Geothermal royalties: an economic solution (Working paper)

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Abstract:
Sustainable development is ensuring that the benefits accruing from resources are left for future generations while also fulfilling the needs of the current generation. Geothermal resources are renewable when developed under controlled levels of extraction. A high rate of extraction can damage the resource or speed up the depletion process, leaving less for future generations. In addition, today's knowledge may not necessarily answer all the questions related to the sustainability of the resource. Today's eco-friendly activities may prove to be harmful in the future. A conservative, step-by-step, approach helps to improve knowledge about the resource and creates opportunities to identify the side effects. It is wise to discourage rapid development when the status of the resource is not fully recognised.

Selected policies must balance the costs and benefits of developments at the margin. Resource extraction may have a wider environmental impact. Royalty payments can be an economic instrument to address the market failure to restrict the exploitation of the resource. Royalties may increase the price to a more realistic level that can balance the needs of both today and the future. A higher cost of the supplied geothermal fluid increases the price of the electricity supplied which, in turn, may encourage better planning. Ultimately, it may increase the value of the resource.

This paper reviews different forms of royalties that can be applied to geothermal developments for electricity production. It analyses and compares the impact of different royalty approaches on a firm's behaviour and whether royalties can guarantee the sustainability of the resource. The result shows that royalties or taxes on profit have no impact on the firm's behaviour. However, royalties on the revenue change firm's behaviour to take a more conservative approach. The results show multiplied effects in reducing the speed of geothermal developments. Therefore, royalties on revenue can be used as an economic instrument to bring the exploitation of geothermal resources down to a more sustainable level.

1. Introduction and background:

Sustainable development is ensuring that the benefits accruing from resources are left for future generations while also fulfilling the needs of the current generation. Geothermal resources are renewable when developed under controlled levels of extraction. A high rate of extraction can damage the resource or speed the depleting process, leaving less for future generations. In addition, today's knowledge may not necessarily answer all the questions related to the sustainability of the resource. Today's eco-friendly activities may prove to be harmful in the future. Ecological sustainability requires deep knowledge and careful scrutiny of our technological choices (Hussen, 2004). A conservative, step-by-step approach helps to improve the knowledge about the resource and creates opportunities to identify the side effects of it. It is wise to discourage rapid development when the status of the resource is not fully recognised.

Fairness, equity and distribution through a time frame that includes future generations must be considered when making decisions on the use and development of natural resources. Market failure in taking care of the scarce natural resources must be corrected by a centralised planner that can impose quantity restrictions by taxation or other economic instruments (Bhattacharyya, 2011). Selected policies must balance the costs and benefits of developments at the margin. Resource extraction may have wider environmental impact and should be well priced to cover the real current and future value of the resource. Royalty payments can be an economic way to address the market failure when there is no market price on geothermal fluid supplied for electricity production. While various royalty methods are used in different countries, the royalty charges have never been used to encourage sustainable development of geothermal resources.

This paper considers royalties as a way to promote sustainable development of geothermal resources. It reviews different forms of royalties that can be applied to geothermal developments for electricity generation. It analyses and compares the impact of different royalty approaches on firms' behaviour and whether selected methods guarantee the sustainability of the resource.

2. Literature:

2.1. Environmental and sustainability issues

"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 is 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).

Efficient use of the resource is about doing the best you can with what you have - your endowment of energy resources (Fisher & Rothkopf, 1989). Although one activity might be encouraged at a particular stage as having proven to be beneficial for society, future data might show disappointing results. Lack of human knowledge leads to uncertainty and increases the risk of any development planning. Resource extraction has a wider environmental impact. A conservative approach to any natural resource development scheme assists to enhance the knowledge about the resource and to identify the side effects of the activity throughout the development period. Any development must take place within sustainable boundaries in order to leave the future generations' share of the resource. 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. 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)

Extraction of mineral resources may contribute towards economic growth but it should be carefully managed. Well-planned policies must ensure the efficient use of the resources. "Government is an important player in the mineral extraction industries, through property right creation and management, licensing and royalties, SOEs, tax expenditures, and environmental regulation" (Sharp & Huang, 2011). The state and characteristics of various resources could differ, and therefore different sets of policies are required to meet future demand while satisfying today's needs. At the end of the day, to keep the resources renewable, the rate of their exploitation should not exceed their regeneration.

