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A New Basis for the Economic Theory of Natural Resources

Ernest Jowsey

A thesis submitted in partial fulfilment of the requirements of

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for the degree of Doctor of Philosophy

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SHEFFIELD HALLAM UNIVERSITY
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ADSETTS CENTRE

ABSTRACT

Practical application of the principles of sustainable development must be based on a consistent and comprehensive theory of natural resources. Examination of current approaches to environmental policies reveals that a range of practical techniques have been developed but their application requires the sound basis of such a systematic theory of natural resources. A review of literature demonstrates that there are a number of economic theories which are based on poorly-defined differences between natural resources. In particular, these resources are generally referred to as "depletable" and "renewable". However, it is apparent that such terms are not clearly specified and closer examination indicates that the term "renewable" typically refers to "biological" resources such as fish and forests. Other renewable resources, including hydro, solar, tidal, wave and wind power are not explicitly addressed by existing economic theories. In reality, the physical and economic characteristics and nature of renewable energy resources are quite different from those of so-called "conventional renewables".

The possibility of formulating a single economic theory of natural resources is explored by first considering the physical processes responsible for resource creation. This leads to the identification of the common physical characteristics of all natural resources. Additionally, the economic characteristics of natural resource utilisation are established. Together, these characteristics enable the real costs of natural resource use to be identified, providing the basis of a single unifying theory of all resources based on a User Cost Function. Two key considerations emerge from this approach. Firstly, in relation to resource depletion, it is necessary to explore the role of rate of consumption relative to rate of supply as a quantitative aspect of resources. Secondly, in relation to pollution, it is necessary to investigate the role of rate of change of entropy as a resource is utilised as a qualitative aspect of resources.

Once the true costs of resource use have been established, natural resources can be classified in a systematic way according to these components of the User Cost Function. Clear differences between different types of natural resource emerge, leading to new terms being proposed to describe different resource types. In order to demonstrate the application of this theory in relation to a natural resource, a case study of geothermal energy is used to calculate the user cost component of depletion for the Geysers geothermal reservoir in California, USA. The relationship between the user cost component of environmental impact and the rate of change of entropy for the resource is explored and an example based on the pollution costs of carbon dioxide emissions is presented. Alternative policy measures which articulate the new theory are considered, especially the subsequent alternative application of differential discount rates to different types of natural resource. Finally, conclusions and recommendations are proposed, including further work on the full derivation of the User Cost Function for a range of different types of resources. This would provide a basis for implementing the economic theory of natural resources through realistic policy measures to help achieve sustainable development.

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1. INTRODUCTION

1.1 Context

This thesis examines whether existing economic theories of natural resources are adequate and, where necessary, considers ways to extend and improve them. Existing economic theories of natural resources distinguish between types of natural resources (both renewable and non-renewable) which appear to have fundamentally different physical characteristics. These physical characteristics have not been explicitly recognised or analysed in existing economic theories of resource exploitation (see Jowsey, 1997, 1998, 1999). The central problems are that existing theories are lacking, flawed, incomplete and not comprehensive because they do not provide a universal theory for all natural resources. The main reason for this is that existing economic theories do not explain, in an objective manner, how different resources to which they apply, are defined. In particular there is no existing economic theory which explains the nature of resources which are generally referred to as "renewable resources", such as hydro, solar, tidal, wave and wind power. These important resources are usually included in economic explanations of resources such as fish and forests. In reality, the physical and economic characteristics and nature of hydro, solar, tidal, wave and wind power are quite different from those of so-called "conventional renewables", which have been addressed by existing economic theories.

In the past thirty years there has been a recognition that economies have a physical underpinning that cannot be ignored if environmental problems are to be avoided and "sustainable development" is to be achieved. At the same time, physical scientists have recognised that problems of pollution and energy use also have a social and economic aspect (Faber et al, 1998). This has not led, however, to new theories of natural resource exploitation. Existing theories date back to the early Twentieth Century in the case of non-renewable resources (Gray, 1914; Hotelling, 1931) and the mid Twentieth Century in the case of renewable resources (Gordon, 1954; Scott, 1955; Schaeffer, 1957). This work investigates whether it is possible to establish a firm physical foundation on which economic theories of natural resource exploitation can be based.

Economists have been slow to recognise the physical basis of economic activity because of their long preoccupation with static and quasi-static analysis in neoclassical economic theory. This is essentially the theory of the efficient operation of markets which was developed in the late Nineteenth and early Twentieth Centuries. It explains how free markets work to distribute resources in a way which will maximise society's welfare. Neoclassical economics argues that the market is the most efficient method of allocating scarce resources and where markets do not exist, they should be created. In the neoclassical economists' view, if natural resources are not being exploited in such a way that society's welfare is maximised, then the reason is 'market failure'. Where it can be shown that there is market failure, then mechanisms can be put in place to correct this, for example, by the application of pollution standards through government regulation, or even the creation of an artificial market using tradeable permits.

If market failure is occurring because of incorrect calculation of the costs involved in natural resource use, then attention must be paid to the economic theory that underpins that cost calculation.

> "The harm done to human health and the environment from burning fossil fuels is not reflected in the price of those fuels, especially coal, in most countries."
> (Economist, 2002).

A recent report by the World Wildlife Fund (WWF, 2002) warns that two new planets the same size as the earth will be needed by 2050 if natural resources continue to be exploited at the current rate. If these calculations are correct it must be true that the total costs of natural resource use are not reflected in resource prices, and there is a catastrophic instance of market failure which urgently requires attention. In modern society almost everything is driven by economics. If the economics is correct, it may be possible to avoid a resource-triggered catastrophe and instead take a sustainable future path.

1.2 Approach

The topic of this thesis originates from the observation that definitions of different types of natural resources as either renewable or non-renewable in economic theories are unsatisfactory. Also, the inclusion of non-biological "flow" resources such as solar power in the same renewable resource category as fish or forests seems to be illogical because of the very different characteristics of such resources. Further investigation leads to the discovery that economic theories of resources are also divided into just two categories: non-renewable or renewable. There seems to be a complete absence of economic theory concerned with non-biological flow resources, although they are becoming increasingly important and are likely to continue to do so as non-renewable resources and biological renewable resources become depleted.

In considering the important economic features of different types of resources (Jowsey, 1997, 1998, 1999) it is apparent that there is a lack of natural science in the background to economic theories of natural resources. This seems to be a weakness because the physical characteristics of the different resources greatly affect the economics of each. Accordingly, it is necessary to review current economic theories of natural resources in order to determine any weaknesses or omissions and then to analyse the physical background to the creation of natural resources in order to provide the basis for a more comprehensive and inclusive economic theory of all natural resources. In reviewing existing natural resource theories it is essential to go back to the origins of economics as a discipline in itself. The earliest considerations of natural resources in economic literature are to be found in the works of Thomas Malthus (Malthus, 1798) and David Ricardo (Ricardo, 1817). Their works were notable for their concentration on the possibility of resource scarcity, which is largely absent from the work of later economists (and especially those of the Neoclassical era), but which re-emerged as a powerful concept again in the 1970s especially after the 1973 oil price shock.

The rise of 'environmental economics' in the late 1960s and 1970s coincided with this new attention to scarcity and with the increasing frequency of pollution incidents around the world. Recognition of the 'materials balance principle' in the 1970's was an important step forward for the new 'environmental economics' (Kneese et al, 1970). This principle states that the mass of residuals flows into the environment from all forms of activity in the system equals the mass of resource flows from the environment. This is based on the First and Second Laws of Thermodynamics. The First Law states that matter/energy cannot be created or destroyed and leads to the conclusion that matter and energy wastes from economic activity must eventually be discharged into the environment. The Second Law is concerned with entropy. Entropy is the extent to which matter and energy is organised or structured. Entropy is low when matter and energy are highly organised and structured, and they are likely to be most useful in this form. Any thermodynamic process will increase the entropy of an isolated system and so the Second Law of Thermodynamics implies that the total amount of concentrated/organised energy and matter in a system will decline over time. This (belated) acceptance of the realities of physical science in economic theories has profound implications.

Acceptance of the materials balance principle has had only a limited impact in natural resource economics. The basic theories of non-renewable and renewable resource economics date back to well before the exposition of the materials balance principle. Moreover, the very distinction between non-renewable and renewable resources becomes blurred if the Laws of Thermodynamics are considered in relation to natural resources. The earth is not an isolated system to all natural resources. Energy is exchanged with other systems and continued resource use is possible even in the long-term when earthly stocks of natural resources are depleted. The long-term 'sustainable' future of resource consumption may well depend on the correct classification or identification of 'sustainable resources' based on natural science and economic relationships.

The realisation of an all-embracing economic theory of natural resources which is founded on the principles of natural science is, thus, a central feature of this thesis. Clearly in order to achieve this, thorough examination of current economic and physical science theories of natural resources is necessary. The work must then, of necessity, become an interdisciplinary process relying on firm physical science foundations to underpin the economic theories which should emerge. If the appropriate theory can be developed and is capable of being applied to all types of natural resources in a logical and consistent way, it becomes possible to formulate policy recommendations for the long-term (for 'sustainable development'). Hence, it is necessary to examine existing natural resource policies and to consider whether they are likely to lead to a sustainable outcome. Subsequently, methods of incorporating the new theory into either existing or new policies for natural resource use must be found in order to make such use more sustainable.

1.3 Aims and Objectives

The principal aim of this thesis is to improve and extend existing economic theories of natural resources in order to enable policy decisions involving natural resources to be made on a more sound theoretical basis. In doing so, it is important to examine theories which currently inform natural resource policies, to identify any weaknesses in them, and to suggest improvements to them. Differences in approach between economists and natural scientists must be analysed and the improved theories which arise should attempt to assimilate these different approaches in an interdisciplinary way. It is then necessary to determine what practical mechanisms could be used to incorporate the new theories into decision-making processes for natural resources in order to secure sustainable natural resource use. As a result, the main objectives of this thesis are:

- to review, critically, current economic theories of natural resources in order to determine whether they lead to sustainable exploitation of resources and, if not, to determine why this is the case;
- to analyse the physical basis of natural resource creation and exploitation in order to base economic theories on a sound natural science foundation;

- to establish the main economic aspects of natural resource exploitation;
- to classify natural resources in a comprehensive way which allows for the movement of resources within categories and which can classify new resources as they are discovered;
- to establish a model of the real economic costs of natural resource use;
- to establish the principles of sustainable management of resources;
- to determine practical mechanisms which can be used in policies to achieve sustainable management of resources.

1.4 Structure

The structure of this thesis is determined by the aims and objectives. Firstly, environmental policies are investigated in order to give a context for the work in Chapter 2. Then a review of existing natural resource theories is necessary, and this has been undertaken in Chapter 3. This includes discussion of methods of classifying natural resources and identification of deficiencies in existing theories. The physical basis of natural resource creation is examined in Chapter 4 which leads to identification of basic elements of resource formation. The implications of the physical creation processes for natural resource exploitation are examined in Chapter 5. From this, certain key physical characteristics of resources emerge. Chapter 6 investigates economic aspects of natural resource exploitation so that certain key economic characteristics emerge. Chapter 7 combines the physical and economic characteristics of resources which have been identified in the analysis of Chapters 4 and 5 in order to formulate a new theory of the real costs of natural resource exploitation. Natural resources are then classified according to the new theory. Chapter 8 is a case study of geothermal energy which demonstrates how the real costs of natural resources can be calculated. In Chapter 9 the question of what constitutes sustainable resource management is addressed and existing natural resource policies are examined. A future sustainable natural resource policy is proposed. Finally, in Chapter 10, conclusions are derived and recommendations for further work arising from this research are made.

2. ENVIRONMENTAL POLICIES

2.1 Context

The environmental system of the earth sustains life by providing air, food and water and enables the creation of economic sub-systems which provide energy and natural resources and sinks for waste and pollution. The world economy had grown to approximately EUR 60 billion by 1900 but now grows by this amount every two years (Goodland, 1991). The speed and scale of this economic development presents a threat to the integrity of the environmental support system which underpins economic activity and this has become apparent in the last thirty years.

> "The future of our planet is in the balance....The present pattern of human activity, accentuated by population growth, should make even the most optimistic about future scientific progress pause and reconsider the wisdom of ignoring these threats to our planet. Unrestrained resource consumption for energy production and other uses, especially if the developing world strives to achieve living standards based on the same level of consumption as the developed, could lead to catastrophic outcomes for the global environment." (Royal Society/National Academy of Sciences, 1992).

There are two crisis areas which are threatening environmental disaster. Firstly, pollution and waste are exceeding the planet's capacity to absorb and convert them. Annual carbon dioxide emissions have quadrupled over the past 50 years and there is growing scientific consensus on the potential impacts on climate of increasing concentrations of greenhouse gases in the atmosphere. Climate change is widely recognised as one of the key environmental challenges facing all countries today. The global average surface temperature has increased over the Twentieth Century by about 0.6° C, snow cover and ice extent have decreased, global average sea level has risen and ocean heat content has increased (Intergovernmental Panel on Climate Change, 2001). Human-induced climate change is threatening to impose very significant shifts in temperatures, rainfall, extremes of weather and sea levels in this century and those that follow. The principal cause is that the concentration of carbon dioxide in the atmosphere has been rising, mainly because of growing use of fossil fuels and the trapping of more solar heat by the atmosphere. The concentration of carbon dioxide is already higher than at any time for millions of years and human-induced climate change now seems inevitable. The UK Meteorological Office has calculated that without action to curb the emission of greenhouse gases, average global temperatures would rise by about 3°C over the next 80 years (Meteorological Office, 2002). The Royal Commission on Environmental Pollution (RCEP) advocates a transformation of energy supply and demand in the UK to counter climate change. As a contribution to global efforts to prevent excessive climate change, the RCEP recommends that the UK should plan to reduce by 60% over the next 50 years the amount of carbon dioxide it produces by burning fossil fuels (Royal Commission on Environmental Pollution, 2000).

The second crisis area that is threatening environmental disaster is growing deterioration of vital renewable resources, such as water, soils, forests, fish and biodiversity. Twenty countries suffer from water stress, having less than 1,000 cubic metres per capita per year, and water's global availability has dropped from 17,000 cubic metres per capita in 1950 to 7,000 in 1998. A sixth of the world's land area, nearly 2 billion hectares, is now degraded as a result of over-grazing and poor farming practices. Since 1970, forest area per 1,000 population has fallen from 11.4 to 7.3 square kilometres. Fish stocks are declining, with about 25% currently depleted or in danger of depletion and another 44% being fished at their biological limit. (United Nations Development Programme, 1998).

There have been many different approaches to assessing and addressing these twin environmental crises. In particular, the relatively new field of ecological economics studies how ecosystems and economic activity interrelate, thus embracing serious environmental problems such as the use of fossil fuels and carbon dioxide concentrations and disposal of nuclear waste. Ecological economics recognises that the economic activities of production and consumption are not independent of the global ecosystem (Faber, Manstetten and Proops, 1996). Physical laws, such as the Laws of Thermodynamics are of relevance when physics enters the scope of economics, as in the study of resources. Ideas about evolution and co-evolution are being generalised from biological science to economics (Norgaard, 1984). Furthermore, the principles of natural science often underlie methods of environmental assessment.

2.2 Environmental Assessment

A variety of techniques have been developed in order to assess impacts on the environment and assist formulation of policy and its application. These include strategic environmental assessment (SEA), environmental impact assessment (EIA), environmental auditing (EA), life-cycle analysis/assessment (LCA), cost-benefit analysis (CBA) and Environmental Cost Benefit Analysis (ECBA). The necessity for special techniques arises because many environmental impacts are not accounted for in the market. If market information is not available, methods must be developed to discover the nature and extent of environmental change. In order to formulate effective environmental policies it is necessary to have accurate information on what is happening to the environment and on what is likely to happen if a particular development goes ahead. SEA has significant relevance for the formulation and implementation of policies and for giving effect to the idea of sustainable development. Sector policies in energy, in transport and so on are frequently formulated and pursued without general assessments of their results in the environment, even though specific projects or programmes such as hydro-electric schemes may have some environmental evaluation. This means that though sector level policies have consequences for sustainable development, they tend to be ignored and remain unanalysed. SEAs can be designed and instituted to reveal the general advantages or disadvantages of a project in terms of its wider environmental relevance. For example, energy policies will probably contain provisions for various regulations, for levels and applications of taxation, and for economic incentives or disincentives which favour some modes of energy production relative to others. Such policy frameworks have differential effects on the volumes, the physical characteristics, and the health conditions arising from particulate emissions and greenhouse gases. SEA aims to assess the comparative results, adding to the currently gathered economic information.

The main principles of SEA can be expressed, as follows:

> "Systematic appraisal entails being clear about objectives, thinking about alternative ways of meeting them, and estimating and presenting the costs and benefits of each potentially worthwhile option. Used properly, appraisal leads to better decisions by policy makers and managers. It encourages both groups to question and justify what they do. It provides a framework for rational thought about the use of limited resources." (HM Treasury, 1991)

Of course, the principles were originally formulated to apply to policy appraisal for reasons of financial efficiency and economy in the use of resources: but they are equally applicable to the examination of the environmental implications of policy. SEA is, therefore, the application of policy appraisal techniques in order to assess the environmental implications of policies, plans and programmes. Governments must deal with the complex interaction between policy, the economy and the environment.

The technique of SEA itself is still in its infancy, though a growing body of literature (for example, Wood and Dejedadour, 1992; Therivel et al, 1992; DoE, 1993; Cuff, 1994) suggests that it is clearly related to, but different from, project-level EIA. The literature suggests that an SEA should incorporate a number of stages including, for example, scoping, providing a description of the affected environment, evaluating the significance of potential impacts, and examining mitigation measures. SEA's should also incorporate extra stages, notably a consideration of alternatives to the proposed policy, plan or programme, and a discussion of the boundary, either spatial or sectoral, which is to be applied in the study (Jowsey and Kellett, 1996). Methods of SEA are as yet ill-defined and diverse. The problems attached to

SEA relate largely to its nature. The emphasis on policy interactions and in many cases inter-departmental co-operation suggests that governmental structures may sometimes be ill-equipped to accommodate the technique. A corporate willingness to take an holistic approach to the environmental implications of policies, plans and programmes is essential to the successful application of SEA, which, as argued here, can promote sustainability. The importance of SEA's in Europe is likely to increase as a result of European Directive 2001/42/EC entitled "On the assessment of certain plans and programmes on the environment" (European Parliament, 2001) which must be implemented by member states by July 2004.

EIA was first used in the 1970's for large projects such as the construction of dams, new towns, large airports, and major intra-city highways using substantial technical analyses in engineering and economics. EIA's can range from very generalised commentaries on potential environmental impact to thorough technical and evaluative analyses of such factors as conservation of species, changes in groundwater processes, profiles of pollution and so on. The sorts of analyses which are used are varied, including CBA and supporting work on hedonic pricing, contingent valuation and other methods (see below). During the 1980's the World Bank received much criticism for ignoring environmental analyses, for example, in large dam projects in India. This led the Bank into adopting the role of EIA's, and the 1992 Earth Summit heightened interest in applying EIA's more generally.

EIA at the level of individual projects is much more clearly defined and accepted by both politicians and developers than is SEA. A considerable body of literature describing the technique and its applications exists (Lee and Wood, 1987; Wathern, 1988; Fortlage, 1990; Glasson et al, 1994; Morris and Therivel, 1994). The method can prove of great benefit in identifying potential environmental threats from new development and provide mechanisms for their mitigation. It should ideally be used in conjunction with SEA because by itself it is incapable of dealing with the question of alternatives to a proposed development, either in the sense of alternative sites or alternative actions, nor can it readily identify the effect of cumulative impacts. Each project is subjected to an analysis of its environmental effects, but the compounded effects over time of, for example, a number of power station developments and their combined effect on air quality, are difficult to establish using EIA alone. It is in respect of individual developments that EIA comes into its own. Here, it provides a rigorous and objective assessment of the likely impacts of a project before it is developed and can prove of enormous benefit in the design of measures to mitigate these impacts. Willingness to consider the full range of potential project impacts on, for example, air quality, water pollution, destruction of ecosystems, contamination by pesticides and toxins are vital prerequisites of any serious environmental impact assessment. Within the European Union (EU), the groundwork for just such an approach has been laid down in Directive 85/337/EEC entitled "On the assessment of the effects of certain public and private projects on the environment" (Council of the European Union, 1997), with which all member states have now complied. Elsewhere progress towards this more rigorous approach to evaluating the environmental effects of projects is patchy.

