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OPTIMAL UTILIZATION OF ENERGY RESOURCES

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This paper is concerned with establishing general principles that should guide the extraction of New Zealand's energy resources. These principles are based on the objective of promoting the general economic and social benefit obtained from the use of the extracted fuel. For a single resource, the central question to be answered is, simply, what quantity of energy should be extracted in each year of the resource's lifetime. For the energy system as a whole the additional question must be answered of what mix of fuels should be used in any year. The bulk of the paper is concerned with the analysis of optimal management of a single energy resource. The general principles for optimal resource extraction are derived, and then applied to the examination of the characteristics of the optimal time paths of energy quantity and price; to the appraisal of the efficiency, in resource management, of various market structures; to the evaluation of various energy pricing policies; and to the examination of circumstances in which market organisation is inefficient and the guidelines for corrective government policy in such cases.

1. PRINCIPLES FOR OPTIMAL RESOURCE MANAGEMENT

The social objective of the management of an energy resource is the maximisation of the net benefit obtained from its use. This net benefit has two dimensions. Within any year it is the net contribution of the energy to the economy, i.e. it is the value in use of the energy less the value of the resources used in its extraction and processing. Also, the resource will last for several years and use value will be derived over its entire life. These two dimensions can be incorporated into a single measure: total present value. This is the total present (or discounted) value, over the lifetime of the resource, of the net benefit obtained from the use of the energy. It can be formally stated as:

$$\text{Total Value} = \sum_t \frac{\text{Use Value}_t - \text{Costs}_t}{(1 + r)^t}$$

where the numerator is the net benefit obtained from the energy extracted in year t and r is the social rate of discount.

The design of extraction policy involves, in essence, selecting the quantity of the resource to extract in each year, subject to the physical constraint that total extraction cannot exceed the initial size of the resource deposit. The design of an optimal extraction policy can therefore be formally expressed as the selection of the sequence of quantities, Q_t, to

$$\text{maximise Total Value, i.e.} \sum_t \frac{\text{Use Value}_t - \text{Cost}_t}{(1 + r)^t}$$

subject to $\Sigma Q_t \leq R$,

where R is the initial size of the resource.

The characteristics of an optimal extraction policy can be derived as follows. Consider any feasible sequence of production quantities, Q_t. Let V_t denote the present value of the benefit obtained from the last unit of Q_t, i.e. V_t is the contribution to economic welfare of the last unit of production in year *t*. If the extraction policy is such that the V's are not equal in all years, then a redesign of the policy can increase the total value obtained from the resource. For any adjacent years where V_t exceeds V_{t+1}, the shifting of one unit of production from $t + 1$ to t will increase the total value obtained from the resource by $(V_t - V_{t+1})$, i.e. by the value gained from extra energy in *t* less the value lost from having less energy in $t + 1$. In fact, for any years for which the V's are unequal, the total value of the resource will be increased by shifting some production away from the years of lower marginal value and into those of higher value. Generally, only some production will be shifted in this way; there will remain some extraction in every year. If V_t exceeds V_{t+1} and some production is shifted from $t + 1$ into t, the difference between the V's narrows and disappears. Additional energy in *t* will be devoted to less productive uses, as the most productive applications are made first, so the net benefit, V_t, of this energy declines. Meanwhile, as less energy is consumed in $t + 1$, the benefit obtained from the marginal unit increases, as less productive uses are curtailed, leaving progressively more important uses. The shifting of production causes the difference $V_t - V_{t+1}$ to be reduced; sufficient re-allocation will bring the two into equality. Once the V's are equal, re-allocation of production will not increase the total resource value, as the loss from reducing production in one year exactly offsets the gain from increased production at some other time. In short, then, if the V's are not equal, a re-design of extraction policy can increase the social value obtained from the resource but if the V's are equal, this value cannot be increased by production re-allocation. The extraction policy for which the V's are equal is, therefore, optimal. This condition for optimal management of a resource can be more formally stated as:

> the time pattern of quantity extraction should be such that V_t, the present value of the net benefit obtained from the last unit extracted in year *t*, is the same for all years.

