SUSTAINABLE DEVELOPMENT OF GEOTHERMAL RESOURCES
AN ECONOMIC ALTERNATIVE

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ABSTRACT:
Sustainable development of renewable resources is aimed at meeting the needs of the current generation while providing for future generations. Geothermal resources are renewable when developed under controlled levels of extraction. High rates of extraction can damage the resource or speed the depleting process, as was the case with The Geysers Geothermal Field in California. Appropriately designed public policy can contribute to sustainable development. Royalty payments are an economic instrument that can be used to reduce depletion and contribute to sustaining the productivity of the geothermal resource. This paper reviews different forms of royalties that can be applied to geothermal resources. It analyses and compares the impact of different royalty regimes on a firm’s behaviour and environmental sustainability. The results show that royalties or taxes on profit have no impact on the firm’s approach to sustainability. Indeed, royalties on profit act only as a wealth transfer from a generator to government. However, royalties on revenue encourage the firm to take a more conservative approach because this is linked to temperature and the extraction rate. Firms have to maintain the temperature to be able to sustain the long-term profitability of the development and generate a positive net present profit over the life of the plant. The results show that higher royalties will adversely impact on investment. An alternative is to set royalty rates as the ratio of the current temperature to the original temperature of the reservoir. A variable royalty rate acts as a user charge for damage done to the resource, thereby reducing the depletion rate.

INTRODUCTION AND BACKGROUND
Geothermal generators are the base-load supplier to the electricity market and have greater advantages than other renewable resources. 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, 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 or do not exist. 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). It can stop firms gaining 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 right creation and management, licensing and royalties, [state owned enterprises] SOEs, 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 level 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 policies (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 and environmental issues.

Economic tools can be used to predict the behaviour of producers and consumers in a market situation. Effective utilisation of resources can be achieved by using knowledge to find the relationship between social institutions and resource depletion. Social and economic tools can prevent social interference with social objectives while utilising resources. 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 set objectives that can limit firms’ activities within certain boundaries. Licensing regulations are the most commonly used policies. Identifying optimal outcomes and uncovering the behavioural problems may assist in designing suitable policies.

Although taxes and royalties are used in different countries to charge for externalities and deduct a governmental share from natural resource developments, there is no evidence showing geothermal royalties or taxes being used to control the depletion rate of geothermal resources. Royalty payments can be an economic way to charge for depletion when the market fails to take care of the natural resource. Environmental taxes and royalties are usually used to encourage better planning, use and development of more efficient technologies, and to compensate for depletion, which are the aims of this study.

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 the 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 more competitive. Therefore it may be the right time to introduce a new policy to control the depletion of this valuable resource.

This paper aims to find an economic instrument that can encourage better planning, use and development of more efficient technologies, and
compensate for depletion when geothermal resources are utilised. 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. It analyses the costs and benefits and the application of royalties in different countries. An economic model is introduced next to test a firm’s reaction to royalty charges and the impact on resource utilisation. Next part analyses and compares the impact of different royalty approaches on the firm’s behaviour and investigates whether selected methods can contribute towards the sustainability of geothermal resources. Finally, 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 royalty on the depletion of geothermal resources.

**LITERATURE**

**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 the low quality resources for the 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 guarantee for future use of the resources (Kesler, 1994).

Hartwick-Solow defined sustainability as an approach that maintains constant real consumption over an indefinite period of time under certain constrains imposed by the scarcity of the resources (Hussen, 2004; Tietenberg, 2006). Hartwick’s Rule expects the principle to remain unchanged over a period of time 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 giving 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 United Nation’s World Commission on environment and development (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, the direction of investments, the orientation of technological development, and institutional changes should all 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. However, the timing of new technologies and resources is unclear and introduction of policies that encourage research and development towards achieving those goals may be of value. The level of value we put on these areas can be found through the discount rates accepted by society, although this may or not be future generations’s wish. 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 is better realised 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 essential 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 respectively about current opportunities to generate jobs, wealth, and income, and willingness to improve or preserve the resource at the status quo. Option value is the current generation’s willingness to preserve the resource for future opportunities.
Cost-benefit analysis is an economic form of finding the optimal level of harvesting. 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 the marginal cost and benefits are occurring 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. It finds the net present value of the costs and benefits before comparing those (Tietenberg, 2006).