The vital prerequisites of successful EIA are participation, the involvement of all affected and interested parties and openness about development proposals from their initial conception. Equally important is an established and clear set of standards relating to pollution thresholds. A cornerstone of EIA is objectivity and quantification of impacts. Prediction of, for example, air pollution from the generation of electricity using natural gas, requires expertise to forecast the new pollution level, setting this against the existing baseline pollution level and, crucially, establishing whether the predicted situation is acceptable. Arriving at this judgement depends upon the existence of established standards. These can take various forms, ranging from measurement of pollution at the point of emission through to standards related to the eventual target of pollution (for example, levels of particulates in the atmosphere or the rate of erosion by acidic rainwater of heritage buildings). Between these two points, various other pollution references are possible, for example, a standard of maximum acceptable pollution in drinking water supplies can be an extremely valuable criterion against which to judge the impact of potential future developments.

EA is a growing commercial field in industrialised nations and mostly focuses on the activities of individual companies which wish to ensure that they are complying with current environmental legislation and to promote their own "green" credentials in a world of increasingly environmentally aware customers and consumers. More generally the results of various environmental policies and economic development activities can usefully be subject to overall monitoring and review. Periodic environmental audits can achieve these purposes. EA consists of an examination of the existing state of the environment and the development of environmental policies covering a range of factors. The scope of such a study would typically include consideration of air, water, waste, noise, energy, land, agriculture, wildlife, open space, transport and townscape. The initial stage can often prove to be the most problematic in that the data required, for example, on air quality, land use, or resource utilisation, may not be readily available or accessible. Where data do exist it may be out of date. Building up a complete state of the environment review may, therefore, be costly. Moreover, continual monitoring to assess the impact of policy change is vital if the expenditure is to prove worthwhile. The outcomes of such a review may prove extremely valuable in identifying areas where immediate action is required in order to avoid major public health or environmental problems. A steady flow of time series data on environmental quality allied to the existence of pollution standards and thresholds allows policy to be established and environmental targets to be devised. Thus a realistic framework for, say, the reduction of greenhouse gas emissions from power stations burning fossil fuels may emerge from such a review. Energy policy may then diversify to include increased prominence for conservation measures and the development of renewable sources of power in order to reduce fossil fuel dependence.

Intrinsic to the development of such targets and policies from the environmental review is an attempt to compare different aspects of environmental quality and value them in a common unit of account. Thus the potential degradation of air quality can then be set against increased availability of electric power in a way which will allow direct comparison to be made. One aspect of the application of all of the methodologies discussed so far, therefore, is the basic usefulness of overall economic appraisal and some analytical endeavour to value environmental assets. However, such valuation requires information on the physical inputs and outputs of specific processes and their impact on the natural environment. LCA consists of tracing energy and material through complex systems. It is a framework for learning about the environmental impacts of products throughout their existence. The approach has two roots: traditional engineering and process analysis, in which materials and energy flows are optimised in production processes; and energy analysis, which developed during the 1970's in the aftermath of the first oil shock (Berkhout, 1996). LCA assesses the environmental aspects and potential impacts associated with a product by:

- compiling an inventory of relevant inputs and outputs of a product system;
- evaluating the potential environmental impacts associated with those inputs and outputs; and
- interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study (International Standards Organisation, 1997).

Interest in the techniques of LCA has grown as firms faced stronger environmental pressure from consumers and regulators, and because there was a growing awareness of the global nature of environmental problems. In response to this, LCA has provided a way of assessing the global impacts of ordinary mass-produced products. The scope, boundaries and level of detail of an LCA study depend on the subject and intended use of the study. The depth and breadth of LCA studies may differ considerably depending on their objectives. LCA studies the environmental aspects and potential impacts throughout a product's life (that is, from cradle to grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.

LCA studies have used different methodological approaches and have produced divergent results (Curran, 1993). One of the main methodological problems of LCA lies in the specifying of system boundaries. The possibility exists of biasing the results of the study by selecting boundaries favourable to the preferred result. There are also difficulties in how resource depletion is assessed in LCA and an additional problem is that LCA typically does not address the economic or social aspects of the product. Nevertheless, LCA has proven to be a valuable tool, with a physical science basis, to document the environmental considerations that need to be part of decision-making toward sustainability. It is a useful tool to choose between one product and another or one process and another. The use of this standardised methodology is now growing rapidly for a large variety of applications (UNEP, 1999). The main problem of LCA, however, is the lack of a theoretically sound single unit of measurement for environmental impacts, which causes problems with comparisons across studies. In order to use a common unit of valuation, LCA practitioners have borrowed techniques from environmental economics, generally, and from CBA, in particular.

CBA has versatility, relevance, and useful analytical qualities for environmental assessment. It can be used to inform SEA's, EIA's, EA's and LCA's. It also has significant possibilities for drawing together many environmental impacts into a common unit of account, usually set in economic terms. Essentially, like conventional private sector investment appraisals, it conveys information on rates of return over investment periods or cycles, on associated benefits and costs, and these indicate project justification or rejection. However, CBA has some significant differences compared with private sector investment appraisal. First, CBA takes a longer view. The conventional time period of investment in private sector projects is in the range from 8 to 15 years, whereas CBAs are sometimes associated with social and public sector investments which have durations of up to 60 years or longer. Since environmental relevance is long term, CBA is, accordingly, more appropriate for environmental assessment than private sector appraisals. Second, CBA tends to be wider than private sector investment appraisal. It is wider in the sense that it can account for (and sometimes measure) *social* costs and *social* benefits (costs and benefits which are outside the market system because they are unpriced).

The use of CBA has expanded since the 1960's, and it is especially relevant in accounting for and valuing environmental assets (such as the ozone layer, fisheries, clean air and water, and so on). Analytical progress in the valuation of environmental assets is still at a very early stage. CBA is one of a range of techniques which can provide quantitative guidance to decision-makers when appraising projects. It is uncontroversial to suggest that all benefits and costs should be accounted before a particular policy or project is implemented. Where CBA is contentious, however, is in its methods of attaching specific numbers or values (especially money values) to costs or benefits which many regard as unquantifiable. For example, a CBA study in Sri Lanka has used a loss of earnings (human capital) approach to quantify the possible future health impacts of pollutants consisting of sulphur dioxide, oxides of nitrogen and particulates (Ranasinghe, 1994). In simple terms, the benefits of a project must be greater than the cost and all costs and benefits are evaluated, both private and social. Environmental costs and benefits are often difficult to predict, however, and to quantify in physical terms. Even when quantified, the process of translation into money values is difficult because markets for effects such as loss of a scenic view or biodiversity loss either do not exist or are imperfect.

CBA is a technique which has been developed and applied chiefly in the public sector where it is used to assess projects in relation to their net benefit to society as a whole. As suggested above, CBA is an extension and development of private sector investment appraisal (which takes into account private costs and benefits) by accounting for the wider social costs and benefits. The technique proceeds in stages by identifying, quantifying and evaluating direct and indirect costs and benefits arising from a project. The main purpose is to bring a greater sense or rationality and objectivity into decision-making. This includes attempts to identify and measure all costs and benefits, including indirect social costs and benefits such as pollution and the value of environmental amenity, notwithstanding the presence of difficulties in achieving comprehensive measurement. Inherently, as a form of economic project appraisal, CBA involves comparisons among alternative ways of fulfilling similar objectives. Such comparisons are achieved by assigning monetised values to all relevant costs and benefits, and deriving the net present value (NPV) of the project using discounted cash flow (DCF) analysis. NPV is the sum of the discounted benefits of a project minus the sum of the discounted costs or losses arising from the project:

$$NPV = \sum B_t/(1+i)^t - \sum C_t/(1+i)^t \qquad \text{Equation 2.1}$$

where: B_t is the benefit from the project in t years;

C_t is the cost of the project in t years;

i is the discount rate;

and t is the number of years over which the project has costs and benefits.

If the sum of the discounted gains exceed the sum of the discounted losses it can be assumed that the project or policy is efficient in terms of its use of resources. Discounting is necessary because the costs and benefits will accrue over a period of time and people attach less weight to a similar benefit or cost in the future than they do to one in the present because of impatience or 'time preference' and the existence of positive interest rates. The existence of positive interest rates means that, for example, £1 hypothetically saved, will accumulate higher returns at, say, a compound interest rate of 10% than at 5%. Then, by the principle of reciprocity, £1 in the future is worth less in the present, discounted at 10% rather than at 5%. Discounting, as specified in the formula above is a technical means of transforming flows of costs and benefits (including environmental flows of costs and benefits) into capital sums. In other words it is the capitalisation of a timestream of flows to a 'present value'. This has significance for environmental assessment beyond its role in project appraisal: it can be used to value and compare environmental assets.

In this context, the discount rate has been defined as:

> "...the return on foregone present consumption that is sacrificed to secure future consumption. In an ideal economy with no market failures, the discount rate is equal to the rate of interest or return on capital investment." (Norgaard and Howarth, 1991).

A positive discount rate means that effectively no weight is given to resource use or welfare beyond a generation hence and so discounting appears to be inconsistent with sustainability. The discount rate recommended by the UK Treasury for use in project appraisal is 3.5%, which would mean that the present value of £1,000,000 received in 10 years time is £709,000. The present value of £1,000,000 received in 50 years time is £179,000. For projects with very long-term impacts, over 30 years, however, the UK Treasury recommends a declining schedule of discount rates should be used rather than the standard rate (HM Treasury, 2003). The subject of discounting will be returned to in more detail in Chapter 9.

Conventional CBA has been primarily concerned with the social and economic costs and benefits of projects. However, provided that relevant costs and benefits can be identified and assigned financial values, it is also possible to take environmental considerations into account specifically. ECBA thus involves the identification, quantification and evaluation of all the environmental effects of a project. For oil drilling and extraction, environmental costs such as the destruction of natural habitats and the effects of global warming due to any rise in the emission of carbon dioxide from increased oil and gas burning must be evaluated if the project is being appraised from a global environmental perspective. The application of ECBA for such purposes can be extremely complex and potentially contentious since any project usually has many diverse environmental impacts and there may be disagreement over their assigned money values. Monetised valuation of environmental effects seems to some to be anathema. Applying crude monetised values to environmental costs such as the loss of a living species seems almost immoral, but it must be regarded only as a unit of account or measuring rod in order to enable comparisons. The practice of putting values on loss of human life is now well-established in conventional CBA which often uses the loss of the sum of future anticipated earnings as a measure (or people's willingness to pay for a reduced risk of death). The practice of attaching money values to environmental effects or services at least emphasises that environmental services (despite the absence of conventional markets for them) are not free. The 'total economic value' of an environmental resource consists of its use value and its non-use value or existence value. This type of value exists because people may value an environmental asset without ever using it or even intending to use it. For example, people may value the continued existence of a particular architectural style in a preserved building, without ever intending to visit it. Environmental economics attempts to take into account both use and non-use values in ECBA using a variety of valuation methods, such as contingent valuation and hedonic pricing.

Each of the environmental appraisal techniques considered above can take into account resource depletion issues, but only as a single factor among many others and usually only qualitatively ("as a tick in a box") to indicate that a finite resource is being depleted. There is no quantification of the impact of depletion and no comparison between resources. The techniques, in essence, come down to subjective judgements of how to value one environmental impact against another.

2.3 Policies for the Environment

Market-based economic systems use price and accounting signals which encourage the over-use of the environment. Currently, market prices do not include the full costs of environmental damage, which can be considerable. For example, accidents, congestion and pollution costs of transport have been estimated at 4% of European Union (EU) gross national product (European Commission, 1998). Measurement of output via gross national product overestimates real growth because it fails to properly account for depletion of natural capital and for pollution damage (Repetto et al, 1989). Over-use of non-market, unpriced environmental goods and services is made worse by the 'public good' nature of many environmental goods and services, that is they are often non-excludable (making charging for them difficult) and non-rival (one person's use or consumption does not impact on anyone else's, at least at first). If the price of environmental goods and services does not reflect their true costs, because there is a divergence between private and social costs, then free markets will not allocate them efficiently. Policies to reinforce or restrain market use of environmental goods and services take three forms: a resource-rights system can create markets in previously free services; economic instruments can be used, such as taxes, fees and levies to correct free market prices; or a direct regulatory ('command and control') approach can use legislation to ensure compliance with environmental standards.

Resource-rights (or property-rights) systems grant formal rights to use water, dispose of waste, harvest wildlife, etc., in the form of legal titles to land, licenses, permits, quotas and leases (Young, 1992). In terms of resource-rights, resources are either:

- open-access or non-property resources where rights are poorly defined;
- private property resources where an individual or corporation has a right to exclude others from using that resource;
- common property resources where a community, either through formal or informal mechanisms controls the resource use;
- state property resources where the government restricts the ways in which a resource can be used.

Environmental goods and services are often open-access resources, such as ocean fisheries and the ozone layer. This can lead to use rates in excess of regenerative capacity leading to resource degradation or depletion. Further, there is little incentive to invest in resource conservation and every incentive to deplete it before someone else does (or before access is restricted). Allocating resource rights to specific communities (usually according to traditional usage which is called 'grandfathering') provides incentives to conserve the asset value of resources. A situation where pollution occurs could then be resolved by bargaining between polluter and sufferer (Coase, 1960). If the sufferer has the property right, the polluter will compensate for polluting up to the point where the benefits of doing so are equal to the costs. Alternatively, if the polluter has the property rights then the sufferers of the pollution will pay to reduce it up to the point where the costs of doing so are equal to the benefits. Theoretically, by ensuring responsibility through ownership, environmental assets would be managed in a sustainable way. In practice, most resource-rights systems need to be supported by a variety of regulatory and fiscal instruments to ensure sustainable resource use. Full specification of rights is necessary so that it is clear who pays and to ensure that all polluters and resource users pay their way. The nature of the environment is such that ascribing property rights to a myriad of dynamic energy- and material-bearing phenomena quickly becomes infeasible (Daly, 1999).

Economic instruments are used to subsidise desirable activities and impose costs on undesirable activities. Firms are then left to decide how best to achieve the subsidy or avoid the costs and so market forces then lead to least-cost solutions and development of new techniques and technologies. Fees, levies and charges are collected from the industry that creates the environmental problem in accordance with the 'Polluter Pays Principle' (PPP). The essence of the PPP is that the price of a good or service should fully reflect its costs of production, including environmental costs. Where the open access nature of environmental goods and services is likely to lead to over-exploitation, the PPP tries to rectify the market failure by 'internalising' the environmental cost by use of pollution taxes, fees and permits which create an incentive for consumers and producers to adopt environmentally-benign practices. The appropriate charge or tax should be equal to the marginal external cost of the pollution but a key weakness of these policies is that this is very difficult to determine. An alternative approach (Baumol and Oates, 1971) decides on the environmental standard to be achieved and then uses the environmental tax in an iterative process over a period of time to bring the level of environmental damage down to the standard.

Carbon taxes have the objective of slowing global climate change, usually in the context of agreed targets for limiting or reducing greenhouse gas emissions. Since emissions are expected to be on an indefinite rising trend, any tax would have to go on rising in order to achieve long-term stabilisation and reduction. The property of carbon taxes which attracts both economists and policy-makers is their ability to achieve a given level of emission reduction at least cost to society overall (Ekins and Barker, 2001). This is because the incentive effects of the tax act to equalise the marginal abatement cost across all polluters/emitters. There is an added dividend if the revenue raised from carbon taxes (or auctioned emission permits – see below) is recycled through the economy by reducing pre-existing distortionary taxes. Such revenues can also be used to alleviate the regressive effects of carbon taxation on low-income groups. A further secondary benefit of a carbon tax is the reduction in emissions of a range of other damaging pollutants (sulphur dioxide, nitrogen dioxide, carbon monoxide, particulate matter, methane and volatile organic compounds) as fossil fuel use is reduced in order to achieve carbon dioxide abatement (Ekins, 1996).

A different form of economic instrument is a security deposit where, for example, a quarry company pays a deposit, which is returned when restoration is complete. If the firm walks away or does not restore to the required standard, the deposit is used for restoration work. Other economic incentives are refunds which are payable when an item is returned to the recycling depot. These are used for cans and bottles in various countries and could be extended to other items such as refrigerators, batteries and oil. Offset arrangements can ensure that the adverse environmental effects of an activity are balanced by complementary environmental improvement elsewhere (paid for by the company involved). These are often considered to be economic instruments, but the strong element of legislation to ensure compliance means they can also be considered to be regulatory measures.

Finally in terms of economic instruments, transferable or tradeable permits can be issued. These have been used with some success in the USA for sulphur dioxide emissions trading (Sorrell and Skea, 1999). Under a regulatory system to control air pollution, firms would tend to invest too little in air-pollution control equipment and try to get away with as much pollution as possible. The authorities would then restrict expansion of production and prevent new entrants to the industry because all of the permitted pollution was being emitted. This would lead to economic stagnation and restriction of competition. To combat this, tradeable emission-permit systems were developed. Environmental standards of air pollution would be set and permits issued to allow existing firms a quota to pollute the atmosphere up to these levels. The permit price can be determined immediately by the market. This enables firms to profit by installing emission-controlled or environmentally-friendly production equipment and then selling surplus emission rights to other firms. Third parties or governments can reduce air pollution by buying emission rights from firms. Governments could set the original standard by giving all the existing firms the right to emit pollution at their current levels ('grandfathering') or by auctioning the permits and then reduce emissions rights each year. In the USA, the Clean Air Acts of the 1970's established permit trading with no reduction in environmental standards and a reduction in costs of compliance compared with a regulatory or 'command and control' system. The Kyoto Protocol in 1997 provided the framework for an international system of greenhouse gas trading between countries with agreed emission targets, together with the provision for 'emission credits' from projects that reduce greenhouse gas emissions in countries without targets (Sorrell and Skea, 1999).

In the UK, a carbon dioxide emissions trading scheme was launched in August 2001, as the world's first economy-wide greenhouse gas emissions trading scheme (DEFRA, 2003). The UK was the first country in the EU to launch a fully developed trading scheme. The UK's target under the EU burden sharing agreement is for 12% reduction in greenhouse gas emissions, but the government also has an additional 'goal' of a 20% reduction in CO2 emissions from 1990 levels by 2010 (Sorrell, 2001). The scheme is designed to reduce the emissions of six "greenhouse" gases:-

Carbon Dioxide

Methane

Nitrous Oxide

Hydrofluorocarbons (HFC's)

Perfluorocarbons

Sulphur hexafluoride

Of these carbon dioxide accounts for over 80% of emissions, and potentially is the easiest to control through reduced energy use. Under the UK emissions trading scheme some 34 organisations voluntarily agreed to a legally-binding obligation to reduce their emissions against 1998-2000 levels, delivering over 4 million tonnes of additional carbon dioxide equivalent emission reductions in 2006. The scheme is also open to the 6000 companies with Climate Change Agreements. These negotiated agreements between business and government set energy-related targets. Companies meeting their targets receive an 80% discount from the Climate Change Levy which is a tax on the use of energy in industry, commerce and the public sector, with offsetting cuts in employers' National Insurance Contributions and additional support for energy efficiency schemes and renewable sources of energy.

The general principle is the creation of an emissions trading market that allows companies that generate emission reductions to benefit financially by selling their "credits", whilst companies who have failed to reduce will be financially penalised by having to buy "credits" to make up their shortfall. The buying and selling prices will be set by market traders, just like any other commodity, and will be driven by supply and demand. Participant emissions trading companies establish a baseline of the average annual emissions of the three years 1998-2000. They then calculate a five year profile (specifying the reduction in annual emissions from their baseline to the end of 2006) together with the budgeted cost of abatement. The reduction is divided into five equal annual targets over 2002 to 2006 with corresponding incentive payments in five equal tranches provided they achieve each of their annual targets. If organisations over-achieve they can either sell the excess allowances, or bank the excess for subsequent years. Under-achievement means they will have to buy the requisite allowances. The tradeable permit system can be extended to other environmental areas, for example, fishing (see Chapter 3). Here, the permit takes the form of a right to take a number of fish from the fishery. If the quotas are freely transferable among fishermen, then an efficient solution to the problem of over-fishing can be realised. Such schemes have been used with considerable success since 1971 in the USA, Canada, Australia (for oysters) and New Zealand (Tietenberg, 1996). The tradeable permit system works by combining resource rights and economic instruments to achieve an efficient solution and combinations of systems are likely to be needed to prevent environmental damage.

Regulation by setting environmental standards which are legally enforced has been favoured by national governments in the past, principally because they can be depended upon to achieve a specified policy target. Such a target could be better ambient environmental quality, reduced risk to human health, or more cost-effective pollution control. This has been achieved using:

- limits in terms of maximum rate of discharge from a pollution source;
- specification of a given degree of pollution control such as the removal of a percentage of particulates from the emission;
- pollution density limits related to discharges/emissions;
- requirement to implement some variant of the 'best practicable means' or 'best available control technology' for pollution reduction;
- discharge bans related to pollution concentration measures or damage costs;
- discharge limits set by reference to the use of specified inputs to or outputs from the production process; (Pearce and Turner, 1990).