The formal derivation of this result can be briefly outlined. If the net benefit from the total energy extracted in year *t* is $U(Q_t) - C(Q_t)$, use value of Q_t less its extraction costs, then the optimal extraction policy is the set of Qt's that:

$$\text{maximise} \quad \sum_t (1 + r)^{-t} \quad (U(Q_t) \;-\; C(Q_t))$$

$$\text{subject to} \qquad \Sigma Q_t \leq R$$

The conditions for this constrained maximum include

$$\frac{U'(Qt) - C'(Qt)}{(1 + r)^t} = s \qquad \text{for all } t,$$

where $U'(Qt)$ and $C'(Qt)$ are, respectively, the use value and the cost of the last unit of Q_t. This condition is precisely that obtained above - the present value of the net benefit obtained from the last unit produced in year t should be the same for every year.

This condition for optimal extraction is relatively simple, yet it has many powerful implications. We now examine the more important of these.

2. GENERAL FEATURES OF OPTIMAL EXTRACTION PATTERNS

(2.1) Time paths of optimal energy prices

When energy is sold, consumers are generally able to purchase whatever quantities they desire at the ruling price. In this case, purchases proceed until the use value of the last unit of energy purchased exactly equals its price. Therefore, the optimality condition can be expressed as

$$(1 + r)^{-t} \ (pt - ct) \ = \ s$$

where c denotes the marginal extraction and processing cost of energy. The optimal price can be derived from this condition; it is

$$pt \ = ct \ + \ s(1 + r)^t$$

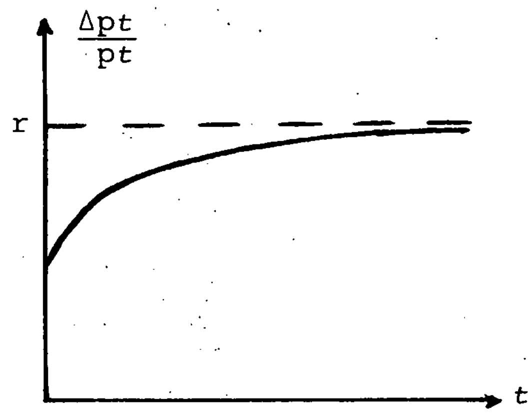
(It should be noted that prices and costs are in constant dollars, i.e. after the effects of inflation have been removed.) The level of pt depends on s which, in turn, depends on demand conditions and the size of the resource, both of which are variables specific to the problem being analysed. However, the rate of change in the optimal price is, except in the unlikely event that costs decline rapidly over time, positive. Therefore, in virtually all cases, the optimal real energy price rises over time.

The specific time profile of these optimal prices depends on the behaviour of marginal costs, ct. One typical case is that of constant marginal extraction cost.

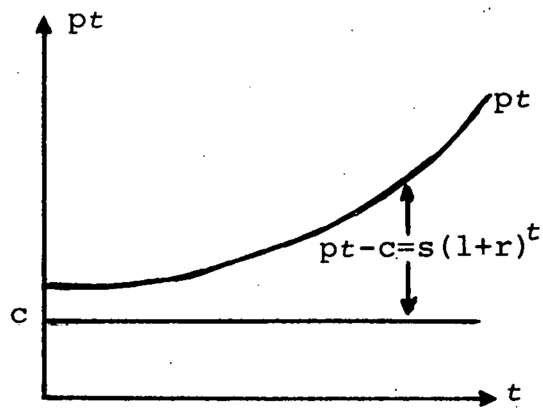
This might apply, for example, in the case of a natural gas field. Here, the rate of increase in the optimal price is

$$\frac{\Delta pt}{pt} = \frac{r}{1 + \frac{c}{s(1 - r)^t}}$$

Therefore, the price should increase over time at an increasing rate, with the rate of increase approaching r. This gives pricing behaviour as:



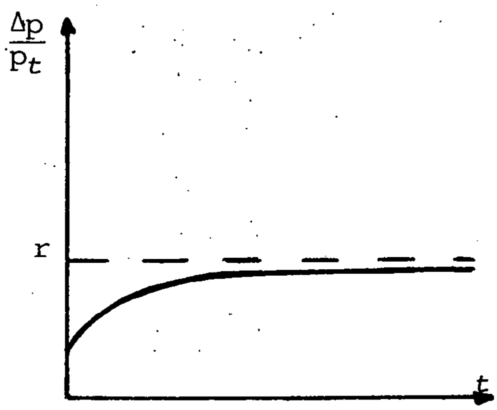
Optimal price growth
Figure I



Optimal price level
Figure II

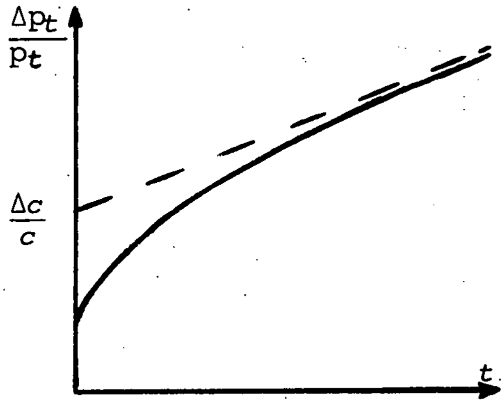
As an example, if the real discount rate is 5% per annum then the optimal energy price rises at a rate approaching 5%. If inflation is proceeding at 10%, then the current dollar energy price should increase at 15% annually.

A second typical case is where marginal extraction cost rises over time. This would be expected in cases where significant depletion effects lead to higher extraction costs, e.g. coal extraction becoming more costly as deeper or thinner or less accessible seams are mined, or oil being extracted by primary, secondary then tertiary recovery methods, or oil being taken from progressively less accessible fields. Here, the optimal energy price rises at a rate between the rate of increase in c and r. Over time, the rate of price increase approaches whichever is larger of r or the rate of increase in c. The two possible time paths for the rate of increase of p are:



Optimal price growth
if r exceeds Δc/c

Figure III



Optimal price growth
if Δc/c exceeds r

Figure IV

(2.2) Time Paths of Optimal Energy Quantities

The quantity pattern of the optimal extraction policy depends critically on the nature of the demand for energy. Drawing on the conclusions about optimal pricing, the price of energy rises at a rate of (approximately) r per annum. As a reasonably general characterisation of demand, consider that demand for this energy form grows at an annual rate g and that the price elasticity of demand is ε. This gives, in continuous time,

$$pt = a\, e^{rt}$$
$$Qt = b\, e^{gt}\, pt^{-\varepsilon}$$

so that the optimal extraction quantities are

$$Qt = (b\, a^{-\varepsilon})\, e^{(g - \varepsilon r)t}$$

and the rate of increase of these quantities is

$$\frac{\Delta Qt}{Qt} = g - \varepsilon r$$

Therefore, the optimal extraction quantities change over time in a regular pattern depending on only three variables - the underlying growth in demand, the price elasticity of demand, and the discount rate. This growth rate can be positive, zero, or negative, depending on the values of these parameters; information about the specifics of a problem is needed to calculate the actual growth rate. Consider several representative cases.

(a) There is no underlying demand growth, $g = 0$. Here, the optimal growth in quantity is $-\varepsilon r$, which is negative; quantity should decline over time. Optimal extraction involves rapid depletion early in the life of the resource, with annual production then declining over time.

(b) Typical energy demand conditions. Probably the most meaningful single value for the underlying growth in demand for energy is 3.25 percent per annum (comprising one percent, due to population increase, plus 2.25 percent, due to a 2.5 percent growth in real per capita incomes and an income elasticity of demand of 0.9). If the price elasticity of demand for energy is 0.5, also a typical figure, and the real discount rate is 5 percent then the optimal quantity growth rate is 0.75 percent. This is a very slow increase in production, despite the significant increase in underlying demand. In fact, the optimal energy growth rate is less than population growth (energy consumption per capita falls), and much less than the rate of economic growth (the energy intensity of production, or the energy : real GNP ratio, falls significantly).

(c) Fast growth in energy demand. Consider the same parameters as in (b) except that the income elasticity of demand has the very high value of 2, so that g is 6 percent. In these conditions, the optimal energy quantity grows at an annual 3.5 percent, the same as the general economic growth rate. Here, the optimal use of energy implies a constant energy: real GNP ratio, but the significant feature of this result is that it takes such strong conditions to generate this behaviour. In general, optimal energy use rises more slowly than general economic production and consumption.

(d) Low price elasticity of demand for energy. A figure of 0.15 is very low as an empirical estimate of energy demand elasticity. For this elasticity, but with other parameters as in (b), the optimal energy use growth rate is 2.5 percent. This growth is still significantly below the rate of economic growth, of 3.5 percent, and reinforces the conclusion that even under extreme assumptions, the optimal energy: real GNP ratio will decline.

(e) High energy demand elasticity. A value of 1 is relatively common as an estimate of the medium-term price elasticity of demand for energy. This value, with the other parameters from (b), implies that optimal energy policy would involve an annual decline of 1.75 percent in energy production. Therefore, in quite feasible circumstances, optimal policy would involve a steady reduction, over time, in the level of energy used.

