Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

An Economic Analysis of Royalties: Application to Geothermal Development

Sam Malafeh and Basil Sharp

Department of Economics, The University of Auckland, PO Box 92019, Auckland, New Zealand

sam.malafeh@auckland.ac.nz

Keywords: Geothermal, economics, property rights, access policy, sustainability, depletion, renewable, free market, royalties, tax

ABSTRACT

Sustainable development of renewable resources is aimed at meeting the needs of the current generation while providing for future generations. 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. Environmental taxes can be used as a depletion charge to encourage wiser planning and use and development of more efficient technologies. About 60 years' experience in geothermal development for electricity production shows that geothermal resources are not sustainable if extracted rapidly. Although taxes and royalties are used in different countries to charge for externalities, there is no evidence of geothermal royalties or taxes being used to control the depletion rate of geothermal resources.

This paper investigates different forms of royalties that can be applied to geothermal developments for electricity generation. An economic model is introduced to test a firm's reaction to royalty charges and the impact on resource. The result shows that ad valorem royalties can encourage firms to develop the resource in a more sustainable manner. 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 instant 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. Application of the variable royalty showed a significant change in firm's investment planning, with lower depletion, compared to the application of non-variable ad valorem royalties. This royalty scheme is linked to depletion and therefore encourages planning that intends to lower the depletion rate. Indeed, the variable ad valorem royalty penalises those who deplete the resource and rewards those attempting to reduce the depletion rate.

1. INTRODUCTION

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.

This paper 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 3 and 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 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.

2. Literature

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.

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 1.

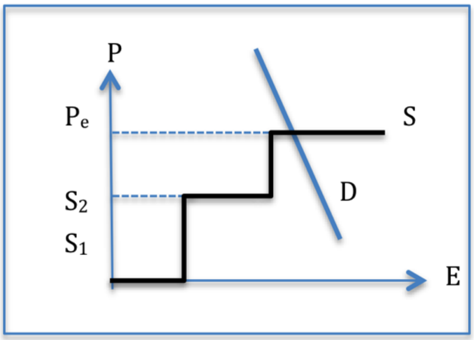

Figure 1: Wholesale electricity supply and demand – example from New Zealand

Figure 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.

2.2.1. 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 a 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. Next section examines two main categories, 'in rem taxes' and 'in personam taxes' (Otto et al., 2006).

2.2.1.1. 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).

2.2.1.2. 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.

2.2.2. Royalty vs. investment with 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.

2.2.3. International application

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.

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 illustrated here will be used to analyse a firm's behaviour in response to different categories of royalties. Firms are assumed to maximise the present value of profit such that the production constraints are met:

$$\max_{q_t^e} \sum_{t=1}^{T} \pi_t = \sum_t^T (\alpha\, P_t\, T_t^e - c) q_t^e \delta^t \tag{1}$$

s.t.

$$R_t \geq \sum_{t-d}^{T} q_{t,k}^e \tag{2}$$

$$T_t^e \geq 150°\text{C} \tag{3}$$

$$q_t^e \geq 0 \tag{4}$$

Time = t = 1, 2, … 35 (T) for a short term development

Constraint (2) requires the total extracted brine to be less than the total existing brine, R_t, at any time. Constraint (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) sets the extraction at greater than or equal to zero. Adding the royalty as a percentage of profit to equation (5) changes it to:

$$\pi_t = (1-r)(\alpha\, P_t\, T_t^e\, q_t^e - c q_t^e)\delta^t \tag{5}$$

Equation (6) shows the situation when the royalty is based on the revenue gained from the development:

$$\pi_t = \big((1-r)\alpha\, P_t\, T_t^e\, q_t^e - c q_t^e\big)\delta^t \tag{6}$$

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. 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 paper 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 km^2 and probably of 6.5km^2. 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).

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 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 1 shows a summary of the findings when APR is applied.

Royalty on profit	Brine extracted per year	Equivalent plant size
No Royalties	16,856,000 tonnes	~ 140 MW
10% Royalty	16,856,000 tonnes	~ 140 MW
99% Royalty	16,856,000 tonnes	~ 140 MW

Table 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 2 shows the final results on the investment decision the firm makes and the temperature after 35 years of operation.