Firms might also prefer the regulatory or command and control approach, because existing firms in an industry are protected from competition by the regulations. This is known as 'regulatory capture', and it occurs where the regulator and the polluter seek common ground and co-operation. Administrators then protect existing firms with subsidies and new entrants are excluded. Regulation, therefore, provides no dynamic incentive for innovation or improvement beyond the targets set, and so leads to inefficient resource use. When environmental damage might be irreversible, or catastrophic or life-threatening, however, the 'precautionary principle' suggests that regulation is probably more dependable than taxation or other economic incentives. The regulations take the form of a 'safe minimum standard' which can be reinforced by pollution charges or taxes or tradeable permits in order to reduce the need for regulatory enforcement and to encourage more economically-efficient resource use. Regulation of the environment requires enforcement. This can be assigned to an independent agency which does not have responsibility for the economic welfare of the regulated sector, in order to avoid regulatory capture (Young, 1992). Liability laws should encourage compliance with specified standards rather than simply avoiding being caught. In the long-run, regulation is much more likely to ensure that resource use remains within constraints necessary to ensure sustainability (Turner et al, 1994). Regulation will certainly be needed to underpin economic instrument and resource-right systems in order to make ecologically sustainable resource use a matter of self-interest.

In the UK environmental protection has traditionally been based on regulation of ambient quality standards and waste emissions standards. The basis on which pollution standards are established in the UK is known as the 'best practicable means'. This was incorporated in the Clean Air Act of 1956, which achieved considerable success in reducing air pollution in London. Policy has been implemented on the basis of negotiations and bargaining with individual polluters, allowing flexibility. Critics have pointed out that this leaves open the possibility of regulatory capture. The Environmental Protection Act of 1990 requires a polluter to select the 'Best Practicable Environmental Option' (BPEO) in cases where substances are released to more than one environmental medium. In addition, standards are to be achieved using the 'Best Available Technology Not Entailing Excessive Cost' (BATNEEC). In this way, 'cleaner' technologies will be introduced by polluters providing they are not excessively costly. EU Directives have now been adopted in the UK and these are less flexible and based on a precautionary approach. The Integrated Pollution Control Directive (IPCC) of 1996 aims to minimise pollution from various point sources within the EU. All installations covered by Annex 1 of the Directive are required to obtain an authorisation (permit) from the authorities in EU countries. Unless they have a permit, they are not allowed to operate. The permits must be based on the concept of Best Available Techniques (BAT), which may mean quite radical improvements must be made by some firms and so an eleven year transition period has been allowed .

2.4 Challenges for Environmental Policies

It is clear that the issues of pollution and waste and resource depletion need to be addressed urgently to avoid major environmental problems. The existing means to do this consist of a variety of techniques for environmental assessment. These techniques are based, essentially, on subjective judgements of how to value one environmental asset against another. Unfortunately, none of these techniques accommodates the question of resource depletion adequately. Instead, the general assumption is often made that the use of so-called renewable resources is "a good thing" whilst the use of all other resources is "bad". However, it is apparent that this assumption is not based on a systematic analysis of natural resources. Such analysis requires clear definitions for different types of natural resources as a foundation for the theoretical treatment of depletion. Although economic theories of natural resource depletion already exist, their coverage of all resources needs to be considered and their objective application has to be investigated. Unless this can be achieved, it will not be possible to formulate and implement means of environmental assessment which are required for the development and application of sound policies for the environment with regard to the utilisation of natural resources.

3. CRITIQUE OF CURRENT ECONOMIC THEORY

3.1 Economic Theory and Natural Resources

Concern about resource depletion is a relatively recent phenomenon which arrived with the modern environmental problems associated with industrialisation. Thomas Malthus, (1766-1834) in his book 'An Essay on the Principle of Population as it Affects the Future Improvement of Society' (Malthus, 1798) foresaw scarcity of resources and, in particular, food, as a constraint upon humanity. He predicted that as food supplies could only increase arithmetically whilst population would increase geometrically, then 'wars, famines and pestilence' would control population growth (hence the description of economics as the 'Dismal Science'). David Ricardo (1772-1823) believed that economic growth must eventually be limited by scarcity of natural resources. Eventually low-grade resources have to be used as higher-grades are exhausted and rising costs will eventually lead to a 'stationary state' of subsistence level output, wages and population (Ricardo, 1817). A. C. Pigou (1877-1959) is often mentioned in environmental economics in the context of Pigovian taxes to internalise an external cost. He did, however, also make a contribution to the debate about scarcity of natural resources and the inter-generational effects of depletion in the context of, among others, fish, coal and soil fertility. He suggested government intervention as the best safeguard for future generations because current individuals are likely to be myopic (Pigou, 1929).

The standard Nineteenth Century neoclassical economic model, which is used to show how a firm's production decisions are made, assumes that there is no interaction between the economy and the environment. Resources are treated as if they are unlimited as inputs into the production process, and any wastes that are generated, although they may increase costs of production in disposing of them, have no impact on the environment. The use of nature creates no special problems for neoclassical economics because, with the growing scarcity of natural resources, their price rises and this stimulates the search for cheaper substitutes. It was not until the environmental problems of the 1950's and 1960's, and the oil crises in the 1970's, that economic theory recognised that the neoclassical view was oversimplified and needed revision.

Earlier, J. S. Mill (1806-1873) had developed the idea that the economic process would end in a 'stationary state' economy with a constant population and a constant stock of physical capital (Mill, 1857). This idea re-emerged in the 1970's when Herman Daly advocated the deliberate creation of a no-growth steady-state economy (Daly, 1973). The central concept was that the economy is a sub-system of the environment and as such it should not become too large relative to the overall biosphere.

A similar idea is the concept of 'Spaceship Earth' (Boulding, 1966) in which K. Boulding argues that anyone who believes in exponential growth that can go on forever in a finite world is either mad or an economist. The earth should be regarded as a spaceship with finite resources and a finite capacity for waste assimilation. As levels of economic activity and population keep growing, both scarcity and waste problems will get worse. In 1968 a group of 30 individuals from 10 countries: economists, natural scientists, mathematicians and businessmen met in Rome to discuss the problems facing humanity. This 'Club of Rome' group published 'The Limits to Growth' (Meadows et al, 1972). Their basic argument was that there must be limits to exponentially growing economic activity, population and pollution because of the finite nature of natural resources. Their models predicted increasing resource scarcity within a very short timescale and a collapse of economic systems in the early part of the Twenty-First Century. It was estimated that there were 550 billion barrels of oil reserves and it was predicted these would be used up in 20 years. Clearly the extent of resource scarcity envisaged in 'Limits to Growth' has not materialised. Between 1970 and 1990, 600 billion barrels of oil were used and yet, in 2000, there were 676 billion barrels of oil reserves in the Middle East alone. New discoveries, improved technology and resource substitution have saved the day at least for the moment, much as they did in agriculture in Malthus's time.

Attention gradually turned away from issues of resource scarcity and towards the problems of pollution during the 1970's. The economy produces waste products which eventually find their way back into the environment, sometimes causing biological changes (contamination) which may then cause damage to animals/plants and their ecosystems (pollution). The successor studies to 'Limits to Growth' namely 'The Global 2000 Report' (Barney, 1980) and the 'Brundtland Report' (World Commission on Environment and Development, 1987) demonstrated that the issue of the environmental effects of resource utilisation was at least as important as the issue of depletion. The 'Materials Balance' approach (Ayres and Kneese, 1969; Kneese et al, 1970) developed the ideas of 'Spaceship Earth' where the earth is seen as a spaceship which is a circular system which needs to recycle materials, reduce wastes, conserve depletable resources and use renewable energy resources where possible. The discharge and emission of wastes into the environment is inevitable and so the external costs of pollution will be widespread. The economy is an open system pulling in materials and energy from the environment and eventually releasing an equivalent amount of waste back into the environment. The 'Materials Balance' approach is based on the First and Second Laws of Thermodynamics. The materials that first enter the economic system are not destroyed by production and consumption activities (First Law); they are, however, dispersed and chemically transformed from low entropy (useful) materials to high entropy (less useful) materials (Second Law).

N. Georgescu-Roegen introduced the entropy concept into economics in the 1970's (Georgescu-Roegen, 1971). This recognises that the economic process transforms stocks of highly concentrated and easily available natural resources into products and wastes, which contain the same matter and energy in lower concentration. These economic processes are irreversible and stocks of such resources as coal and metal ores are permanently reduced by economic action while the stock of wastes is permanently increased. Hence the economic process is entropic, it neither creates nor consumes matter and energy, but only transforms low entropy (high quality) into high entropy (low quality). All economic actions (including recycling) devalue energy and/or matter and leave less available energy/matter for future generations. Even a steady-state economy would inevitably increase entropy and so could not be sustainable (Faber et al, 1998). The concept of entropy will be investigated further in Chapters 4 and 5.

The concept of sustainable economic growth or development may have originated in the modern era in the 1980 World Conservation Strategy of the International Union for the Conservation of Natural Resources. This body contended that sustainability is a strategic concept involving the lasting utilisation of natural resources, the preservation of genetic diversity and ecosystem maintenance (Kula, 1994). By 1987, the report of the United Nations World Commission on Environment and Development entitled 'Our Common Future' but also known as the Brundtland Report (WCED, 1987) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The need to consider intragenerational equity and intergenerational equity are central themes of sustainability.

Intragenerational equity means fairness to all members of the current generation and encompasses ideals such as the elimination of world poverty and hunger, and ensuring that pollution does not damage the well-being of current populations. Intergenerational equity means fairness to members of future generations by ensuring that activities undertaken in the present do not compromise their living standards. The principle of intergenerational equity is a key feature of sustainability, but it may be compromised by the way in which economists treat the future. Economic analysis assumes that a given unit of benefit or cost matters more if it is experienced now than if it occurs in the future (Pearce and Turner, 1990). One reason for this is that people have impatience or 'time preference' for benefits in the present, rather than at some future date. Another reason is that capital is productive and so £100's worth of resources used now will generate more than £100's worth of resources in the future. In order to take into account time preference and the productivity of capital, economists 'discount' future costs and benefits so that their value in the present is lower. One important result of discounting is to discriminate against future generations because their costs and benefits are reduced in value relative to those in the present. This has implications for intergenerational equity.

In terms of natural resources, sustainability requires that successive generations face no greater constraints on the use of natural resources than are experienced by the current generation. This may seem impossible given that some natural resources are effectively depleted with use. If any of these resources are used by the present generation, then they are unavailable for future generations. The problem is to maintain productive or consumption potential over time, and literature on this has concentrated on arguments about whether natural capital (of which natural resources are an important part), can be substituted by man-made assets to leave a constant capital stock (Solow, 1986 and 1991; Costanza and Daly, 1992). There is further consideration of the sustainable management of natural resources in Chapter 9.

Traditionally, natural resources are divided into two categories, renewable and non-renewable. Renewable resources are capable of regeneration within a relatively short timespan, so that using them does not deplete them forever. Non-renewable resources are created over long time periods and as a result they are often regarded as fixed stock resources.

3.2 Non-renewable Resource Economics

3.2.1 The Hotelling Principle

Non-renewable, depletable or exhaustible resources are primary materials such as minerals and fossil fuels which are extracted from the earth. They are regarded as fixed in quantity because they are created over very long time spans, although the total quantity available is likely to be unknown. The basis of the economics of non-renewable resources was formulated by Gray (Gray, 1914), and Hotelling (Hotelling, 1931), although some of the principles can be traced back as far as Ricardo and even Adam Smith (Smith, 1776). Hotelling considered the economics of the depletion of exhaustible resources, and, in particular, mineral resources. This was done in relation to the concerns of the conservation movement of the time and their concerns about the world's disappearing supplies of minerals and timber. The 'conservationist' view was that exhaustible resources are being extracted too quickly and sold too cheaply, or in Hotelling's words:

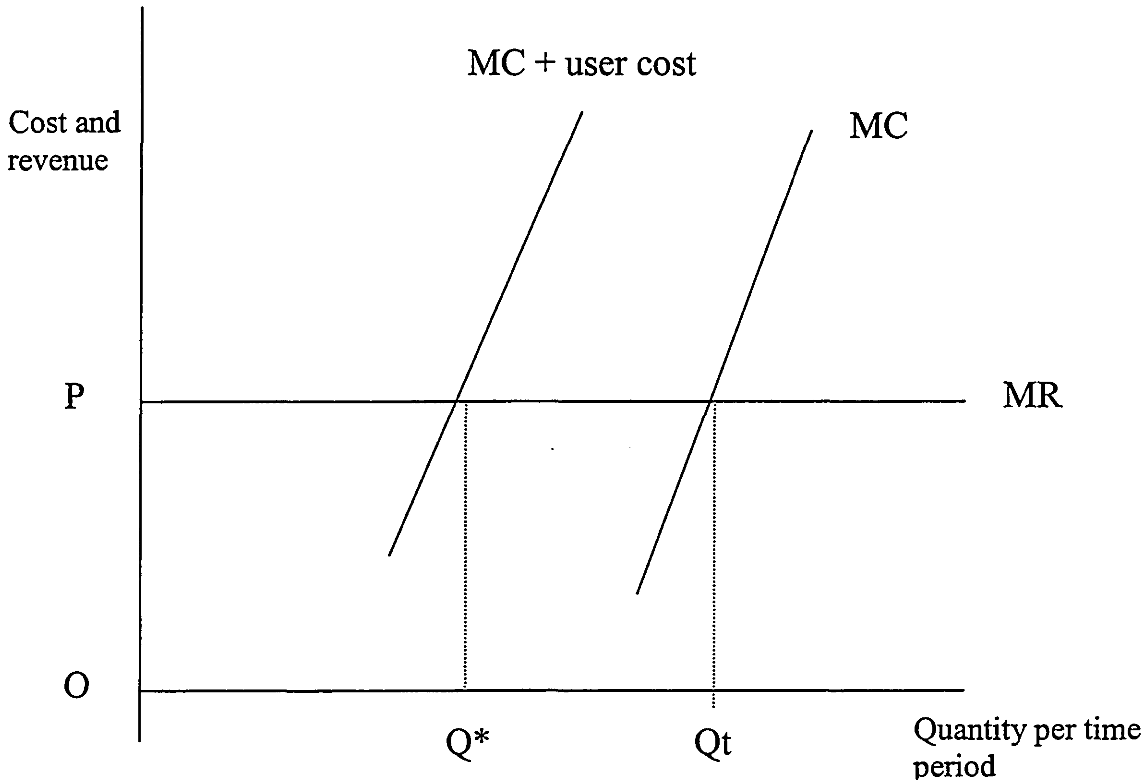
> "selfishly exploited at too rapid a rate, and that in consequence of their excessive cheapness they are being produced and consumed wastefully" (Hotelling, 1931).

In Hotelling's economic theory of exhaustible resource depletion, resource use is determined by the market mechanism and perfect markets should result in a social optimum use of resources which is 'Pareto optimal' (an efficiency criterion requiring that no-one can be made better off without someone else being made worse off). If market forces do not provide sufficient incentive to conservation for future generations, then this must be the result of market failure: decision-makers preferring excessive current rates of extraction to the detriment of future generations. Hotelling's work focused on the question of whether regulation to reduce production was the correct policy.

The distinguishing feature of the production-economics of depletable resources is that each unit of the resource can be extracted only once and so the current choice of extraction rate influences the future rate of production and the life of the resource. Production decisions today must take forgone future net benefits into account. The opportunity cost of current extraction includes the impact on future profits – the 'user cost'. This means that an important question for non-renewable resource economics is when to use such resources, that is, what is the optimum rate of consumption. Profits could be maximised by postponing extraction if price is expected to rise; and price can be expected to rise as a resource is depleted because user cost will rise. The effect of user cost on output is illustrated in Figure 2.1.

In a competitive market if only the current marginal cost (incremental cost of the last or marginal unit of output) is considered, then output will be at Qt in Figure 3.1. This is because the intersection between the marginal cost curve MC and the marginal revenue curve MR (which equals the price) gives the profit maximising output. Since extraction in the current period affects extraction in future periods, this imposes an additional opportunity cost or 'user cost' which reduces current output to Q*. This effectively conserves resources for the future.

Figure 3.1 User Costs of Depletable Resources



For a profit-maximising resource producer, in the absence of positive interest rates, total profits will be maximised by equalising marginal profits in each year:

$MP_t = MP_{t+1} = MP_{t+2} = \ldots\ldots MP_{t+n}$ (Equation 3.1)

If the marginal profit is greater in year $_{t+1}$ than in year $_t$:

$MP_{t+1} > MP_t$ (Equation 3.2)

then a greater profit would be possible by increasing the rate of extraction in year $_{t+1}$ (by transferring/delaying production from year $_t$ to year $_{t+1}$). As long as $MP_{t+1} > MP_t$ this process will continue. As long as those marginal profits are different, a switch in production occurs which increases total profits. The process will come to an end when:

$MP_{t+1} = MP_t$ (Equation 3.3)

Total profits must then be at a maximum. The rate of extraction chosen in order to maximise profits under the assumptions of constant marginal costs and zero discount or interest rates will be that which equalises marginal profits in each year.

Conventional analysis introduces discount rates at this point. Discount rates take account of the 'time value of money' – the perception that money received in the present is worth more than the same sum received at some time in the future. The perceived worth of money changes over time and discounting must be applied to future profits. A justification which can be made for the existence of discount rates is that consumption grows over time and, therefore, an additional unit of consumption will be worth less to the average person in the future than to the average person now because the former will be more affluent. Since the increase in consumption over time will be determined by the marginal product of capital (one unit of output invested today will give greater than one unit of extra consumption tomorrow) then there is some equivalence between the discount rate and the market rate of interest, which is also determined by the productivity of capital. The condition for choosing the optimum rate of extraction for a depletable resource where there is a positive discount rate is that the discounted or present value of marginal profits must be constant (equal) or:

$$P_0 - MC_0 = \frac{P_1 - MC_1}{(1+r)} = \frac{P_2 - MC_2}{(1+r)^2} = \ldots\ldots\ldots \frac{P_t - MC_t}{(1+r)^t} \qquad \text{(Equation 3.4)}$$

where:

P_t = the price of the non-renewable resource in year t

MC_t = the marginal cost of production in year t

r = the discount rate.

A firm, rather than maximising current profits, will instead seek to maximise the sum of discounted marginal profits over time. Generally, the condition for choosing the optimum rate of extraction in successive years is:

$$\frac{P_t - MC_t}{(1+r)^t} = \frac{P_{t+1} - MC_{t+1}}{(1+r)^{t+1}} \qquad \text{(Equation 3.5)}$$

or,

$$\frac{P_t - MC_t}{(1+r)^t} = \frac{P_{t+1} - MC_{t+1}}{(1+r)^t(1+r)} \qquad \text{(Equation 3.6)}$$

which becomes:

$$Pt - MCt = \frac{P_{t+1} - MC_{t+1}}{(1+r)} \qquad \text{(Equation 3.7)}$$

therefore, $P_{t+1} = (1+r)(P_t - MC_t) + MC_{t+1}$ (Equation 3.8) or, $$P_{t+1} = (1+r)P_t + \{MC_{t+1} - (1+r)MC\}$$ (Equation 3.9)

and assuming that the present value of the marginal cost of production is equal in every year $(i.e.\ MC_{t+1} = (1+r)MC_t)$

then

$$P_{t+1} = (1+r)P_t$$ (Equation 3.10)

and,

$$\frac{P_{t+1} - P_t}{Pt} = \frac{(1+r)P_t - P_t}{Pt} = 1 + r - 1 = r$$ (Equation 3.11)

From Equation 3.11, the proportional change in the price or value of the resource from one year to the next is equal to the discount rate r. Given optimum depletion and constant present values of the marginal cost of production, the proportional change or rate of change of the price of a resource over a given period is equal to the discount rate or interest rate for that period. The optimal profile of the resource's price over time is to rise at a rate equal to the rate of interest, while the magnitude of the price will depend on the resource's scarcity relative to current demand.