(f) Low discount rate. Consider the case of the discount rate being zero, i.e. today's decision-makers see no difference between income or enjoyment today and at any time in the future. Optimal energy extraction would grow at 3.25 percent in this case, slightly less rapidly than the economy.

The conclusions as to the nature of the optimal time pattern of energy production can be summarised in four general points:

- there can be relatively large differences in the optimal policy depending on the numerical values of the three critical parameters;
- in not atypical cases, optimal extraction involves declining energy production (in absolute terms, as well as per capita and per dollar of real GNP);
- in typical conditions, optimal extraction involves a rise in per capita energy use over time;
- in most conditions, optimal energy quantity rises less rapidly than the economy (the energy: real GNP ratio falls over time).

(2.3) Efficiency of Extraction in Competitive Markets

If extraction takes place under competitive market conditions then the extraction pattern will be socially optimal. It is taken that each producer plans his extraction so as to maximise the present value of his profits. Thus, he selects his quantities so as to:

$$\text{maximise} \quad \Sigma\ (1 + r)^{-t}\ (\text{Revenue } (Qt) - \text{Cost } (Qt))$$

A necessary condition for this profit maximum is

$$\frac{\text{marginal revenue } (Qt) - \text{marginal cost } (Qt)}{(1 + r)^{t}} = d \text{ for all } t.$$

In a competitive market, marginal revenue equals the price. In turn, price indicates what consumers are willing to pay for the energy, so price gives the marginal use value of Qt. Therefore, extraction will be such that

$$\frac{\text{marginal use value } (Qt) - \text{marginal cost } (Qt)}{(1 + r)^{t}} = d \text{ for all } t.$$

This is precisely the condition for optimal resource management, that the present value of marginal net benefit from extraction is the same in all years. Hence, the extraction pattern produced in a competitive market is socially optimal. There are some qualifications to this conclusion developed later in this paper but the general conclusion remains that leaving energy resource management to competitive market force will result in socially optimal management of these resources. Conversely, there are no general grounds for criticism of the market system as a mechanism for managing a nation's energy resources.

3. SOME FACTORS INFLUENCING OPTIMAL EXTRACTION

(3.1) Competing Fuels; Demand Conditions

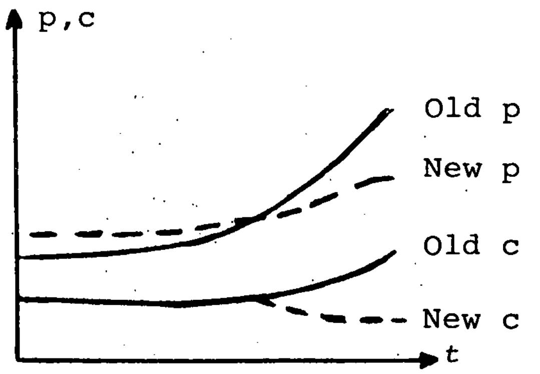
The optimal depletion of a particular energy resource will be markedly affected by the prices and availabilities of other energy sources and fuels. Compare the optimal extraction of a resource under two sets of conditions: continuation of present conditions in other fuel markets, and greater future availability and lower prices of other fuels. Prices of other fuels might fall because of a collapse in OPEC, or the discovery of huge, low cost new resources in New Zealand, or the discovery of low cost new technologies for electricity generation. In the status quo case, optimal depletion of the specified resource involves quantity growth at rate $g - \varepsilon r$. In the alternative case, competition from low price substitute fuels reduces the underlying growth in demand for this fuel to $g - d$, and the optimal growth rate to $g - \varepsilon r - d$. The future availability of cheap substitute fuels therefore reduces the optimal growth of use of the specified fuel, changing the extraction pattern to relatively greater use in the present (to make more use of this fuel while it is still in comparatively high demand), and relatively less use in the future.

The converse case of the effect of reduced future availability of alternative fuels can be analysed similarly. Some possible causes of increases in the future prices of alternative fuels are increasing world scarcity of oil, or because OPEC further exploits its power to raise oil prices or because of increases in electricity prices as may be caused by a decision not to use nuclear power. Any such change would make alternative fuels more expensive, diverting demand towards the energy form under consideration. This would increase the underlying growth rate of demand for this energy, raising the optimal quantity growth rate from $(g - \varepsilon r)$ to $(g - \varepsilon r + d)$. This means that the optimal extraction policy would involve reduced initial supply, with production then rising more rapidly. In short, optimal policy involves the shifting of extraction towards the future, towards the time of relatively high demand for the resource.