Geothermal resources are different from oil because the resource is "continually being replenished by an on-going flow of heat from depth by conduction or by convection of water. The resupply of the heat can be greater than ten precent of the recoverable heat calculated from storage. Experience since then in geothermal systems such as Wairakei-Tauhara and Nesjavellir has demonstrated that in favourable situations recharge can supply a substantial proportion of the heat extracted and can extend the productive life of the resource" (Clotworthy et al., 2010). Therefore, geothermal resources can be renewable if certain conditions are met. It is important to maintain the temperature and pressure in the long run. Developers may not necessarily pay attention to the renewability of the resource if the short-term return of the project is high, usually around 30 years. Firms are profit maximisers and put more value on the net present value of any development they participate in. It is policy makers' responsibility to make arrangements that maintain the sustainability of the resources and address the common pool problems. It is to introduce policies that enforce optimal use of the resources in a sustainable manner while controlling the externalities. Policy makers can either invest in finding solutions for the use of the resources or ask the developers to come up with justified plans that can address the aforementioned issues. A panel of experts, with current knowledge and information, can review the suggested justifications. Nevertheless, there is no guarantee that the existing information and knowledge will remain valid in the near future. Therefore, there is a need for a risk component to be added to the justification of the projects.

2.2. Sustainable development of geothermal resources:

Geothermal development may contribute towards the adequacy and security of electricity supply and eventually lead to higher economic growth. However, the economic growth must not occur at the expense of the environmental damage (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 geothermal reservoir, and change to habitats (Luketina, 2011). Bromley, Mongillo, and Rybach (2006) state that with appropriate management, the geothermal system can be utilised over the long term (~100 years) then be 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 an infinite amount of time (Rybach, 2007). This study will be limited to finding ways of correcting the cooling issues and expanding the life of the reservoir.

Geothermal is not a fully renewable resource (Rybach, 2010; Rybach, Megel, & Eugster, 2000). Under limited production, the geothermal reservoir can be sustained for longer 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 (e.g. The Geysers)" (Rybach & Mongillo, 2006). The regulatory body may force the producers to reinject one hundred precent of the extracted brine to the reservoir and limit the temperature drop to a particular amount, but it cannot stop the temperature drop from its original status. The Geysers, a field of steaming fumaroles located 115 kilometres north of San Francisco in California, was predicted to produce 3000 megawatts of electricity by 1990. However, the development stopped at around 2000 megawatts. Involved parties came to realize 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 1500 megawatts and developers started to condense and reinject some of the used steam back to the ground to help the reservoir recover. David Anderson, director of the Geothermal Resources Council in Sacramento, believes that nothing should be taken for granted until everything about the reservoir is clear (Kerr, 1991).

M. J. O'Sullivan and Mannington (2005) show that it may take 300 years for Wairakei geothermal reservoir in New Zealand 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). Information about a reservoir is never perfect. Although the initial information is gathered through exploratory drilling and testing, monitoring the real response to the extraction will show the actual behaviour of the reservoir. The 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 take years until the reservoir's real behaviour is known (Axelsson, 2010). Therefore, a mechanism must exist to slow the extraction process and the size of it to allow for better understanding of the reservoir's behaviour. Taxes, voluntary agreements, subsidies, regulations, and information campaigns can be used to stimulate innovation and investment for cleaner and more sustainable technology (Philips, 2010). In New Zealand's current market situation, the electricity generated from geothermal resources is offered for almost free to the market and there is no penalty for driving the temperature of the reservoir down. Therefore, future generations may have to pay a high price for the remaining poor quality resources, if there are any left. The question here would be whether the geothermal fluid should be available for free to the market, as it is now, or if there should be any charge for that.

