system is necessary to control the energy extracted while maximising net benefits.

The recovery period for different geothermal systems varies. However, in general, the lower the temperature is driven by extraction, the longer it will take the
reservoir to recover and achieve the original temperature. Driving the temperature to lower than the sustainable level may irreversibly damage the reservoir. Figure 3.1 shows the growth rate as a function of temperature (T) for a particular geothermal system. This is usually the estimated recovery rate of the system. Any point on the growth curve, \([T_i, T_0]\), is a sustainable level of harvesting. \(T_0\) is the original temperature when the system is at the natural equilibrium and there is no temperature growth. The highest part of the curve is the maximum sustainability level. The temperature growth rate is higher at this point than the points closer to the original equilibrium (Rybach et al., 2000). Reducing the temperature to a level close to the lowest part of the graph on the left hand side may make the temperature irreversible and damage the system. The socially optimal level of extraction depends on the growth curve, benefits and the cost of extraction.

![Temperature growth rate/sustainable harvesting level](image)

**Figure 3.1.** Temperature growth rate/sustainable harvesting level

In the case of oil, extraction will eventually reduce the pressure of the reservoir and increase the pumping cost. Although pressure is an issue in geothermal development as well, it can be addressed by reinjecting the brine back into the reservoir to maintain the pressure of the reservoir. In most geothermal systems, fluid supply plays a crucial role in extending the life of the system. Although the heat
flow has to be natural, the fluid supply can be artificial and can come from reinjection. Production levels in The Geysers Geothermal Field, in California, began to decline in the late 1980s because of lack of fluids (Dickson & Fanelli, 2004). Axelsson and Stefansson (2003) show that an increase in the rate of reinjection reduces the rate of decline in a reservoir’s temperature/pressure and eventually its production level. This is particularly true for the vapour-dominated systems (Kaya et al., 2011). It is known that “…the energy production potential of geothermal systems is primarily determined by the pressure decline caused by production” (Axelsson et al., 2004).

Reinjection is essential for sustainable utilisation of the geothermal system (Axelsson, 2010; Axelsson & Stefansson, 2003). Infield reinjection provides pressure support and reduces the risk for potential subsidence. The reinjection strategy depends on the characteristics of the geothermal reservoir (Bromley et al., 2006; Rybach, 2003). “A reinjection plan should be developed as early as possible in field development and it should be flexible as it is likely to change with time” (Kaya et al., 2011). Kawerau Geothermal Field in New Zealand is another example where reinjection increases the peak flow rate (Bloomer, 1998).

Gringarten (1978) evaluated reservoir lifetime and heat recovery factors in geothermal aquifers used for urban heating. Gringarten found that the life of the reservoir depends on the development scheme. Reinjection of heat-depleted water enhances heat recovery and increases the lifetime of the reservoir. Cappetti et al. (1995) also confirm the positive relation between reinjection and maintaining reservoir pressure through their study on Larderello-Valle Secolo in Italy. Reinjection also permits the recovery of heat contained in the rock and is therefore essential for maintaining the sustainability of geothermal systems. Maintaining the pressure keeps the ratio of water to steam constant and consequently maintains the production level of the wells (Armstead, 1983).
Although reinjection contributes towards maintaining the pressure, it creates a zone of injected water around the injection well at a different temperature from that of the native water (Ling & Kun, 2004; Rybach et al., 2000). That zone will grow with time, and will eventually reach the production well, referred to as breakthrough. After breakthrough occurs, the water temperature is no longer constant at the production well. The higher the level of extraction and reinjection, the more the temperature is likely to fall.

Gringarten (1978) identifies the reservoir’s characteristics, distance between the production and injection wells and extraction as the main factors contributing to the lifetime of the reservoir and its renewability. As stated earlier, the extraction rate can have a negative effect on the temperature of the brine when the temperature recovery rate of the reservoir is low. The temperature recovery rate varies for different reservoirs and depends on the conductivity of the rocks to the source of the reservoir’s heat (Blair & Cassel, 1979). The temperature of the production brine may go down if the reinjected cold brine migrates at higher speed to the production wells. The migration speed may depend on the fractures and the characteristics of the individual reservoir, but in general the further away the reinjection the longer it will take the cold brine to arrive at the production wells (Bodvarsson & Stefansson, 1987).

Declining resource temperature has a negative impact on electricity generation and reduces the efficiency of the operation (Blair & Cassel, 1979). Figure 3.2 shows the effect of reinjected water on a particular geothermal field. The solid line shows the temperature drop with a higher rate of extraction while the dotted line shows the situation when the extraction rate is lower. In this case, reinjection starts at the period ‘u’ with the assumption that it will reach the main zone without any delay. The temperature starts declining as soon as the extraction starts and pressure drops. In figure 3.2, \( T_0 \) is the original temperature of the reservoir and \( T_i \) is the new equilibrium after a few years of extraction with the higher rate. The dotted line shows a smaller decline in the temperature when the extraction is less. The solid
line is the case when the extraction rate is higher and therefore temperature drops faster than the case with lower extraction rate.

![Graph showing temperature change over time](image)

**Figure 3.2.** The reinjection effect on temperature of the geothermal reservoir

### 3.3. Economic model

Although the literature on sustainable development of geothermal resources considers reinjection as a solution that will extend the life of the reservoir, multiple ownership of land that limits access to the entire reservoir has not been considered. Not having access to the whole resource may reduce the efficiency of the utilisation when there is less space available for siting the production and reinjection wells and one party cannot exclude others. Limited access to the land can limit the distance between the production and reinjection wells and lead to faster reduction of temperature, which may lower the economic benefit from utilisation of the geothermal resource.
Golabi and Scherer (1981) aimed to find the optimal extraction rate for a geothermal reservoir under closed access. Temperature drops when extracting energy from a geothermal reservoir as the pressure goes down. There is a positive physical relationship between temperature and pressure. At a constant rate of extraction the temperature will drop to a certain point and slowly reach equilibrium. The equilibrium depends on the characteristics of the reservoir, the level of pressure, the permeability of the rocks and the ability of the brine to flow through the pores, and the level of heat conduction from the core of the Earth. The system may never reach the equilibrium level if the extraction rate is higher than the system’s recovery capacity. Therefore, a high extraction rate can damage the reservoir and it might take hundreds of years before the system recovers.

Given the fact that the reinjection is necessary to maintain the reservoir’s pressure and the risk of temperature drop while reinjecting, this chapter analyses different access policies to identify the policy that can best support the renewability of the resource into the future while optimising benefits from the resource. An optimisation model is used to compare the effect of development on the reservoir’s temperature under different policies. The characteristics of geothermal systems may vary significantly between different geothermal fields. Therefore, finding a production model that works for every individual resource may not be possible. However, all models share some general behaviour that can be used to develop a generic production model. A simple production model was adopted from Golabi and Scherer’s (1981) work to simulate the optimisation problem. The aim is to maximise the profit of individual firms, k, by using the production function with production constraints.

The production function is subject to the availability of brine at a given temperature, $T^e$, higher than a certain level ($T^e \geq x = 150^\circ C$). It is assumed that the brine temperature must be at least 150°C for electricity production development. The production function has a direct relationship with the quantity of extracted brine, $q_{t,k}^e$, and the temperature of extracted brine, $T_{t,k}^e$ at time $t$ ($t \in T$). Electricity
generation level depends on the conversion factor, \( \alpha \), that is used to map electricity produced per litre of brine, as shown in equation below:

\[
Q_{k,t} = \alpha \frac{T_{t,k}^e}{q_{t,k}^e}
\]  

(3.1)

Total production from a reservoir depends on the number of years, \( T \), of production and the number of firms operating on that reservoir \((k \in (A, B))\). Total net present value of profit from development of a geothermal reservoir depends on the net present value of the revenue gained and the cost of production \((c)\), including operating and fixed costs, by different operating firms. Golabi and Scherer (1981) shows a positive relationship between the extraction rate and discount rate and a negative relationship between the extraction rate and the future energy price. Using \( \delta^t \) as the discount rate the present value of profit at time \( t \) will be as follows:

\[
\pi_{t,k} = \left( P_{t,k} Q_{t,k} - cq_{t,k}^e \right) \delta^t
\]  

(3.2)

\[
k = A, B \text{ (firms)}
\]

\[
t = 1, 2, \ldots 35 \text{ (T)} \quad \text{short term development}
\]

Firm \( k \) is assumed to maximise the present value of profit such that the production constraints are met:
\[ \max_{q_{t,k}^e} \sum_{t=1}^{T} \pi_{t,k} = \sum_{t}^{T}(\alpha P_{t,k} T_{t,k}^e - c)q_{t,k}^e \delta^t \]  

\[ \text{s.t.} \]

\[ R_t \geq \sum_{t-d}^{T} q_{t,k}^e \]  

\[ T_{t,k}^e \geq 150^\circ\text{C} \]  

\[ q_{t,k}^e \geq 0 \]  

Constraint (3.4) requires the total extracted brine to be less than the total existing brine, \( R_t \), at any time. \( d \) indicates the amount of time the cooling reinjected water takes to reach the production well. Constraint (3.5) is the limit on the brine temperature that can be used by a generator to produce electricity. The brine temperature should usually be more than 150°C to enable a large geothermal electricity plant to operate. Constraint (3.6) sets the extraction at greater than or equal to zero.

One hundred percent of the extracted brine is assumed to be reinjected to the reservoir at 120°C. Locations of the extraction and reinjection wells are usually selected through engineering modelling that optimises the life of the reservoir. Although the location for reinjection could vary for different systems, usually points around the edges of the reservoir are selected. The longer the distance between the extraction and the reinjection well the slower the temperature drop is expected to be. Tracer tests are used to understand the heat transfer through the channel/space in the production/reinjection zone. In this study, the liquid and heat transfer system is assumed to be given and remain constant through the model. Cold water is initially assumed to take three years (\( d=3 \)) to reach the production wells when the optimal reinjection location is selected.
The amount of extractable brine depends on the original reservoir size, extracted brine, and the time that reinjected brine will take to reach the main reservoir area. It is assumed that there is a natural recovery of the temperature with the rate of $\gamma$ (The heat recovery process is shown in chapter 2). Inflow is assumed to be only from reinjection and not rainwater – rainwater may reduce the rate of recovery. It is also assumed that firms chose a fixed level of production and have to maintain this for the entire life of the plant.

The temperature of the extracted brine is assumed to be equal to the temperature of the reservoir. The reservoir’s temperature at any time depends on the temperature of the previous period, the temperature of the reinjected brine and the time the reinjected brine took to reach the main reservoir area. It follows the physical rule of mixing liquids with different temperatures (Golabi & Scherer, 1981).

3.4. Application

Multiple ownership of the land over which the geothermal reservoir is located on is a characteristic of the New Zealand geothermal system. Rotokawa II (Nga Awa Purua), located in the central North Island of New Zealand, is an example of a geothermal system with fragmented land ownership (Bouche, 2007). The Rotokawa reservoir is located at depths of 950m and below. It is a high-temperature geothermal field with typical chloride water at 320-330°C at depths below 1500m. The reservoir is fed by an up-flow at depth from the south of the field near Lake Rotokawa. The reservoir has a proven area of 3.3 km² and probably of 6.5km². The reservoir fluid is neutral alkali chloride water typical of high temperature fields in the Taupo Volcanic Zone (Grant, 2007). The capital cost of the project was $430 million and operating costs are estimated to be around $16.5 million per year.
(Grant, 2007; Reeve, 2007). Figure 3.3 shows the land ownership with access to Rotokawa reservoir. The dotted area shows the reservoir’s boundary. There are ten land parcels with access to this reservoir.
Figure 3.3. Rotokawa geothermal field (MRP, 2007; Reeve, 2007)
Using this example, a case study analyses the effect of geothermal development on temperature and economic benefits when there is a unitisation agreement in place, and compares this to the situation when multiple developers with limited surface access operate on a reservoir. It is assumed that existing information allows for a power plant with a total capacity of 280 MWe that can operate for 35 years when reinjected brine takes one year to reach the production wells. Two pieces of land, x and y, are assumed to be owned by two firms A and B respectively. The area of x is larger than y. The two firms are assumed to have the capacity and knowledge to develop the field themselves or the ability to hire contractors to do it for them. Therefore, there are no financial restrictions and the technology and cost functions are assumed to be identical for the two developers. Firms have to reinject within the boundaries of the geothermal resource where they have access. Therefore, firm B has to reinject the brine closer to the production well. The lag period is assumed to be shorter for firm B with the smaller piece of land.

Three cases are considered. In case one, a unitisation agreement allows both firms to reinject far away from the extraction wells \((d_A=d_B=3)\). This requires the firms to have access to each others’ land to find the optimal reinjection location. In cases two and three, firms operate independently and there is no agreement in place. Therefore, firms have to reinject within their boundaries. Case two assumes that firm A, with access to a larger land area, will reinject far from the extraction wells, and firm B will reinject closer to the extraction wells based on their limited access to the surface of the reservoir \((d_A=3 \text{ and } d_B=1)\). Further reinjection requires higher investment and maintenance costs. There could be an incentive for both firms to reinject closer if it leads to higher individual profit. Case three analyses the outcome of a situation when both firms reinject close to the extraction wells \((d_A=1 \text{ and } d_B=1)\).