Ad valorem royalty	Brine million tonnes/year	Plant size MW	Temp at year 35	NPV of profit NZ$ million
No	16. 8	~ 140	150°C	320
10%	14. 9	~ 124	154°C	225
20%	10. 5	~ 88	174°C	148
30%	7. 5	~ 62	206°C	87

Table 2: Investment decision – ad valorem royalties

Figure 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.

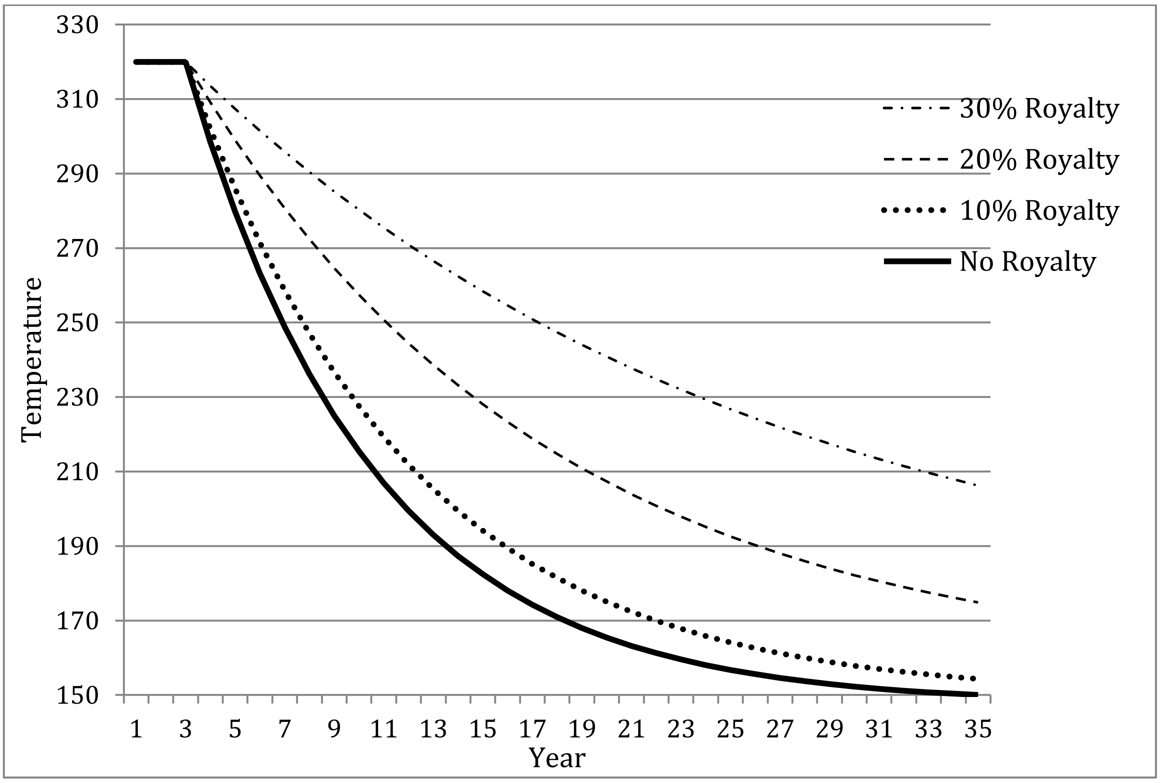

Figure 2: The impact of royalties on revenue on the investment decision and change in the temperature of the reservoir

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 paper has not yet been met.

Finding the right tax level is a major challenge with environmental taxes (Maatta & Anttonen, 2006). The aim of this paper 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 7 and 8:

$$\pi_t = \left((1 - r_t)P_t\, Q_t\, q_t^e - cq_t^e\right)\delta^t \tag{7}$$

$$r_t = \frac{temperature\ (t)}{temperature\ (0)} \quad \text{(Variable Royalty)} \tag{8}$$

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 3 shows the outcome when variable ad valorem royalties are applied in comparison to fixed ad valorem royalties.

Ad valorem royalty	**Brine million tonnes/year**	**Plant size MW**	**Temp at year 35**	**Profit NPV NZ$ million**
No	16. 8	~ 140	150°C	320
10%	14. 9	~ 124	154°C	225
20%	10. 5	~ 88	174°C	148
30%	7. 5	~ 62	206°C	87
r_t (0% to 31%)	6. 7	~ 55	218°C	171m

Table 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 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 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.