Monopoly is one solution to consider in relation to the exploitation of scarce natural resources. It may remove the competition and slow the extraction rate, which, in turn, will encourage the sustainability of the resource. However, the production rate will be affected by the demand function (Hotelling, 1931). Considering geothermal generators as the base-load producers for the electricity market, especially in New Zealand, higher demand may lead to a higher extraction rate of geothermal resources. In this sense, geothermal plants work as price takers. The electricity produced is offered for free to the market and the final auction price is where supply and demand intersect. Therefore, the geothermal developers do not necessarily act as efficient as monopolistic firms. The competitive nature of the market puts the sustainability of the resource at risk. The risk is triggered when the resources are offered for free to the generators who can stay in the market as long as they cover their operations' costs. Pricing the geothermal fluid or penalty on the damage may change the scenario.

2.3. Market situation for geothermal fluid

"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. In practice, however, it is hard to balance the rate of steam or water production to the rate at which water is recharged to the system, and the drilling and pumping perturb the chemical balance of the system" (Kesler, 1994, p. 159). The State has the ownership of the geothermal resources in Alaska and Western States of the U.S. In most cases, state ownership of the water resources will automatically secure the ownership right for government (Bloomquist, 1986). In New Zealand, the Crown has ownership of the water resources and regulates the access. Geothermal resources are natural resources belonging to the nation and are regulated by the Crown and local governments. In the U.S. system, developers have to bid to access the areas that have identified resources. In New Zealand, landowners have access to the resources but need local government approval and have to obtain consent for the use of resources.

In New Zealand, the landowners have the right to charge an access fee for granting access to geothermal resources on their land. However, there has never been a royalty charge that can contribute towards resource sustainability. The royalty charges can also be used for further research and exploration. A careful consideration is required to find the rentals, access fees, royalties, and duration of the consent.

Environmental taxes, subsidies, emission-trading schemes, regulatory instruments to control the development, and voluntary approaches are some economic instruments for reducing the environmental damage (Milne, Ashiabor, Cavaliere, Deketelaere, & Lye, 2003). State involvement in the development of natural resources is necessary to secure an adequate share of the economic rent associated with resource depletion. It is important to internalise the externalities by considering the environmental effects and future generations' share of the natural resources. The aim is to stop the developers from gaining excessive profit from free resources while reducing the availability of the resources for future use. In the absence of government regulations, firms only consider the accounting profit by using tangible data. This is more evident when there is no market and no price for certain natural resources. It may lead to overdevelopment and overexploitation of the resource. "The real problem with water resources, for example, is that they are over-allocated because they are not priced" (Sharp, 2012).

2.4. Are royalties the answer?

Voluntary approaches are uncommon unless it contributes towards firms' long-term profitability, if they consider it. Voluntary approaches to reducing the externalities are only possible if there are strong economic incentives (Milne et al., 2003). Tax may be a solution to reduce the externalities. Tax on suppliers adds the external cost to the production of goods. It shifts the supply curve up to the social cost level. It is necessary to impose the tax when suppliers are not ready to bear 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.

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 to the auction hoping that the conventional electricity generators will submit a price higher or equal to their marginal cost that will eventually lead to a higher market price for electricity. Therefore, the final price depends on the offers received from the conventional fuel generators and the demand at any particular time (Evans & Meade, 2005). Hence, the geothermal generators are price takers and have little power to pass the extra cost to the consumers in the short run. Figure 1 shows an approximate demand and supply curve, S_1, for New Zealand's electricity market. The left hand side of the supply curve with the lower price range covers the prices offered by wind, hydro, and geothermal power generators. The right hand side of the supply curve with the higher price range covers the bids offered by thermal generators. The graph shows that, in the short-run, the increase in the price of the renewable resources (left hand side of the supply curve) will not increase the electricity price significantly. This may make it more difficult for the unconventional generators to operate, with a higher cost. In the long-term the new supply curve, S_2, may push the price up with unconventional generators offering the electricity produced to a price higher than zero. Therefore, it will force the market to adjust with the real value of the resource.