Demand for a fuel can change independently of prices and availabilities of other fuels. For example, demand would be reduced by energy conservation practices, or by a reduction in the rate of economic growth while the introduction of new energy-intensive goods and services would increase demand. These changes alter the underlying demand growth rate and therefore the optimal rate of increase in production. Faster demand growth shifts the optimal extraction pattern towards the future, slower demand growth shifts it towards the present. In either case, production is shifted towards the time of relatively higher demand.

(3.2) Extraction Costs

Any extraction policy is based upon specified extraction and processing costs. A change in these costs will alter the optimal quantity sequence. These effects can be illustrated by examining the effects, on optimal quantities, of the future introduction of a new, low cost extractive technology. Optimal extraction is now based upon lower future costs so will involve lower future prices and, correspondingly, higher future quantities. Less is available for present use so, to reduce present demand, prices must initially be higher. In short, extraction is delayed, the resource is partially conserved until the reduction in the cost of extraction permits a greater net benefit from each unit of energy.



Effect of Costs on Prices

Figure V.

(In the converse case of a rise in future extraction costs, extraction should be accelerated so that more production occurs in the present, when cost conditions are comparatively favourable.)

(3.3) The Discount Rate

In business decisions, the discount rate is related to market interest rates. A systematic change in these interest rates will alter the discount rate and this, in turn, will alter the time-pattern of resource extraction.

A reduction in the discount rate increases the value of future, relative to present, benefit; optimal extraction policy responds by delaying production in order to gain this higher benefit. Formally, the optimal quantity growth rate rises from $(g - \varepsilon r)$ to $(g - \varepsilon(r-d))$ i.e. by εd. This implies that future production is greater, which permits less present production. Therefore, a reduction in the discount rate twists the optimal extraction pattern, with less initial production, a faster growth in production, and more future extraction. Conversely, a rise in the discount rate reduces the present value of future benefits, and optimal extraction policy responds by shifting production forward in time, towards the period of higher value; there is higher initial production, and slower growth in production.

4. EVALUATION OF COMMON ENERGY PRICING POLICIES

Implicit in the conditions for optimal resource exploitation is a condition for resource pricing. The general features of this pricing have already been discussed. It is also possible to use this pricing rule as a criterion against which to assess various commonly used energy pricing schemes. In the present section, this approach is used to appraise three common pricing schemes - pricing to cover costs, maintenance of a constant real price, and the sale of energy at a subsidised price.

Consider the pricing of energy at cost, specifically, price equal to marginal cost. This means that, for all t:

$$p_t - c_t = 0$$

This can be compared to the optimal price structure:

$$p_t - c_t = s(1 + r)^t$$

There are no circumstances in which the two pricing schemes are equivalent; even a zero discount rate requires that price exceed cost, and s can never be zero in optimal resource allocation as this is equivalent to investing in a zero yield project when positive yield investments are available elsewhere. Therefore, pricing at cost leads to mismanagement of the resource, i.e. to the sacrifice of some of the benefit that could be obtained from the energy. The resource should be priced above cost; if it is priced at cost then too much is demanded and the resource is too rapidly depleted. The cheapness of the energy today leads to its currently being used in low productivity applications, to the resource being rapidly depleted, and to the sacrifice of higher productivity applications in the future. If the policy of pricing at cost is intended to promote the interests of energy consumers, then the actual outcome of the policy is exactly the reverse - it aids today's consumers but extracts an even greater sacrifice from future purchasers.

Another common energy pricing policy is to maintain prices above cost but at a constant real level, i.e. to adjust prices upwards at the same rate as general inflation. This means that p_t is constant so, as c_t can be expected to be either constant or rising, $p_t - c_t$ will be either constant or falling. This cannot be optimal, since the correct price rises over time, at a rate approaching the discount rate. Therefore, a constant real energy price leads to a mismanagement of energy resources: the price does not increase sufficiently rapidly so quantity rises at too great a rate and the resource is exhausted too soon. Rather than aiding consumers, this policy aids the present generation at the expense of a greater loss of benefit in the future.