The economic study should show that the present value of the net benefits are maximised to justify the policy. A development may benefit society by creating jobs, wealth for the owners, and goods for consumers. Conversely, it may cost society by degrading the ecosystem, changing the wildlife habitat and recreational opportunities, and impacting on possible future income and employment. The efficient allocation of resources may not necessarily lead to inter-temporal fairness. In an intergenerational model the allocation of resources depends heavily on the discount rate, which is selected by present rights holders. It always lets the current generation take and use more of the resource when the discount rate is greater than zero. To be fair, future generations should not be any worse off than the current generation, based on the sustainability definition given earlier. The objective therefore is to find an optimal level of harvesting that maximises the net present value of the 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 need the geothermal resources at their current status?
- Will there be other resources available for electricity production?

In the dynamic efficiency model the current generation gains higher benefits at the expense of future generations. The higher the discount rate, the lower the current generation values the future generations’ need. Despite difficulties around the dynamic efficiency model, it is our best method of calculating the net present value of the resource by considering current rights holders’ willingness.

A geothermal system is a combination of a heat source, a reservoir and a fluid that transfers the heat (Dickson & Fanelli, 2004). “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 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-Taupiri and Nesjavellir has demonstrated that in favourable situations recharge can extend the productive life of the resource” (Cloworthy et al., 2010).

Geothermal development may contribute towards the adequacy and security of electricity supply, which eventually leads to higher economic growth. However, the economic growth should not occur at the expense of environmental damage, particularly when the marginal social cost is higher than marginal social benefit (Philips, 2010). Geothermal developments can have several effects on the resource, 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 geothermal resource is a renewable and environmentally friendly source of energy, certain conditions have to be met to
keep it sustainable. To enable a long-term development, it is important to maintain the temperature and pressure in the long run. 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. However, a 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 will decline over time. If all production stopped, then 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 the 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; 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 clear (Kerr, 1991).

As mentioned earlier, the level of sustainability depends on the discount rate and the value rights holders put on future generations’ need and willingness to have the resource. It is a complicated task to identify and enforce an optimal level of extraction that allow for an appropriate duration. Under limited production, a geothermal reservoir can be sustained for a longer period of time (Bromley, Mongillo, & Rybach, 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, Megel, & Eugster, 2000). Bromley et al. (2006) state that with appropriate management, the geothermal system can be utilised over the long term (~100 years) then retired for recovery. Although the recovery of temperature and pressure will follow, the recovery of the temperature is always slower than the pressure. 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 after 100 years of production. Time and size of the production play a vital role in the sustainability of geothermal resources (Rybach, 2003; Rybach & Mongillo, 2006).

A geothermal development may be seen as sustainable if it can maintain the geothermal features and productivity for 100 to 300 years (Axelsson et al., 2005). However, experience in some of the large developments such as The Geysers, Rotorua and Ohaaki show shorter commercial life of the 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 3000MW of electricity by 1990. However, the development stopped at around 2000MW. Involved parties came to realise that the field underneath was running dry and the steam pressure had reduced in the wells. The resource was overloaded and it depleted faster than expected, due to lack of sufficient water to produce steam. Generation went down to 1500MW and developers started to condense and re-inject some of the used steam back to the ground to help the reservoir recover.

Rotorua in New Zealand is another example of excessive use of a geothermal resource in the 1980s and 1990s when geothermal heating systems were encouraged. Households accessed the geothermal resource under their property for their heating system. The 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 pressure 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, 2012b). Geothermal fields are different and recovery is not always possible. Ohaki is another case where excessive extraction led to lower productivity in a short period of time. The plant was commissioned in 1989 with the capacity of 114MWe. However, the field’s limitation led to production being reduced to as low as 30MWe. Further investment, including drilling new wells, helped to increase the production level to 60MWe but to date the original level has not been restored. There have also been significant environmental effects including subsidence leading to flooding (NZGA, 2012a).

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 the main priority when firms try to cover their operating costs. Developers may not necessarily pay attention to the renewability and sustainability of the resource if the short-term return of the project is high (usually around 30 to 35 years) and is linked to the life of the plant. Economic tools can be used to introduce policies that encourage sustainability when that leads to higher net value for society. In case of geothermal, the aim of the policy should be to reduce the rate of reduction in the temperature of the reservoir, and the depletion rate.