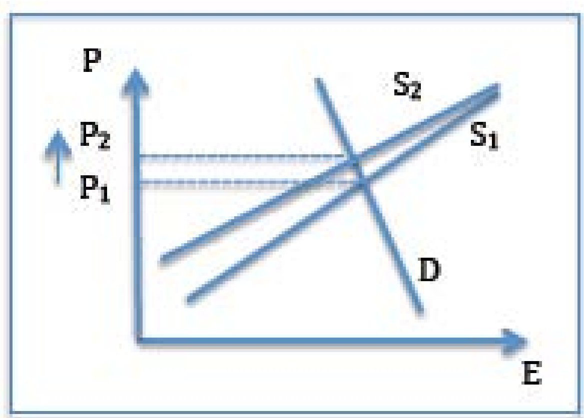

Figure 1: Wholesale electricity supply and demand – example from New Zealand

The X-axis shows the quantity of electricity and the Y-axis shows the price of it. S_1 is the supply curve before any tax and D is the demand curve. New Zealand electricity demand curve has a very steep slope. It might move to the left or right depending on the timing of the day or the season, peak and off-peak. P_1 stands for the market equilibrium price before any tax. Tax on suppliers may shift the supply curve up to S_2, although there is no guarantee. Unconventional generators may still offer their produced electricity for free, depending on market conditions.

Taxation might acquire the nation's share from the use of the geothermal resources, but lack of a royalty payment leads to free supply of this valuable resource to the market. Government regulation, such as quotas, may limit the use of the resource to ensure the sustainability but per-harvest/effort royalty will capture the external cost of the activity (Falk, 1991).

Royalties can be an answer to address the issue. The new cost, from royalties, is aiming at adding the social cost of the utilisation to the actual cost of development in order to make it more realistic (Bhattacharyya, 2011). The wholesale price of electricity may rise in the long run, which in turn will increase the electricity price in the consumers' market. The public will make the final decision by moving or not moving the marginal social benefit curve (demand curve). It will be more beneficial for the nation not to have the geothermal developments if the price does not cover the cost. Kahn and Goldman (1987) found that the introduction of new taxes or higher cost will slow or delay the more capital-incentive projects like geothermal and small hydro. The inclusion of real cost will encourage the investment to happen at the right time and when it is required (Golabi & Scherer, 1981).

"Royalty is an owner's claim to net resource value" (Bradley & Watkins, 1987). It is a an option to attach a price to the available resources based on the realised value of the resources (Lund, 2009). The 'resource rent royalty' (RRR) is a levy on the net cash flow. It considers the revenue gained from using the resource. The pure rent tax (PRT) considers the cost of the operation to find the profit while the RRR only considers the gross revenue. Different types of royalties are discussed later in this paper. This study concentrates on creating a mechanism that can encourage a more sustainable development approaches for geothermal resources.

Royalty may increase the price to a more realistic level that can balance today's and future's needs. It may assist in reducing the depletion rate. Royalties may help to correct the market by imposing a cost to make the price more realistic while it is linked to the discount rate – showing the future value of the resource (Fisher & Rothkopf, 1989; Sutherland, 1996). Royalties are similar to Pigouvian tax which is used to charge for the marginal environmental damage (Bhattacharyya, 2011).

In 1987, the introduction of royalty payment and voluntary ceasing of the wells for those who did not want to continue the use of the geothermal resource helped to reduce the geothermal extraction from Rotorua geothermal field, which eventually resulted in signs of the 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 the fixed charge on the amount of extracted brine and aimed at reducing the domestic use of the geothermal fluid and encouraging reinjection. The Rotorua royalty regime was successful in achieving its goals, although it did not reduce the commercial use of the resource. The successful experience can be repeated again by introducing the royalties on the commercial use of geothermal resources in New Zealand.