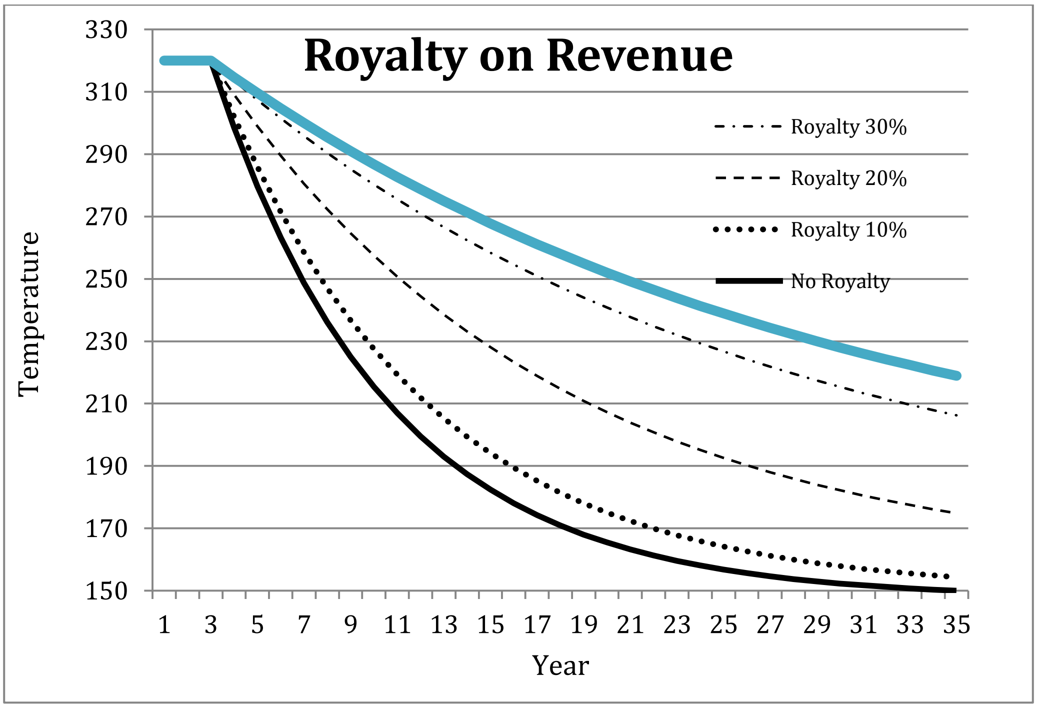

Figure 3: Temperature path – royalties on revenue

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. 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).

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. The aim of this paper 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 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 paper 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 paper 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.

REFERENCES

Axelsson, G.: *Management of geothermal resources*. Paper presented at the Geothermal training programme, Tianjin, China.

Axelsson, G. (2010). Sustainable geothermal utilisation - case histories; definitions; research issues and modelling. *Geometrics, 39*(4), (2008), 283-291.

Axelsson, G., Stefansson, V., Bjornsson, G., & Liu, J.: *Sustainable management of geothermal resources and utilisation for 100 - 300 years.* Paper presented at the World Geothermal Congress, Antalya, Turkey (2005).

Benito, F. A.: *The role of government in Philippine geothermal energy development.* Paper presented at the 20th anniversary workshop, geothermal training programme, Reykjavik, Iceland (1998).

Bhattacharyya, S. C.: *Energy economics: concepts, issues, markets and governance*. London: Springer (2011).

Bloomquist, R. G.: A review and analysis of the adequacy of the U.S. legal, institutional and financial framework for geothermal development. *Geothermics, 15*(1), (1986), 45.

Bloomquist, R. G.: *United States geothermal policy - provision of access adn encouraging project development*. Paper presented at the International geothermal conference, Reykjavik, Iceland (2003).

Boast, R.: *Resource management law reform : geothermal energy : Maori and related issues*. Wellington [N.Z.]: Ministry for the Environment (1989).

Bouche, D.: *Rotokawa resource consent: project description*. Mighty River Power. Retrieved from http://202.74.224.54/content/1022/2. Project Description.pdf (2007).

Bradley, P. G., & Watkins, G. C.: Net value royalties: practical tool or economics' illusion. *Resource policy, 13*(4), (1987), 9.