Finally, some types of energy are sold at a subsidy, with market price falling below cost. This means that $p_t - c_t$ is negative. Optimal pricing requires $p_t - c_t = s(1 + r)^t$ which requires that price exceeds cost by a margin that increases over time. Therefore, the subsidised price will fall far below the optimal price, and quantity will correspondingly be too high. Also, as the subsidised price grows less rapidly than the optimal price, quantity will increase too rapidly. The effect of the subsidy then, is that the initial level and growth rate of production are excessive so that, compared to optimal resource management, the resource is exhausted too soon. If the subsidy policy is aimed at stimulating employment in the extraction industry, for example, then it does have this effect in the short run but it reduces this employment in the long run and reduces the welfare of society as a whole by causing the premature exhaustion of the resource.

5. PROBLEMS IN MARKET MANAGEMENT OF RESOURCES

(5.1) Extraction in Non-competitive Markets

The conditions for socially optimal resource extraction are satisfied by an industry operating in a competitive market environment. But, what happens if extraction is undertaken by producers operating in non-competitive conditions? This question is relevant in appraising the likely efficiency of, for example, a single producer controlling a nation's entire natural gas supply. If the producer does not exploit his market power at all, but instead behaves exactly like a competitive producer, then extraction remains optimal - it is performance, not structure, that matters - but if the monopolist exploits his market power, an inefficient allocation of resources will result.

Consider the case where extraction is in the hands of a single producer who seeks maximum profits. He chooses extraction quantities over the planning horizon so as to:

$$\text{maximise} \quad \Sigma\ (1 + r)^{-t}(\text{Revenue } (Q^t) - \text{Costs } (Q^t))$$

subject to $\Sigma Qt = R$. A necessary condition for this maximisation is:

$$\text{Marginal Revenue } (Qt) - \text{Marginal Cost } (Qt) = a(1+r)^t \quad \text{for all } t.$$

It can be shown that marginal revenue is $pt(1 - \frac{1}{\varepsilon})$ where ε is the price elasticity of demand for this fuel, so the profit maximisation conditions are:

$$pt - ct - \frac{pt}{\varepsilon} = a(1 + r)^t \qquad \text{for all } t.$$

This differs from the condition for socially optimal extraction by the inclusion of the term pt/ε. Therefore, profit maximisation under non-competitive market conditions leads to resource extraction that is non-optimal; from a societal viewpoint, the resource is mismanaged. Compared to the optimal price equation, the non-competitive price equation has an additional term subtracted from price to equate price less cost to $a(1 + r)^t$. This means that the non-competitive price is too high, so quantity extracted is too low, compared to the optimal pattern.

This conclusion can also be illustrated in non-mathematical terms. The non-competitive producer has two ways of increasing revenue - the extraction and sale of additional energy quantities, or the exercising of market power to raise energy prices. The critical factor is this control over price. The producer can extract additional income by reducing quantity and raising price. Thus, the producer forces the price above the competitive level, collecting maximum profits on a smaller quantity, and leaving more of the resource in the ground for future sale.

Although the quantity produced under non-competitive conditions is too small, the rate of growth of this quantity is the same as the optimal growth rate. The rate of change of the non-competitive price approaches r per annum (from the above equation), exactly the same as the rate of change in the optimal price. Demand, changing inversely with price, therefore rises at the same rate in both cases. Thus, the specific problem with the management of resources by a non-competitive producer is not that production grows at the wrong rate, but rather that the entire time pattern of production is too low. This behaviour implies that too much of the resource is being left for the future; future consumers are gaining but this is more than offset by the loss to present consumers. Therefore, non-competitive or monopoly control of energy resources leads to too much conservation, which reduces the social benefit derived from a nation's energy resources.

What should government policy be towards monopoly or other non-competitive conditions in energy production? The objective of government policy should be to move production towards, and if possible attain, the optimal pattern. This involves raising the level of extraction Several policy instruments are availabl - price control or quantity control can be used, or the government can try to stimulate competition, for example by licensing new producers, permitting the development of new energy deposits, or breaking existing producers into competing units. It is unlikely that such action will move extraction precisely to the optimal pattern, so from a practical point of view, it is relevant to ask whether government action is likely to improve social welfare at all. Profit maximising prices in non-competitive conditions satisfy:

$$\frac{p_t - c_t}{(1 + r)^t} = a + \frac{p_t}{\varepsilon} \frac{1}{(1 + r)^t}$$