3. Economic model

Although royalties are being used as a source of income from the geothermal resources in many countries, they have never been used as an economic instrument to restrict the exploitation of the resource. Royalty payment can also be used in studying the changes to surface thermal features and the impact of geothermal developments on the sustainability of the resource. The inclusion of the social cost to the price of the geothermal fluid will lead to the establishment of a real price for the resource.

An optimisation model is used aiming at studying firm's behaviour when royalties are added. The model is used to review the options for creating a market that lead to:

- A conservative approach in developing geothermal resources that can maintain the temperature and expand the life of the reservoir,
- Compensation for resource exhaustion,
- Encourage the developers to come up with more efficient technologies that ensure the sustainability of the resource while planning for new projects.

Royalties on profit and revenue are the two categories tested through the optimisation model. The first part is to review category A when there is a royalty charge on the profit. The second part reviews the impact of the royalty charges on the revenue gained from the sale of the electricity produced. Both models will use the current average electricity price and assume that firms use 100% of the extracted brine for electricity production and reinject 100% of the brine back into the reservoir. The characteristics of geothermal systems may vary significantly between different geothermal fields. Therefore, finding a production model that works for every individual resource may not be possible. However, all models share some general behaviour that can be used to develop a generic production model. A simple production model was adopted from Golabi and Scherer's (1981) work to simulate the optimisation problem. The aim is to maximise the profit, as any firm does, by using the production function below with production constraints:

$$\text{Max: } \Pi = R - C \qquad (1)$$

Subject to:

$$T_i \geq x = 150\,°C \qquad (2)$$

The profit function is the difference between revenue gained by generating electricity and the cost of production. Firms are assumed to behave as profit maximising entities. There is no environmental constraint as the model studies the firm's behaviour in a free market. The production function is subject to the availability of brine at a given temperature, T_i, higher than a certain level ($T_i \geq x = 150$°C). It is assumed that the brine temperature must be at least 150°C for electricity production development. The production function has a direct relationship with the quantity of extracted brine, $q^e_{t,k}$, and the temperature of the extracted brine, $T^e_{t,k}$. The electricity generation level depends on conversion factor, α, that is used to map electricity produced per litre of brine, as shown in equation below:

$$Q_{k,t} = \alpha T^{e}_{t,k} q^{e}_{t,k} \quad (3)$$

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*. Total profit from the development of a geothermal reservoir depends on the net present value of the revenue gained and the cost of production (c), including operation and fixed cost, by different operating firms. Golabi (1981) shows a positive relationship between the extraction rate and discount rate and a negative relationship between the extraction rate and the future energy price. Using δ^t as the discount rate the profit function will be as follows:

$$\pi_{t,k} = (P_{t,k} Q_{k,t} q^{e}_{t,k} - c q^{e}_{t,k}) \delta^{t} \quad (4)$$

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

$$\max_{q^{e}_{t,k}} \sum_{t=1}^{T} \pi_{t,k} = \sum_{t}^{T} (\alpha P_{t,k} T^{e}_{t,k} - c) q^{e}_{t,k} \delta^{t} \quad (5)$$

s.t.

$$R_t \geq \sum_{t-d}^{T} q^{e}_{t,k} \ \forall t \quad (6)$$

$$T^{e}_{t,k} \geq 150°C \quad (7)$$

$$q^{e}_{t,k} \geq 0 \quad (8)$$

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 generator to produce electricity. The brine temperature should usually be more than 150 $°C$ to enable a large geothermal electricity plant to operate. Constraint (8) sets the extraction at greater or equal to zero. This constraint assumes that extraction is not negative. Adding the royalty as a percentage of profit to equation (4) changes it to:

$$\pi_{t,k} = (1-r)(P_{t,k} Q_{t,k} q^{e}_{t,k} - c q^{e}_{t,k}) \delta^{t} \quad (9)$$