Firms will fully utilise the resource to maximise their profit. Both firms are price takers and have to accept the average electricity price offered by the market. This is true for the geothermal power companies in New Zealand as they offer their generated electricity for around $0 to the New Zealand wholesale auction and
accept the equilibrium price that comes from the auction. New Zealand’s wholesale electricity price is on average around $60-70/MW. The electricity price for this work is set at NZ$60/MW and is assumed to increase by 3% per year, in nominal terms (MED/MT, 2011). Historical data show that the electricity price has been increasing at a rate higher than or equal to the inflation rate. According to the New Zealand Treasury information the discount rate for infrastructure is set to 8% per annum (NZ-Treasury, 2008).

The cost of wells and the initial stages of testing are embedded into the total capital cost. There is no new technological progress and the operating costs are assumed to increase by the rate of inflation during the life of the plant. The level of production is limited to the available technology and installed plant.

Data related to the production function and the characteristics of the reservoir are from Rotokawa II (Nga Awa Purua). Nga Awa Purua is a 140 MW project that uses 16,425,000 tonnes of geothermal fluid per year (average extraction rate of 45,000 to 50,000 tonnes per day) to generate 1,200 GWh of electricity per year (Bouche, 2007). Extraction is limited to the mentioned yearly geothermal fluid. Considering the total yearly production, geothermal fluid extraction per year, and the temperature of the fluid, the conversion factor, $\alpha$, can be found to be around 0.00023 (16,425,000 tonnes $\times$ 320°C $\times$ 0.00023 = 1,200 GWh). The temperature of the extracted brine is assumed to be 320°C at the start of extraction. It is also assumed that the reservoir temperature will increase at a rate of 1% per year, and the returning brine’s temperature will increase by 10%. The temperature of the reinjected brine will increase as it moves through the hot rocks to reach the main part of the reservoir and the extraction wells. The rate of increase in the temperature of the colder reinjected brine is higher than the rate of increase in the temperature of the main reservoir. It is shown that the rate of recovery is faster when the temperature is further from the original equilibrium (Bromley et al., 2006; O’Sullivan et al., 2010; Rybach, 2003).
3.5. Findings and discussion

The New Zealand system allows multiple firms to develop a geothermal resource for electricity generation, under certain conditions. In the suggested model it is assumed that at time zero both firms A and B, operating on land x and y with access to a geothermal resource will start geothermal power plants on their own land. In case one, firms A and B share the land and have access to the entire reservoir and can reinject on each other’s land. They can build a total of 280 MW of electricity plant, 140 MW each. The result from case one shows that temperature drops to 170°C after 35 years of operation. The total net present value of the operation is around $490 million. In case two, where firms have to reinject within their boundaries, firm B reinjects closer and firm A reinjects further away from the extraction wells. The temperature drops to 161°C after 35 years of operation. This shows around 9% lower temperature at the end of operation in comparison to case one when the two firms are able to cooperate to optimise the reinjection. The net present value of the total profit gained by the two firms for case two is around $484 million, which is lower than the total profit gained in case one. Case three analyses the possibility of both firms reinjecting closer to the extraction wells, mainly to reduce the capital and maintenance cost of having longer pipes and related machineries. The results show a lower temperature than either of the other two cases and also lower total net present value of profit. Table 3.1 shows the results.
Figure 3.4 shows the temperature level during the operation life of 35 years. The graph shows a later breakthrough point when there is an agreement between the operators \((d_A=3 \text{ and } d_B=3)\), in comparison to the case two and three with no agreement. In the absence of access to the optimal reinjection point, reinjected brine takes a shorter time to reach the production/extraction wells and consequently the temperature drops at a faster rate. The curve is flatter when it is closer to the final years of the project. This is the consequence of the limitation imposed on the developers to reinject at no less than a certain temperature, around 120°C, and the electricity generation constraint that requires the brine temperature to be at least 150°C.
In an ideal scenario, the most efficient way of developing this geothermal resource is to select case one, which maximises the net present value of the total profit. However, it is not always straightforward to reach agreement. Given the current New Zealand system that allows for multiple access, cases two and three are possibilities. Firms have to consider other right holders' plans before investing. The higher total net present value of profit in case two compared to case three does not translate to higher net present value of profits for both firms. Table 3.2 shows the net present value of the profit made by each firm in different scenarios.

Figure 3.4. Temperature change across 35 years of production by two firms
### Table 3.2. Net present value of the profit for each firm with different reinjection strategies

<table>
<thead>
<tr>
<th>Firm B</th>
<th>Firm A</th>
<th>d=1</th>
<th>d=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 3</td>
<td>A: $233m ✓</td>
<td>Case 2</td>
<td>A: $219m</td>
</tr>
<tr>
<td></td>
<td>B: $233m ❌</td>
<td></td>
<td>B: $264m ❌</td>
</tr>
<tr>
<td></td>
<td>Total: $466m</td>
<td></td>
<td>Total: $483m</td>
</tr>
<tr>
<td>d=3</td>
<td>Not applicable</td>
<td>Case 1</td>
<td>A: $245m ✓</td>
</tr>
<tr>
<td></td>
<td>Firm B doesn’t have enough land</td>
<td></td>
<td>B: $245m</td>
</tr>
<tr>
<td></td>
<td>Total: $490m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In case one, with a higher total NPV, firms are assumed to receive a half share of NZ$490 million. However, if the firms do not agree with the terms of the agreement then firm B has to reinject a shorter distance from the production well, due to their land restriction. Therefore, total profit drops to NZ$483 million. The cold reinjected brine reduces the productivity of the reservoir. Firm A’s higher capital and maintenance cost lower its profit in comparison to firm B. Further investigation shows that a move by firm A to reinject at a shorter distance increases its profit. Therefore, firm A is better off to reinject closer if the other firm is doing so. ($d_A=3$ and $d_B=1$.)

Despite the tangible financial benefits of an agreement between the operating firms, achieving agreement is not straightforward. Considerations include distribution of wealth, and firms’ understanding about their position in the market. A non-cooperative game will be created when firms make strategic decisions. Each firm
has to take into account the decisions that others might make when planning for their investment. Table 3.2 shows the possible outcome of the game. In this situation firm A can choose from a reinjection plan that takes brine three years \((d_A=3)\) to reach the production well or a plan that takes one year \((d_A=1)\). Firm B has similar choices. However, firm B cannot reinject further, with three years’ lag, without cooperating with firm A, because of lack of access to the land. The entries in the matrix denote the firms’ payoff as a result of their decisions. In this game if firm B chooses \(d_B=1\) then it is better for firm A to choose \(d_A=1\) (to make $233 million profit in comparison to $219 million profit if it chooses \(d_A=3\)), and if firm B chooses \(d_B=3\) and agrees to cooperate, then it is best for firm A to choose \(d_A=3\).

What will firm B do? The table shows that firm B’s best choice is independent of the choice made by firm A. If firm A chooses \(d_A=1\) then it is better for firm B to choose \(d_B=1\), and if firm A chooses \(d_A=3\), then it is best for firm B to choose \(d_B=1\), to make $264 million profit in comparison to $245 million profit (if it chose \(d_B=3\) and agreed to cooperate). Therefore, firm B’s dominant strategy is to choose \(d_B=1\) regardless of what firm A does.

Firm B has incentive to not accept an agreement, as it can generate higher profit regardless of firm A’s decision. Firms may also consider other benefits such as employment, improved competitive advantage through skills gained, and potential for new opportunities from the heat extracted, such as horticulture.

Both firms are assumed to be rational, act in their own self-interest and be fully aware of regularities in the behaviour of others. Therefore, a Nash equilibrium is reached when both firms are worse off by not signing a cooperation agreement. “In Nash equilibrium, every agent must be doing the very best he or she can, given the actions of all other agents. It is easy to see that when all agents have reached such a point, none has any incentive to change unilaterally what he or she is doing, so the situation is sensibly viewed as an equilibrium” (Jehle & Reny, 2001, p. 160). The
total profit gained is higher but at least one firm’s individual profit is lower when they sign an agreement to optimise the total operation.

The findings also show that the temperature drops at a faster rate in the multiple ownership system in comparison to unitisation. The higher temperature-drop rate means faster depletion of the reservoir, which leads to inefficiency, and unproductivity of the resource after 35 years. The results show lower total net present value of the profit from the multiple access development in comparison to the unitisation model. This will eventually mean a lower current return from the resource and also less value for future generations. The results raise concerns about multiple access geothermal developments. They show that individual landowners’ rights to access the geothermal resource may work against the sustainability of the reservoir and the total net present value of profit that may be obtained from development of the resource.

3.6. Conclusion

Well-defined property rights enable rights holders to realise the full economic value of their resources. Ownership of a resource is about the level of control over the bundle of rights attached to it. These rights include the right to exclude others, exclusivity, securing the period of use, duration, quality of title and transferability. Government rules and regulations impact the quality of the bundle of rights attached to the resource that, in turn, impact on the value of the resource. Given the significant cost of constructing a geothermal power plant, investors will require secure and, ideally, excludable rights. Regulation on how and when to develop a geothermal resource can have a significant impact on the life of the reservoir and the profitability of geothermal development.
Geothermal resources are migratory and therefore exclusivity may play a vital role when developing a resource that is accessible by multiple parties. The New Zealand system allows for multiple operators to develop power plants on a geothermal reservoir. It was shown in chapter two that lack of certainty and exclusivity reduces the incentive for longer-term investment when developing a geothermal resource. This chapter analyses the economic return and the impact on the reservoir when multiple firms compete to develop a geothermal resource, in comparison to a unitisation model. An optimisation model is used to estimate the consequences of restricted access and the final outcome.

Although geothermal resources are often described as renewable, renewability depends on the size and timing of the exploitation, the distance between the production and reinjection wells, and the heat recovery factor. Extraction rates that are higher than the recovery rates will drive the temperature and pressure down and deplete the resource. Therefore, successful geothermal system management controls the energy extracted to maximise net benefits.

The literature around reinjection and its impact on the sustainability of a resource is reviewed in this chapter. While reinjection affects the temperature and life of the reservoir, the literature shows that in most cases, reinjection is essential to control the pressure and extend the life of the reservoir. It is demonstrated that multiple access to a geothermal resource in a fragmented land ownership system may lead to reinjection closer to the production wells due to lack of availability of space. Therefore, a breakthrough may occur earlier than if reinjection is undertaken further away from the production wells.

Using the previous studies and mathematical modelling around geothermal development, a production model was developed to study the outcome of a 280 MW development with a unitisation arrangement and access to the entire reservoir, in comparison to a similar development shared by two owners with partial access to
the reservoir. Data from the Rotokawa reservoir in New Zealand was used in the optimisation model.

The study demonstrates that a non-cooperative game is created when firms make their strategic decisions. The dominant strategy for the firm with limited access being to not accept the unitisation deal. Both firms are shown to reinject closer to the production wells to maximise their own net present value of profit in a non-cooperative situation, which leads to faster temperature drop. Each firm will also make less net present value of profit than if they agreed on unitisation. The results also show lower total net present value of profit from the multiple access development, in comparison to the unitisation model. This will eventually mean lower current returns from the resource and less value for future generations.

In a fragmented land ownership system with multiple access to a resource, lack of available space for reinjection may lead to faster depletion of the resource and lower profit. Therefore, careful consideration is required when determining the access policy for geothermal development in a fragmented land ownership system.
Chapter 4

An economic analysis of royalties:

Application to geothermal development
Chapter 4

An economic analysis of royalties: application to geothermal development

4.1. Introduction and background

Geothermal generators are a base-load supplier to the New Zealand electricity market and have greater advantages over other renewable resources, such as wind, hydro and solar power. They can contribute towards security and reliability of supply and consequently to economic growth. Although geothermal resources are usually considered renewable sources of electricity, the degree of renewability depends on the extraction and heat regeneration rate. A high rate of extraction can speed the depleting process and reduce the productivity of the geothermal resource.

Sustainable development of renewable resources is aimed at meeting the needs of the current generation while providing for future generations. Fairness, equity and distribution through a timeframe that includes future generations are to be considered when making decisions on the use and development of natural resources. Fairness is about how we treat future generations’ endowment, including determining how much of the natural resources the current generation should leave for future generations, and how efficiently the current generation should use the natural resources. Efficient use of the resource is about doing the best you can with what you have – your endowment of energy resources (Fisher & Rothkopf, 1989). Any development should take place within sustainable boundaries if a goal is to leave future generations a share of the resource. “The sustainable criterion suggests that, at a minimum, future generations should be left no worse off than current
generations” (Tietenberg, 2006, p. 94). According to this definition, any allocation that leaves less for future generations is unfair.

Under certain conditions, competitive markets may lead to efficient allocation of resources. However, the market simply fails when those conditions are not met. Market failure in taking care of scarce natural resources may be corrected by imposing quantity restrictions, taxation or the use of other economic instruments (Bhattacharyya, 2011). In some situations, government intervention may lead to a more efficient outcome in a failed market. “Regulation directly limits the influence of private owners on resource allocation; wealth redistribution indirectly does the same” (Demsetz, 2002, p. S669). Economic policy can stop firms generating excessive profit from using freely available natural resources. Therefore, appropriately designed public policy can contribute towards sustainable development.