This is the present value of the net benefit of the last unit of production is year t, or V_t in the earlier notation. Therefore,

$$V_{t+1} - V_t = \frac{1}{\varepsilon} \cdot \frac{p_{t+1}}{(1+r)^{t+1}} \cdot \left(1 - \frac{p_t}{p_{t+1}} (1+r)\right)$$

For positive costs, prices will be rising at a rate less than r, so the right hand side of this expression is negative. I.e. V exceeds V + 1, or in extraction under non-competitive conditions, the net benefit of the last unit produced in each year falls over time. This means that an acceleration of extraction moves quantity from periods of low to high benefit, and so increases social welfare. Any government policy that has the effect of shifting extraction forward in time will improve the total social benefit obtained from the resource. Therefore, even if government corrective policy is in fact incorrect, provided it accelerates resource extraction, it is still likely to increase the social value obtained from the energy resource.

(5.2) Insufficient Allowance for the Future

The relative importance given the future in allocation decisions depends on the discount rate. If the private discount rate exceeds the socially appropriate rate, then the resource extraction pattern generated by the market ceases to be socially optimal. In such a case, the market places what, from a social point of view, is an excessive discount on future benefits, resulting in insufficient weight being accorded the future in the design of extraction policy and, therefore, in over-rapid resource depletion.

There are three commonly held reasons for suggesting that market decisions do not accord as much importance to the future as would be required by underlying social values. Technically, this means that the market discount rate exceeds the social discount rate.

(a) As future citizens are unrepresented in today's markets, their interests, especially concerning investment and conservation of resources, are not fully allowed for in today's market decisions. In other words, this is the conservationist argument that the present generation should make greater allowance for its descendants.

(b) It is frequently argued in economics that the present generation systematically underestimates its own preferences for the future. This means that the present generation would be better off, although it would realise this only in the future, if it were forced to make greater provision for the future.

(c) Taxes, together with investment risk and capital market imperfections, prevent private investment from exploiting all those opportunities that are economically justified; too little investment occurs, i.e. too little is set aside for the future.

Each of these arguments implies that when judged on social criteria, market decisions give too little weight to the future. If these arguments are accepted, then the market discount rate is too high, and the pattern of resource extraction emerging from a competitive market is sub-optimal. The nature of the resource mismanagement is that, as the market gives insufficient weight to the future, resource depletion is too rapid.

The pattern of energy prices prevailing under competitive market conditions is:

$$pt - ct = s(1 + r)^t$$

The energy produced in year t under this extraction policy has a marginal present social value of Vt:

$$Vt = \frac{pt - ct}{(1 + \delta)^t} = s\left(\frac{1 + r}{1 + \delta}\right)^t$$

$$\text{so} \quad Vt{+}1 - Vt = s\left(\frac{1 + r}{1 + \delta}\right)^t \left(\frac{r - \delta}{1 + \delta}\right)$$

$$> 0 \quad \text{as} \quad r > \delta$$

Since the last unit produced in $t + 1$ has greater social value than the last unit in t, the shifting of some production from t to $t + 1$, would increase the total social value of the resource. This identifies the market problem in these circumstances · market extraction is too rapid - but it also provides the basis for the design of corrective government action. Any policy that delays energy production, compared to the market pattern, will increase the social benefit obtained from the energy deposit. Two policies that would have this effect are taxes on energy sales (designed to raise the market price of energy, not to reduce the income of energy producers), or quantity ceilings on extraction, e.g. as imposed by licensing or permit arrangements.

(5.3) Incorrect Pricing

There are two common cases, apart from an incorrect discount rate, in which market prices might not reflect correct economic values. The first is the case of "external costs of production" where some of the social costs of production are not charged to the producer. A primary example of external costs in energy use is that the environmental damage caused by the extraction and use of energy is charged to neither producer nor consumer. This "unpaid" cost results in the market production of energy being greater than is socially optimal. Extraction under competitive market conditions is characterised by

$$\frac{pt - ct}{(1 + r)^t} = s$$

If x is the marginal external cost of this energy in production and use, then the present value of the net social benefit of the last unit extracted in t is:

$$Vt = \frac{pt - ct - x}{(1 + r)^t}$$

$$Vt = s - \frac{x}{(1+r)^t}$$

and $$Vt+1 - Vt = \frac{r}{(1+r)^{t+1}} > 0$$

As the last unit produced in $t + 1$ has greater social value than the last unit in t, the shifting of some production from t to $t + 1$ would increase social welfare. Thus, the market, by ignoring the external costs of production, extracts energy too rapidly. Any government policy that causes delay in the extraction pattern would increase the social benefit obtained from the resource.