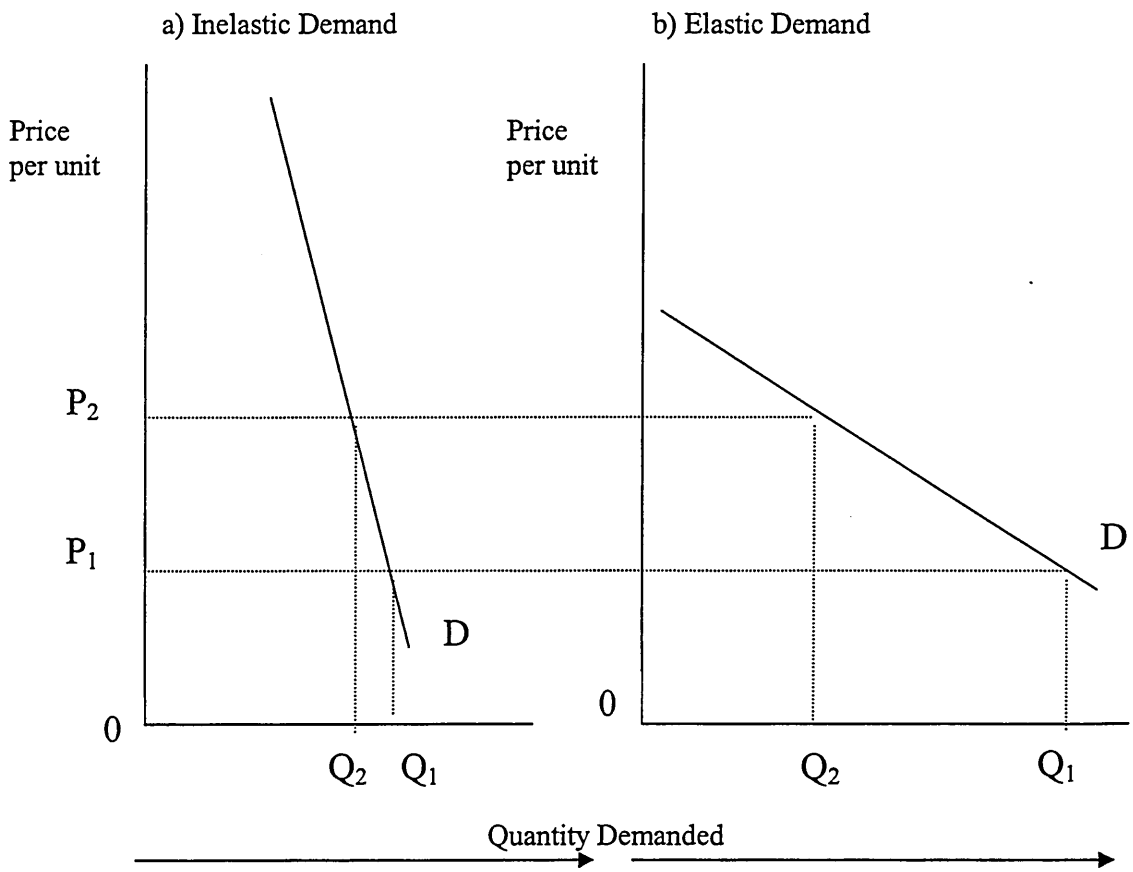
An alternative, more intuitive explanation of this may be appropriate at this point. A resource owner has to decide whether to extract all of the resource immediately; or to leave it in the ground; or to extract it at some intermediate rate of production. Leaving the resource in the ground requires a return at least equal to other investments, or the market rate of interest. Conservation adds more to wealth if the resource price rises by more than the interest rate. This is equivalent to capital gain versus interest income. Resources in the ground are capital assets and the growth in capital value of the resource remaining in the ground should equal the interest rate. So non-renewable resource prices should rise over time at a rate equal to the rate of interest. If the resource price rises by less than the rate of interest then it is optimal to extract immediately. As a result production will rise and so price will fall until the expected price rise is equal to the interest rate. If the resource price rises by more than the interest rate, owners prefer to leave the resource in the ground and this reduces production, which raises current prices until the gap between the current price and next year's price is equal to the rate of interest. The intermediate situation is that the resource will be extracted over a period of time and this will only occur if the price of the resource is rising at a rate equal to the rate of interest.

According to the Hotelling principle, society gains by conservation of a non-renewable resource only if its price is expected to rise at a rate that is at least as high as the interest rate. The rate of extraction of any non-renewable resource should be such that its price increases at a rate equal to the interest rate. With an annual interest rate of, for example, 10% then the price of the resource should be rising at 10% per annum. The appropriate rate of extraction is that which achieves such growth in price in a perfect market. If the price of the resource is rising by more than 10%, there is too little current extraction. If the price is rising by less than 10%, there is too much current extraction. Therefore, a higher rate of interest means more extraction.

For a social optimum, the Hotelling principle requires that the growth rate of the resource price should be equal to the social discount rate (the discount rate which is appropriate to society as a whole and which may incorporate society's valuation of the welfare of future generations). The actual rate of extraction depends on demand in the market (see Figure 3.2). If there is relatively low demand at all prices then the rate of extraction will be small. If there are few substitutes and purchasers are prepared to pay large sums rather than do without the resource, the demand curve will be relatively inelastic. Elasticity of demand refers to the responsiveness of quantity demanded to a change in price of a resource. If there is a small response or change in quantity demanded as the price of the resource rises, then the demand curve is described as 'inelastic' as in Figure 3.2a.

If there is a large response or change in quantity demanded as the price of the resource rises, then the demand curve is described as 'elastic' as in Figure 3.2b. Inelastic demand will lead to a relatively even rate of extraction with small reductions in output each year driving up prices at the required rate. If substitutes are relatively easily found when the price of the resource rises then consumption now will be greater in order to increase prices at the required rate (with an elastic demand curve a bigger reduction in output is needed to raise prices by the desired amount). This is illustrated in Figure 3.2 where with inelastic demand (in Figure 3.2a) only a small reduction in output from Q_1 to Q_2 is required, while a much larger reduction in output is required (in Figure 3.2b), from Q_1 to Q_2, to achieve the same increase in price. The market seems to provide a defence mechanism against shortages or depletion here. The resource with fewer substitutes, which is presumably more essential, is extracted more slowly. Less essential resources with more available substitutes are extracted more quickly.

Figure 3.2 Resource Elasticities

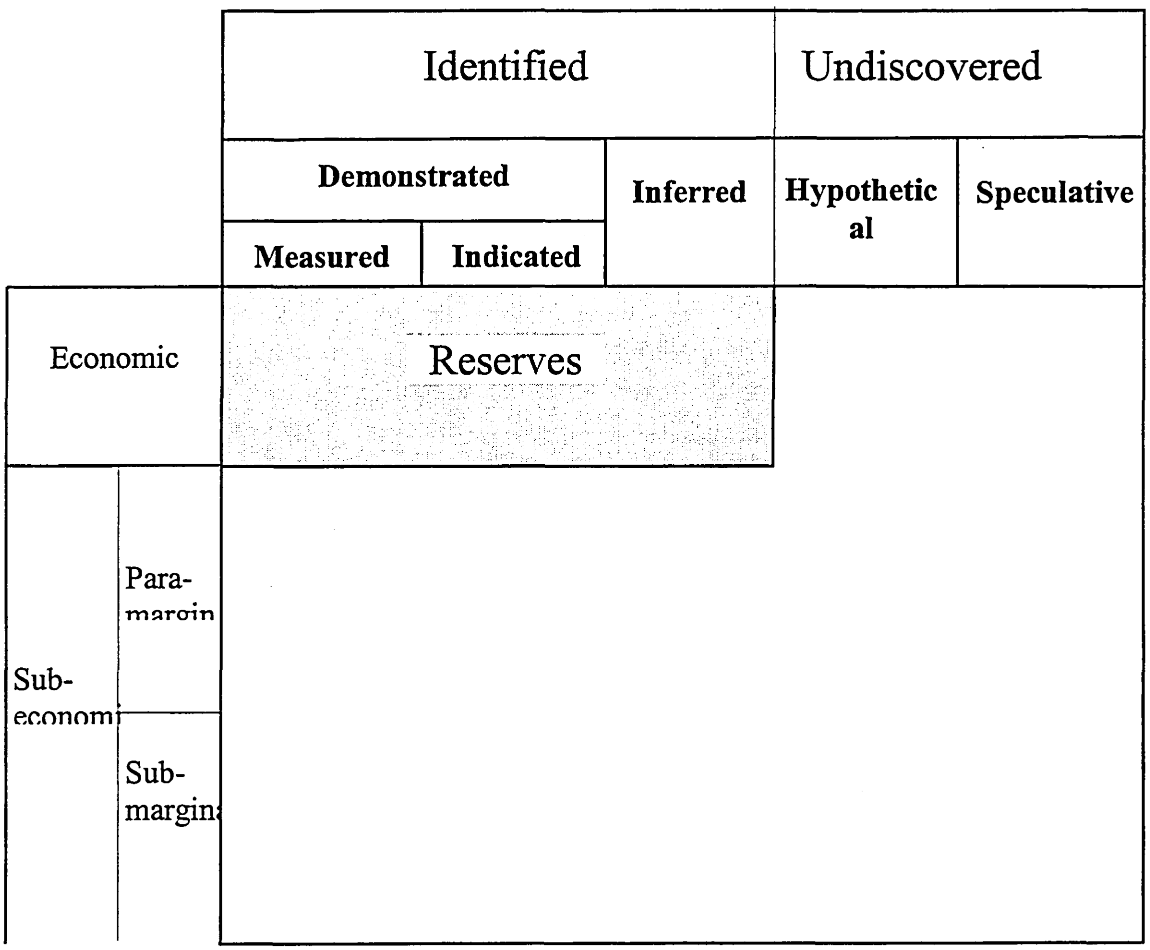


The price system or market mechanism should, therefore, provide conservation mechanisms. By following private profit incentives, resource owners are led to conserve the resource in a manner that is consistent with society's needs. It has already been shown that the optimal extraction pattern for society of a non-renewable resource occurs when its price rises are at a rate equal to the social discount rate. The rising price encourages *conservation* with consumers becoming more economical in use of the resource. Uses of the resource which have low profitability may be discontinued, while uses with high profitability will continue only if their value at the margin is enough to justify the higher price. This process is well illustrated by the case of oil after the 1973 price rise by the Organisation of Petroleum Exporting Countries (OPEC). The rising price also encourages *exploration* for new sources of supply (such as offshore drilling for oil post-1973). *Innovation* is also encouraged to develop new products to substitute for the resource whose price has risen, new processes to use the resource more economically, and new processes that use alternative resources. The market mechanism should promote exploration, conservation, innovation and substitution as non-renewable resource prices rise and, ultimately, a 'switch point' will be reached where the price is sufficiently high to switch demand from the non-renewable resource to a renewable resource substitute (assuming that one exists).

3.2.2. Resource Classification

To examine whether natural resources in general are becoming more scarce, physical measures could be used such as quantities of known reserves, or economic indicators such as market prices, resource rents and marginal exploration costs. Physical measures, however, are of limited use if considered in isolation from economics. Reserves of natural resources are affected not just by physical quantity but also by economic feasibility as illustrated by the McKelvey diagram in Figure 3.3.

Figure 3.3 Total Resources



Conventional classification for depletable resources. (From McKelvey (1974), with permission from Butterworth-Heinemann journals, Elsevier Science Ltd, Kidlington, UK).

Terms used and their definitions

Identified resources	Specific bodies of mineral-bearing material whose location, quality and quantity are known from geological evidence, supported by engineering measurements.
Measured resources	Material for which quantity and quality estimates are within a margin of error of less than 20%, from geologically well-known sample sites.
Indicated resources	Material for which quantity and quality have been estimated partly from sample analyses and partly from reasonable geological projections.
Inferred resources	Material in unexplored extensions of demonstrated resources based on geological projections.
Undiscovered resources	Unspecified bodies of mineral-bearing material surmised to exists on the basis of broad geological knowledge and theory.
Hypothetical resources	Undiscovered materials reasonably expected to exist in a known mining district under known geological conditions.
Speculative resources	Undiscovered materials that may occur either in known types of deposits in favourable geological settings where no discoveries have been made, or in as yet unknown types of deposits that remain to be recognised.

Although the physical limit of crustal abundance is an absolute limit to reserves this is unlikely to be encountered because the economic barrier of prohibitive cost will be reached long before this point because the most inaccessible and lowest grade resources will be very high cost. If price were to be high enough, however, even these would be exploited. Moreover, natural resources are not uniform in quality and location, and the quantity available is not known with certainty. As can be seen from Figure 3.3, only a small part of total resources can be termed 'reserves'. These are resources, which are both identified, in terms of location, quality and quantity and economic, in that they can be extracted profitably with current prices and technology. The views of V. E. McKelvey, a natural scientist, and H. Hotelling, an economist, are to some extent reconciled by this two dimensional classification. For McKelvey, the resources which are as yet 'undiscovered' enter the spectrum of total resources, despite the uncertainty which there must be about their existence. For Hotelling, resources which have not been 'demonstrated' to exist play no part in the determination of prices of natural resources, hence his assumption of a fixed stock of a resource. The McKelvey diagram represents the first attempt to combine physical and economic measures of resources.

There is, however, little evidence of rising prices of non-renewable resources and few, if any, resources approach complete depletion. It may be that market signals are not feeding through to the price of non-renewable resources and as a result the consumer does not see rising prices. This amounts to a form of market failure which prevents the price system from doing its job. Market failure in the case of non-renewable resources is then a key issue which requires investigation. The main reasons for its occurrence are as follows:

- Insufficient or imperfect information
- Poorly defined property rights
- Tax incentives
- Hidden exploration costs
- Hidden external costs

Resource owners may not have sufficient information to determine the optimal extraction rate. In particular, they may not know the extent of world stocks of the resource (because other companies and other countries conceal such information) or even the current extraction rate from other producers. As a result they will find it difficult to estimate the rate of price rise and thus when to raise or lower their current rates of extraction. The Hotelling Principle assumes that the level of stocks is known, but for the reasons outlined here, this assumption may be unrealistic.

A property right is a bundle of characteristics that convey certain powers to the owner of the right. The owner of a resource can normally prevent others from using or exploiting the resource without permission. Open access to resources where property rights are not clearly defined can lead to exploitation at too fast a rate, and although these situations are rare for non-renewable resources they do exist, for example where oil fields cross national or ownership boundaries. If the property right is insecure or uncertain, perhaps because of political uncertainty, then rapid extraction will be encouraged.

Tax incentives or tax breaks may mean that the consumer never sees the price signal feeding through to the price of non-renewable resources. Depletion allowances (provisions to exempt from income tax part of income from resource extraction) are used in the United States, Canada and the United Kingdom to compensate firms for the wasting nature of the resources they extract. If these tax concessions are significant enough, few of the uncompensated costs (user costs) of resource depletion will be suffered by the extractor firms with the result that the consumer never sees the price signal feeding through to the price of non-renewable resources. It may even be that the tax system makes non-renewable resources look like renewable resources in that the price does not rise as more of the resource is depleted so that the depletion effect on prices is removed.

As resources become depleted, exploration costs should rise and rising real marginal cost of exploration (the cost of finding one more unit of the resource) should indicate increasing scarcity. It should also feed through to prices encouraging actions to alleviate depletion. It may be, however, that the consumer never pays the exploration costs either because of tax breaks (as above) or government subsidies or because companies do not pass them on in the form of increased price to consumers. New technology can also have an effect here if new exploration techniques greatly reduce marginal exploration costs or if improved extraction techniques mean that only lower grade resources need be discovered.

A further possibility which could explain the observation of falling resource prices to consumers, or at least prices which are rising by less than market rates of interest, is that external costs of pollution and environmental degradation are not included in prices to consumers. In developed countries some of these costs are now being included on a local scale via the restoration plans of extraction companies, but many costs remain uncompensated, especially those which are global, rather than local. These costs are potentially very high indeed (for example, global warming and ozone depletion) and prices could be much lower than they should be if they are not included.

3.2.3 Measures of Scarcity

As was observed by Barnett and Morse (Barnett and Morse,1963), there is little evidence of increasing resource scarcity from prices or costs. In order to empirically test whether costs of resources were rising over time, Barnett and Morse used an index of real (inflation adjusted) extraction costs per unit:

$$C = \frac{(\alpha L + \beta K)}{Q} \qquad \text{(Equation 3.12)}$$

Where C = Cost

L = Labour

K = Capital

Q = Quantity of resource extracted

α and β are weights to aggregate inputs to reflect their relative importance in the production process.

Rising real marginal extraction costs should indicate increasing resource scarcity and extraction costs per unit are an approximation of this which is easier to calculate. The main problem with this measure of scarcity is the possibility that rapid technical progress will cause costs to fall, even if resource scarcity is increasing. Using this real unit extraction costs measure for the period 1870 to 1957 no evidence of increasing scarcity of non-renewable resources was found (Barnett and Morse, 1963; Barnett, 1979). If anything, resources seemed to be becoming more plentiful and they explained this by suggesting it was the result of discovery of new deposits, substitution of more abundant lower grade deposits as higher grades were depleted, and technical advances in exploration, extraction and processing. Regression analysis has been used to update this work up to 1966 and it showed that the cost of mineral commodities fell at a faster rate from 1957 to 1966 compared to the period before 1957 (Johnson et al, 1980). Further updating of the unit cost analysis was undertaken to test for a significant increase in scarcity from 1960 to 1980 (Hall and Hall, 1984). It was found that the unit cost of petroleum and coal began to increase in the 1970's, before the OPEC price increases.

Marginal discovery cost has been investigated as an indicator of scarcity (Devarajan and Fisher, 1982). It was found that this rose for oil discovery in the United States of America between 1946 and 1971. The price paths of 12 non-renewable resources in the USA were examined for the period between 1870 and 1978 (Slade, 1982). It was concluded that the long-run price path for natural resources is U-shaped because of the effects of technical change and then depletion. For 11 out of the 12 resources there were significant U-shapes and all had passed the minimum point of their curves, indicating increasing scarcity. The implication of this is that in the early stages of exploitation of a resource, the rate of technological change offsets ore-grade decline and costs fall, allowing falling real prices. If the two opposing forces, technological change and falling ore-grade counterbalance each other, there would then be a period of stable prices. At some point, however, as depletion proceeds, the rate of technological progress would not be able to offset the decline in ore grades and then costs and prices would increase. This explanation seems entirely plausible, suggesting that the falling real price phase for natural resources is temporary, and that the future may see an upward trend in resource prices. The implications for sustainable use of resources are obvious.

The most convincing studies of scarcity have looked at the increasing cost of extracting natural resources in terms of energy used (Hall et al., 1986; Gever et al., 1986; Cleveland, 1993). The basic proposition of these studies is that lower quality resources require more energy to upgrade them to a given, usable state. So, more energy is required to refine copper metal from lower grade ore and more energy is required to pump oil from deeper and smaller oil fields. According to these studies, the energy cost of extracting oil, gas and coal increased by 40 per cent from 1970 to the 1990's, indicating a significant increase in scarcity.

Given that market forces should lead to the price of depletable resources rising as they are depleted (although as has been shown there are several reasons why this price signal can become obscured) there should come a point at which it is economic to change from using depletable resources to using a renewable resource. At this 'switch' point the cost of using the renewable resource is exactly equal to the cost of using the depletable resource and any further use of the depletable resources will mean that the renewable resource is now cheaper to use. The economics of non-renewable resources are dominated by the Hotelling Principle. This has meant that the market has been relied upon to deplete non-renewable resources in an optimal way, even allowing for the welfare of future generations if user costs of non-renewable resources are taken into account by resource decision makers. Depletion is not, however, the whole story. Use of non-renewable resources adds to pollution in the environment and the costs of this are usually not reflected in market prices. A key issue then is whether renewable resources are disadvantaged because the true costs of non-renewable resources are not being recognised by economic theory.

3.3 Renewable Resource Economics

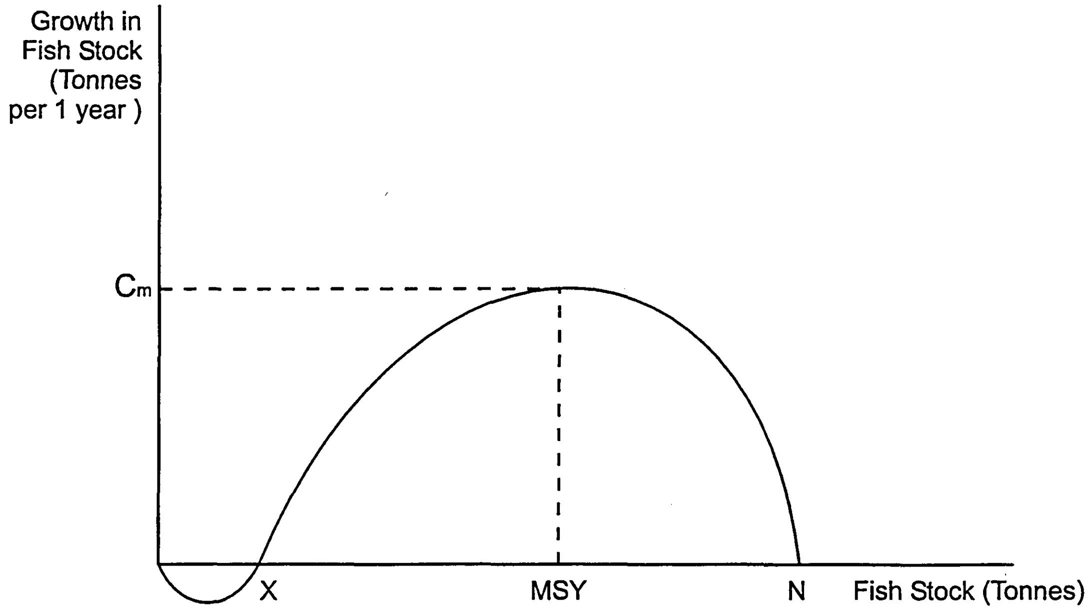
Almost all economic theory concerned with renewable resources is in fact about biological resources such as forests and fisheries. In many studies the distinction between such resources and non-biological resources such as solar power, wind power and wave power is not even mentioned. In other studies it is mentioned but not addressed.