Similar to market failure, government failure can reduce incentives for better practice. “Government is an important player in the mineral extraction industries, through property rights creation and management, licensing and royalties, [state owned enterprises], tax expenditures, and environmental regulation” (Sharp & Huang, 2011). Government rules and regulations may reduce or remove some resource owners’ rights. For instance, land use regulations may restrict owners’ rights to use their property how they choose. Meanwhile, well-defined property rights are necessary to encourage economic activity. Therefore, selected policies should be in place to balance the costs and benefits of sustainable development. Efficiency in production and allocation of natural resources, competitive markets, market failure, and remedies are the four key areas to be considered by government when developing natural resource policy (Fisher & Rothkopf, 1989). Market allocation can be efficient under certain conditions but it is “presumably the notion of market failure that spurs political demands for government efforts to promote conservation” (Fisher & Rothkopf, 1989). Corrective actions or remedies are
inevitable when the market fails to address resource allocation (pricing) and environmental issues (externalities).

Various policies have been set to influence and control the behaviour and activities of resource firms when developing a natural resource. Most of these policies are designed to influence firms’ behaviour and limit their activities to within certain boundaries. Effective utilisation of resources can be achieved by using knowledge to find the relationship between social institutions and resource depletion. Economic tools can be used to predict the behaviour of producers and consumers in a market situation. Social and economic tools can prevent social interference with social objectives while utilising resources. Identifying optimal outcomes and uncovering behavioural problems may assist in designing suitable policies.

About 60 years’ experience in geothermal development for electricity production shows that geothermal resources are not sustainable if extracted rapidly. Unfortunately, literature around the sustainability of geothermal resources is limited. The availability of geothermal resources and demand for clean energy has led to rapid growth in utilising geothermal resources, while little attention has been paid to contemporaneous and inter-temporal externalities, except where there is a direct impact on current production. Carbon trading and similar schemes are now being introduced around the world, making renewable energies such as geothermal more competitive. As the demand for renewable sources of energy increases, it is timely to consider policies that contribute to geothermal energy being available over a relatively long period.

Environmental taxes can be used as a depletion charge to encourage wiser planning and use and development of more efficient technologies. Although taxes and royalties are used in different countries to charge for externalities and deduct a governmental share from the profit/revenue derived from natural resource developments, there is no evidence of geothermal royalties or taxes being used to control the depletion rate of geothermal resources.
Chapter 2 demonstrated that a longer-term plan is more economically beneficial when developing geothermal resources. However, with insecurity of return and in the absence of exclusive rights with guaranteed duration, firms have less incentive to choose longer-term plans. Shorter-term operations reduce the net present value of the profit gained from the geothermal development.

This chapter examines a range of economic instruments that can contribute towards lowering the depletion rate of geothermal resource while allowing the firm to operate at a profitable level. First, it reviews the issues around sustainability of geothermal resources and the economic efficiency of developments. It then investigates different forms of royalties that can be applied to geothermal developments for electricity generation. Third, it analyses the costs and benefits of royalties and reviews the application of royalties in different countries. An economic model is introduced in sections 4.3 and 4.4 to test a firm’s reaction to royalty charges and the impact on resource utilisation. This model is used to analyse and compare the impact of different royalty approaches on the firm’s behaviour and investigates whether selected methods can contribute towards longer-term planning when developing geothermal resources. Finally, in section 4.5, a variable royalty rate as the ratio of the current temperature to the original temperature of the reservoir is implemented to analyse the impact of such a royalty on the depletion of geothermal resources.

4.2. Literature

4.2.1. Sustainability and economic growth

“We have not been following Mother Nature’s system and it is unclear just how much longer we will be able to flaunt her authority” (Kesler, 1994, p. 116). The
consumption of natural resources has rapidly increased in the last few decades, perhaps leaving only low quality resources for future generations. As natural resources become scarcer, it becomes more important to establish policies that provide citizens with a clean environment, governments with a fair share of profits, investors with a reasonable return, and a guarantee of future use of resources (Kesler, 1994).

Hartwick-Solow defined sustainability as an approach that maintains constant real consumption over an indefinite period of time under certain constraints imposed by the scarcity of resources (Hussen, 2004; Tietenberg, 2006). Hartwick’s Rule expects the principle to remain unchanged over a period of time in order to be called sustainable. In 1987, the United Nations World Commission on Environment and Development (UNWCED) prepared a report on sustainable development. The report was the first major international effort of its kind. However, it did not cover many of the environmental issues. In 1992, the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro produced an international agreement setting out a “plan of action for the future, which took into account a wide range of economic, social, and environmental issues” (Luketina, 2011). According to the UNWCED report (1987), sustainable development is a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

To provide for a sustainable approach, the exploitation of resources, direction of investments, orientation of technological development, and institutional changes should take the needs of future generations into consideration while planning for current development. It may be argued that, with the discovery of new resources and access to better technologies, future generations will be better off regardless of what current generations leave for them (Luketina, 2010). However, the timing of new technologies and resource recovery is unclear and introduction of policies that encourage research and development towards achieving those goals may be of value. The weight placed on valuing the resources is found through the discount
rates adopted by society, although the value that will be accepted by future generations is currently unknown. An important question to answer is how much the current generation should value its natural resources.

In economics, the environment is a valuable asset that provides a variety of services. The value of those services become increasingly apparent when resources become scarce. Similar to any other asset, “...we wish to prevent undue depreciation of the value of this asset so that it may continue to provide aesthetic and life-sustaining services” (Tietenberg, 2006, pp. 14, 15). Therefore, it is necessary to optimise economic gain from natural resources. The total economic value of an environmental resource may include the use, non-use, and option value of the resource. Use and non-use values are about current opportunities to generate jobs, wealth, and income, and willingness to improve or preserve the resource at the status quo, respectively. Option value is the current generation’s willingness to preserve the resource for future opportunities.

Cost-benefit analysis aims to find the optimal level of harvest/utilisation. Normative analysis requires first finding the optimal outcome or harvesting level; secondly, uncovering the behavioural sources of the problem; and third, using knowledge and information to design an appropriate policy. Static efficiency criteria are met when the net benefits are maximised by achieving marginal benefits higher than or equal to the marginal cost. Static efficiency is useful when marginal costs and benefits occur at the same time. Meanwhile, dynamic efficiency is used when the benefits and costs occur in different time periods, when tomorrow's usage depends on today's use. Dynamic efficiency is used to find the net present value of the costs and benefits of alternative strategies (Tietenberg, 2006).

Economic analysis should show that the present value of the net benefits are maximised to justify a given policy. Development may benefit society by creating jobs, wealth for owners, and goods for consumers. Conversely, it may add to social costs by degrading the ecosystem, changing wildlife habitat and recreational
opportunities, and impacting on possible future income and employment opportunities.

In an intergenerational model the allocation of resources depends heavily on the discount rate, which is adopted by present rights holders. Based on the sustainability definition given earlier, to be fair, future generations should not be any worse off than the current generation. The objective therefore is to find an optimal level of harvest/utilisation that maximises the net present value of net benefits. There are a number of complex questions to be answered before an optimal level is found. The questions are:

- How long should the resource last for?
- How much of the existing resources should be left for future generations?
- Will future generations require geothermal resources preserved at their current status?
- Will other resources be available for electricity production?

A geothermal system is a combination of a heat source, a reservoir and a fluid that transfers the heat (Dickson & Fanelli, 2004). Geothermal resources with temperatures higher than 150°C can be used for large commercial electricity generation. Geothermal resources are different from oil because the resource is “continually being replenished by an ongoing flow of heat from depth by conduction or by convection of water. Experience in geothermal systems such as Wairakei-Tauhara and Nesjavellir has demonstrated that in favourable situations recharge can extend the productive life of the resource” (Clotworthy et al., 2010).

Geothermal development may contribute towards the adequacy and security of electricity supply, which eventually leads to higher economic growth. However, economic growth should not occur at the expense of environmental damage, particularly when the marginal social cost is higher than the marginal social benefit (Philips, 2010). Geothermal developments can affect the resource in several ways.
including but not limited to: cooling of the reservoir; subsidence; reduction of fluid resulting in changes to surface features and habitats; hydrothermal eruptions; interference with existing takes; and changes in the location of the heat and fluid. Discharge of geothermal fluid may lead to contamination of ground water, cooling of the geothermal reservoir, and change to habitats (Luketina, 2011).

“The challenge for managing renewable resources involves the maintenance of an efficient, sustainable flow” (Tietenberg, 2006, p. 133). Although a geothermal resource is a renewable and relatively clean source of energy, certain conditions have to be met to keep it sustainable. To enable long-term development, it is important to maintain the temperature and pressure of the reservoir into the future. In most cases, at low levels of exploitation of a geothermal field the energy resource can last indefinitely, and any associated natural features may not be noticeably affected, depending on proximity of wells to the features, e.g. geysers and springs. However, large-scale development effectively mines heat from the resource, and thereby the amount of heat available to the development and any natural features associated with the field decline over time. If all production is stopped, the energy resource should recover over a long period, but is likely to suffer some permanent changes (Boast, 1989).

Information about a reservoir is never perfect. Although initial information is gathered through exploratory drilling and testing, monitoring the real response to extraction will show the actual behaviour of the reservoir. Information collected includes, but is not limited to: “knowledge on the volume, geometry and boundary conditions of a reservoir; knowledge on the properties of the reservoir rocks, i.e. permeability, porosity, heat capacity and heat conductivity; [and] knowledge on the physical conditions in a reservoir, determined by the temperature and pressure distribution” (Axelsson, 2008). It may be years before the reservoir’s real behaviour is known (Axelsson, 2010). Therefore, a mechanism to slow the extraction process and scale will allow for better understanding of the reservoir’s behaviour. David Anderson, director of the Geothermal Resources Council in Sacramento, believes
that in geothermal development nothing should be taken for granted until everything about the reservoir is known (Kerr, 1991).

As mentioned earlier, the level of sustainability of a geothermal system, amongst other things, depends on the discount rate and the value right holders put on future generations’ preference. It is a complicated task to identify and enforce an optimal level of extraction that allows for an appropriate duration. Under limited production, a geothermal reservoir can be sustained for a long period of time (Bromley et al., 2006). However, “excessive production is often pursued, mainly for economic reasons, such as to obtain quick payback of investments, with reservoir depletion the result” (Rybach & Mongillo, 2006). Under excessive utilisation, geothermal energy and features cannot be maintained for a long period of time (Rybach, 2010; Rybach et al., 2000). Bromley et al. (2006) state that with appropriate management, a geothermal system can be utilised over a long term (~100 years), then retired for recovery. Although the recovery of temperature and pressure will follow, temperature recovery is always slower than the pressure recovery. The recovery is usually faster at the start and then slows down. It may take the resource an indefinite amount of time to reach the original state (Rybach, 2007). According to O’Sullivan and Mannington (2005) it may take Wairakei geothermal reservoir in New Zealand 300 years to recover to almost its pre-production state after 100 years of production. Time and size of production play a vital role in the sustainability of geothermal resources (Rybach, 2003; Rybach & Mongillo, 2006).

Geothermal development may be perceived as sustainable if it can maintain the geothermal features and productivity for 100 to 300 years (Axelsson et al., 2005). However, experience in some large developments such as The Geysers, Rotorua and Ohaaki show shorter commercial life of geothermal reservoirs as the result of overexploitation and shorter-term planning. The Geysers Geothermal Field, a field of steaming fumaroles located 115 kilometres north of San Francisco in California, was predicted to produce 3000 MW of electricity by 1990. However, development
stopped at around 2000 MW. Involved parties came to realise that the field underneath was running dry and steam pressure had reduced in the wells. The resource was overloaded and had depleted faster than expected, due to lack of sufficient water to produce steam. Generation went down to about half (Axelsson, 2010) and developers started to condense and reinject some of the used steam back into the ground to help the reservoir recover.

Rotorua in New Zealand is another example of excessive use of a geothermal resource in the 1970s and 1980s when geothermal heating systems were encouraged. Households accessed the geothermal resource under their properties for heating. Popularity of the scheme led to too much extraction from the reservoir by individuals and eventually the reservoir’s pressure dropped to a lower than acceptable level (O’Shaughnessy, 2000; Scott & Cody, 2000). The move led to subsidence and damaged some of the tourist attractions around the area.

Most geothermal developments in New Zealand extract more heat than the regeneration level. “However, where pressures have been reduced significantly by exploitation, as at Wairakei, in some cases the rate of replenishment from depth has increased several-fold to match the discharge rate” (NZGA, 2012).

Ohaaki is another case where excessive extraction led to lower productivity in a short period of time. The plant was commissioned in 1989 with a capacity of 114MW. However, field limitation led to production being reduced to as low as 30MW. Further investment, including drilling new wells, helped to increase the production level to 60MW but to date the original level has not been restored. There have also been significant environmental effects including subsidence leading to flooding (NZGA, 2012).

In general, regulations for energy utilisation are necessary to encourage conservative development while discouraging higher-risk investments (Demsetz, 2002). Sustainability of the resource may not be a priority for firms seeking to cover
their operating costs. Developers may not necessarily pay attention to the renewability and sustainability of a resource if the short-term return of the project is high (usually around 30 to 35 years) and linked to the life of the plant. Economic policy can be used to encourage longer-term planning when they lead to higher net present value of profit. In chapter 2 it was shown that the net present value of the profit is higher when the geothermal resource is utilised for 70 years in comparison to 35 years. However, it was shown in chapters 2 and 3 that due to lack of exclusivity and a guaranteed duration, investors may exhaust the resource in a shorter period and drive the temperature down to a non-commercially viable level. Therefore, in case of geothermal resources, one aim of policy should be to reduce the depletion rate.