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

$$\pi_{t,k} = ((1-r) P_{t,k} Q_{t,k} q^{e}_{t,k} - c q^{e}_{t,k}) \delta^{t} \quad (10)$$

One hundred percent of the brine is assumed to be reinjected to the reservoir. Cold water is assumed to take three periods, three years, to reach the production wells (d=3). 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 γ. 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 can choose a fixed level of production and have to keep it approximately the same for the entire life of the plant. It is generally difficult for the geothermal plants to regularly vary the production rate. The temperature change will damage the pipes and other equipment attached to the system. It will create cracks in the long run and it is not economical to apply such changes, unless the price of electricity is so high that it can cover the cost. However, it is assumed that there will be no change throughout the life of the plant.

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

4. Application

Through this model a case study is introduced to review and compare the effect of geothermal development on the temperature when there are royalty charges on profit, case A, in comparison to when royalties are based on the generated revenue, case B. It is assumed that the existing information allows for 140 MW plant development. There is only one landowner and the developer has full access to the entire reservoir and can therefore use the optimal location 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 review is to find the first best option to add charges to geothermal developers that force or encourage them to take a more conservative approach in developing the resource and/or come up with more efficient technologies that can optimise the use of the resource.

It is assumed that firms do not have any other investment option and do not care about 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. Case A assumes that there is a royalty charge on the profit made by the firm. In this case royalty works as a tax on the gross income generated by the firm before paying any other taxes to the government. Case B assumes that there is a royalty charge on the revenue generated by the firm, regardless of the investment and cost of production. Revenue will be calculated using the average market price. 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 are assumed to be profit maximisers. They 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 market. This in turn is true for the geothermal power companies in New Zealand as they offer their generated electricity for around $0 to New Zealand wholesale auction and accept the equilibrium price that comes from the auction. New Zealand's wholesale electricity price is on average around $60-70/MW. The electricity price for this work is set at NZ$60/MW and is assumed to increase by 3% per year. 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 the New Zealand Treasury information, the discount rate for infrastructure is set to 8% per annum (NZ-Treasury, 2008). The life of the project is assumed to be 35 years. The cost of wells and the initial stages of testing are embedded into the total capital cost. There is no new technological progress and the operation cost is assumed to increase by the rate of inflation during the life of the plant. The level of production is limited to the available technology and installed plant.
Data related to the production function and the characteristics of the reservoir are from Rotokawa II (Nga Awa Purua) 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 operational cost is 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). The extraction is limited to the mentioned yearly geothermal fluid. Considering the total yearly production, geothermal fluid extraction per year, and the temperature of the fluid, the conversion factor, α, 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 $^\circ C$ at the start. It is also assumed that the reservoir temperature will increase with a rate of 1% per year, 100 years' recovery, 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. It is shown that the rate of recovery is faster when the temperature is further from the main equilibrium (M. O'Sullivan, Yeh, & Mannington, 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 the extraction cost depend on the extraction rate, breakthrough point, and the life of the project. The optimal extraction rate is found through computer programming, GAMS.

4. Results and discussion:

In case A there is a royalty charge on the profit made by the firm. In this case royalty works as a tax on the gross income generated by the firm before paying any other taxes to the government. Different ratios of the tax were applied to the case but the outcome was unique. In all cases, the firm has not changed its behaviour and has produced exactly the same amount. The investment decision is the same and the firm is going for the same capacity production as long as there is a positive net return. It was assumed that firms do not have any other investment option and therefore do not care about the size of the net return when it is positive. The study shows that even with 99% royalty/tax imposed on the profit, the firm has not changed its investment and production behaviour.