3.3.1 Economics of Fisheries

Literature on renewable resources relies heavily on the paper by H. Scott Gordon entitled "The Economic Theory of a Common Property Resource: the Fishery" (Gordon, 1954) and the paper by M.D. Schaefer which suggested the relationship between the growth of fish populations and the size of fish populations (Schaefer, 1957). In doing so, Schaefer laid the foundations for a bio-economic model which aims to maximise returns from fishing (or forestry) subject to the constraint of resource dynamics. Common property versus private property issues in fisheries were explored in another paper (Scott, 1955). The importance of discount rates in the dynamic theory of fisheries and forests has been identified (Copes, 1972; Clark, 1973). These identified the conflict between the natural rate of growth of the resource and the rate of discount; and further analysed the risk of extinction of a species. Later influential works (Christy, 1973; Brown, 1974) focused on methods of management of fisheries in the face of considerable depletion of fish stocks. This culminated in proposals for Individual Transferable Quotas (ITQ) (Christy, 1973; Retting and Gintner, 1978) which relied heavily on the work on tradable permits in controlling pollution (Dales, 1968). Open access problems of fisheries are discussed in a paper by F.W. Bell entitled "Mitigating the Tragedy of the Commons" (Bell, 1986) and by others (Munro, 1982; Scott, 1989).

The approach adopted by existing literature begins by constructing a bio-economic model of a fishery and then considering the impact of open access and of discount rates. Biological renewable resources are those for which the stock can be continually replenished by the reproductive nature of plants and animals. The economics of these resources, such as fisheries and forests is dominated by the possibility of over-exploitation. The possibility exists that such resources would become exhaustible if they are over-exploited beyond their capacity to recover (i.e. they are not managed effectively). In these circumstances, if the critical minimum population of fish etc., is not maintained, then the flow of renewable resources becomes a stock of a depletable resource. Such resources then must be managed in a sustainable way so that only additions to stocks, or the 'sustainable yield' are harvested. Schaefer suggested a relationship between the growth of the fish population and the size of the fish population (Schaefer,1957). This is illustrated in Figure 3.4.

Figure 3.4 Maximum Sustainable Yield

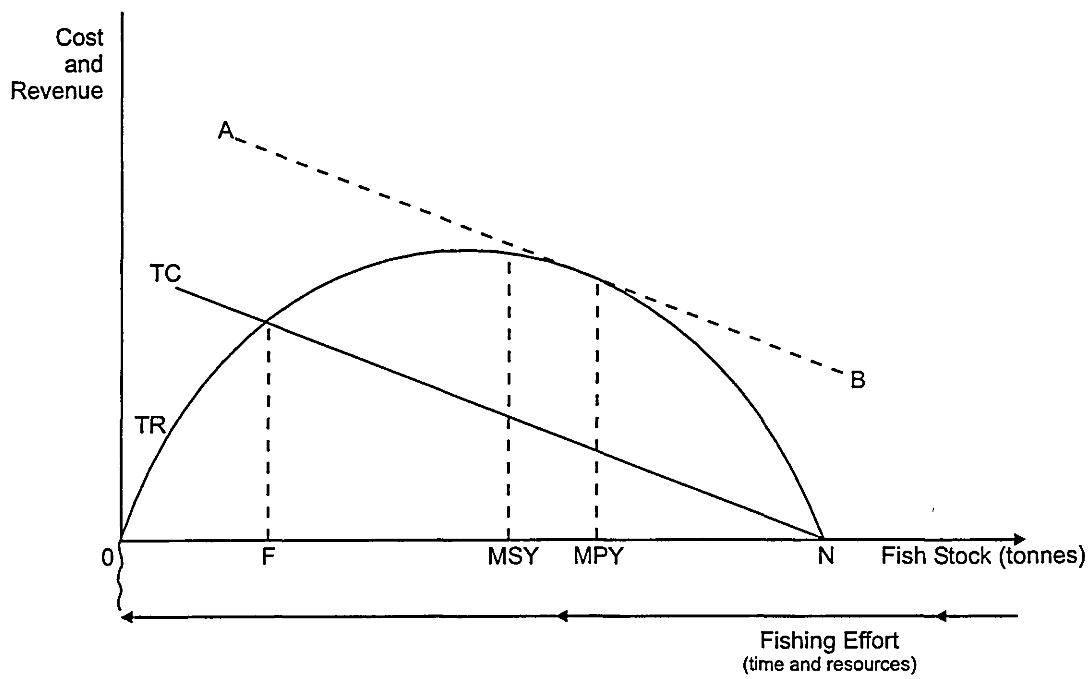


The growth rate of the fish stock depends on the size of the fish stock/population (or biomass) which cannot exceed a given level, such as N in Figure 3.4 because of environmental constraints. The growth rate is slow at low stock levels because of the difficulties of fish finding other fish to breed with. It increases to a maximum level C_m at the turning point of the curve, then declines to N, the maximum carrying capacity. The growth of stocks slows as fish compete for food supplies until the maximum population is reached. At this point the fish stock cannot grow any larger because of the constraint of lack of food. This is a totally natural situation, which does not depend on humans. However humans want to know the maximum sustainable yield (MSY) which is the number of fish (in tonnes per year) which can be caught without depleting the stock. The MSY equates to the stock which gives the highest growth rate (catch rate) of C_m. Beyond this point the size of sustainable catches declines as shown in Figure 3.4.

N is the natural equilibrium stock which would exist in the absence of outside influences. A 'sustainable yield' would be a size of catch which equals the growth rate of the fish population. MSY gives the maximum sustainable yield C_m. It is the fish stock/population which yields maximum growth and, hence, maximum sustainable catches: C_m. A larger fish stock than MSY would give a reduced yield because of pressure on (fish) food supplies. Larger catches than C_m would lead to reduced population sizes. If the fish population was reduced to a level smaller than X then extinction would follow as X represents the minimum viable population (below this level of fish stock, the fish cannot find each other with sufficient frequency to reproduce themselves).

The size of catch which would maximise fishing industry profits is less than the maximum sustainable yield because costs of fishing have to be taken into account. The profit maximising catch/fish population would be that which maximises revenue (or catch size, since constant prices are assumed) minus costs. Assuming that marginal costs are constant and that higher fishing costs imply greater fishing effort and, therefore, a lower fish stock/population, the profit maximising catch will be less than the maximum sustainable yield, (see Figure 3.5).

Figure 3.5 Maximum Profit Yield



In Figure 3.5 fishing costs are introduced on the x-axis, increasing from right to left along with fishing effort (defined as the amount of time and other resources devoted to fishing). At high levels of fish stocks costs are lower. Costs increase as the size of the fish stock declines. The maximum profit yield MPY is shown where the slope of the total cost curve TC is equal to the slope of the total revenue curve TR (AB being parallel to the total cost curve). Where the slopes of TC and TR are equal, marginal revenue is equal to marginal cost - the profit maximising condition. The profit is shown by the distance between the total revenue and the total cost curves and it is clearly greater at MPY than MSY. The profit maximising level of fishing effort MPY gives a larger size of fish population than the maximum sustainable yield, MSY level of effort. If costs were to increase then the profit maximising level of catch would fall; if costs decreased then the profit maximising catch would be nearer the maximum sustainable yield. Of course if fishing costs were zero then the profit maximising catch would be equal to the maximum sustainable yield. The maximum sustainable yield is a biological concept which does not take into account costs of fishing. The optimum or profit maximising catch clearly must take costs into account and if the fishing resource is owned by a profit maximising economic agent, then it will be managed in a sustainable way with catches less than the maximum sustainable yield.

Problems are likely to occur, however, if the fishing resource is one with open access. If anyone is free to enter the fishery and catch fish then individual fishermen/boat owners will base their decision on whether to enter and catch fish on the possibility of making an individual profit. If the price of fish at least covers the average costs of fishing then more fishermen/boat owners will enter. In Figure 3.5, entry will continue while TR is in excess of TC and the level of fishing effort will be OF which results in a lower fish population than either the maximum profit level or the maximum sustainable yield level. At the effort level F, with a far greater fishing fleet than that needed for the profit maximising level of catches, costs will be higher than they would be for MPY. Moreover, the size of the fish population is reduced and growth rates will be affected because the catch is greater than the maximum sustainable yield. This is because open-access leads fishermen to harvest more at each fish population size since they ignore any user costs (defined here as the forgone value of using a resource now and thus preventing its use in the future) or external costs (those costs not taken into account by the market). It is technically possible for the cost function in Figure 3.5 to be sufficiently steep that it intersects the total revenue curve to the right of the maximum sustainable yield. This could happen if fish stocks decline and their 'finding costs' increase. Total cost is not independent of the fish stock/population. If costs were very high then open-access would not lead to over-exploitation or extinction. Examples of over-exploitation of open-access fisheries are easy to find, however, and new technology makes fish easier (and cheaper) to find and catch. In general if property rights do not exist (open access) then new entrants will remove the scarcity rent (otherwise known as the net price or resource rent or royalty) in the fishing industry and force profits to zero. The size of catch which would maximise fishing industry profits is less than the maximum sustainable yield which, in turn, is less than the size of catch which would result from open access. Extinction can, therefore, occur if the costs of catching the few remaining fish (including costs on future generations) are less than the benefits. Fortunately, for several species, the cost of catching the last few fish is likely to be well in excess of their market value. There is no guarantee, however, that the few remaining fish will be able to build up stocks again.

The problem of over-fishing with open access occurs because fishermen ignore the asset value of the fishery and simply maximise the use value (i.e. maximising current revenue from use of the resource in the current time period). It is a classic example of a 'Tragedy of the Commons' (see Garrett Hardin, 1968). Acting alone fishermen have no incentive to conserve the resource. If fisheries could be 'privatised' (as in the case of fish farms) a solution would present itself because the resource owner would also consider its asset value. Fishermen must collectively equate price to the sum of marginal cost (MC) plus the user cost. If the harvest is below the MSY then there will be no additional user costs (because consumption of a unit of the resource today does not reduce the amount available for consumption in the future) and the MC of the current harvest is the relevant cost. If, however, the harvest exceeds the MSY then there will be a user cost which requires a reduction in harvest levels if catches are to be sustainable. Fishermen are unlikely to recognise this user cost, and even if they did, they may be unable or unwilling to act on it, as it is a social cost rather than a private cost in an open access fishery. This, of course, is a classic case of an externality, which is one form of market failure which increases the likelihood of open access leading to extinction of a species. The extinction of one species may, of course, have implications for the survival of many other species in a complex ecological system. User costs would then be considerable.

The question of how to 'internalise the externality', or find some mechanism of making fishermen take the additional user costs (or social costs) into account, has led to several management policies for fisheries. Traditional solutions to the problem of over-fishing have aimed to reduce catches by restricting the number of boats, or net sizes, or size of catch, or number of days that fishing is allowed. These solutions have encountered considerable enforcement problems and have had limited success.

> "Even if the global fleet is successfully downsized, many experts believe that sustainable management of global fisheries will require some solution to the problem of open access. Otherwise, the fishing effort may not be reduced enough or in a manner that promotes the conservation of stocks."
> (World Resources, 1997).

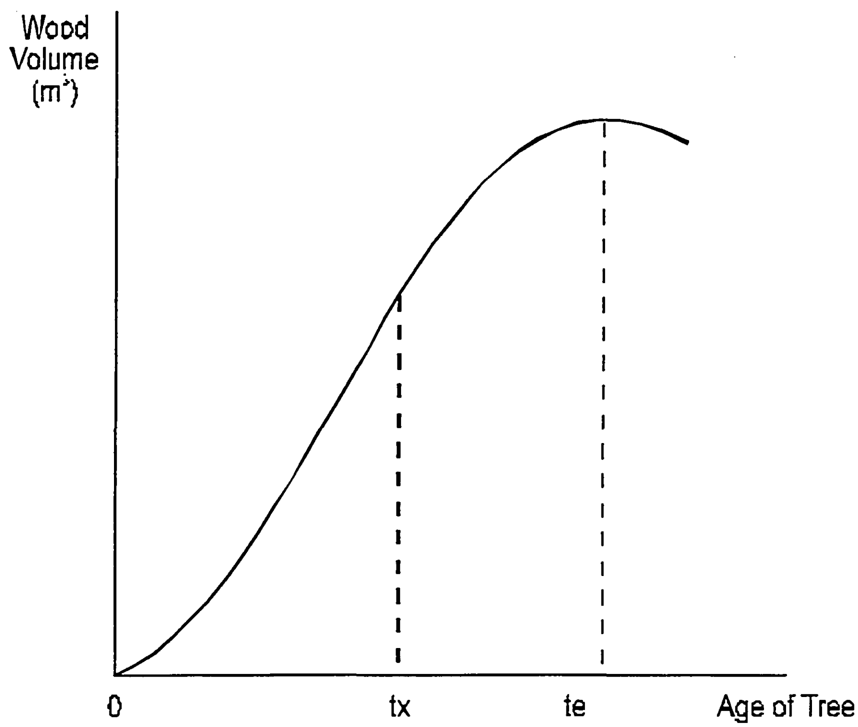
Using economic incentives to achieve catch reductions offers the possibility of preserving stocks while maintaining incomes of fishermen. The classic Pigovian Tax solution to the problem of an externality (the user cost) could be applied using a landings tax (a tax per unit of fish landed). An alternative is to introduce Individual Transferable Quotas (ITQ's) which are now being used in several fisheries around the world with some success. An efficient quota system sets the total amount of fish catch allowed by the quotas equal to the efficient (MSY) catch for the fishery. Quotas can then be bought and sold as private property, giving an incentive to protect the resource in order to maintain the value of the quota in the future. There are, of course, problems and potential disadvantages of ITQ's, but they do provide a method of persuading fishermen to consider the asset value of an open access fishery.

It is necessary to introduce time into this static analysis of biological resource economics. Schaefer's work has been developed to produce a dynamic theory of fisheries (Copes, 1972; Clark et al, 1979). The fish stock as well as being a potentially renewable resource can also be regarded as a capital asset and the harvest level yield of fish can be compared with the rate of return on any other capital asset. The higher the discount rate, the higher the cost in terms of foregone current income to the resource owner of maintaining any given resource stock. High discount rates in other sectors will mean a higher return is necessary from the fishery and any positive discount rate will mean that the efficient level of effort would be increased beyond that of the static efficient sustained yield. Indeed, if the discount rate is high then it may be optimal to exhaust the resource as quickly as possible and invest the proceeds in other assets whose value will increase much faster. This possibility is reinforced if the regenerative capacity of the resource is slow. This result is very similar to the Hotelling Principle for optimal depletion of a non-renewable resource and of course if the rate of growth of the biological renewable resource was zero, there would be no difference between it and a depletable resource. This highlights one of the key issues in defining or classifying a resource, which is its 'growth rate' relative to its exploitation rate. Fish stocks with very low growth rates may suffer the fate of rapid depletion in order to invest the proceeds elsewhere. As long as the fish stock growth rate exceeds the discount rate this will not be the case. If, however, the growth rate is lower than the discount rate, extinction can occur (Tietenberg 1996). The possibility of extinction arises because no special consideration is given to the unique nature of a biological renewable resource which has no substitute. There seems to be no way that the external cost of the extinction of a unique natural resource can be incorporated into the discount rate.

3.3.2 Economics of Forests

As with fish, forests can be seen as an output and a capital good. When harvested, trees produce a saleable commodity, but, if not harvested they are a capital good giving increased growth the following year. A forest owner can decide whether to harvest or wait for additional growth. The time-lag between planting and harvesting can be more than 25 years, however, which is much more than for other renewable resources. Growth rates of particular forests or stands of trees will vary according to many factors including: soil fertility, type of tree, weather, susceptibility to fire or pollution and the amount of care devoted to the trees. Figure 3.6 shows a growth cycle for a representative tree.

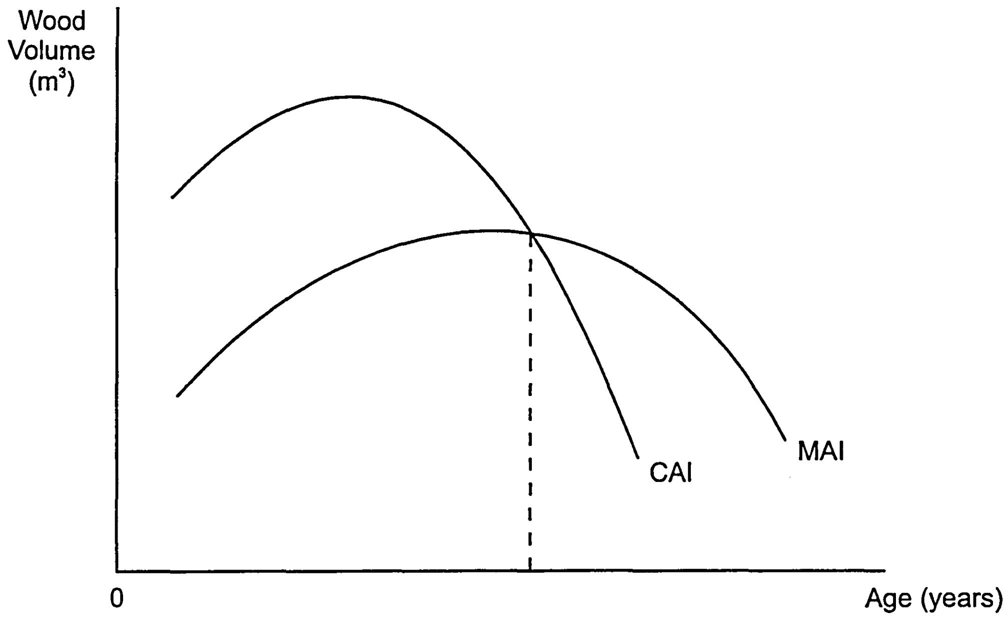
Figure 3.6 Tree Growth Cycle



There is an early period of limited growth, followed by rapid growth which slows towards age te. The maximum wood volume is obtained when each tree is te years old. Beyond tx the growth rate slows. Beyond age te the tree begins to decay. For maximum wood volumes the forest should be harvested when the Mean Annual Increment (MAI) is maximised. The MAI represents the average rate of increase of wood volume from planting to any point in time. It can be calculated by dividing the volume of wood by the age of the trees in years. The concept is similar to that of average product in traditional neo-classical economics. The

Current Annual Increment (CAI) represents the annual rate of increase in volume at any point in time and is similar to marginal product in conventional neo-classical economics. The CAI curve cuts the MAI curve at the maximum point and this intersection represents the maximum average rate of volume production which can be maintained by felling and replanting in an even aged plantation. These concepts are illustrated in Figure 3.7.

Figure 3.7 Mean Annual Increment and Current Annual Increment



Forestry management practices are generally based on the MAI relationship, although in practice, the best time to harvest a tree or stand of trees depends on a number of factors. These include the final use of the wood, cost of harvesting and of replanting, demand conditions, and the cost of managing the forest.

In contrast to the economics of fisheries it is neither useful or necessary to consider open-access problems in the analysis of forestry economics (although it may be of great importance in considerations of deforestation in less developed countries). It is, however, useful to investigate the impact of discount rates on forestry economics. Positive discount rates, which take the time value of money into account, shorten the time until the stand of trees is harvested. It has been shown that, for Douglas Firs, whereas the MAI (which represents maximum undiscounted net benefits) is reached at 135 years, a discount rate of only 2 per cent reduces the maximum benefit period to 68 years and a discount rate of 4 per cent reduces it to 40 years (Tietenberg, 1996). Furthermore, higher interest rates imply shorter harvesting periods because they mitigate against the slow timber growth that occurs as the stand of trees reaches maturity. An interest rate of say, 5 per cent, while the volume of timber is only growing at 3 per cent, means that it is more profitable to cut the trees and invest the proceeds to gain the higher rate of return on financial investments. Once interest rates are introduced into the analysis, a direct comparison can be made between the increase in the value of the timber while it is growing and the increase in value which would be gained by harvesting and investing the proceeds.

The analysis so far has considered a single stand of trees to be planted and harvested when the present value of net benefits is maximised. It is more realistic to assume that once harvested, the land will be replanted and the process begins again. Delaying the harvest delays replanting and, therefore, the next harvest. The cost of delaying the next harvest must be less than the gain from increased tree growth. If replanting is assumed then the optimal time to harvest (the optimal rotation) is shorter. Offsetting the shortening effect on optimal rotation of positive discount rates and of replanting, however, is the fact that relative prices of timber have been rising over time. If prices are rising, then the value of the growth rate of the timber will be increased and this will tend to delay the harvest and increase the optimal rotation. A further influence on the optimal rotation period could be the use of the forest as an amenity or wildlife habitat, the value of which is recognised. This would have the effect of lengthening the time to harvest if the assumption is made that these amenity or wildlife benefits increase with the age of the forest.