4.2.2. Taxes and royalties

“Geothermal power comes close to being a ‘free lunch’, but does not make it” (Kesler, 1994, p. 159). In addition, there is no penalty for driving the temperature of the reservoir down, apart from lower future income for the firm. Therefore, future generations may have to pay a high price for the remaining poor quality resources, if there are any left. The question here is whether there is an economic tool that can encourage better and more sustainable use of resources. Voluntary approaches, regulatory instruments, and environmental taxes may be used as policy instruments to reduce the environmental damage. These instruments can also be used to stimulate innovation and investment in cleaner and more sustainable technology (Philips, 2010).

In theory, monopoly slows the depletion of scarce natural resources. Absence of competition may slow the extraction rate as firms can offer the same product at a
higher price, which, in turn, can encourage the sustainability of the resource. Despite the effect of demand, in general, exploitation is likely to take longer in a monopolistic situation than in a competitive market (Hotelling, 1931). Considering geothermal generators are base-load producers for the electricity market, higher demand may lead to a higher extraction rate of geothermal resources. In New Zealand, electricity produced from the geothermal resource receives a price equal to the market equilibrium price. In this sense, geothermal plants have no control over price and work as price takers. Therefore, monopoly is not relevant in the New Zealand market.

Voluntary approaches can be another way to encourage sustainable development. However, voluntary approaches are uncommon unless they contribute towards long-term profitability. Voluntary approaches to reducing externalities are only possible if there are strong economic incentives and rewards. They are demand driven (Brau & Carraro, 2006), and generally linked to consumers’ information and awareness. In the case of geothermal resources, consumers commonly see the resource as being renewable. The complexity around the renewability of geothermal resources makes it difficult, although not impossible, to rely on voluntary approaches by firms.

Use of regulatory instruments is another way to control the development of natural resources. Well-established institutional arrangements can contribute towards efficient use of resources. However, regulations rely on the information available. In case of geothermal information is often incomplete and in some cases inaccessible. Most developments require ongoing planning and changes in order to meet the sustainability criteria. In addition, resource characteristics vary for different geothermal fields. Therefore, setting boundaries to control geothermal development may not necessarily lead to the most efficient outcome. A policy that reacts to the outcome of developers’ actions may be more effective in managing the development of a geothermal resource.
Although government regulation, such as quotas, may limit the use of the resource to ensure sustainability, per-harvest/effort royalties can be used to capture the external cost of the activity (Falk, 1991). Environmental taxes, subsidies and/or emission-trading schemes are some economic instruments for reducing environmental damage (Milne et al., 2003). Economic instruments associated with environmental management can take two forms: punitive tax or penalties, and incentive rewards (O'Shaughnessy, 2000). The tax system is one of many social institutions that can impact resource depletion. Taxation is used to internalise the contemporaneous and/or inter-temporal externalities, i.e. pollution or depletion, and increase the price to encourage better technologies and the use of substitutes when available. Carbon tax is an obvious example in the literature where taxes are used to reduce the emissions produced as the result of human activities. Absence of real market price for natural resources may lead to overdevelopment and overexploitation of the resource, especially when access is not restricted. “The real problem with water resources, for example, is that they are over-allocated because they are not priced” (Sharp, 2012).

Economic instruments create price signals for firms and consumers. These are aimed at internalising the contemporaneous and inter-temporal externalities to include the real cost in the production model based on the scarcity of the resource and the environmental damage. “This approach allows firms and individuals greater flexibility in their energy and environmental decisions, reducing cost to the economic system” (Migliavacca, 2006, pp. 269, 270). In theory, an appropriate tax on suppliers shifts the supply curve up to the social cost level. It is necessary to impose a tax when suppliers are not ready to voluntarily consider the external costs of production. The impact of the tax on market price depends on suppliers’ market power and the elasticity of the supply and demand curve. In some situations, suppliers are able to pass the extra cost to consumers and therefore there will be no change in their behaviour. The tax system is economically effective if it forces suppliers to find more efficient ways to develop resources or find substitutes, and encourages consumers to take more efficient approach.
The inclusion of external costs encourages investment to happen at the right time and when it is required (Golabi & Scherer, 1981). For instance, in 1987, the introduction of a royalty payment and voluntary ceasing of wells for those who did not want to continue using the geothermal resource helped to reduce the geothermal extraction from Rotorua geothermal field, and eventually resulted in signs of recovery for the reservoir (Scott & Cody, 2000). Royalty is a unique form of taxation applied to natural resources and intellectual property. The Rotorua royalty regime was based on a fixed charge on the amount of extracted brine and aimed to reduce the domestic use of geothermal fluid and encourage reinjection. Although many opposed the move, it eventually led to fluid pressure recovery and enhancement of the natural features of the resource, including surface springs and geysers (O'Shaughnessy, 2000).

As this example relates to residential access to and use of geothermal resources, it is important to analyse the effectiveness of such royalty or tax on the commercial use of geothermal resources in New Zealand. To analyse the effectiveness of the tax/royalty, it is necessary to check suppliers’ ability to pass the tax/royalty cost to consumers – market power. New Zealand’s electricity market has an auction system where suppliers submit the price and quantity of the electricity supplied 24 hours before the auction. The market price will be equal to the equilibrium price at auction. Electricity suppliers with renewable sources usually submit a zero price, expecting the conventional electricity generators to submit a price higher than or equal to their marginal cost, eventually leading to a positive market price, as shown in figure 4.1.
Figure 4.1. Wholesale electricity supply and demand – example from New Zealand

Figure 4.1 illustrates the demand, D, and supply curve, S, for New Zealand’s wholesale electricity market. The X-axis shows the quantity of electricity and the Y-axis shows the price. The New Zealand electricity demand curve is inelastic and shifts during peak and off-peak times (Evans & Meade, 2005). $P_e$ stands for the market equilibrium price. Renewable generators, e.g. geothermal, create the left side of the supply curve ($S_1$). Renewable generators, with lower variable cost, usually bid at a lower price than conventional fuel generators. The market price is the intersection of the supply and demand curve. Based on the current New Zealand demand and supply, the market price is indeed the intersection of the conventional fuel generators’ supply curve and the demand curve. All generators receive the same market price, $P_e$, regardless of their bid.

Adding royalties to geothermal generators may lift the left side of the supply curve up to $S_2$. However, as illustrated, the short-term equilibrium price remains unchanged. The wholesale electricity price depends on the offers received from the
conventional fuel generators and the demand at any particular time (Evans & Meade, 2005). Hence, geothermal generators are price takers and have little power to pass the royalty cost to the consumers in the short term.

### 4.2.3. Royalty options

“Royalty is an owner’s claim to net resource value” (Bradley & Watkins, 1987). It enables owners to attach a price to the available resource (Lund, 2009). Royalties are usage-based payments made by developers to rights holders for the right to ongoing use of an asset (Bradley & Watkins, 1987; Otto et al., 2006). Therefore, identification of the rights holders and the licensee is essential. The application of royalties is more complex if resource ownership is not clear. Geothermal development in New Zealand was first regulated through the Geothermal Energy Act 1953 and the Geothermal Energy Regulations 1961. Section 3(1) of the Act states that “…the sole right to tap, take, use and apply geothermal energy on or under the land shall vest in the Crown, whether the land has been alienated from the Crown or not” ("Geothermal Energy Act 1953," 1953). Maori rights were recognised by including cooking, heating, washing and bathing, which were the main uses of geothermal resources by Maori at the time of the legislation. Section 354 of the Resource Management Act 1991 (RMA) states that those resources vested by the Crown before the RMA came into force will remain under Crown ownership (RMA, 1991). This includes rights allocated through the Geothermal Energy Act 1953. Most of the currently known New Zealand geothermal resources were identified between 1953 and 1991 and therefore it may be concluded that the Crown owns all those existing geothermal resources. Regardless of the ownership of the geothermal resources the RMA has provision to allow central government to set resource rent or royalties. This is stated at section 360, ‘Regulations’, as:
(1) The Governor-General may from time to time, by Order in Council, make regulations for all or any of the following purposes:

(c) Prescribing the amount, methods for calculating the amount, and circumstances and manner if which holders of resource consents are liable to pay for: ... (iv) the use of geothermal energy... (RMA, 1991)

Royalties may help to correct the market by imposing a cost to increase the price in order to cover the externalities (Fisher & Rothkopf, 1989; Sutherland, 1996). In the mining industry, royalties are “payment to the owner of the mineral resource in return for the removal of the minerals from the land. The royalty, as the instrument for compensation, is payment in return for the permission that, first, gives the mining company access to the minerals and secondly, gives the company the right to develop the resource for its own benefit.” (Otto et al., 2006, p. 41). It is a charge that the owner of the resource puts on the value lost from the resource. While geothermal resources are generally considered to be renewable, they deplete, and the quality of the resource goes down, when a large commercial power plant operates on the reservoir. Therefore, geothermal is similar to the mining industry when the loss of value and reduction in productivity is considered.

There are different ways of approaching a royalty assessment. Depending on the type of royalty selected, there will be a different impact on both the licensee and the investors. Appendices C and D shows different type of taxes levied on the mining industry, their basis, objectives of tax types, and their prevalence. Next section examines two main categories, ‘in rem taxes’ and ‘in personam taxes’ (Otto et al., 2006).
In rem taxes

‘In rem tax’ is a form of tax applied to production without considering the cost of operation or investment. It can be in the form of a unit-based royalty, ad valorem royalty (AVR), sales and excise tax (e.g. goods and services tax in New Zealand), property or capital tax, import duty, export duty, withholding on remitted loan interest, withholding on imported services, value-added tax, registration fees, rent or usage fees, or stamp tax. The first two forms discussed here are the types of royalties that can be applied to geothermal resources.

A unit-based royalty is a fee applied to units of production. It is linked to the operation size and the amount of extracted natural resource. Fixed-fee unit royalties remove the government’s opportunity for higher income if the value of the resource increases. However, adding options for review and increase in accordance with the official inflation rate (consumer price index – CPI) may address this. Simple administration, lower volatility, and assurance for an income stream are the biggest advantages of unit royalties (O'Faircheallaigh, 1998).

The ad valorem royalty or resource rent royalty (RRR) is a levy on net cash flow. It considers the revenue gained from using the resource. Ad valorem royalties must be paid regardless of the profitability of the operation (Kesler, 1994) and can be in the form of reserve tax or severance tax. Reserve tax is a levy on the physical property or the percentage of the value of the property. Proponents of reserve tax believe it is an extension to property tax concepts. Opponents believe that the mineral has no value before being extracted and the actual value of the resource is only realised when it is extracted and offered to the market.

Ad valorem severance tax is a charge on the units of production, based on the market price. This tax is usually around one-eighth of the production value in the oil
and gas industry (Kesler, 1994). Hotelling (1931) argues that “such a tax, of so much per unit of material extracted from the mine, tends to conservation” and postpones exhaustion of the resource. Ad valorem severance tax will be considered as the main way of applying ad valorem royalties in this study. The unit of production will be the MWh electricity generated and sold at the wholesale market price. This in turn shows the amount of extracted brine and heat, as both have positive impacts on electricity generation in a geothermal power plant.

Ad valorem royalties do not take exploration, development, and operating costs into consideration (Bradley & Watkins, 1987). The developer is the only party that carries the exploration and/or development risk if the royalty is calculated directly on the revenue generated. One way of encouraging investment is to not charge royalties until the entire invested capital for exploration and/or development is recovered (Bradley & Watkins, 1987).

In personam taxes

Income tax, or accounting profits royalty (APR), is another way of charging for the use of natural resources. APR is calculated as a percentage of operating profit. It can have a sliding scale such that the percentage of tax increases as profit increases (Kesler, 1994). Charges on profit will capture the exploration and running cost of the project and create an incentive for investors who only have to pay tax when they make positive profit.

However, depending on the market, APR may not necessarily lead to a higher market price, and the resource will still be available for free. Literature also shows that profit tax has no effect if interest income is excluded (Burness, 1976). In
addition, the collected royalty will depend on the cyclical rise and fall in price of the final products. Royalties on profit may also encourage developers to shift their income to other entities with lower tax rates. Limited information makes the implementation process more complicated (Sutherland, 1996). Income-shifting refers to hidden actions that firms take to hide the cost side of the profit calculation when there is asymmetric information (Lund, 2009). Cost has many components and firms with multiple entities and units can shift the profit from one entity to another. For example, in geothermal development landowners involved in the development can apply a higher access fee to lower the operational profit of their electricity plant. Similarly, gen-tailors can shift the costs from retail business to their generation business in order to show a lower profit. Income transfer can be limited by accepting qualified costs to be included in the profit calculation.

Governments may have an incentive to generate more revenue by increasing the tax rate when the services provided by resource have higher price. “In British Columbia, the government responded [to the increase in price during the oil crisis] by levying extra taxes, in the form of royalties, that were retroactive to the start of 1974” (Kesler, 1994, p. 109). To allow for more tax on profit, the Canadian Federal Government did not allow firms to include provincial taxes and royalties in the calculation of federal tax. “This resulted in an extremely high tax burden, which essentially nullified profit in 1975.” (Kesler, 1994, p. 109). The availability of inexpensive energy resources is an obvious target for governments to generate revenue. It is important to realise that the purpose of tax on resources should not be to generate income for governments to balance their budgets. Therefore, careful consideration is required, when determining royalties, to incentivise investors whose contribution may generate significant national benefit.
Careful consideration is required when adding to the cost of geothermal development. The development and use of geothermal resources may have significant national and regional benefits such as employment, security of electricity supply, regional development, and rent income for landowners. Adding cost to the extraction of geothermal fluid will increase the running cost of geothermal plants. Higher operational costs may make geothermal developments uneconomic and drive generators out of the market, unless the average price of electricity increases at a higher rate than the increase in the operational cost of the geothermal generator. It is therefore important to allow for a reasonable profit to guarantee future investment. Therefore policies should encourage investment and support developers when required.