**Taxes and royalties**

“Geothermal power comes close to being a ‘free lunch’, but does not make it. After all, magma should remain hot enough to power a geothermal system for hundreds or thousands of years, long after we will have found alternate energy sources” (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 any economic tool that can encourage better use of the resources. Environmental taxes, subsidies, emission-trading schemes, regulatory instruments to control development, and voluntary approaches are some economic instruments for reducing environmental damage (Milne et al., 2003). These instruments can also be used to stimulate innovation and investment in cleaner and more sustainable technology (Philips, 2010).

Monopoly can be a solution to slow the depleting rate when dealing with scarce natural resources. Absence of competition may slow the extraction rate as firms can offer the same product at a higher price to the market, which, in turn, can encourage the sustainability of the resource. Despite the effect of the demand function, in general, exploitation is likely to take longer time in a monopolistic situation than in a market competition situation (Hotelling, 1931). Considering geothermal generators are the base-load producers for the electricity market higher demand may lead to a higher extraction rate of geothermal resources. In New Zealand, the electricity produced from the geothermal resource is offered for free to the auction but 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 cannot be considered as an option in the New Zealand market scenario.

Voluntary approaches are uncommon unless they contribute towards firms’ 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 case of geothermal, consumers commonly see the resource as being renewable. The complexity around the renewability of geothermal resources makes it more difficult, although not impossible, to rely on voluntary approaches by firms.
Regulation can be used to control the development of natural resources. Well-defined property rights and well-established institutional arrangements can contribute towards efficient use of resources. However, incomplete and inaccessible information may lead to ineffective regulatory instruments. In New Zealand, government has to invest to find the real state of geothermal resources and predict the future while receiving almost no revenue from the development of the resources.

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 important to resource depletion. Taxation is used to internalise the externalities and increase the price to encourage better technologies and the use of substitutes when available. Carbon tax and cap and trade are obvious examples in the literature where taxes are used to reduce the emissions produced as the result of human activities. Absence of a 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 can be used to create price signals for firms and consumers. These internalise the 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). 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 the production. The impact of the tax on the market price may depend 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 effective because it forces suppliers to find more efficient ways to develop the resource or find substitutes and encourages consumers to take a more conservative approach (e.g. energy-saving light bulbs).

Lack of a royalty payment leads to free supply of valuable resources to the market. Government regulation, such as quotas, may limit the use of the resource to ensure sustainability but per-harvest/effort royalty will capture the external cost of the activity (Falk, 1991). “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). The new cost, from royalties, is aiming at adding the depletion cost of the utilisation to the actual cost of development in order to make it more realistic (Bhattacharyya, 2011). Kahn and Goldman (1987) find that the introduction of new taxes or higher cost will slow or delay more capital-incentive projects like wind and small hydro.

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 the wells for those who did not want to continue using the geothermal resource helped to reduce the geothermal extraction from Rotorua geothermal field, which eventually resulted in signs of recovery for the reservoir (Scott & Cody, 2000). 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). The royalty regime was based on a fixed charge on the amount of extracted brine and aimed to reduce the domestic use of the geothermal fluid and encourage reinjection. The Rotorua royalty regime was successful in achieving its goals of preventing household use of geothermal resources and controlling the pressure, although it did not reduce the commercial use of the resource. The successful experience can be used to set new royalties that can contribute towards slowing the depletion of the geothermal resources.

Royalty options

Royalties are a unique form of taxation applied to natural resources and intellectual properties. Royalties are taxes on gross production value. 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, it is essential to first identify the rights holders and the licensee. The evolution of royalties is more complex if the 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). 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 a provision to allow local or central government to collect 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)

Royalty may help to correct the market by imposing a cost to make the price more realistic while it is linked to the discount rate (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 form 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 second, 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 mine puts on the value lost from the resource. Geothermal resources are generally considered to be renewable. However, 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. Involved parties do not always agree on the type of royalties, even if they agree on their existence. This section examines the two main categories of ‘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 unit-based royalty, ad valorem royalty (AVR), sales and excise tax (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, and stamp tax. The first three forms are discussed here as the types of royalties that can be applied to geothermal resources.