Alternatively, the imposition of taxes or charges for environmental damage would force producers to take these costs into consideration in their decisions and could result in the market extraction pattern being optimal.

The other common instance of the market price failing to reflect true economic value is the case of foreign exchange. In New Zealand, the administratively set foreign exchange rate underestimates the value of foreign exchange to the economy. The market value of the output of a local oil field, for example, is heavily influenced by the price of the imported oil that it replaces. Therefore, if the exchange rate undervalues foreign exchange, the market underestimates the true economic value of the oil. Then, as the producer does not receive this full benefit for the oil, he does not produce as much as is economically desirable. Formally, an analysis similar to that for the case of external costs applies, giving:

$$V_{t+1} - V_t = - \frac{ir}{(1+r)^{t+1}} < 0$$

where i is the amount by which the actual exchange rate understates the true value of foreign exchange. Market exploitation of the oil is, therefore, too slow; social welfare would be increased if extraction were accelerated.

6. PRINCIPLES FOR OPTIMAL FUEL MIX

The economy has available to it, at any one time, many different energy sources and fuels. What principles should guide the choice of fuels so as to promote social welfare? Optimal energy use requires that, at any time, the fuel that can most cheaply provide an energy service should be used for that service. In practice, the suitability of different fuels for different uses, together with locational differences in fuel demands and supplies, mean that it will be most efficient for the economy to use a range of fuels simultaneously.

This optimality condition can be demonstrated by considering the choice between the use of high and low cost deposits as the source of a particular fuel. As the fuel is the same, energy from either source has the same gross benefit, but because of the cost difference, the net benefit is greater for the low cost source. The choice is to deplete the low cost source first then move on to the high cost energy, or to work in the reverse order. The essence of this choice is whether to take the high net benefit now or to save it for the future. The preferred extraction sequence can readily be derived. Let energy from source I, the low cost deposit, cost c while energy from source II costs more, c + d. Each unit of fuel yields benefit b, regardless of its source. If I is depleted now and source II is used in the future, the present value of the net social benefit gained from the energy is:

$$NPV\ (I,\ II) = (b - c) + (b - c - d)/(1 + r)$$

Alternatively, the net present value of benefit if the high cost source is used first is:

$$NPV\ (II,\ I) = (b - c - d) + (b - c)/(1 + r)$$

The difference between these values is:

$$NPV\ (I,\ II) - NPV\ (II,\ I) = rd/(1 + r) > 0$$

Thus, the total social value of the energy obtained from the two sources is greater if the cheaper source is used first. In general, social value is maximised if, for every energy function, that energy source is used that can provide the fuel at least cost.

The policy implications of this result are direct. In developing a nation's energy resources, for example within the context of a national energy plan, the deposits with the least cost of extraction, processing and delivery should be developed and exploited first. Conversely, any policy that aims to protect or subsidise high cost producers, to keep them in operation against the competition of less costly sources and more efficient producers, is economically inefficient, and results in a loss of potential benefit that the society could obtain from the exploitation of its energy resources.

As an illustration of these results, consider the question of how best to use Maui natural gas. Many energy uses, e.g. thermal electricity generation, central heating or process heating, can be satisfied by either petroleum or natural gas. Which involves the lesser cost to the New Zealand economy? Refined petroleum costs, on average, \$2.60 per million Btu. Because of the high import content of petroleum, the true economic cost may be even higher: if the true cost of foreign exchange is 25 percent above the set price, then the economic cost of petroleum is around \$3.25 per million Btu. Natural gas, to replace some of this petroleum, would cost around \$1.80 per million Btu (this is a very rough estimate of the delivered cost of natural gas, based on cost data for Kapuni gas). Natural gas is clearly a cheaper energy source; its cost is, as an order of magnitude, half that of petroleum. The conditions for optimal fuel mix indicate, therefore, that natural gas should replace oil in those uses where substitution is directly feasible.

This paper has established a set of principles characterising the efficient management of energy resources. These principles are relatively straightforward, yet are powerful in terms of their practical implications. The greater part of the analysis has, in fact, been concerned with the application of these principles to issues in the organisation and control of resource extraction. The policy ramifications of the theory of optimal resource depletion are established; the remaining step is to incorporate the insights so provided into the energy policy that is currently being formulated in New Zealand.