High charges on geothermal developments may reduce the incentive for investment and also challenge the employment and economic opportunities in rural areas. However, governments can put royalty revenue into relief funds to overcome such future problems. Alberta Heritage Fund is an example of such an arrangement, investing in businesses that will provide employment in the future when oil revenues are no longer there. Minnesota “allots 50% of its severance tax revenue to a fund for use in the northern part of the state where iron ore is produced, and other states use some of the revenues for environmental cleanup” (Kesler, 1994, p. 112).

To allow for expensive high-tech exploration research in areas with unknown resources, governments can provide support and encouragement agreements with those developers who are ready to take high risks. These are areas in which there has been no previous research conducted on the existence and quality of resources. In the North American system, royalty payments are usually lower for areas with a higher risk of exploration. Developers are granted access rights with a lower access
rate when they are prepared to take a higher risk during the exploration period (Bloomquist, 1986). Taxation must aim to reduce the level of less desirable activities while promoting the more desirable ones (Kesler, 1994). For example, an appropriately designed carbon tax can discourage pollution and encourage less polluting technologies.

‘Tax holiday’ and ‘earned depletion’ are other methods to encourage investment. A ‘tax holiday’ supports the development when there is a high level of unemployment or significant national need. “Prior to 1973, the Canadian federal tax code permitted a three-year tax-free production period for new mines. Unfortunately, this led to wasteful extraction practices such as high-grading, the removal of only the highest-grade ore, during the tax holiday in order to maximise profit. This made it harder to mine remaining low-grade ore and caused many mines to close prematurely” (Kesler, 1994, p. 111).

In the ‘earned depletion’ system, corporations were able to deduct four-thirds of exploration and other qualified expenditures. “Earned depletion was discontinued in Canada after 1989. The Canadian tax code retains a deduction of 25% of resource profits, which is very similar to percentage depletion as applied in the United States. Because of the importance of mineral production to the Canadian economy, other deductions have been allowed from time to time, including flow-through financing, in which individuals can deduct the cost of exploration ventures directly from current income” (Kesler, 1994, p. 111).

Governments can also offer relief packages when there is a significant national need to increase electricity production or encourage investment. It is important for the government to respond to forecasted demand well in advance and encourage investment when needed for the future. Indeed, investments should take place when aggregated social benefit is higher than aggregated social cost.
Royalties have been used internationally as a vehicle to generate income from natural resources. In New Zealand, geothermal resources are natural resources belonging to the nation and are regulated by the Crown and local government. Landowners have to obtain consent to develop geothermal resources located on their land. In the United States of America, the state has ownership of the geothermal resources in Alaska and the western states (Bloomquist, 1986). In the USA system, developers have to bid to access areas that have identified resources.

In New Zealand, “for mineral permits where production is valued at more than $100,000 per year there is a requirement to pay a royalty to the Government of either 1% of sales revenue (ad valorem royalty or AVR) or 5% of profits (accounting profit royalty or APR), whichever is the greater in any given year. Where revenues are less than $1 million per year, the APR royalty does not need to be paid as only the AVR royalty [is] applied” (Guerin, 2003, pp. 33 - footnote). Mining in New Zealand includes greenstone (pounamu), petroleum, gold, silver, coal, ironsand, aggregate, limestone, clay, dolomite, marble, pumice, salt, serpentinite, and zeolite, but not geothermal. New Zealand’s petroleum royalty is the maximum of either an ad valorem royalty of 5% applied to net revenue derived from sale, or 20% accounting profits royalty where profit is determined after allowing for direct and indirect costs (Sharp & Huang, 2011). In New Zealand, the government has never applied a royalty on the commercial use of geothermal resources. Landowners usually charge an access fee and rental for space used for geothermal plant and pipes. There is provision in the RMA to charge for royalties by local government but it has never been applied (RMA, 1991).

In the states of South and Western Australia the Crown owns the geothermal resources and royalties are 2.5% of the wellhead value. The minister assesses the
value at the wellhead geothermal, which can be taken from the market price of energy ("Petroleum and geothermal energy Act," 2000; "Petroleum and Geothermal Energy Resources Act," 1967). In Australia’s Northern Territory, the Crown owns the resource on behalf of the Territorians. The government can grant exclusive rights for exploration and extraction of geothermal energy. No decision has been made on the calculation of royalties ("Northern Territory proposal to introduce a geothermal energy bill," 2008).

In the North American system, royalties applied to the direct use of geothermal resources is calculated differently to royalties on electricity produced. In the case of electricity generation, royalties are based on the price of steam or electricity, while royalties on direct use are based on the value of the heat energy available. Heat value is determined by considering the cost of equivalent fuels (Bloomquist, 1986, 2003). In California, “Total federal geothermal royalties amounted to [US]$9.5 million in 2011” (U.S.D.I, 2012). In 2005, California changed its geothermal royalties calculation. Under the new system, geothermal royalties are now between 1% and 2.5% for the first 10 years of operation and between 2% and 5% after 10 years (Neron-Bancel, 2008). The lower royalty rate during the first 10 years of operation is intended to allow developers to recover some of their investment cost.

In Indonesia, geothermal operators are required to pay 2.5% of their royalties to the regulatory body. Twenty percent of the revenue gained from geothermal royalties goes to the central government and eighty percent to the local/regional government (Harsaputra, 2008).

In the Philippines, there is a 1.5% royalty tax based on the market value of the energy produced or utilised from geothermal operation. There is no charge if the development does not reach the production stage. Operators must report the quantity and value of the sale to the minister at the end of each month. “Under the law, contractor’s revenue may not exceed 40% of the net value from its geothermal operations. ... The 60% government royalty on revenue effectively makes
geothermal steam prices non-competitive with other alternative fuels” (Benito, 1998).

Analysis of the international experience shows that royalties are being used as a source of income for government from the resource owned by states. These royalties were never intended to reduce the depletion rate. The low royalties applied in different countries had little or no impact on the size and duration of development plans.

4.3. Economic model

Although royalties are being used as a source of income from geothermal resources in many countries, they have never been used as an economic instrument to control the depletion of resources on an ongoing basis. This section examines the effect of various royalty arrangements on the utilisation of geothermal resources. The inclusion of royalty charges in the price of geothermal fluid may lead to the establishment of a price which encourages longer-term planning and slows the depletion rate. An optimisation model is used to study a firm’s behaviour when royalties are used to control depletion. The model is used to review the options for creating a system that influences the utilisation rate and leads to:

- Planning for development of geothermal resources that can maintain temperature and therefore extend the expected life of the reservoir
- More efficient technologies that ensure the sustainability of the resource
- Compensation or user charges for damage done to the resource.
Ad valorem royalty (AVR) and accounting profits royalty (APR) are the two categories of royalties tested through the optimisation model. AVR as the ratio of the current temperature to the original temperature will be used in the final step to test the impact on the firm’s behaviour. It is assumed that there is only one firm with exclusive rights and access to the entire reservoir to develop the resource. The unit of production is the amount of electricity generated, MWh, and sold according to the New Zealand electricity market’s average wholesale price. The amount of electricity produced is directly linked to the amount of extracted brine and heat.

The characteristics of geothermal systems may vary significantly between different geothermal fields. Therefore, finding a production model that works for every individual resource may not be possible. However, all models share some general behaviour that can be used to develop a generic production model. The profit maximisation model developed in chapter 2 will be used to analyse a firm’s behaviour in response to different categories of royalties. The assumptions and information related to the data used are listed in appendices A and B, respectively. Firms are assumed to maximise the present value of profit such that the production constraints are met:

\[
\max q_t^e \sum_{t=1}^{T} \pi_t = \sum_{t}^{T} (\alpha P_t T_t^e - c) q_t^e \delta^t
\]

s.t.

\[
R_t \geq \sum_{d-k}^{T} q_t^{e,k}
\]

\[
T_t^e \geq 150^\circ C
\]

\[
q_t^e \geq 0
\]

Time = t = 1, 2, ... 35 (T) for a short term development
Constraint (4.2) requires the total extracted brine to be less than the total existing brine, $R_t$, at any time. Constraint (4.3) is the limit on the brine temperature that can be used by the generator to produce electricity. The brine temperature generally needs to be more than 150°C to enable a large geothermal electricity plant to operate. Constraint (4.4) sets the extraction at greater than or equal to zero. Adding the royalty as a percentage of profit to equation (4.5) changes it to:

$$\pi_t = (1 - r)(\alpha P_t T^e_t q^e_t - cq^e_t)\delta^t$$  \hspace{1cm} (4.5)$$

Equation (4.6) shows the situation when the royalty is based on the revenue gained from the development:

$$\pi_t = \left((1 - r)\alpha P_t T^e_t q^e_t - cq^e_t\right)\delta^t$$  \hspace{1cm} (4.6)$$

All the other assumptions remain as stated in chapter 2 and demonstrated in appendices A and B. The reinjected cold water is assumed to take three years (d=3) to reach the production wells. The temperature of the extracted brine is assumed to be equal to the temperature of the reservoir. The reservoir’s temperature at any time depends on the temperature at the previous period, the temperature of the reinjected brine and the time the reinjected brine took to reach the main reservoir area. It follows the physical rule of mixing liquids with different temperatures (Golabi & Scherer, 1981).
4.4. Application and results

It is assumed that the existing information allows for a 140 MW plant development that can successfully operate for 35 years. There is only one landowner and the developer has full access to the entire reservoir and can therefore select optimal locations for the extraction and reinjection wells. There is no financial restriction and the technology and cost functions are constant during the life of the plant. As mentioned earlier, an aim of this chapter is to find an economic instrument that encourages developers to come up with more efficient ways to use the resource. It is assumed that the firm do not have other investment options and is seeking a positive net return on investment. Therefore, firms will invest as long as there is scope for positive net present value of return on investment. Different ratios of royalties on revenue and profit will be examined to check the impact when the size and ratio of the royalties change.

Data related to the production function and characteristics of the reservoir are from the Rotokawa II (Nga Awa Purua) development located in the central North Island of New Zealand (Bouche, 2007). The Rotokawa reservoir is located at depths of 950m and below. It is a high-temperature geothermal field with typical chloride water at 320-330°C at depths below 1500m (MRP, 2007). The reservoir is fed by an up-flow at depth from the south of the field near Lake Rotokawa. The reservoir has a proven area of 3.3 km² and probably of 6.5km². The reservoir fluid is neutral alkali chloride water typical of high temperature fields in the Taupo Volcanic Zone in New Zealand (Grant, 2007). This project had $430 million of capital cost and the operating costs are estimated to be around $16.5 million per year (Grant, 2007; Reeve, 2007). Full information about the assumptions and the data is listed in appendices A and B.

At the outset an accounting profits royalty (APR) is applied to the firm’s profit maximisation model. APR works as a tax on the profit generated by the firm before
any other taxes are paid to the government. Different ratios of APR are applied but the outcome is unique. The results show that a higher APR does not lead to change in the firm’s investment and generation plan. It was assumed that firms did not have any other investment options and therefore were not influenced by the size of the net return (when positive). Therefore, as illustrated in table 4.1, the size of investment remains the same even with 99% APR while the net present value of the profit is positive. However, future investment may be affected, as a lower net profit leads to lower availability of future funds. Table 4.1 shows a summary of the findings when APR is applied.

<table>
<thead>
<tr>
<th>Royalty on profit</th>
<th>Brine extracted per year</th>
<th>Equivalent plant size</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Royalties</td>
<td>16,856,000 tonnes</td>
<td>~ 140 MW</td>
</tr>
<tr>
<td>10% Royalty</td>
<td>16,856,000 tonnes</td>
<td>~ 140 MW</td>
</tr>
<tr>
<td>99% Royalty</td>
<td>16,856,000 tonnes</td>
<td>~ 140 MW</td>
</tr>
</tbody>
</table>

Table 4.1. Investment decision - accounting profits royalties

An ad valorem royalty is levied on revenue generated by the firm regardless of investment and production costs. Revenue is calculated using the average market price. Different rates of royalties have been applied in order to analyse the differing outcomes. The results show the firm is sensitive to royalties on revenue and behave accordingly when making an investment and production plan. Three rates of 10%,
20%, and 30% ad valorem royalties were applied. The results demonstrate that the higher the royalty rate, the greater the impact on the size of the plant the firm plans to build. Table 4.2 shows the final results on the investment decision the firm makes and the temperature after 35 years of operation.