Unit-based royalty is a feed fee applied to units of production. It encourages a wiser investment towards a profitable project. 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 by CPI may address this. It may also lead to more complexity in the near future and a higher transaction cost, as there is a need for negotiation at the point of review. Simple
administration, lower volatility, and assurance for an income stream are the biggest advantages of unit royalties (OFaircheallaigh, 1998).

The ad valorem royalty or resource rent royalty (RRR) is a levy on the 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 will be realised when it is extracted and offered to the market.

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. 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.

Opponents again argue that the resource has no value if not extracted and that developers run a significant risk through extraction. However, a risk component part of considerations for severance tax. Severance tax also imposes uncertainty for future income of local government. OFaircheallaigh (1998) suggests a rental payment and a floor price to solve the uncertainty issue for the governing body. However, rental payment and a floor price work against the developers and discourage investment. Royalty on revenue will not capture efforts made by developers, as it does not take into account development cost. Ad valorem royalties do not take the exploration and development cost 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). The royalty rate should be lower when the government is not ready to share the risk. Lower royalty rates attract investors (Bradley & Watkins, 1987). However, a significant concern here is whether to allow geothermal resources to be used as a free source of electricity production.

**In personam taxes**

Income tax, or accounting profit royalty (APR), is another way of charging for the use of the natural resources. It 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 the 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, this may not necessarily lead to a higher market price, and the resource will still be available for free. 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). The income-shifting problem refers to the cost side of the profit calculation when there is asymmetric information (Lund, 2009). Cost has many components and can be used to shift the profit from an entity to another. For example, in geothermal development landowners can apply a higher access fee to lower the operational profit of their electricity plant. This may be more common when landowners are involved in the development. Income transfer can be limited by accepting qualified costs to be included in the profit calculation.

Governments may have incentive to generate more revenue by increasing the tax level when the resource has a 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 makes these an obvious target for governments to generate revenue. It is important to realise that the purpose of tax on resources is not to generate income for governments to balance their budgets. Therefore, careful consideration is required, when dealing with royalties, to incentivise investors whose contribution may generate significant national benefit.

**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 western states. In most cases, state ownership of water resources will automatically secure the ownership rights for government (Bloomquist, 1986). In the USA system, developers have to bid to access the areas that have identified resources.

In New Zealand, there has never been a royalty applied by government for the use of geothermal resources. New Zealand’s petroleum royalty is the maximum of either an ad valorem royalty of five per cent applied to net revenue derived from sale, or twenty per cent accounting profit royalty where profit is determined after allowing for direct and indirect costs (Sharp & Huang, 2011). A percentage of the gross profit will be used for profit-based royalties. “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 AVT royalty applied” (Guerin, 2003, p 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. Landowners usually charge an access fee and a 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 25% of the wellhead value. The minister assesses the value at the wellhead geothermal. It can be taken from the market price of the energy (DMITRE, 1967, 2000). In Australia’s Northern Territory, the Crown owns the resource on behalf of the Territorians. Government can grant exclusive rights for exploration and extraction of geothermal energy. There is no decision on the calculation of royalties ("Northern Territory proposal to introduce a geothermal energy bill,” 2008).

In the American system, royalties applied to the direct use of geothermal resources are calculated differently to the royalties on electricity produced. In case of electricity generation, royalties are based on the price of steam or electricity, while on direct use, royalties 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 2011, California, with 6 geothermal fields, 31 power plants and total production of 425MW of electricity, generated around $9.5 million in royalties (U.S.D.I, 2012). In 2005, California changed its geothermal royalties calculation. Under the new system, geothermal royalty is 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 application 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.

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 is closer to the social price of this natural resource, and slows the depletion rate. An optimisation model is used to study a firm’s behaviour when royalties are used to control the depletion. The model is used to review the options for creating a system that influences the utilisation rate and leads to:

- Better planning in developing geothermal resources that can maintain the temperature and expand the life of the reservoir,
- More efficient technologies that ensure the sustainability of the resource,
- Compensation or user charges for the damage done to the resource.

Ad valorem royalty (AVR) and accounting profit royalty (APR) are the two categories tested through the optimisation model. The first step in the model is to review category A (APR) when there is a royalty charge on the profit. The second step reviews the impact of royalty charges on the revenue gained from the sale of the electricity produced, category B (AVR). Royalty 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 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.