Brau, R., & Carraro, C.: The economic analysis of voluntary approaches to environmental protection. In A. Cavaliere, H. Ashiabor, K. Deketelaere, L. Kreiser & J. Milne (Eds.), *Critical Issues in Environmental Taxation: International and comparative perspectives* (Vol. III, pp. 593 - 626). New York, the United States: Oxford University Press (2006).

Bromley, C., Mongillo, M., & Rybach, L.: *Sustainable utilisation strategies and promotion of beneficial environmental effects - having your cake and eating it too*. Paper presented at the New Zealand Geothermal Workshop, Auckland, New Zealand (2006).

Burness, H. S.: On the taxation of nonreplenishable natural resources. *Journal of Environmental Economics and Management, 3*, (1976), 289-311.

Demsetz, H.: Towards a theory of property rights II: the competition between private and collective ownership. *Journal of Legal Studies, 31*(2), (2002).

Dickson, M. H., & Fanelli, M.: What is geothermal energy? Retrieved May, 2009, from http://www.geothermal-energy.org/314,what_is_geothermal_energy.html (2004).

Dickson, M. H., & Fanelli, M.: What is geothermal energy? Retrieved February, 2010, from http://www.geothermal-energy.org/314,what_is_geothermal_energy.html (2004).

Evans, L. T., & Meade, R. B.: *Alternating currents or counter-revolution? : contemporary electricity reform in New Zealand*. Wellington [N.Z.]: Victoria University Press (2005).

Falk, I.: Dynamical ecologic taxes: public control for interrelated renewable resources. *Resource and Energy, 13,* (1991).

Fisher, A. C., & Rothkopf, M. H.: Market failure and energy policy: a rationale for selective conservation. *Energy Policy, 17*(4), (1989).

Geothermal Energy Act 1953, New Zealand Government (1953).

Golabi, K., & Scherer, C. R.: Extraction timing and economic incentives for geothermal reservoir management. *Journal of Environmental Economics and Management, 8*(2), (1981), 156-174.

Grant, M. A.: *Rotokawa reservoir and response to production*. Auckland: Mighty River Power. Retrieved from http://www.mightyriverpower.co.nz/Generation/Projects/Rotokawa/Reports/ (2007).

Guerin, K.: *Property rights and environmental policy: a New Zealand perspective*. Wellington: New Zealand TreasuryRetrieved from http://www.treasury.govt.nz/publications/research-policy/wp/2003/03-02/twp03-02.pdf (2003).

Harsaputra, A. I.: Indonesia power, wika, win geothermal auctions. *The Jakarta Post* (2008).

Hotelling, H.: The economics of exhaustible resources. *Journal of policital economy, 39*(2), (1931), 137-175.

Hussen, A. M.: *Principles of environmental economics*. New York: Routledge (2004).

Kahn, E., & Goldman, C. A.: Impact of tax reform on renewable energy and cogeneration projects. *Energy Economics, 9*(4), (1987), 215-226.

Kerr, R. A.: Geothermal Tragedy of the Commons. *Science, 253*(5016), (1991), 134-135.

Kesler, S. E.: *Mineral resources, economics, and the environment*. Toronto, Canada: Maxwell Macmillan (1994).

Kestin, J., Dipoppo, R., Khalifa, H. E., & Ryley, D. J.: *Sourcebook on the production of electricity from geothermal energy*. Washington, D.C.: U.S. Dept. of Energy, Assistant Secretary for Resource Applications For sale by the Supt. of Docs., U.S. G.P.O. (1980).

Luketina, K.: *Sustainablity and the democratic process.* Paper presented at the World Geothermal Congress Bali, Indonesia (2010).

Luketina, K.: *Geothermal regulation in New Zealand*. Waikato, New Zealand: Waikato Regional Council, New Zealand (2011).

Lund, D.: Rent taxation for nonrenewable resources. *Annual review of resource economics, 1*(1), 20, (2009).

Maatta, K., & Anttonen, L.: Environmental effectiveness of different policy instruments. In A. Cavaliere, H. Ashiabor, K. Deketelaere, L. Kreiser & J. Milne (Eds.), *Critical Issues in Environmental Taxation: International and comparative perspectives* (Vol. III, pp. 627 - 642). New York, the United States: Oxford University Press, (2006).

Migliavacca, S.: Environmental taxation and the double dividend hypothesis. In A. Cavaliere, H. Ashiabor, K. Deketelaere, L. Kreiser & J. Milne (Eds.), *Critical Issues in Environmental Taxation: International and comparative perspectives* (Vol. III, pp. 267 - 283). New York, the United States: Oxford University Press (2006).