<table>
<thead>
<tr>
<th>Ad valorem royalty</th>
<th>Brine million tonnes/year</th>
<th>Plant size MW</th>
<th>Temp at year 35</th>
<th>NPV of profit NZ$ million</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>16.8</td>
<td>~ 140</td>
<td>150°C</td>
<td>320</td>
</tr>
<tr>
<td>10%</td>
<td>14.9</td>
<td>~ 124</td>
<td>154°C</td>
<td>225</td>
</tr>
<tr>
<td>20%</td>
<td>10.5</td>
<td>~ 88</td>
<td>174°C</td>
<td>148</td>
</tr>
<tr>
<td>30%</td>
<td>7.5</td>
<td>~ 62</td>
<td>206°C</td>
<td>87</td>
</tr>
</tbody>
</table>

Table 4.2. Investment decision – ad valorem royalties

Figure 4.2 shows the temperature path with the application of different ad valorem royalty rates. A smoother temperature drop path and higher final temperature at year 35 is evident when higher ad valorem royalty rate is applied. The graph shows that the higher the rate of the ad valorem royalty is, the less the temperature drop is likely to be in 35 years. Therefore, policy can reduce the depletion rate. In other words, a higher temperature at year 35 will make the resource available for further development at that point.
It is important to note that this can only be a short-term solution. In the long term, increase in demand and lack of investment may drive prices up, which may lead to resources becoming more economical to develop. However, the long-term electricity price is left to the market and depends on the availability of alternatives as well as demand.

**Figure 4.2.** The impact of royalties on revenue on the investment decision and change in the temperature of the reservoir
4.5. An alternative model

The previous section shows that a royalty on revenue works to control the temperature and extend the life of the reservoir. The findings show that the higher the rate of the ad valorem royalty, the more restricted investments will be, and thus the lower the rate of temperature drop. However, although the policy encourages lower investment and smaller plant size, it does not offer any reward for the effort a firm puts in to reduce the depletion rate. Hence the aim of this chapter has not yet been met.

Finding the right tax level is a major challenge with environmental taxes (Maatta & Anttonen, 2006). The aim of this chapter is to examine economic instruments that can contribute towards lowering the depletion rate of geothermal resource while allowing the firm to operate at a profitable level. Therefore, a penalty or user charge on the amount of temperature drop is investigated. The ratio of the current temperature to the original temperature is used as the ratio to calculate the royalties firms have to pay at each stage, \( r_t \). Therefore, the royalty ratio is variable and depends on the temperature at time \( t \) relative to the original temperature. The royalty rate is applied to the revenue earned by the firm at each period to calculate the depletion charge, as illustrated in equations 4.7 and 4.8:

\[
\pi_t = \left( (1 - r_t) P_t q_t^e - c q_t^e \right) \delta^t \\
(4.7)
\]

\[
r_t = \frac{\text{temperature (t)}}{\text{temperature (0)}}, \quad \text{(Variable Royalty)} \\
(4.8)
\]
This alternative links the royalty to the temperature drop and the revenue earned. It creates incentive for voluntarily developing the resource more efficiently. It links the royalty ratio to both the depletion rate and the current economic situation or consumers’ willingness to pay (electricity price). The optimal level of investment will eventually depend on the current discount rate as well as the current demand. Table 4.3 shows the outcome when variable ad valorem royalties are applied in comparison to fixed ad valorem royalties.

<table>
<thead>
<tr>
<th>Ad valorem royalty</th>
<th>Brine million tonnes/year</th>
<th>Plant size MW</th>
<th>Temp at year 35°C</th>
<th>Profit NPV NZ$ million</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>16.8</td>
<td>~ 140</td>
<td>150°C</td>
<td>320</td>
</tr>
<tr>
<td>10%</td>
<td>14.9</td>
<td>~ 124</td>
<td>154°C</td>
<td>225</td>
</tr>
<tr>
<td>20%</td>
<td>10.5</td>
<td>~ 88</td>
<td>174°C</td>
<td>148</td>
</tr>
<tr>
<td>30%</td>
<td>7.5</td>
<td>~ 62</td>
<td>206°C</td>
<td>87</td>
</tr>
<tr>
<td>$r_t$ (0% to 31%)</td>
<td>6.7</td>
<td>~ 55</td>
<td>218°C</td>
<td>171m</td>
</tr>
</tbody>
</table>

**Table 4.3.** Royalty as the ratio of temperature at time $t$ to the original temperature, when applied as a variable AVR.
Using the original assumptions, the results show that a firm ex ante chooses a smaller investment and takes a more sustainable approach in comparison to no royalties or with fixed ad valorem royalties of up to 30%. The royalty rate changes from 0% during the first few years to around 31% in year 35 while the firm is still making a positive net present profit. A lower rate of royalties during the first few years of operation compensates for the significant upfront capital investment faced by geothermal developers.

Table 4.3 shows that the firm makes a lower profit than the situation where there is no royalty. The firm also makes more profit than when there is a fixed 20% royalty charge on revenue, but less profit than with a 10% fixed royalty. The most important outcome of a variable royalty rate is the sustainability of the resource. The top solid line in figure 4.3 shows a flatter and smoother temperature drop path for variable royalties compared to fixed rate royalties. The temperature in year 35 stays around 218°C, which in terms of maintaining temperature in the resource is better than any other outcome in this study.
The alternative policy, $r_t$, reduces the depletion rate of the geothermal resource. There is additional gain through royalties collected by government. Additionally, the resource will be available for further development at year 35. This allows for further use of the resource, which in turn adds to the net present value, as illustrated in chapter two. The new policy is encouraging and rewarding. The royalty charge will be on the value of the loss of the resource (depreciation or depletion charge).

**Figure 4.3.** Temperature path – royalties on revenue
4.6. Conclusion

Geothermal generators supply base-load to the electricity market and geothermal resources have greater advantages than other renewable resources. They contribute towards security and adequacy of supply which eventually leads to higher economic growth. In economics, the environment is a valuable asset that provides a variety of services. Although geothermal resources are in general considered to be renewable, a high rate of extraction can speed the depletion process and reduce the productivity of a geothermal resource. A geothermal resource is an economically valuable asset that provides a variety of services. The value of those services is better realised when geothermal resources become scarce. Similar to any other asset, it is prudent to prevent undue depreciation of geothermal reservoirs. Therefore, it is necessary to optimise the economic gain from the development of geothermal resources.

In the previous chapters it was found that a longer-term operation (70 years) is economically optimal when compared to a shorter-term operation (35 years). However, as demonstrated in previous chapters, lack of exclusive rights and guaranteed duration can lead to shorter-term investments. Therefore, a policy encouraging longer-term investment would result in greater net present value of the profit and lower depletion rate. The aim of this chapter is to examine economic instruments that can contribute towards lowering the depletion rate of geothermal resource while allowing the firm to operate at a profitable level.

Monopoly and voluntary approaches were identified as options that are not feasible in the New Zealand situation. In addition, incomplete and inaccessible information makes the use of control regulations difficult. Although taxes and royalties are used in different countries to charge for externalities and deduct a government share from natural resource developments, there is no evidence showing geothermal
royalties or taxes are used to control the depletion rate of geothermal resources. Internationally, royalties applied to geothermal developments are used mainly to derive income from the resource, and are too small to impact on development firms’ behaviour.

Royalties are usage-based payments made by developers to right holders for the right to ongoing use of an asset. They are essentially a price for depreciating the resource. Based on the evidence, the Crown has the right to charge royalties. In-rem taxes and in personam taxes are considered as the main categories of royalties on natural resources. These two categories include different types of taxes, of which ad valorem royalty and accounting profits royalty are used to analyse the effect of applying such a taxation system to the development of geothermal resources. In New Zealand, there are royalties on oil and other minerals. The Resource Management Act 1991 allows for royalties to be charged by central central government and collected by regional government, but this has never been applied.

An optimisation model is developed to analyse firm’s behaviour in the market situation and reaction to the new policy. Data and investment information from Rotokawa II (Nga Awa Purua) power plant was used to run the optimisation. Nga Awa Purua is a 140 MW geothermal power plant with access to Rotokawa geothermal field in the central North Island of New Zealand. The Rotokawa reservoir is located at depths of 950m and below with temperatures of around 320-330°C.

In line with the literature, the outcomes of this study show that an accounting profits royalty has no impact on firm’s investment decision. Conversely, ad valorem royalty encourages smaller plants and therefore lowers the depletion rate for geothermal reservoirs. It shows the firm is sensitive to royalties on revenue and behave accordingly when making an investment and production plan. The results show that higher royalty rates lead to smaller plant sizes.
Despite the effectiveness of ad valorem royalties in reducing plant size and depletion rate, they do not offer any incentive to firms to take more efficient and preventive approaches (by investing in new technology or wiser planning). A variable royalty on revenue was introduced as the ratio of the temperature at time t to the original temperature. The newly introduced royalty scheme is linked to depletion and therefore encourages wiser planning. It penalises those who depreciate the resource and rewards those putting effort into reducing the depletion rate by reducing their royalty payment.

Applying the new tool, the results show a significant change in the firm’s investment plans compared to the no royalty case. The temperature at year 35 is also higher than all other cases analysed with or without royalties. Therefore, the policy meets the aim of this chapter to lower the depletion rate of geothermal resource while allowing the firm to operate at a profitable level. The resource temperature at year 35 is at a level that can be used for further development.

The results show that in a situation when the market fails to control the depletion rate of geothermal resources, e.g. Ohaaki, the introduction of royalty charges on revenue can keep the market under control to restrict the size of development to a less depleting level. The findings show that the higher the rate of the royalty the more restricted investments will be, which leads to a lower depletion rate. They also show that a variable ad valorem royalty that is linked to temperature drop reduces the depletion rate of geothermal resource. Therefore, variable ad valorem royalties based on the ratio of the temperature at time t to the original temperature can be used as the basis of a user charges policy to control the depletion rate of geothermal resources while keeping the geothermal development at a profitable level.

For simplicity, this chapter assumed that multiple access to the reservoir is not allowed. A more challenging task would be to apply this newly introduced economic tool to a multiple-development scenario where participating firms contribute
towards the depletion of a geothermal reservoir. Further studies could be undertaken on this topic.
Chapter 5

Conclusion
Chapter 5

Conclusion

The objectives of this thesis are to analyse current New Zealand policy related to development of geothermal resources, identify areas for improvement, and suggest economic instruments that may contribute towards reducing depletion rates while allowing firms to operate at profitable levels. A geothermal resource is a valuable environmental asset that provides basis for a variety of services. The last few decades of geothermal development show that geothermal resources used for commercial electricity production generally experience temperature and/or pressure decline. The depreciation of this asset is a cost to society and should be managed to prevent the cost surpassing the benefits. There are a number of questions to be answered to establish the optimal level of utilisation/harvesting. The questions are:

• How long should the resource last for?
• How much of the resource should be left for future generations?
• Will future generations require geothermal resources to be preserved at their current status?
• Will other resources be available for electricity production?

Answering these questions is complex when multiple agents are involved in the development of a geothermal resource. Although there is a body of literature on the sustainability of geothermal resources, there is little focusing on access policies, especially in the case of multiple landowners with limited access to the same geothermal reservoir. This thesis analyses the property rights of geothermal resources and the issues that arise in a multiple access scenario. It uses specific examples to answer some of the critical questions around access policy. The first question is whether current property rights arrangements lead to lower depletion
rates while allowing for higher net present value of profit from geothermal resource development. Addressing this question includes identifying the components of property rights, and then determining whether policy allows rights holders to optimise benefits by exercising their rights. The second question is whether multiple-access policy leads to higher net present value of profit and lower depletion rates when the solution is left to the free market. The third question is whether there is an economic policy that can encourage sustainable use of resources while allowing firms to operate at profitable levels.

This chapter summarises the main results of this thesis. Economic development of geothermal resources and the economic model used to study the impact of policies on firms’ behaviour are discussed in section 5.1 and 5.2. Section 5.3 demonstrates the findings around existing property rights of geothermal resources and issues around exclusivity and duration. Section 5.4 illustrates the result of a multiple-access scenario with a possible market solution. The outcome of using an economic policy to reduce depletion rates while allowing firms to operate at a profitable level is discussed in section 5.5. The chapter concludes with suggestions for further research.

5.1. Economic development of geothermal resources

Geothermal generators are the base-load supplier to the electricity market and have advantages over other renewable resources, such as wind, hydro and solar. They can contribute significantly towards security and reliability of supply and consequently to economic growth. In 2009, NZ$0.35 billion worth of electricity was generated from geothermal energy in New Zealand and this is expected to increase to NZ$1 billion per annum by 2025. The substantial contribution geothermal makes
to electricity supply and the economy means it is important that geothermal resources are used efficiently.

There has been rapid growth in the use of geothermal resources for electricity production in the last three decades. New Zealand’s geothermal installed capacity increased by 50% from 2003 to 2010, from 421 MW to 628 MW. In 2010, the United States of America (USA), the Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland, Japan, El Salvador, and Kenya were the top ten countries in the world with the highest installed capacity of geothermal power generation.

Since 1958, New Zealand has utilised different models of geothermal resource development. These models include: state-owned development, e.g. Wairakei; privately developed geothermal projects, e.g. Mokai in Taupo (developed by Maori); joint ventures, e.g. Rotokawa II (Nga Awa Purua), 75% owned by Mighty River Power (a state-owned enterprise) and 25% owned by Tauhara North No 2 Trust (a Maori trust); multiple access to a single field by different operators, e.g. Kawerau in the Bay of Plenty, with three independent firms, Kawerau Geothermal Limited (Mighty River Power), Ngati Tuwharetoa Geothermal Assets Ltd, and Geothermal Developments Ltd (Boast, 1989). Well-defined and enforced institutional arrangements are essential to the successful development of geothermal resources via any of the above models.