The economic theories of fisheries and forests are essentially the same theory. The bioeconomic concepts of MSY and MAI are very similar, and although there are differences in time to maturity and access/ownership, the key economic principle of comparison of biological growth rates (and revenue growth) with discount rate is crucial to exploitation decisions. The economic theory of renewable resources is really economic theory of biological renewable resources. It has roots in biological and economic concepts, but it does not explain the economics of renewable energy sources such as hydro, solar, tidal, wind and wave power.

3.4 The Theoretical Void

Conventional classification of resources as 'renewable' or 'non-renewable' is inadequate. The renewable resources include at least two groups of resources which have quite different characteristics. The first group can be described as 'biological' renewables which encompasses fish, forests, whales and biomass among others. The second group comprises hydro, solar, tidal, wind and wave power which are non-biological, continuous flow resources (Jowsey, 1997). Due to their different characteristics it is probable that these two types of renewable resources have different economics. Existing literature about the economics of resources largely ignores these differences and discusses the economics of renewable resources largely in terms of fisheries and forests, treating the theory of hydro, solar, tidal, wind and wave power as the theory of renewable resources (see, for example, Bowers, 1977, and Kula, 1994). Fishery and forest economics are not general cases, but specific cases with their own economics.

Where there is some recognition of the differences between biological renewables and continuous flow resources, it has limited influence on subsequent economic theories. In the classic paper 'The Economics of the Coming Spaceship Earth', the likely importance of solar power as renewable energy in the near future is recognised (Boulding, 1966). Another work (Hartwick and Olewiler, 1986) discusses renewable energy supplies, which are recognised as all being derived from solar energy. Despite detailed discussion of types of renewable energy resource, no economic theory of such resources is presented. Economic theories for non-renewable resources and biological renewable resources, by contrast, are considered in detail. Elsewhere (Rees, 1985), a clear distinction is made between stock and flow resources, but then there is only a detailed discussion of biological renewables. Renewable resources are classified as either 'renewable energy flow resources' or 'renewable but exhaustible stock resources' in another work (Perman, Ma and McGilvray, 1996). Furthermore, renewable stock resources are divided into 'renewable biological stock resources' and 'renewable physical stock resources', the latter being "capable of regeneration in relatively short periods of time through physical as well as biological transformation processes". Examples given include soil structures, aquifers and the earth's ozone layer. Whilst these assets are useful, indeed, essential resources, they are not directly used by humans as other resources are, such as fish, coal and wind power. They are more akin to a *natural infrastructure*, which is essential in order that exploitation of other resources can take place. Although the distinction between renewable *stock* resources and renewable *flow* resources is emphasised, subsequent economic analysis is confined to the former, concentrating on fisheries and forests. Another author (Tietenberg, 1996) clearly distinguishes between renewable resources which are dependent on humans for their continued existence (such as fish) and those for which the flow is independent of humans (such as solar energy). However, Tietenberg's economic analysis of different types of resources omits the latter category.

Other authors (Jones and Hollier, 1997) distinguish between "flow or organic resources which are capable of reproducing themselves and are clearly affected by human action in that they can be depleted, sustained or increased" and "continuous resources, which are available irrespective of our actions yet can be modified to suit our needs". Unfortunately, the description of organic resources as 'flow resources' clouds the issue as, clearly, resources such as solar and wind power are flow rather than stock resources. In this analysis, however, water is correctly described as a renewable resource on a global scale (as it is continuously available via the hydrological cycle) but a non-renewable resource on a local scale in certain geographical locations where replenishment of underground aquifers would take thousands of years. Probably the best, very concise, discussion of classification of natural resources takes place in a work which divides renewable resources into unconditionally renewable resources such as solar, tidal and wind power and conditionally renewable resources such as fish, crops and ecosystems (Young, 1992). However, this cautions against recognising only the *use value* of a resource when it contributes to a productive process (the neoclassical economist viewpoint) and adopts the wider view of resources which "recognises that many renewable resources *maintain* the integrity of ecosystems; *provide ecological services* by assimilating and absorbing waste; and make a significant contribution to *environmental amenity, aesthetic and cultural values*". These functions of renewable resources contribute to what was termed earlier in this thesis 'natural infrastructure' which is frequently ignored by economists because it is regarded as a 'free good' without a market price.

Nowhere in prominent existing literature is there a full discussion of the economics of hydro, solar, tidal, wind and wave power, whether they are given this title or another, such as 'abiotic flow resources' or 'continuous resources' or 'renewable energy resources'. Moreover, most of the existing work on the economics of resources fails to distinguish between biological resources and hydro, solar, tidal, wind and wave power, and treats the theory of biological renewable resource economics as if it is the whole story, which clearly it is not. Economic theories of resources are, therefore, neither rigorous or complete. There is a need for a theory which can explain the production and consumption economics of all natural resources and which can cope with the transition of a resource from one category to another (for example if fish become a depletable stock resource), and with new resources as they arise. Explanation of the economics of all natural resources is required in order to understand fully the implications and consequences of their use in the economic process.

Neoclassical economics assumes perpetual growth with no limits to resource inputs or outputs from production processes. In theoretical economics there is no 'irreversibility' concept (Samuelson, 1983). Since the 1970's and the 'Materials Balance' approach there has been a perception that economic analysis has become divorced from its biophysical foundations. Environmentalists recognise that the economic activities of production and consumption are subject to the laws of thermodynamics and that they impact upon the global ecosystem. The two main areas of concern in economy-environment interaction are the depletion of natural resources and the production of pollution. As explained here, there are reasons to believe that market forces will provide some protection from depletion problems, although market failures are common. Pollution problems, however, often go unrecognised for considerable periods of time before they are recognised. There are no signals from prices to indicate the beginning of a pollution problem. Examples of pollution problems which were unexpected are easy to find (the hole in the ozone layer, algal bloom from fertiliser run-off, acid rain etc.). Recognition that the problems of resource depletion and pollution are linked by the laws of thermodynamics should promote a better, inter-disciplinary, understanding of economy-environment interaction. The entropy concept is an important way of measuring the quality of natural resources and for understanding the irreversible nature of environmental and resource processes. The existing economic theories of natural resources are not adequate. There is a theoretical void because there is no unifying theory of resources. There needs to be a reconciliation between the views of natural scientists and economists. Accordingly it is necessary to investigate the physical science of natural resources.

4. PHYSICAL PROCESSES OF RESOURCE CREATION

4.1 Natural Science and Economics

Since the advent of the 'Materials Balance' approach to environmental economics (Ayres and Kneese, 1969; Kneese et al, 1970) there has been a recognition by many economists that economies have a physical underpinning which must be understood in order to address the problems of environmental economics. Relationships between economics and thermodynamics have been considered since the 1970's by some economists (Georgescu-Roegen, 1971; Proops, 1983; Ruth, 1993) and this has helped understanding of the dynamic nature of economic systems which have been described as continuously converting ordered low entropy resources into high entropy waste heat in order to maintain themselves. Physical scientists developed an energy theory of value following the energy crisis of 1973 which drew heavily on economics (e.g. Gilliland, 1975) but was flawed in assuming that energy is non-substitutable since it can be substituted to a limited extent by capital and labour (Faber et al, 1998).

Economic theories of natural resource utilisation need a physical basis because production processes are irreversible and this must be recognised in order to understand fully the consequences of economic activity. Examples of irreversibility are the combustion of fossil fuels, destruction of wilderness areas and dissipation of matter which is not recycled. In conventional theoretical economics, however, there is no constraint on ever-increasing production; in other words, no irreversibility concept. Economists tend to concentrate on social limitations to economic activity such as market structures, market failures and innovation. Natural scientists, however, see economies as being constrained by physical factors such as energy availability. A combination of both viewpoints is likely to be closer to reality, with physical constraints on economic growth being important in the long run, but eliciting a social response in the form of greater commitment to research and development and technical change. Understanding of the inter-relationship between economists and natural scientists is particularly important in consideration of the utilisation of natural resources, because physical constraints on resource availability will inevitably impinge upon economic activity at some stage. Hence, it is necessary to establish the perspective of natural scientists especially concerning the understanding that the universe is comprised of energy and matter which are governed by four fundamental forces.

4.1.1 Four Fundamental Forces

The energy and matter which comprise the universe are governed by one or more of four fundamental forces which are: gravitational force, electro-magnetic force, and strong and weak nuclear forces (Sutton, 1988). Gravitation is the weakest of the fundamental forces, although it has an infinite range. It derives from the existence of *mass*. Mass is the source of a *field* that maps the strength and direction of the gravitational force at all points in space and time. Gravity is the most familiar force and it holds matter together in the form of planets, stars and galaxies. Electro-magnetic force is stronger than gravity over a shorter range. This is the force which binds matter on the much smaller atomic scale - holding electrons in place around the nucleus and atoms in place relative to each other. Strong nuclear force and weak nuclear force are sub-atomic forces which determine the behaviour of matter on the subatomic scale. The strong nuclear force holds the protons (and neutrons) together within the nucleus, while the weak nuclear force operates within nuclei to prevent the decay of isolated neutrons (Sutton, 1989). These four fundamental forces operate in isolation or in combination to give rise to the physical processes which create matter and energy.

4.1.2 Matter and Energy Creation

There are a number of astronomical theories which attempt to explain the creation of the universe. Whichever are correct, both energy and matter, which comprise the physical world, were created. In the creation of the universe, according to the 'big bang' theory (Hubble, 1954), fundamental particles – protons, neutrons and electrons, were formed by strong and weak nuclear forces. Gravity then caused concentration or clustering of this elemental matter, mainly in the form of hydrogen and helium, into gas clouds, which led to the formation of stars as gravitational pressure increased. The increased temperature and pressure caused by gravity initiated nuclear fusion reactions, which led to the creation of further energy and matter in the form of all other elements. The entire periodic table of elements was created in stars in this way.

As the life of a star proceeds, a series of different elements are produced by nuclear reactions governed chiefly by strong and weak nuclear forces. Layers of different elements accumulate. The balance between the inward gravitational pressure and outward radiation pressure determines whether these layers fall into the core of the star or are shed off into space. Under the most dramatic circumstances, a stellar explosion can occur, in the form of a supernova, which results in most of the matter produced by the star being flung into space. Such matter is held together by gravity to form tenuous gas clouds, or, in more concentrated form, gas planets which may be 'aborted' stars. At their greatest density, accretion rings containing elements such as iron and silicon form around existing stars, and this eventually leads to the formation of rocky planets (Hawking, 1995). The processes involved in the formation of stars, planets and other accumulations of matter and energy in the universe are generally referred to as astronomical processes.

In the gas clouds and on the planets, reactions between elements can occur through electromagnetic forces which create combinations called compounds by means of basic chemistry. Chemical reactions are less likely or slower to occur when matter is in solid form; they take place more quickly when matter is in liquid form (liquified or dissolved) and more quickly still when matter is in gaseous form. The pace of these simple chemical reactions depends on the relative concentration and mobility of the elements involved. Some of the reactions in the gas clouds create water, which may then be accumulated and transported to the rocky planets by comets. Water is important because it has the ability to dissolve certain solids, which enables further chemical reactions to take place. Other chemical reactions occur in the liquid cores of the rocky planets. These liquid cores are formed by internal gravitational pressure and external interaction between the planets and their orbiting moons. Yet more chemistry takes place in the atmospheres of rocky planets, which are created by gravitational attraction of gases. A range of inorganic chemical compounds is thus formed from elements by chemical reactions driven by the electro-magnetic force. Energy is available to assist these chemical processes, either directly from the stars (e.g. the Sun) or indirectly, as energy from stars drives movement in the atmosphere of planets, known collectively as meteorological processes, which helps gas mixing and contributes to a water cycle. This basic cycling of water, known as the hydrological process, has phase changes from liquid to gas to liquid, which helps to dissolve solid elements and compounds so that they can mix and react further (Shepherd and Shepherd, 1997). In this way elements and compounds are mobilised and can accumulate.

Geological processes, representing all transport mechanisms responsible for the movement of elements and inorganic compounds within solid planets, also play a part in the accumulation of matter. Heat from tectonic and volcanic activity, caused by gravity, convection currents and radioactive decay, is an important input into chemical processes. Gases such as carbon dioxide are generated and added to the atmosphere. Tectonic action, consisting of the movement of solid masses across the surface of planets, also gives rise to differences in surface heights or topography of the planet, which, in combination with water, creates land, rivers and seas. Once this variable topography is established, from combined atmospheric, geological and hydrological processes, further chemistry occurs and, crucially, through further geological processes, makes possible the temporary accumulation of elements and inorganic compounds (Jowsey, 2001a). These accumulations, which have relatively high concentrations of certain elements and compounds, are referred to as ore bodies or deposits.

Meanwhile, gas clouds in space consist of a cocktail of increasingly complicated compounds among which more and more complex reactions occur. Energy from stars and elements, including carbon, hydrogen and oxygen, create bigger molecules, making possible organic chemical reactions through the electro-magnetic force. These processes, occurring either in the gas clouds (brought to planets by gravity) or in the oceans, lead to self-replicating organic chemical reactions known as life. Biological processes involving organic compounds, atmosphere, and the water cycle can then occur, which enable the existence of life to continue by means of growth and reproduction. The interaction of life with geological, meteorological and hydrological processes and energy from stars and other sources creates complex ecological systems on certain planets (although the only evidence to date is from our own planet).

All carbon-based life is referred to as biomass, and it participates in a continuous flow of carbon through a planet, known as the carbon cycle. All life forms die and the carbon they contain is either taken up directly by other life forms, or is released into the atmosphere as carbon dioxide, methane or other carbon-based gases, or is deposited eventually in solid or liquid forms as various hydrocarbon, carbonate or other compounds. Carbon-based gases, especially carbon dioxide, can be taken up again by life forms, particularly plants, thereby assisting the formation of new biomass. The deposition of carbon in solid or liquid forms and compounds contributes to its accumulation within the planet. Geological processes are involved in this deposition and concentration so that various accumulations can arise, including solid carbon in a range of purity and forms, from diamonds to coal, hydrocarbons such as oil and natural gas, mixtures such as peat, and carbonates such as limestones, sandstones, chalk, etc. Although this carbon can be effectively 'locked away' in these 'carbon sinks', it can be released again naturally, mainly by geological, meteorological and hydrological processes involving the exposure and erosion of carbon-based accumulations.

4.1.3 Physical Processes

The existence and transformation of matter and/or energy depends upon the physical process which leads to its creation and possible accumulation. These physical processes can be summarised as follows:

- nuclear processes
- astronomical processes
- chemical processes
- meteorological processes
- hydrological processes
- geological processes
- biological processes
- ecological processes.

Each of these processes involves different combinations of the four fundamental forces. Nuclear processes include both fission and fusion. Nuclear fission is a nuclear reaction whereby a heavy atomic nucleus, such as uranium, splits into two or more parts with the release of energy. Nuclear fusion is a nuclear reaction whereby atomic nuclei of low atomic number fuse to form a heavier nucleus with the release of energy. Astronomical processes include gravitational attraction between stars, planets, gas clouds and other celestial bodies, and subsequent nuclear processes. Chemical processes involve one or more elements or compounds which are combinations of elements, reacting or combining to form other substances, either spontaneously or as a result of an input of energy, such as heat or irradiation. Chemical reaction involves partial or complete transfer of one or more electrons between atoms and a rearrangement of atoms to form different molecules or compounds. Hence the electro-magnetic force governs this type of process. Meteorological processes are those which involve movements of the atmosphere and its interactions with the surface of the planet, or other body which has a gaseous outer layer. Hydrological processes relate to the movement of water over the surface of the Earth and the hydrological cycle which involves evaporation, transpiration and condensation. Geological processes are those which occur within the structure of a planet, such as the Earth, or similar body and consist of the movement of rocks and minerals composed of elements or compounds, as a result of tectonic or volcanic activities and meteorological and/or hydrological processes. Biological processes relate to living organisms and are the result of electromagnetic force and organic chemistry. Ecological processes involve interaction between living organisms and the environment.

4.1.4 Entropy

All of the matter mentioned above, in all its complex forms, is eventually recycled. Stars are born, evolve, grow old and die, then form new stars and planets. Planets are broken up, consumed by new stars, or form new planets (Henbest, 1988). Gas clouds are also recycled in astronomic processes. The Laws of Thermodynamics govern the involvement of energy in all such processes (Clausius, 1867). The First Law contends that the energy of the universe remains constant, which means that energy and matter can neither be created nor destroyed. The implications of this for resource economics are considerable. The Second Law of Thermodynamics, also called the Entropy Law, asserts that the entropy of the universe at all times moves toward a maximum, as explained below. The implications of this law for resource economics are less obvious, but nevertheless, considerable. Consideration of the implications of entropy for resource creation processes is, therefore, important in the formulation of a theory of resource creation.

The First Law of Thermodynamics is popularly stated as "energy is conserved." Matter is also continuously being transformed. Energy is also recycled, but entropy ensures that it is gradually degraded. The Second Law of Thermodynamics contends that the entropy of an isolated system always increases. Entropy is a measure of the disorder of a system. There are two aspects which define any given form of energy; its quantity and quality. It is the quantity of energy which is conserved; quality degrades. The more ordered a form of energy, the greater its quality. Entropy is an inverse measure of this quality. If a form of energy is relatively chaotic, it has greater entropy. Heat involves the random motion of atoms and/or molecules and hence, is a more chaotic, lower quality form of energy than work. Therefore, it has relatively higher entropy. When a concentrated source of energy, such as hydrocarbon fuel, is burned in air, it produces heat. Under such circumstances, entropy increases. No conversion from one form of energy to another is completely efficient and the consumption of energy is an irreversible process. Since matter or mass can be converted to energy (mass is a form of energy as Einstein articulated in the equation $E=mc^2$ where E is energy, m is mass and c is the speed of light) then mass is also subject to entropy and there is, therefore, a constant degrading of mass and energy (Einstein, 1920).

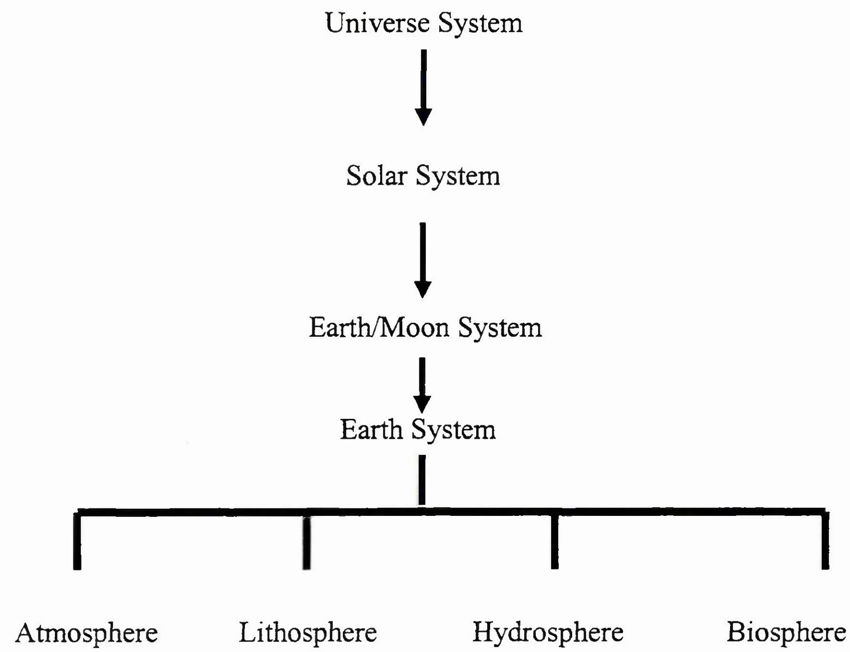
Some energy is always lost during conversion, and the rest, once used is no longer available for further work (Tietenberg, 1996). This can be illustrated using the example of the internal combustion engine. The hydrocarbons used in an internal combustion engine are in a state of low entropy – the bonds between the atoms are a form of order. When this fuel is burned with oxygen, the bonds break releasing energy and creating different compounds, such as carbon dioxide and water in addition to heat. Within the engine, the heat is used to drive a piston in a given direction (Cassedy and Grossman, 1998). In effect, the random motion of the combustion products is forced to act in a more ordered manner by the nature of the mechanical arrangement of the piston. Work is the outcome of the force on the piston which is a more ordered form of energy and, hence, has relatively lower entropy. Viewed completely, the overall entropy of the system, which comprises the engine, increases, since a small amount of work, with relatively lower entropy, is generated with a larger amount of heat, with relatively higher entropy.