A profit maximisation model with no environmental constraint is used to study the firm’s market behaviour and its reaction to the new policy. The only constraints are those directly related to production. It is assumed that firms are self-interested and seek maximum profit. “Maximising behaviour is accepted as the norm; each decision maker is assumed to be motivated by self-interest and to move efficiently to the most preferred operating position open” (Furubotn & Pejovich, 1972).

The simple model of electricity generation was adopted from Golabi and Scherer’s (1981) work to simulate the optimisation problem:

\[
\text{max: } \Pi_k = \text{Revenue} - \text{Cost} \quad (1)
\]

Subject to:

\[
T^e \geq x = 150^\circ C \quad (2)
\]

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. Production has a direct relationship with the quantity of extracted brine, \(q_{e,k}\), and the temperature of extracted brine, \(T_{e,k}\). The electricity generation level depends on the conversion factor, \(\alpha\), that is used to map electricity produced per litre of brine, as shown in the equation below:
\[ Q_{k,t} = \alpha T_{t,k}^e q_{t,k} \]  

Total production from a reservoir depends on the number of years, t, of the production and the number of firms operating on that reservoir, k. Golabi (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 the profit function will be as follow:

\[ \pi_{t,k} = (P_{t,k} Q_{t,k} q_{t,k}^e - c q_{t,k}^e) \delta^t \] (4)

Firms are assumed to maximise the present value of profit such that the production constraints are met:

\[ \max_{q_{t,k}^e} \sum_{t=1}^{T} \pi_{t,k} = \sum_{t=1}^{T} (\alpha P_{t,k} T_{t,k}^e - c)q_{t,k}^e \delta^t \] (5)

s.t.

\[ R_t \geq \sum_{t=d}^{T} q_{t,k}^e \] (6)

\[ T_{t,k}^e \geq 150^\circ \text{C} \] (7)

\[ q_{t,k}^e \geq 0 \] (8)

Constraint (6) requires the total extracted brine to be less than the total existing brine at any time. Constraint (7) is the limit on the brine temperature that can be used by a generator to produce electricity. The brine temperature is usually more than 150°C to enable a large geothermal electricity plant to operate. Constraint (8) sets extraction at greater or equal to zero. Adding the royalty as a percentage of profit to equation (4) changes it to:

\[ \pi_{t,k} = (1 - r)(P_{t,k} Q_{t,k} q_{t,k}^e - c q_{t,k}^e) \delta^t \] (9)

Equation (10) shows the situation when the royalty is based on the revenue gained from the development:

\[ \pi_{t,k} = ((1 - r)P_{t,k} Q_{t,k} q_{t,k}^e - c q_{t,k}^e) \delta^t \] (10)

The extracted brine is assumed to be only used for electricity production and one hundred percent of the extracted brine is assumed to be reinjected to the reservoir at 120°C. The location 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. The tracer test is important 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 remain constant through the model. The reinjected cold water is assumed to take three years (d=3) to reach the production wells. The amount of the 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 the temperature with the rate of \( \gamma \). Inflow is assumed to be only from the reinjection and not rainwater – rainwater may reduce the rate of recovery. It is also assumed that firms chose a fixed level of production, which they have to keep 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). The temperature change may damage pipes and other equipment attached to the system. It is not economical to apply such changes, unless the price of electricity is so high that it can cover the cost of installing new pipes. 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 generation 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 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).

**APPLICATION**

It is assumed that the existing information allows for a 140 MWe 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, the aim of this paper is to find an economic instrument that encourages developers to come up with more efficient ways to optimise the use of the resource. It is assumed that firms do not have other investment options and are not concerned with the amount of net return on investment. Therefore, firms will invest as long as there is scope for positive net present value of the 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.

Firms will fully utilise the resource when it is beneficial for them to do so, to maximise their profit. Firms are price takers and have to accept the average prices offered by the market. 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 (MED/MT, 2011). New Zealand historical data shows that the electricity price has been increasing with a rate equal to or higher than the inflation rate. According to 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 in the total capital cost. There is no new technological progress and operation costs are assumed to increase at the rate of inflation during the life of the plant.

Data related to the production function and the 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).