Secure property rights are essential for the development and sustainable use of geothermal resources for electricity production. The realised value of a geothermal resource is dependent on its attached bundle of rights. Lack of well-defined property rights reduces this value. First, access to land where a potential site is located must be negotiated with surface landowners, who may or may not own the resource. Multiple ownership can create barriers to obtaining agreement for development and access to finance, and can also reduce the economic return to owners. Electricity generators, with access to technology, expertise and finance, are
obvious potential partners for the development of geothermal resources underlying Maori land.

Secondly, given the significant cost of constructing a geothermal power plant, investors require secure and, ideally, excludable rights. As an illustration, the recently completed Rotokawa II (Nga Awa Purua) geothermal power station in the central North Island of New Zealand cost around NZ$430 million, of which around NZ$60 million was invested in pre-construction activities. In New Zealand, the resource (i.e. the thermal properties of the reservoir) is owned by the Crown who, through statutory law, provides the legal foundations for regulations and policy regarding access and sustainable use. Therefore, once a joint venture arrangement has combined the interests of developer and landowners, the rate of utilisation and future access to the resource, including by other parties, remains to be determined. Dilutions to excludability may arise from multiple landowners spanning a reservoir and potentially allowing entry to their land to developers intending to access the resource. Further, property arrangements determine the distribution of benefits between parties to the development, the commercial operator, landowners, and the resource owner.

Under certain conditions, competitive markets may lead to efficient allocation of resources. However, the market fails when those conditions are not met or do not exist. Market failure to manage scarce natural resources may be corrected by imposing quantity restrictions, taxation and/or other economic instruments. In some situations, government intervention may lead to a more efficient outcome in a failed market. Economic policy can be used to stop firms generating excessive profit from freely available natural resources. Therefore, appropriately designed policy can contribute towards sustainable development.

Although geothermal resources are usually considered renewable sources of electricity, the degree of renewability depends on the extraction and heat regeneration rate. A high rate of extraction can speed the depletion process and
reduce the productivity of the geothermal resource. About 60 years of geothermal development for electricity production at a commercial scale shows that geothermal resources are not sustainable if over-extracted. However, literature around the sustainability of geothermal resources is limited.

Although New Zealand was the first country to adopt an environmentally sustainable management scheme for geothermal resources, its fragmented land ownership system and issues around ownership and property rights of resources have to be addressed for policy to be more effective. Finding an integrated way of developing resources has been an ongoing issue. The New Zealand Government has instigated changes to access policy in an attempt to improve the development process. The two most recent approaches are known as single tapper policy and multiple access policy. In this thesis, economic tools are used to predict producer and consumer behaviour in market situations with different policies.

Chapter 1 of this thesis introduced geothermal energy use and availability and externalities associated with geothermal development. It demonstrated the economic benefits of geothermal development for electricity production and highlighted the possible issues around its development. The chapter briefly reviewed New Zealand regulations, issues around ownership and property rights and indigenous rights to use geothermal resources. It also reviewed the literature around economic modelling for sustainable development of natural resources, which forms the basis of the model used in this thesis.

5.2. Economic model

An economic model was developed to study firms’ behaviour when maximising the
net present value of their profit, using data sourced from Rotokawa field and the
development of Rotokawa II (Nga Awa Purua) power station. The Rotokawa
reservoir is located at depths of 950m and below. It is a high-temperature
geothermal field with typical chloride water at 320-330°C at depths below 1500m.
The reservoir fluid is neutral alkali chloride water typical of high-temperature fields in the Taupo Volcanic Zone in New Zealand. This project required NZ$430 million of
capital cost. Operational costs are estimated to be around NZ$16.5 million per year.

According to the ‘fundamental equation’, illustrated in chapter 1, the optimal level of
extraction depends on the marginal net growth rate, the marginal value of the stock
relative to the marginal value of harvest/extract, and the discount rate. The
fundamental equation can be used to find the ‘bio-economic optimum’. The bio-
economic optimum is the level of extraction that keeps the resource sustainable
while taking into account the economic costs. A policy mechanism can be considered
appropriate when it controls or encourages extraction at the bio-economic optimum
level. A geothermal development model that takes into account firms’ reactions to
different policies while maximising profit, is developed in chapter 2. The model can
be used to identify the policy that maintains extraction rates at the bio-economic optimum level.

5.3. Property rights of geothermal resources in New Zealand

The first question posed in this thesis is whether current property rights
arrangements lead to lower depletion rates while allowing higher net present value
of profit from geothermal resource development. Chapter 2 addressed the question
by first reviewing the property rights of natural resources and particularly
geothermal resources. It then considered the implications of property rights in New
Zealand, including early history, historical changes and myths around the spirituality of geothermal resources. It was noted that the communal ownership model utilised by Maori did not fit well with the European tradition of individual ownership. Hence, the Native Land Court replaced communal control over land with a title system that divided land into blocks owned by individuals. The chapter continued by analysing the property rights associated with geothermal resources and examining incentives for developers to slow depletion rates of resources used for electricity generation.

The emergence of property rights, including the market failure in assuming that property rights are perfectly identified, allocated and enforced, are discussed in chapter 2. This chapter also emphasised the importance of property rights when seeking contractual agreements, the role of property rights in economic growth and wealth distribution, and that well-defined property rights show the real actors in the economy and identify those who bear the rewards and costs of resource-use decisions. Exclusivity, duration, quality of title and transferability are identified as the four main components of property rights associated with geothermal resources. Reducing these components attenuates the bundle of property rights and decreases the value of the resources.

In addition to consideration of the components of property rights, the external impact of different activities on others needs to be considered when allocating rights to resource owners. Externalities can impact on the wealth generated by others at the current time or in the future. Negative externalities may lower economic performance. For instance, subsidence due to a drop in pressure level in a geothermal field may be an unwanted outcome from geothermal development. It may damage the geothermal features associated with a geothermal system and reduce the possibility of generating income from those features. Property rights can therefore be considered an economic instrument that can be utilised to internalise the externalities.
Ownership of a resource is about having the power to manage, dispose of, and receive income and/or enjoyment from that resource. In the New Zealand system, ownership of land is separate to the ownership of geothermal resources located on or under that land – i.e. the owner of the land may not necessarily be the owner of the geothermal resources. The land ownership system in New Zealand is comprised of general (freehold), Maori and Crown lands. Most New Zealand geothermal systems are located on lands with fragmented ownership that can include any of these three ownership systems.

According to the Resource Management Act 1991, regardless of the ownership of the land or resource, the government (regional or national) has control over all geothermal resources and is responsible for their sustainability. The current New Zealand system allows for multiple access to resources. Chapter 2 developed a model to test the current system and its impact on the net present value of the profit gained and the depletion of resources. The results showed a higher net present value of profit for developments that are planned to take place over a longer period of time. A higher net present value of profit should incentivise firms to select longer-term options. However, a complicating factor is that firms have no guarantee that they will be the sole developer of a resource. When they have to apply for a new resource consent at year 35, competition is opened to other firms with the right to access the resource. Therefore, in the absence of exclusivity and guaranteed long-term duration, a shorter-term operation will be more desirable for firms, and consequently overly intensive extraction may take place.

Chapter 2’s results illustrate that, in the current New Zealand situation where firms face uncertainty about future use of and access to resources (due to lack of exclusivity and long-term duration of rights), incentives for longer-term investment are reduced, lowering the net present value of profit from geothermal resource development. Therefore, when designing policies careful consideration is required, to ensure the development of geothermal resources located on land with
fragmented ownership and multiple rights holders is managed. Multiple-access policy can lead to lower net present value of profit from the resource.

5.4. Challenges in a multiple access scenario

The second question posed by thesis is whether multiple access policy leads to higher net present value of profit and lower depletion rate when the solution is left to the free market. Chapter 3 reviewed the issues around renewability of geothermal resources, and demonstrated that a geothermal resource is renewable when the heat extraction rate is less than or equal to the natural heat transfer and recovery of the geothermal system. The chapter then surveyed the literature around sustainability of geothermal resources and the importance of reinjection in maintaining the pressure of geothermal reservoirs. It noted that infield reinjection provides pressure support and reduces the risk for potential subsidence, and declining resource temperature and pressure has negative impacts on the productivity of a field for generating electricity.

Although reinjection contributes towards maintaining pressure, it creates a zone of injected water around the injection well at a different temperature from the native water. That zone will grow over time and eventually reach the production well, referred to as breakthrough. The further away the reinjection, the lesser the negative impact on the temperature. However, reinjection has to happen within a certain boundary to maintain pressure.

Developers need access to an entire field to find the optimal location for reinjection. As most of New Zealand’s geothermal resources are located on land with fragmented ownership, access to fields is limited to the area of access secured by a
particular developer. In addition, the current New Zealand system allows for multiple developments. Chapter 3 compared unitisation with non-cooperation by analysing three cases. Case one assumed that firms agreed to work together to develop the resource. Case two considered the situation where one firm reinjected far from the extraction wells and the other firm reinjected closer to the extraction wells, due to restricted access to the resource. Case three assumed that both firms reinjected close to the extraction wells to minimise the cost related to the length of pipe and wells.

The results from chapter 3 demonstrate a non-cooperative game when firms make strategic decisions. The dominant strategy for firms with limited access is to not accept a unitisation deal. Indeed, limited access discourages collaboration. In a non-cooperative situation, both firms reinjected closer to the production wells to maximise their own net present value of profit which led to more rapid temperature drop. The net present value of the profit for both firms was also lower than with a unitisation agreement. The results show lower total net present value of profit from a multiple access development, in comparison to the unitisation model. This will eventually mean lower current returns from the resource and less value for future generations.

5.5. An economic analysis of royalties: application to geothermal development

The third question posed by this thesis is whether there is an economic policy that can encourage sustainable use of resources while allowing firms to operate at profitable levels. In chapters 2 and 3 it was found that a longer-term operation (70 years) is economically more efficient than a shorter-term operation (35 years).
Therefore, 70 years’ operation is the optimal time to use a resource in comparison to 35 years. However, lack of exclusivity and duration rights can lead to shorter-term investments. Therefore, a policy encouraging longer-term investment would result in greater economic benefits. Chapter 4 examined a range of economic instruments that can contribute towards lowering the depletion rate of geothermal resources while allowing firms to operate at profitable levels.

Economic tools can be used to predict producer and consumer behaviour in a market situation. Monopoly, voluntary approaches, use of control regulations and taxation were analysed as possible solutions to reduce the depletion. Monopoly and voluntary approaches were identified as options that are not feasible in the New Zealand situation. In addition, incomplete and inaccessible information makes the use of control regulations difficult. Although taxes and royalties are used in different countries to charge for externalities and deduct a government share from natural resource developments, there is no evidence that geothermal royalties or taxes are used to control depletion rates of geothermal resources. Internationally, royalties applied to geothermal developments are used mainly to derive income from resources, and are too small to impact on development firms’ behaviour.

Royalties are usage-based payments made by developers to rights holders for the ongoing use of an asset. They are essentially a price for depreciating a resource. Ad valorem royalty and accounting profits royalty were used to analyse the effect of applying such a taxation system to the development of geothermal resources. The Resource Management Act 1991 allows for royalties to be charged by central or local governments, but this has never been applied.

The outcomes of chapter 4 demonstrated that an accounting profits royalty has no impact on firm’s investment decisions. Conversely, ad valorem royalty encourages smaller plants and therefore lowers the depletion rate for geothermal reservoirs. It showed that firms are sensitive to royalties on revenue and behave accordingly
when making an investment and production plan. The results showed that the higher the royalty rate, the greater the impact on the size of the plant.

Despite the effectiveness of ad valorem royalties in reducing plant size and depletion rates, they do not offer any incentive to firms to take more efficient and preventive approaches, for instance by investing in new technology. A variable ad valorem royalty was introduced as the ratio of the temperature at time ‘t’ to the original temperature. This royalty scheme is linked to depletion and therefore encourages planning that intends to lower the depletion rate. It penalises those who deplete the resource and rewards those attempting to reduce the depletion rate.

Application of the variable royalty showed a significant change in firm’s investment planning compared to the application of non-variable ad valorem royalties. Results showed a higher temperature at year 35, in comparison to all other analysed cases with or without royalties. They also showed a net present value of profit greater than the profit for a 20 percent ad valorem royalty. Therefore, the policy met the aim of this chapter, to lower the depletion rate while keeping firms at a profitable level. The resource temperature at year 35 is at a level that can be used for further development. It also penalises those depleting the resource and encourages investment in new technologies to lower the depletion rate.

5.6. **Concluding points**

This thesis analysed current New Zealand policy related to development of geothermal resources, identified areas for improvement, and suggested economic instruments that may contribute towards reducing depletion rates while allowing firms to operate at profitable levels. The importance of property rights...
arrangements and the allocation of those rights were reviewed. It was illustrated that different policies can have a significant impact on firms’ behaviour. The importance of exclusivity and long-term duration of rights, and the impact those rights can have on the net present value of profit and the resource depletion rates are shown in chapters 2 and 3. The results demonstrated that lack of exclusivity and long-term duration of the rights leads to faster depletion of resources and lower net present value of the profit to firms. The results from chapter 3 showed that in a fragmented land ownership system, the market fails to correct firms’ engagement in a non-cooperative game. Therefore, lower net present value of profit and a higher depletion rate will result.