Milne, J. E., Ashiabor, H., Cavaliere, A., Deketelaere, K., & Lye, L. H.: *Critical issues in environmental taxation : international and comparative perspectives*. Richmond, England: Richmond Law & Tax (2003).

MRP.: *Rotokawa geothermal development: proposed system management plan*. Mighty River Power. Retrieved from http://202.74.224.54/content/1014/11. Proposed SMP.pdf (2007).

Neron-Bancel, T.: *Geothermal revenue under the energy policy Act 2005: income distribution at Federal, state, and county levels*. Washington D.C., USA: Geothermal Energy Association (2008).

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

NZGA.: New Zealand Geothermal Fields. Retrieved September, 2012, from http://www.nzgeothermal.org.nz/nz_geo_fields.html (2012).

NZGA.: Sustainability. Retrieved December, 2012, from http://www.nzgeothermal.org.nz/sustainability.html (2012).

O'Faircheallaigh, C.: Indigenous people and mineral taxation regimes. *Resource policy, 24*(4), (1998), 11.

O'Shaughnessy, B. W.: Use of economic instruments in management of Rotorua geothermal field, New Zealand. *Geothermics* (29), (2000), 17.

O'Sullivan, M., & Mannington, W.: *Renewability of the Wairakei-Tauhara geothermal resource.* Paper presented at the World Geothermal Congress, Antalya, Turkey (2005).

Otto, J., Andrews, C., Cawood, F., Doggett, M., Guj, P., Stermole, F., Stermole, J., & Tilton, J.: *Mining royalties: a global study of their impact on investors, government, and civil society*. Washington DC: The World Bank (2006).

Owens, B.: *An economic vauation of a geothermal production tax credit*. USA: National renewable energy laboratory (2002).

Petroleum and geothermal energy Act, Department for Manufacturing, Innovation, Trade, Resources and Energy, Australian Government (2000).

Petroleum and Geothermal Energy Resources Act, Western Australian Government (1967).

Philips, J.: Evaluating the level and nature of sustainable development for a geothermal power plant. *Renewable and sustainable energy reviews, 14*, (2010), 2414-2425.

Reeve, D.: *Economic benefits of Rotokawa II*. Mighty River Power. Retrieved from http://www.mightyriverpower.co.nz/content/1019/16. Economic benefits.pdf (2007).

Resource Management Act 1991 - Nov 2012 update, (1991).

Rybach, L.: Geothermal energy: sustainability and the environment. *Geometrics, 32*(4-6), (2003), 463-470.

Rybach, L.: *Geothermal sustainability.* Paper presented at the European Geothermal Congress, Unterhaching, Germany (2007).

Rybach, L.: *"The future of geothermal energy" and its challenges.* Paper presented at the World Geothermal Congress, Bali, Indonesia (2010).

Rybach, L., Megel, T., & Eugster, W. J.: *At what time scale are geothermal resources renewable?* Paper presented at the World geothermal congress, Kyushu-Tohoku, Japan (2000).

Rybach, L., & Mongillo, M.: Geothermal sustainability - a review with identified research needs. *GRC Transactions, 30*, (2006), 1083-1090.

Scott, B. J., & Cody, A. D.: Response of the Rotorua geothermal system to exploitation and varying management regimes. *Geothermics*(29), (2000), 20.

Sharp, B.: Highlights of 2011: the case for economics. *Media release - Business School - The University of Auckland* Retrieved from http://www.business.auckland.ac.nz/uoa/home/about/news-and-media/news/news/template/news_item.jsp?cid=458203 (2012).

Sharp, B., & Huang, C.-C.: Managing mineral resources: tough development choices ahead. *University of Auckland Business Review, 14*(1), (2011), 5.

Sutherland, R. J.: The economics of energy conservation policy. *Energy policy, 24*(4), (1996), 8.

Tietenberg, T. H.: *Environmental and natural resource economics* (7th ed.). Boston: Addison Wesley (2006).

U.S.D.I.: Geothermal. Retrieved 21 April, 2012, from http://www.blm.gov/ca/st/en/prog/energy/geothermal.html (2012).

UN.: *Report of the World Commission on environment and development: our common future*. New York City: United Nation. Retrieved from http://www.un-documents.net/wced-ocf.htm (1987).