Rotokawa II (Nga Awa Purua) is a 140MW 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 1,200GWh of electricity per year (Bouche, 2007). Considering the total yearly production, geothermal fluid extraction per year, and the temperature of the fluid, the conversion factor, \( \frac{m^3}{\text{GWh}} \), can be found to be around 0.00023 (16,425,000 tonnes X 320°C X 0.00023 = 1,200GWh). The temperature of the extracted brine is assumed to be 320°C at the start. 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 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. Geothermal literature shows that the rate of recovery is faster when the temperature is further from the main equilibrium (M. O'Sullivan et al., 2010; Rybach, 2003).

The extraction is restricted to the amount of available brine and also the capacity of the plant. The extracted brine will be reinjected to the reservoir after going through the power generation process. Both revenue and extraction costs depend on the extraction rate, breakthrough point, and the life of the project.

**RESULT AND DISCUSSION**

In case A, accounting profit royalty (APR) works as a tax on the profit generated by the firm before paying any other taxes to the government. Different ratios of the APR are applied to the case but the outcome is unique. A higher rate of APR has not led to change in the firm’s investment and generation plan. It was assumed that firms do not have any other investment options and therefore do not care about the size of the net return when it is positive. Therefore, firms will go ahead with their investment plan even with 99% APR. However, the future investment may be effected,
as less net profit leads to lower availability of future funds.

In case B, the ad valorem royalty is charged on revenue generated by the firm regardless of the investment and production cost. Revenue is calculated using the average market price. Different rates of royalties are applied to review the outcomes. The results show that firms are sensitive to royalties on the revenue and behave accordingly when making an investment and production plan. Three rates of 10%, 20%, and 30% ad valorem royalties are applied to the case. The results show that the higher the royalty rate, the greater the impact on the size of the plant the firm plans to build. Table 1 shows the final results on the investment decision firm makes and the temperature after 35 years of operation.

Table 1: Investment decision – ad valorem royalties

<table>
<thead>
<tr>
<th>Ad valorem royalty</th>
<th>Brine million t/y</th>
<th>Plant size</th>
<th>Temp at year 35</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>16.8</td>
<td>~ 140 MW</td>
<td>150°C</td>
</tr>
<tr>
<td>10%</td>
<td>14.9</td>
<td>~ 124 MW</td>
<td>154°C</td>
</tr>
<tr>
<td>20%</td>
<td>10.5</td>
<td>~ 88 MW</td>
<td>174°C</td>
</tr>
<tr>
<td>30%</td>
<td>7.5</td>
<td>~ 62 MW</td>
<td>206°C</td>
</tr>
</tbody>
</table>

**AN ALTERNATIVE MODEL**

Economic efficiency must be considered when introducing alternatives. 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 the investments will be and thus the lower the rate of temperature drop. The specific amount of the royalty that optimises the extraction rate is unknown.

Finding the right tax level is a major problem with environmental taxes (Maatta & Anttonen, 2006). The aim of this paper is to find an economic instrument that can be used to control the temperature and reduce the depletion rate during the use of a geothermal plant. Therefore, a penalty or user charge on the amount of temperature drop seems reasonable. Firms could pay a compensation fee or penalty for depleting the resource. The ratio of the current temperature to the original temperature could be used as the ratio to calculate the royalties firms have to pay at each stage. Therefore, the royalty ratio would be variable and depend on the temperature at time t relative to the original temperature. The royalty rate would be applied to the revenue earned by the firm at each period to calculate the depletion charge. The new alternative links the royalty to the temperature drop and the revenue earned. It creates an incentive for a voluntary approach to develop the resource in a more efficient way. 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 2 shows the outcome of the study when the variable royalties are applied in comparison to the fixed ad valorem royalty.

Table 2: Royalty as the ratio of temperature at time t to the original temperature, when applied as a variable AVR

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

Using the original assumptions the results show that firms choose a smaller investment and take 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 up front capital investment faced by geothermal developers.

The findings show that the firm makes a lower profit than the situation where there was 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 is the sustainability of the resource. The top solid line in figure 1 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 is better than any other outcome in this study.

![Figure 1: Temperature path – royalties on revenue](image)

**CONCLUSION**

The result shows 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 the revenue can keep the market under control and restrict the size of the development. The findings show that the higher the rate of the royalty the more restricted investments will be, which leads to lower depletion rate. It also shows that a variable ad valorem royalty that is linked to temperature drop can be the best option to control firms’ behaviour in taking care of the 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 charge policy to control the depletion rate of geothermal resources. The case will be more complicated if the resource is shared by multiple developers and require determination of how to share the user charge.

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