The Second Law of Thermodynamics implies that the total amount of usefully concentrated matter and energy in an isolated system must decline over time, and this has been interpreted as implying limits to the sustainability or continuity of economic growth (Georgescu-Roegen, 1971). The Earth, however, is not a closed physical system, since it exchanges energy with outside systems (Halliday and Resnick, 1988). As a result, some positive level of continued resource use is possible on a sustained basis, using, for example, solar energy-powered recycling of matter (Young, 1991). It has, however, been argued that sustained economic growth is not possible because current rates of material and energy use already exceed solar recycling potential (Daly, 1987). In terms of the universe, all accumulations of energy and matter are temporary and arise out of the flow of energy and matter as described above. The flow of energy and matter cannot be completely cyclical because of entropy. Ultimately the universe either keeps on expanding with entropy increasing, or eventually collapses (the 'big crunch') and may re-form again (the 'big bang') which would be the ultimate recycling.

4.1.5 Systems Analysis

The physical processes described in Section 4.1.3 cause energy and matter to flow through different systems and, in certain instances, to accumulate temporarily. The Universe can be divided, for simplicity, into a number of "environments" or systems. These systems are: the Universe system, the Solar system, the Earth/Moon system, the Earth system, the atmosphere, the lithosphere, the hydrosphere and the biosphere. The Universe is the sum of all potentially knowable objects – millions of galaxies of stars, solar systems and the matter between them. It is vast in time and space (10^{10} years old and 10^{10} light years across) and is expanding. The Solar system comprises the Sun and the astronomical bodies gravitationally bound to it, including nine major planets and their satellites, immense numbers of minor planets, comets and meteoroids. The Earth/Moon system comprises our planet and its principal natural satellite, which orbits every 27.32 days causing a gravitational pull on the Earth. The Earth system includes the four subsystems of atmosphere, lithosphere, hydrosphere and biosphere. The atmosphere is the gaseous envelope surrounding the Earth. It is composed of nitrogen, oxygen, argon, carbon dioxide and other gases plus water vapour. The lithosphere is the rigid outer part of the earth consisting of the crust and upper mantle. The hydrosphere is the waters of the Earth's surface. The biosphere is the sub-system of the Earth system that is occupied by living organisms. These systems can be related to each other as shown in Figure 4.1.

Figure 4.1 Resource Systems



4.2 Demonstration of Resource Creation

4.2.1 Examples of Resource Creation

The physical characteristics of resources and the nature of resource flow can be demonstrated further by considering specific examples. The examples given here are of three types of resources identified in an earlier work (Jowsey, 1998). The first resource considered is solar energy, which is often described as renewable. The second resource is wood, which again is often described as renewable, but only with careful management in order that it is not over-exploited and depleted. Finally, coal, a non-renewable resource is considered.

4.2.2 Solar Energy

More than 99 per cent of energy entering the global ecosystem is from the Sun; the rest being from geothermal or gravity sources (Mather and Chapman, 1995). Most forms of energy which are used by humans are of solar origin; the exceptions being nuclear, tidal and geothermal. The Sun is composed of 70 per cent hydrogen, 28 per cent helium and 2 per cent of all the other elements. Energy is produced in the Sun as a result of nuclear fusion reactions. The main nuclear reaction that generates heat inside the sun is called the proton-proton (or p-p) chain (Gribbin, 1993). This involves two hydrogen protons colliding and fusing to form deuteron, emitting a neutrino and a positron in the process. Another proton can then tunnel into the deuteron, producing a nucleus of helium-3. Finally, when two nuclei of helium-3 collide they form a stable nucleus of helium-4 (an alpha particle), ejecting two protons in the process. Four protons have been transformed into an alpha particle and while the energy produced per atom is small (due to a small mass difference which is converted to energy), this occurs sufficiently frequently to generate the Sun's heat. This heat is transmitted by radiation to Earth in units of energy called photons, which interact with the Earth's atmosphere and surface. Approximately 30 per cent of solar radiation intercepted by the Earth is directly reflected back into space (Shepherd and Shepherd, 1997). The remaining 70 per cent is absorbed by the atmosphere and land and water surfaces. The strength of solar radiation at the outer edge of the Earth's atmosphere when the Earth is at its average distance from the sun is called the solar constant, the mean value of which is 1.36 kW/m^2. Energy received at the earth's surface (about 1kW/m^2) is less than the solar constant because of absorption and scattering of radiant energy as photons interact with the atmosphere.

Clearly, the governing process in the creation of solar energy is nuclear fusion. Radiant heat and light are both forms of electromagnetic radiation with varying wavelengths. Although on average it takes a photon ten million years to reach the surface of the sun from its core (on a 'random walk') it then travels the 93 million miles to the earth in just eight and a half minutes (Gribbin, 1993). The supply of solar energy represents an inexhaustible resource in relation to human timescales, and it is not affected by human activities (although excessive pollution of the atmosphere could greatly reduce surface temperature and the ability to generate electricity from solar energy). The solar energy received by the Earth each day is equivalent to 200,000 times the total world electricity generating capacity, although the high cost of its collection, conversion and storage have obviously limited its exploitation so far.

Natural collection of solar energy occurs in the atmosphere, the oceans and in plants. Winds are produced by the interaction of energy from the sun, with the oceans and the atmosphere. Rainfall and the potential energy of water in rivers and streams are produced by the hydrological cycle which uses almost one-third of the solar energy reaching the Earth's atmosphere (most of the rest being directly converted to heat). Oceans absorb solar energy and as a result there are temperature gradients or vertical variations in temperature which can be as great as 20°C over a distance of a few hundred metres.

A small fraction of the solar energy reaching the earth is absorbed in the leaves of plants as a result of photosynthesis. Photosynthesis converts carbon dioxide and water into simple carbohydrates which begin the carbon cycle (Scurlock and Hall, 1991). Through this process, solar energy plays a crucial role in contributing to the growth of plant life (biomass) which is vital for food requirements of animal life and which, in the form of wood fuel, makes an important contribution to world energy supply. Biomass is also transformed by organic decay into fossil fuels such as coal, oil and natural gas, which are of considerable importance in world energy production. The rate of supply of solar energy is relatively constant and will remain so for hundreds of millions of years, making solar energy a continuous natural resource. It can be seen from this description that the principal process involved in the creation of solar energy is the nuclear process of fusion which is governed by weak and strong nuclear forces.

4.2.3 Wood

Creation of wood or timber as a natural resource is clearly linked to solar energy. The process of photosynthesis in green plants transforms light energy from the sun into chemical energy. This process is governed by the electro-magnetic force. Photosynthesis captures light energy and uses it to convert water, carbon dioxide and minerals into oxygen and energy-rich organic compounds. The importance of this process in sustaining life is obvious, since without it there would be no gaseous oxygen on earth. Photosynthesis is also responsible for the formation of fossil fuels. In chemical terms, photosynthesis is a light-energised oxidation-reduction process. Oxidation means the removal of electrons from a molecule, while reduction means the gain of electrons by a molecule. The energy of light is used to drive the reduction of water (H_2O), producing oxygen gas (O_2), hydrogen ions (H+), and electrons. Most of the removed electrons and hydrogen ions are transferred to carbon dioxide (CO_2) which is contained in organic products. Other electrons and hydrogen ions are used to reduce nitrate and sulfate to amino and sulfhydril groups in amino acids which form proteins. Carbohydrates, mainly starch and sucrose, are the main direct organic products of photosynthesis. This process is represented in the following equation:

$$CO_2 + 2H_2O \xrightarrow[\text{green plants}]{\text{light}} (CH_2O) + O_2 + H_2O \qquad \text{(Equation 4.1)}$$

Biomass resources are created by photosynthesis. They are a major renewable resource and wood or timber is the major biomass resource. More than one quarter of the Earth's surface is forest area, with the most productive forest areas located in the tropics. The amount of wood which can be harvested annually for fuel depends on the rate of annual carbon fixation (photosynthesis) which is possible in a region. The world's forests produce an estimated annual growth increment of wood of about 13 x 10^9 tonnes, of which about one eighth is harvested (Cassedy and Grossman, 1998). About half of the annual increment of wood is used as fuel, providing about 7 per cent of total world energy production. Wood is the main or only fuel for 30-40 per cent of the world's population, mainly in less developed countries, many of which are severely depleting their forest resources. The main processes involved in the creation of wood are chemical and depend on the electro-magnetic force.

4.2.4 Coal

Coal is a hard, combustible, sedimentary rock consisting of 70-90 per cent organic material (carbon, hydrogen, nitrogen and oxygen) and inorganic mineral substances such as sulphur, and smaller amounts of potentially toxic substances such as mercury and lead. Coal and peat are formed from vegetation which grew in wetland swamp or river estuary areas, in tropical climates, about 300 million years ago, during the Carboniferous and Permian periods. When the vegetation died it fell into the swamp and decayed under almost airless conditions in a microbiological process forming peat. Where the peat was covered by sandy sediments (possibly as sea level rose) it was transformed into coal by the increased pressure and sometimes volcanic heat. The plant material from which coal is derived is composed of organic compounds, including cellulose, lignin, fats, waxes and tannins. The current rate of accumulation of coal is clearly much less than the rate of extraction and use by humans and so coal is regarded as an exhaustible source of energy.

The rate of accumulation of peat is much greater than that of coal, and has been estimated at about three tonnes per hectare per year. It does not accumulate conveniently, however, being distributed over a large land area, and it is also being consumed at a much faster rate than it accumulates. Coal, peat, oil and natural gas are forms of chemical energy, ultimately created by solar radiation and locked by geological processes into energy stores. The physical processes involved in the creation of coal include: biological processes in the photosynthesis of plants; chemical processes as the vegetation is transformed; and gravitation in the pressurisation of the plant residue. Natural processes such as geological exposure, weathering and oxidation would eventually lead to the degradation of coal, peat, oil and natural gas deposits, transforming them into carbon dioxide more slowly than is the case with human exploitation of them as a fuel resource.

4.2.5 Common Features of Resource Creation

Clearly the common 'flow element' for each of the resources considered above is solar energy. Solar power exists as a continuous natural resource flow and cannot be depleted. Solar energy is also available indirectly after conversion by photosynthesis into wood/biomass, which is a potentially renewable resource flow which can be depleted if not carefully managed. Finally, solar energy is available indirectly after being 'locked away' for thousands of years as fossil fuel, which is a non-renewable resource which will be dissipated naturally or depleted by use.

In terms of resource use in relation to timescales of formation, the use of solar energy at one particular point in time will not affect the amount that can be used in the future. For wood/biomass, the time needed to regenerate the resource should be the critical factor influencing resource utilisation decisions (the fact that it is not is cause for concern). For coal and other non-renewable resources, the regeneration rate is not relevant to human timescales and so the consumption of one unit of the resource means that the stock for future consumption is reduced forever. The concept of resource 'flow' is crucial to understanding the nature of different types of resources. The essential difference between resources, which is crucial to decisions on their exploitation, lies in the comparison of the timescales for their formation relative to the timescales over which they are utilised. This will be considered further in Chapter 5 on resource exploitation.

4.3 Resources

4.3.1 Accumulations

The result of the physical processes described in Section 3.1.3 is accumulations of matter and energy which are widely referred to as 'resources'. They can be defined as concentrations or accumulations of matter or energy which are attractive for life forms. Life forms are interested in the quantity and quality of energy and matter because they provide a higher level of energy or matter (compared with normal 'background' levels) which is easier to exploit by life forms to support their continued existence. Not all accumulations are resources, but they are potential resources. Some accumulations may be harmful to life forms, such as the sudden release of volcanic energy and matter or the accumulation of uranium. Where there is a natural release of concentrated matter and/or energy, it can be regarded as a resource if humans can exploit it (for example geothermal power from hot springs). Flows of energy and matter through systems are governed by processes which lead to temporary accumulations over varying timescales. Sufficient quantity and quality makes concentrations of energy and matter easier to know about, easier to find, and easier to exploit. The flow within a system can be identified as a flow between small sub-systems – a flow across the boundary between sub-systems. An example of an accumulation which occurs as a flow across the boundary between systems is the tidal forces which act on all bodies of water on Earth (actually on all the Earth, including the lithosphere) due to gravitational interactions in the 'Earth/Moon system'. Others occur in the form of energy, sediment, food, life forms, etc., at certain boundaries between the hydrosphere and the lithosphere, that is, the coastline of oceans/seas and, specifically, particular types of estuary. Life forms exploit the accumulations of matter or energy by interrupting the natural cycle of resource creation and recycling. Accumulations of matter and energy, which become resources to the life forms which exploit them, arise from the four fundamental forces via physical processes such as chemical or biological processes, operating in a system which is a sub-system of the Universe. If the accumulation is sufficiently great in quantity and quality, then the matter/energy becomes a resource which can be exploited by life forms. Humans have used technology to enable them to exploit accumulations of matter and energy which would not have been regarded as resources in the past, or by other species. Given that all such accumulations are based on a flow of energy and/or matter, then such resources have timescales for creation which depend on the four fundamental forces and subsequent physical processes.

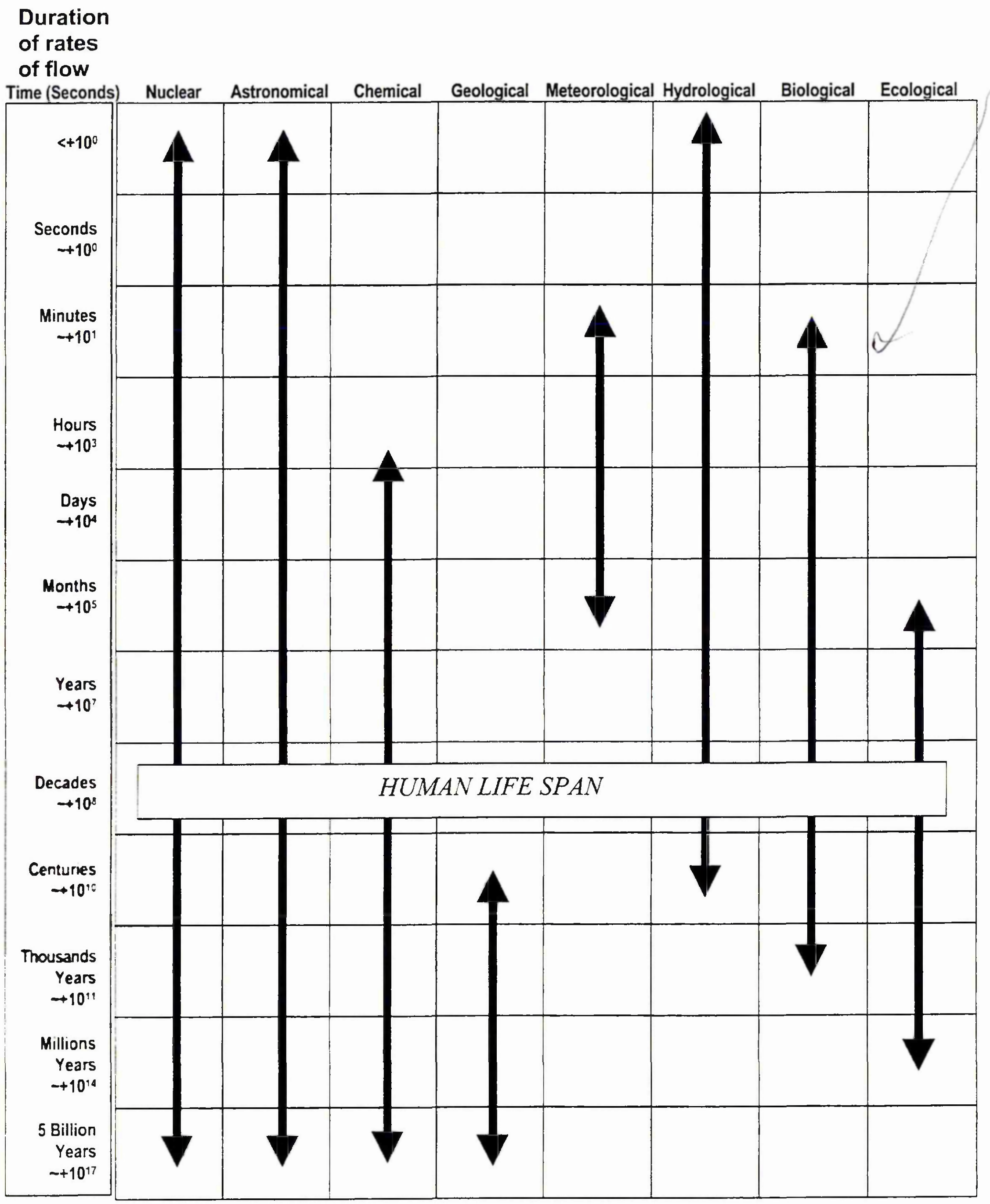
4.3.2 Timescales of Accumulation

It has been argued that all resources are in fact a flow and, hence, traditional classification of resources as 'renewable' or 'non-renewable' overlooks this. Even fossil fuels are still being formed, although considerably more slowly than they are being used. Currently each year the world burns as much fossil fuel as the Earth produced in almost a million years (Griffiths, 1999). Nuclear processes, which result in accumulations of matter and energy, take place over varying lengths of time from instantaneous to billions of years. Astronomical processes also take enormously varying lengths of time. Some, like the effect of the Moon's gravity in causing tides and tidal energy, are frequent, daily occurrences. Others, such as the creation of planets from the material of a dying star, can take hundreds of millions of years. Chemical processes also take varying lengths of time, although currently some of the most important in terms of resource creation are those which lead to the formation of fossil fuels, which take hundreds of thousands of years. Meteorological processes, on the other hand, create wind energy on an irregular daily basis, while hydrological processes can create a potential form of energy used by humans, in the form of hydro power, virtually constantly. Geological processes, which play a part in the formation of fossil fuels, metals and geothermal energy, take place over periods of time from thousands of years to billions of years. Evolutionary ecological processes which create fish, fauna and biomass take place over thousands of years, but the biological processes which reproduce these resources take place over periods of time from minutes to thousands of years.

The timescales for the processes which create accumulations of matter and energy are illustrated in Figure 4.2. The vertical axis identifies periods of time, in seconds, from less than one second to 5 billion years. The arrows represent the period of time over which each physical process operates in the accumulation of energy/matter. Each physical process creates accumulations of matter and energy which form the basis of human perceptions of resources. Figure 4.2 summarises the resource creation processes described in Section 4.1.3 of this thesis. The timescales over which matter and energy are accumulated vary from instantaneous to billions of years (5 billion years being selected as the upper limit as it is the approximate length of time for which the Earth has existed).

Some physical processes (meteorological, hydrological, biological and ecological) create accumulations over relatively short timescales. Others (nuclear and astronomical) create accumulations over the entire range of time depicted, from instantaneously to 5 billion years, the resource creation process being a continuous flow over such vastly different timescales. The identification of 'human life span' in the diagram shows that resource creation processes occur over longer periods of time than 'three score years and ten', that being taken as average life span of people in the twenty-first century. It is clear that most accumulations of matter and energy which humans regard as resources are created over longer timescales than the length of human life (and, indeed, human society). Processes which extend below this line in Figure 4.2 present problems of perception for humans in terms of resource definition and exploitation and this will be considered further in Chapter 5 on resource exploitation.

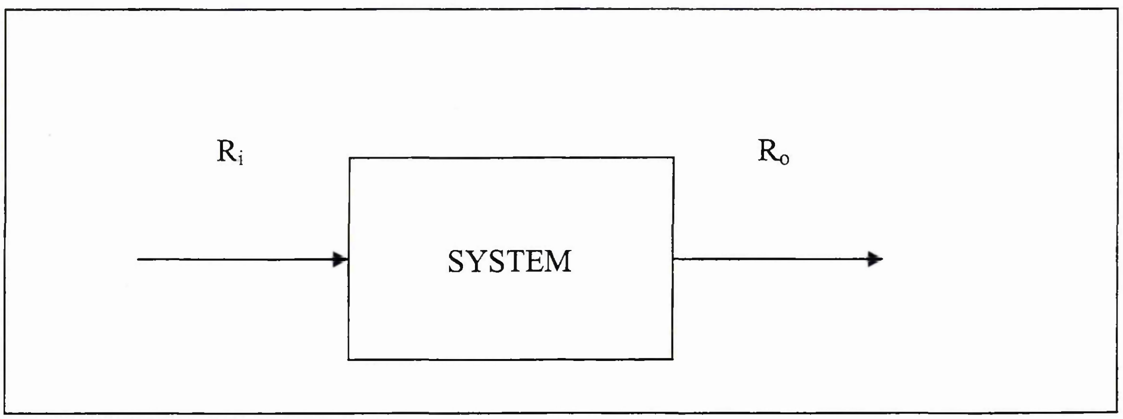
Figure 4.2 Timescales of Accumulation of Matter and Energy



4.3.3 Resource Formation

Subsequent investigation of the physical characteristics of resources is based on the hypothesis that all resources derive from flows of energy and/or matter over varying timescales through a system or environment. The system in which the resource arises determines the nature of the resource. For example, the biosphere is a system which encompasses all organic material and living things. Solar radiation leads to the transformation and creation of many resources within the biosphere, but these resources are not the same as solar radiation as a resource. This is because solar radiation can be regarded as a resource at the surface of the Earth, which is a source of energy, such as heat, light etc., in itself. Systems, such as the Earth and its biosphere, may overlap, but they are separate and they encompass and define different resources. There is a flow of energy through every system, for example, in the biosphere energy is captured from the Sun by trees through photosynthesis, then released by the decomposition of wood. While the Universe as a whole is a closed system within which entropy must increase, within that, temporary structures emerge in smaller systems. For these smaller systems to exist, there must be sustained inputs and outputs. The basic elements of resource formation can be summarised diagrammatically in Figure 3.3.