This thesis also analysed and investigated the use of an economic tool to lower depletion rates while allowing firms to operate at a profitable level when developing geothermal resources. This is the first time a study using property rights and other economic instruments to identify policies that can lower geothermal resource depletion while contributing to firm profitability and economic growth has been undertaken. It was shown that a variable ad valorem royalty linked to resource depletion encouraged developers to reduce the depletion rate while operating at a profitable level.

This study can be expanded by analysing the sensitivity of the results to different characteristics of geothermal reservoirs, applying different temperature recovery rate, different reinjection strategies, and to include inflow of natural rainwater and magma from the earth. The economic model could also be expanded to consider both temperature and pressure and also use different methods of calculating the temperature. A more challenging task would be to apply this newly introduced economic tool to a multiple-development scenario where participating firms contribute to the depletion of a geothermal reservoir. Further studies could be undertaken on this topic. The model introduced in this thesis could also be developed further to cover other economic aspects of geothermal resource and test the policies affecting geothermal developments. A more complete study would
consider the social benefits of geothermal development while considering other available energy resources and demand for electricity supply.
References
References


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Northern Territory proposal to introduce a geothermal energy bill, Discussion paper (2008).


Sanyal, S. K. (2004). *Cost of geothermal power and factors that affect it*. Paper presented at the Twenty-ninth workshop on geothermal reservoir engineering, Stanford University, Stanford, California, USA.


Appendices
### Appendix A: Model assumptions

<table>
<thead>
<tr>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir used in the model allows for 140 MW plant to operate for 35 years</td>
<td></td>
</tr>
<tr>
<td>The temperature drops to 150°C at year 35 when the plant size is 140 MW</td>
<td></td>
</tr>
<tr>
<td>$T_{e,k}^t$: Temperature of extracted brine at time $t$ by firm $k$</td>
<td></td>
</tr>
<tr>
<td>$q_{e,k}^t$: Quantity of extracted brine at time $t$ by firm $k$</td>
<td></td>
</tr>
<tr>
<td>$Q_{k,t}$: Electricity produced at time $t$ by firm $k$</td>
<td></td>
</tr>
<tr>
<td>$\delta^t$: Discount rate at time $t$</td>
<td></td>
</tr>
<tr>
<td>$\alpha$: Conversion factor</td>
<td></td>
</tr>
<tr>
<td>$\pi_{t,k}$: Profit gained at time $t$ by firm $k$</td>
<td></td>
</tr>
<tr>
<td>$R_t$: Quantity available brine</td>
<td></td>
</tr>
<tr>
<td>$\gamma$: Temperature recover rate</td>
<td></td>
</tr>
<tr>
<td>$d$: Lag period – number of years it takes reinjected brine to reach the production well</td>
<td></td>
</tr>
<tr>
<td>One hundred percent of extracted brine is reinjected</td>
<td></td>
</tr>
<tr>
<td>Inflow is only from the reinjection – no rain water</td>
<td></td>
</tr>
<tr>
<td>Average wholesale electricity price: NZ$60/MWh</td>
<td></td>
</tr>
</tbody>
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**Appendix B: Rotokawa field and project information**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial temperature</td>
<td>320°C</td>
</tr>
<tr>
<td>Reservoir area - proven</td>
<td>3.3 km²</td>
</tr>
<tr>
<td>Reservoir area - probably</td>
<td>6.5 km²</td>
</tr>
<tr>
<td>Extracted brine for 149 MW electricity plant</td>
<td>16,425,000 tonnes of geothermal fluid per year</td>
</tr>
<tr>
<td>Capital cost (140 MW electricity plant)</td>
<td>NZ$430 million</td>
</tr>
<tr>
<td>Estimated operational cost</td>
<td>NZ$16.5 million</td>
</tr>
</tbody>
</table>
Appendix C: Different form of taxes levied on mining industry, and their basis (Otto et al., 2006)

<table>
<thead>
<tr>
<th>Tax type</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In rem taxes (unit or value based)</strong></td>
<td></td>
</tr>
<tr>
<td>Unit-based royalties</td>
<td>Set charge per unit</td>
</tr>
<tr>
<td>Ad Valorem based royalty</td>
<td>% of mineral’s value (definition of value may vary)</td>
</tr>
<tr>
<td>Sales and excise tax</td>
<td>% of value of sales</td>
</tr>
<tr>
<td>Property or capital tax</td>
<td>% of value of property or capital</td>
</tr>
<tr>
<td>Import duty</td>
<td>% of value of imports (usually)</td>
</tr>
<tr>
<td>Export duty</td>
<td>% of value of exports</td>
</tr>
<tr>
<td>Withholding on remitted loan interest</td>
<td>% of of loan interest value</td>
</tr>
<tr>
<td>Withholding on imported services</td>
<td>% of value of services</td>
</tr>
<tr>
<td>Value-added tax</td>
<td>% of the value of the good or service</td>
</tr>
<tr>
<td>Registration fees</td>
<td>Set charge per registration event</td>
</tr>
<tr>
<td>Rent or usage fees</td>
<td>Set charges per unit area</td>
</tr>
<tr>
<td>Stamp tax</td>
<td>Set charge per transaction or % of value of the transaction</td>
</tr>
<tr>
<td><strong>In personam taxes (net revenue based)</strong></td>
<td></td>
</tr>
<tr>
<td>Income tax</td>
<td>% of income</td>
</tr>
<tr>
<td>Capital gain tax</td>
<td>% of profit on disposal of capital assets</td>
</tr>
<tr>
<td>Additional profits tax</td>
<td>% of additional profits</td>
</tr>
<tr>
<td>Excess profits tax</td>
<td>% of excess profits</td>
</tr>
<tr>
<td>Net profits royalty or net value royalty</td>
<td>% of mineral’s value less allowable costs</td>
</tr>
<tr>
<td>Withholding on remitted profits or dividends</td>
<td>% of remitted value</td>
</tr>
</tbody>
</table>
**Appendix D:** Policy objectives of tax types and their prevalence (Otto et al., 2006)

<table>
<thead>
<tr>
<th>Tax type</th>
<th>Objective</th>
<th>Prevalence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In rem taxes (unit or value based)</strong></td>
<td></td>
<td></td>
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<tr>
<td>Unit-based royalties</td>
<td>To provide stable and certain revenues (stable because commodity price fluctuations have no impact); an ownership transfer payment</td>
<td>Commonly used, particularly for industrial and bulk</td>
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<td>Ad Valorem based royalty</td>
<td>To provide at least some revenue; an ownership transfer payment</td>
<td>Commonly used</td>
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<tr>
<td>Sales and excise tax</td>
<td>To provide revenue based on the volume of economic activity; a tax on inputs</td>
<td>VAT has replaced sales tax in many nations; excise tax may be reserved for special items such as fuel</td>
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<tr>
<td>Property or capital tax</td>
<td>To provide stable revenue based on the value of the physical plant; often goes to the local level of government</td>
<td>Commonly used</td>
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<tr>
<td>Rent or usage fees</td>
<td>To provide stable revenue, often to local government for land use</td>
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<tr>
<td><strong>In personam taxes (net revenue based)</strong></td>
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<tr>
<td>Income tax</td>
<td>To provide revenue based on ability to pay</td>
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<tr>
<td>Additional profits tax</td>
<td>To capture a part of exceptionally high profits</td>
<td>Very rare</td>
</tr>
<tr>
<td>Excess profits tax</td>
<td>To capture a part of exceptionally high profit</td>
<td>Very rare</td>
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<tr>
<td>Net profits royalty or net value royalty</td>
<td>To provide revenue based on ability to pay</td>
<td>Mainly used in nations with well-developed tax administration</td>
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Appendix E: GAMS programming for the economic model

GAMS Rev 236  WEX-VS8 23.6.5 x86/MS

$TITLE maximisation of Geothermal Reservoir

$ONTEXT
One firm 140 MW simple model
Reinjection – 3 period
Discount rate = 8%
$OFFTEXT

Scalar

alpha  electricity conversion rate       /0.00023/
gin    regeneration rate in reservoir   /0.01/
gout   regeneration rate moving brine   /0.02/
v     inflation on electricity per year   /0.04/
cint   cost of extraction per year - times q /1/
cccint capital cost per litre of brine - incl interest /1.81/
discount the discount rate             /0.08/
i     inflation                        /0.03/
Rint   Initial reservoir stock         /200000000/
TRint  Initial reservoir temperature   /320/
Pint   Initial electricity price       /60/
d1     t periods: reinjection to main   /3/;

SETS

   t      time       /1*35/;

Parameter

Ti Temperature that is reinjected by firm k in period t;
Ti = 120;

Parameter

Mint minimum temperature for electricity production;
Mint = 150;

Parameter

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\[ c(t) \quad \text{operational cost; } \\
\text{ } \quad c(t) = \text{cint} \times (1+i)^{\text{ord}(t)}; \]

PARAMETERS

\[ \delta(t) \quad \text{discount factor; } \]
\[ \delta(t) = (1/(1+\text{discount}))^{\text{ord}(t)}; \]

Parameter

\[ P(t) \quad \text{Price of electricity; } \]
\[ P(t) = \text{Pint}(1+v)^{\text{ord}(t)}; \]

display P

Variables

\[ q(t) \quad \text{quantity extracted each period by firm 1 } \]
\[ R(t) \quad \text{quantity of extractable brine in reservoir } \]
\[ TR(t) \quad \text{reservoir temperature } \]
\[ \text{Te}(t) \quad \text{Temperature of extracted brine in period } t \]
\[ Q1(t) \quad \text{electricity produced by firm 1 in period } t \]

PROFIT profits earned by firm k in period;

positive variables Q1 R qe

Equations

\[ \text{res1}(t) \quad \text{constraint on first periods of } R(t) \]
\[ \text{res2}(t) \quad \text{constraint on minimum reserve} \]
\[ \text{res3}(t) \quad \text{constraint on temperature for production purpose} \]

\[ \text{temp}(t) \quad \text{temperature of reservoir} \]
\[ \text{Etemp}(t) \quad \text{temperature of extracted brine} \]
\[ \text{Elec1}(t) \quad \text{electricity produced by firm 1 in period } t \]

Pie objective function;

\[ \text{TR.UP}(t) = \text{TRINT}; \]
\[ \text{qe.L} = 1; \]
\[ \text{qe.up} = \text{Rint}; \]
res1(t).  \[ R(t) = E = (RINT - \text{ord}(t) \times (qe)) \left( \text{ord}(t) \text{ LT} d1 \right) + (RINT - (d1 \times qe)) \left( \text{ord}(t) \text{ GE} d1 \right); \]

res2(t).  \[ \text{RINT} = G = \left( (1 + d1) \times qe \right); \]
res3(t).  \[ \text{TE}(t) = G = \text{Mint}; \]

\text{temp}(t).  \[ \text{TR}(t) = E = \text{TRINT} \left( \text{ord}(t) \text{ LE} d1 \right) + \left( (R(t) \times \text{TR}(t-1)) \times (1+\text{gin}) \right) + (qe \times T_{i}(1+\text{gout} \times d1)) / (R(t) + qe) \left( \text{ord}(t) \text{ GT} d1 \right); \]

\text{Etemp}(t).  \[ \text{TE}(t) = E = \text{TR}(t); \]

\text{Elec1}(t).  \[ Q1(t) = E = \alpha \times \text{TE}(t) \times (qe); \]

Pie.  \[ \text{PROFIT} = E = \text{sum}(t, (((P(t) \times Q1(t)) - (qe \times (c(t) + \text{ccint})))) \times \text{delta}(t)); \]

MODEL GEO /ALL/;

SOLVE GEO USING nlp MAXIMIZING PROFIT;

Display delta
Display c
display R.L;
display Q1.L;
display TR.L;
display TE.L;
display qe.L;
display Profit.L;
display profit.up;
Appendix F: Temperature results for chapter 2

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Litre per year  | 9,665,545  | 16,856,000
Total profit    | 251,596,100 | 282,453,300
### Appendix G: Temperature results for chapter 3

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**Appendix H:** Temperature change for chapter 4 and NPV

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</table>

| liter per year | 16,856,960 | 14,915,410 | 10,569,390 | 7,549,750 | 6,717,079 |
| NPV          | 320,419,500 | 225,942,200 | 148,479,900 | 87,741,580 | 171,106,100 |
Appendix I: Geothermal related definitions

Geothermal field (IGA, 2013):

Geothermal field is a geographical definition, usually indicating an area of geothermal activity at the earth’s surface. In cases without surface activity this term may be used to indicate the area at the surface corresponding to the geothermal reservoir below.

Geothermal system:

A geothermal system is a combination of a heat source, a reservoir and a fluid that transfers the heat (Dickson & Fanelli, 2004). A geothermal system requires heat, permeability, and water (GEA, 2013). In general, “Geothermal systems related to young igneous intrusions in the upper crust that can include magma, hot dry rock, and convective hydrothermal systems” (Kestin et al., 1980, p. 7).

Geothermal reservoir (GEA, 2013):

When water is heated by the earth’s heat, hot water or steam can be trapped in permeable and porous rocks under a layer of impermeable rock and a geothermal reservoir can form. This hot geothermal water can manifest itself on the surface as hot springs or geysers, but most of it stays deep underground, trapped in cracks and porous rock. This natural collection of hot water is called a geothermal reservoir.

Geothermal fluid (GEA, 2013):

Geothermal water is called geothermal fluid.