In case B there is a royalty charge on the revenue generated by the firm, regardless of the investment and cost of production. Revenue is calculated using the average market price. Different rates of royalties are applied to review the outcomes. The results show that firms are very sensitive to the royalties on the revenue and behave accordingly when making an investment and production decision. Three rates of 10%, 20%, and 30% royalties on the revenue are applied to the case. The results show that the bigger the royalty rate, the greater the impact on the size of the plant that the firm is planning to build. The final temperature for the cases with the highest royalty is significantly higher than the original case after 35 years. Therefore, the policy can be more successful in restricting the developments to certain amounts without putting it into any policy. It is important to note that this can only be a short-term solution. The prices can go up in the long term, which may lead to the resources becoming more economical to develop, and the exploitation will expand. However, the final market decision is made by the nation after considering the net social benefit against the social cost. Figure 2 shows the temperature path for the 4 different cases when the royalty is imposed on revenue. Series 1, 2, 3, and 4 are showing the cases when there are 10%, 20%, and 30% royalties respectively.

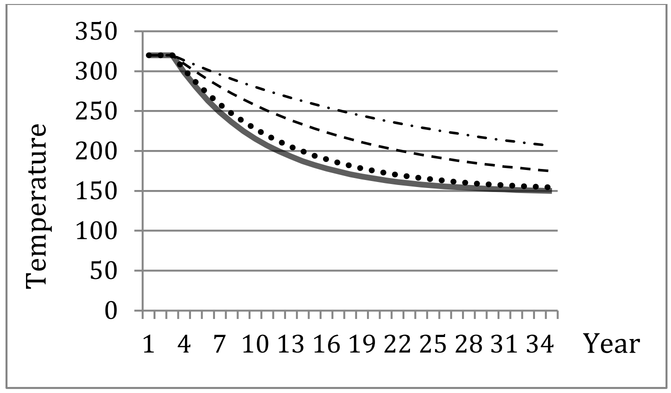

Figure 2: The impact of royalties on reservoir's temperature

This case study shows that, in a situation when the market fails to control the development of geothermal resources to a sustainable level, 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 the investments will be. The study shows that royalties on the profit have no impact on the firm's decision about the size of the investment.

5. Conclusion:

Geothermal resources are renewable when developed under controlled levels of extraction, when the rate of extraction is smaller than the rate of regeneration. A high rate of extraction can damage the resource or speed the depleting process, leaving less for future generations. Ecological sustainability requires deep knowledge and careful scrutiny of our technological choices, which may require time to develop. Market failure in taking care of the scarce natural resources must be corrected by the government, which can impose quantity restrictions by taxation or other economic instruments.

Fairness, equity and distribution through a time frame that includes future generations must be considered when making decisions on the use and development of natural resources. This paper, as a means to restrict the exploitation size, suggests royalties. Although royalties are being used as a source of income from the geothermal resources in many countries, they have never been used as an economic instrument to restrict the exploitation of the resource. Royalties can be on profit or revenue. Using the previous studies and the mathematical modelling around geothermal development, a production model was developed to study and compare the outcome of a 140 MW geothermal plant development with royalty charge on the profit in one case and on revenue in another case. Data from the Rotokawa reservoir in New Zealand was used in the optimisation model.

The study shows that royalties on the profit has no impact on a firm's decision about the size of the investment. However, the study shows that royalties on the revenue changes the firm's behaviour when developing the resources. Indeed, the higher the rate of royalty is, the more careful firms are in planning for new plants. The firm in this case decides to go for a smaller plant when the royalty charge on revenue increases. The impact is multiplied when the royalty rate is increased to a higher level. Therefore, this case study shows that, in a situation when the market fails to control the development of geothermal resources to a sustainable level, introduction of royalties on the revenue keeps the market under control to restrict the size of the development to a more sustainable level. Therefore, a high rate of royalty on revenue is suggested as an economic instrument to restrict the size of geothermal developments to a level closer to the sustainable level of extraction.

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