Figure 4.3 Basic Elements of Resource Formation



Energy and/or matter flows into the system at a rate of R_i (amount per unit time) and flows out at a rate of R_o. These flow rates are governed by one or more natural processes and the system represents the environment in which the resource arises. For example, one relevant resource would be "solar radiation". Many systems could be considered where this resource arises. If solar radiation is considered at the "land surface of the Earth" then the system under consideration would be the boundary or interface between the atmosphere and the lithosphere. This uniquely defines the environments through which the solar radiation flows. With this particular choice of definition, other environments are excluded, especially the biosphere. Hence, a system is being considered where solar radiation falls on the land surface of the Earth at a rate, R_i. The rate of output, R_o, consists of the sum of all the rates by which the solar radiation is dissipated by the surface of the Earth. This includes re-radiation into the atmosphere and absorption by the Earth. Only a small amount of solar radiation may be stored in the surface of the Earth during this process so that it can be assumed that;

$$R_i \sim R_o \qquad \text{(Equation 4.2)}$$

It should be apparent that Equation 4.2 is a universal means of representing resource formation where only current flows can occur. It is the basic flow condition on which all resource formation is based. With a number of other processes, such as the formation of mineral deposits, significant accumulation or storage can occur over a period of time. With mineral deposits, the system under consideration is chiefly the lithosphere, but may also consist of the hydrosphere. In this instance, the rate of inflow is greater than the rate of outflow for a given period of time in the past, T'. Since the rates of inflow and outflow may have been different in the past from those which are occurring in the present, it is necessary to distinguish these as the past rate of input, R'_i, and the past rate of output, R'_o. Since $R'_i > R'_o$, then the energy and/or matter accumulates in the system, leading to the creation of a stock, S, of energy and/or matter. Hence;

$$S = (R'_i - R'_o)T' \qquad \text{(Equation 4.3)}$$

In addition to such past stock formation, an inflow and an outflow of energy and/or matter may be still continuing in the present. Consequently, the total amount of energy and/or matter, A, present in the system over a future period of time, T, can be fully summarised as follows;

$$A = S + (R_i - R_o)T$$

or

$$A = (R'_i - R'_o)T' + (R_i - R_o)T \qquad \text{(Equation 4.4)}$$

It should be apparent that Equation 4.4 is a universal means of representing natural resource formation where stocks can arise.

The three resource formation equations are purely natural science relationships which do not have any human intervention aspects. For hydro, solar, tidal, wave and wind power, the defining conditions are: $R_i = R_o$, and $S = 0$.

For metals, non-metallic minerals, fossil fuels and uranium, the defining condition is: $R_i' > R_o'$, which leads to $S > 0$. These conditions represent non-renewable resources as discussed in a Working Paper (Jowsey, 1997). For these resources, if they are naturally depleting, then $R_o > R_i$. If they are accumulating in a system, then $R_i > R_o$. And if they are in steady state, $R_i = R_o$. Any of these three situations could occur at a given time.

For biomass, fish and fauna resources, which were discussed in another Working Paper (Jowsey, 1998), the defining condition is: $R_i' > R_o'$ which leads to $S > 0$, which is the same as for metals, non-metallic minerals, fossil fuels and uranium. Fish, fauna and biomass can be in steady state, with $R_i = R_o$. Or they can be in a situation where the flow cannot be sustained, $R_o > R_i$. Or they can be in a situation where stocks are accumulating in a system, $R_i < R_o$. This means that in terms of physical formation, using these simple defining conditions, there are only two types of resources: those for which $R_i = R_o$, and $S = 0$; and those for which $R_i' > R_o'$, which leads to $S > 0$.

Once resource exploitation is considered, there may be further defining conditions which lead to a more complex classification of resources. In particular, the time taken to build a stock of a resource and the rate at which stocks can be replenished, may become important considerations. In purely physical terms, however, there are only two types of resource: those for which stocks can accumulate, and those which are continuous flow resources, without the possibility of stock accumulation. Humans can exploit either the flow of matter/energy through a system, or the stock of matter/energy in a system.

A sound physical process foundation for further consideration of the economics of natural resources has been established here. All accumulations of matter and energy which become termed resources can be incorporated into the framework outlined here, and into the resource equations introduced in Section 4.3.3. The concept of resources as a flow has been clearly established, and the role of entropy in the resource creation process has been identified and explained. Timescales of resource creation and the possibility of stocks accumulating have been identified as critical factors affecting the creation and availability of resources. It is now necessary to identify the implications of the physical processes of resource creation for the economics of natural resources. Some of the characteristics of resources which are worthy of further consideration are: resource flow and the system boundary conditions which have been discussed earlier. Also important in terms of resource definition and exploitation are: concentration, accessibility, human needs, human perceptions and available technology and these are investigated next.

5 PHYSICAL ASPECTS OF NATURAL RESOURCE EXPLOITATION

5.1 Definition of Natural Resources

The standard dictionary definition of a resource is "a stock or supply which can be drawn on" (Thompson, 1998). Many of the natural resources which are of interest from the points of view of both natural scientists and economists would be encompassed by this definition. Coal, for example, which was considered in some detail in Chapter 4, might be considered a stock which can be drawn on. However, other natural resources such as solar power or timber, would not be covered fully by this definition. Solar power is a flow of energy, and timber can be perceived as a stock or a flow, depending on how it is exploited. A typical scientific definition of a natural resource is "naturally occurring material, including energy, useful for supporting life" (Ernst, 2000). There is not necessarily a human aspect to this scientific definition. The life form being supported by natural resources is not necessarily human. Other life forms are also interested in accumulations of matter and/or energy in order to satisfy their wants. The physical processes described in Chapter 4 lead to accumulations of matter and energy.

All life forms have an 'interest' in accumulations or concentrations of matter and/or energy, and not just humans. For example, fish are attracted to areas in the ocean where there is an abundance of food. This might suggest that this feature only arises in the biosphere where one life form feeds on another. However, this is not the case. Land animals and birds are attracted to 'concentrations' of water (so the hydrosphere comes into play). Birds of prey exploit currents of warm air in the atmosphere to reduce energy used in flight. Furthermore, some basic life forms (bacteria, etc.) can exploit hot mineral flows. These are archaeons, the creatures which have been found living around deep-sea hydrothermal vents where they use the concentration of geothermal heat and minerals, such as sulphur (Steel, 2001). All life forms exploit resources (food) in the biosphere, some exploit resources in the hydrosphere (water) and a few exploit resources in the lithosphere (hot minerals). Hence, it cannot be said that humans are the only life forms which exploit 'resources'. The main distinction of humans may be that they are the only life forms which exploit such concentrations extensively and have developed technologies in order to do so. Human ingenuity and technology may be a current constraint on resource availability, but ultimately the limit is set by the physical availability of the flows of matter and energy through systems. Subsequent discussion will, henceforth, be confined to the relationship between humans and natural resources.

Economists frequently put the term 'resources' together with the concept of scarcity, meaning scarce in relation to human wants. There is, therefore, a human aspect to the term for economists. Furthermore, a definition of resources from the earth sciences perspective (Cook, 1976) states that:

> "In the sense of earth resources, the term encompasses naturally occurring materials which are important to man and his activities".

This definition bridges the physical and economic worlds. Using the term 'materials' is inadequate in that it does not encompass forms of energy such as solar power. The phrase "which are important to man and his activities", however, brings in the human economic dimension.

Many economists regard natural resources solely as inputs to the productive process. In this regard, such resources are used to satisfy human wants for goods and services. Natural resources, known collectively as "land" to economists, are "free gifts of nature", such as soil, fish, minerals, etc. These are combined with human resources, such as mental and physical capabilities, which economists call "labour"; and with man-made aids to further production, such as tools, factories and machinery, which economists refer to as "capital". Often a fourth factor of production is distinguished. This is "entrepreneurship", which is the willingness and ability of entrepreneurs to take risks and organise the other factors of production in order to produce goods and services.

Environmental economists also recognise a number of free productive services offered by the environment. These include environmental inputs, such as air and water which are used in many productive processes; waste assimilation and processing by ecological systems; and environmental systems maintenance processes, which sustain climatic conditions and support the renewal of biological entities. In this wider environmentalist view, natural resources can contribute to utility (briefly defined here as satisfaction or usefulness to humans) directly, as when areas of beauty are visited for recreation, as well as indirectly through their role as inputs to the productive process. This wider view of natural resources recognises that they can make a significant contribution to life support systems, environmental amenity, aesthetic and cultural values. These have been described elsewhere as "natural infrastructure" (Jowsey, 1999).

Discussion of resource creation in Chapter 4 described the processes involved exclusively in relation to physical accumulations of matter and/or energy. These are physical accumulations capable of being used in a multitude of different ways by humans. Every accumulation is a potential natural resource. They remain accumulations of matter and/or energy until they are exploited. In order to be exploited, their presence must be perceived, their capacity to satisfy human wants must be recognised, and ways of using them must be devised (Zimmerman, 1951). Natural resources are, then, dynamic in that they can change over time as knowledge and technology change. This was illustrated by Figure 3.3 in relation to resource classification (McKelvey, 1974). In the broadest sense, natural resources are defined here as *any forms of accumulated matter and/or energy, which are made direct use of by society.* This definition is comprehensive in that it covers all forms of resources, and in that it encompasses natural science concepts and economic concepts. At this stage, the way in which the natural resource is used or exploited is not important. This will be considered further in later Sections. Of more significance are the physical characteristics of natural resources, which relate to matter and/or energy. These physical characteristics are important in determining the uses to which these natural resources can be put by humans and, indeed, the way that they are used.

5.2 Physical Characteristics of Natural Resources

A key conclusion of Chapter 4 was that all resources are, in fact, a flow. The duration of the rates of flow varies enormously, and some of the flow rates are considerably longer than the timescales with which humans are used to dealing and so human perception of such resources is that they are a stock (see Figure 4.2). If humans exploit an accumulation of energy and/or matter, they intercept the flow between the natural input and output from the system. Hence, less of the inflow reaches the natural outflow, depending on the amount of energy and/or matter extracted. Under these circumstances, the rate of resource utilisation, R_u, is given by:

$$R_u \leq R_i \qquad \text{(Equation 5.1)}$$

Where R_i is the rate of resource inflow into a system.

If the resource includes a temporary stock of energy and/or matter, then this can also be exploited so that resource utilisation over a period of time is given by:

$$R_u \leq (R'_i - R'_o)\frac{T'}{T} + R_i \qquad \text{(Equation 5.2)}$$

Where R'_i is the past rate of resource input into the system, R'_o is the past rate of resource output from the system , T' is the period of past time, and T is future time. Equations 5.1 and 5.2 place limits or constraints on the rate of resource utilisation available to humankind. Where no stocks of a natural resource are available, maximum exploitation is where:

$$R_u = R_i; \qquad \text{(Equation 5.3)}$$

and where stocks are available, maximum exploitation is where:

$$R_u = (R'_i - R'_o)\frac{T'}{T} + R_i \qquad \text{(Equation 5.4)}$$

For certain resources, such as solar, wind and hydro power, the rate of current input is greater than zero ($R_i > 0$) and the rate of past input is approximately equal to the rate of past output ($R'_i \sim R'_o$). The (temporary) existence, or otherwise, of stocks of matter and/or energy within a system is an important determining feature of resource exploitation. It is also important in the use of resources, because the existence of stocks makes possible a sudden release of large amounts of high entropy matter and/or energy at a rapid rate, and this may cause problems for the life supporting capacity of the system.

The critical physical characteristics which determine natural resource exploitation can be identified from Equations 5.1 to 5.4 as the rate of flow of resource and time. To these, it is necessary to add entropy, as it can be associated in Equations 5.1 to 5.4 with the resource inflow (R_i) which is of low entropy, and resource outflow (R_o) which is of high entropy. Resource inflow has to be relatively low entropy, compared to resource outflow, because the natural order of physical systems results in the gradual increase of entropy. Within sub-systems there may be temporary decreases in entropy, for example as stocks of fossil fuels accumulate, but they are only brought about by an eventual overall increase in entropy. Clearly, rates of flow of resources through a system are of fundamental importance to the issues of whether they can be exploited and how they can be exploited. Comparative rates of flow are important to resource exploitation and the relationships between R_u, R_i, R'_i and R'_o will be important when classifying resources in Chapter 7. Time is also of fundamental importance, both in the sense of the length of time, or timescale, necessary to re-create a unit of the resource and, where stocks are relevant, the length of time necessary for stocks to build up. Entropy is significant because low entropy accumulations of matter and energy are what life forms are interested in as resources, because this means they are easier to exploit as more return can be obtained from a given effort. Those accumulations which are more concentrated than others are more attractive because less effort is required to exploit them.

5.2.1 Comparative Rates of Flow

In Chapter 4 it was established that resources flow through systems at differing rates. The rate of flow of a resource through a system is critical because it determines the maximum amount of the resource which can be exploited by humans. Humans, by exploiting natural resources, effectively intercept the natural flow of such resources through systems. Some of the natural flow of a resource through a system is diverted for human exploitation. This interference with a natural system has consequences if the exploitation of the resource is greater than the natural rate of flow of the resource through the system. Exploitation at a rate which is less than or equal to the natural rate of flow of the resource through the system will not cause depletion of the natural resource and is unlikely to cause excessive pollution. Exploitation at rates in excess of the natural rate of flow of the resource through the system, however, will have consequences for both resource depletion/exhaustion and pollution. Depletion/exhaustion of a natural resource will be a significant problem if that resource has no substitutes (or substitutes which are very expensive). Pollution will occur if exploitation of the resource greatly increases the rate of change of entropy in the system, and this will be explored in Section 5.2.5.

5.2.2. Comparative Timescales

The determinants of the timescales of resource creation are the physical processes which create resources. Such processes were described in Chapter 3 and include the following:

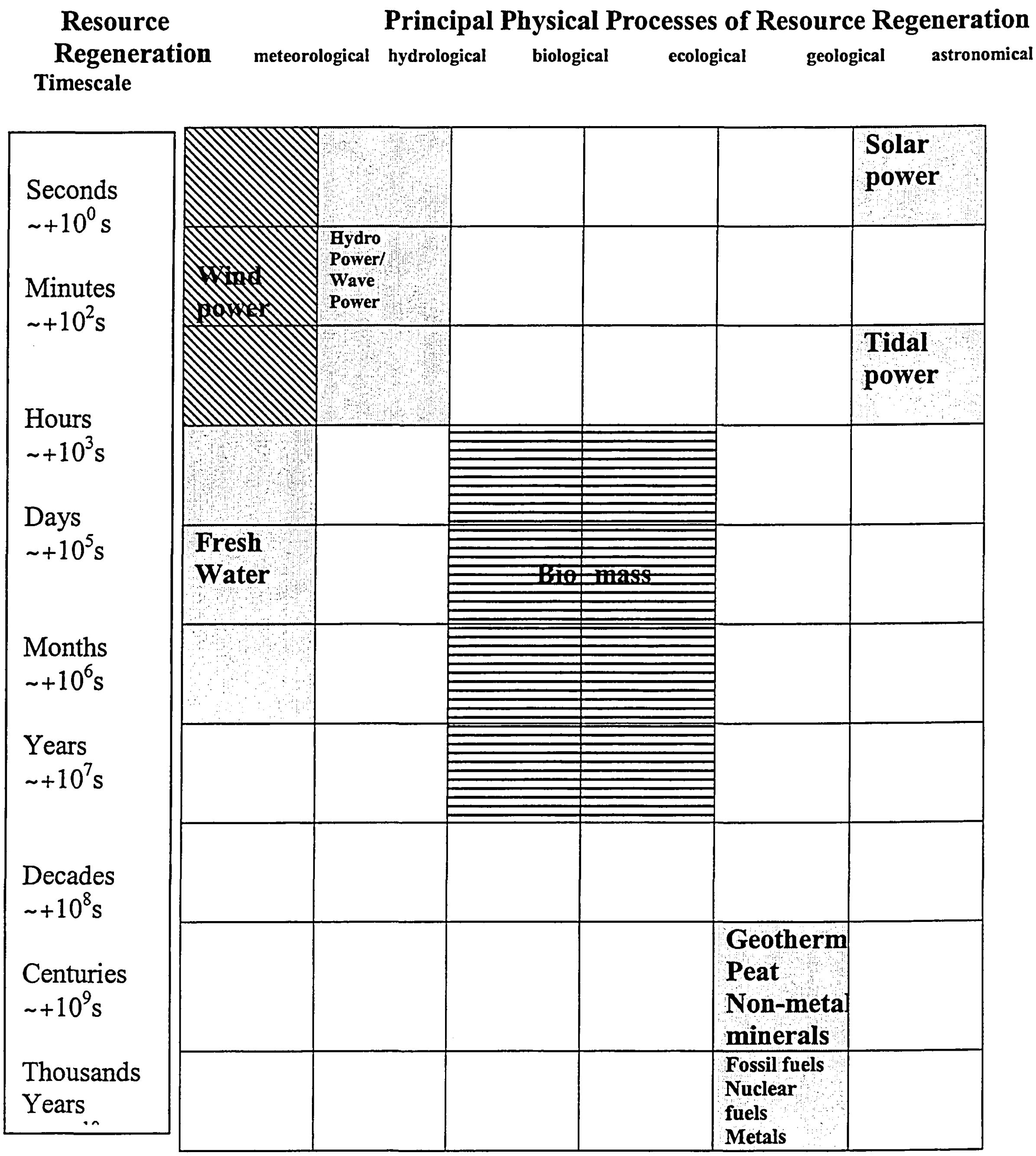
Astronomical
Biological
Chemical
Ecological
Geological
Hydrological
Meteorological
Nuclear

The duration of the times taken to create resources by these processes varies enormously. Nuclear processes, for example, can create resources over timescales ranging from almost instantaneously up to billions of years, while, in contrast, meteorological processes create resources over relatively short periods of time from minutes to months. Astronomical processes, such as the creation of planets (and, therefore, geothermal energy and other resources) from the material of a dying star, can take hundreds of millions of years. Chemical processes also take varying lengths of time, although the most important in terms of energy resource creation are those which, in combination with biological and geological processes, are involved in the formation of fossil fuels, which takes millions of years. Meteorological processes, on the other hand, create wind power on an irregular yet daily basis, while hydrological processes can create a potential form of energy used by humans, in the form of hydro power, a cyclical flow which is virtually constant but may have seasonal variations. Geological processes, which play a part in the formation of fossil fuels, metals and geothermal energy, take place over millions of years. Biological and ecological processes which create biological species, take place over millions of years of evolution. By contrast, the regeneration of such biological entities as a resource takes place over relatively short periods of time from days to decades, depending on reproductive habits. Similarly, the effect of the moon's gravity in causing tides and tidal power on the earth, is regular and measured in hours.

Although resource creation times are important, in terms of resource availability, what is more significant is regeneration time, that is, the length of time it takes to replace a unit of a resource when it is expended or depleted either naturally, or by human exploitation. More than one physical process can be involved in the regeneration of a resource. Metals are regenerated by astronomical, nuclear and geological processes over millions of years. It is possible to organise different resources in the form of a matrix, as shown in Figure 5.1, which represents the types of processes involved and the relative timescales over which the resources regenerate. Such processes are shown on the horizontal axis at the top of the matrix. On the vertical axis of the matrix, the 'resource regeneration timescale' is measured which represents the length of time (shown as an order of magnitude in seconds) it takes to replace a unit of the resource if it is naturally dissipated or depleted. The resources considered in Figure 5.1 represent a wide spectrum of types of resources. They are:

Biomass (representing all organic life forms)	Wind power
Fossil fuels	Nuclear fuels
Fresh Water	Peat
Geothermal power	Solar power
Hydro power	Tidal power
Metals	Non-metallic minerals
Wave power	

Figure 5.1 Resource Regeneration Matrix



The physical processes involved in the regeneration of each resource are the *principal* processes involved in each case. Hence, non-metallic minerals are principally the result of geological processes, although hydrological, chemical and biological processes may also be involved to some extent. Many processes are involved in the regeneration of a resource, but the most important issue is the regeneration time relative to human timescales. Astronomical, nuclear and geological processes are involved in the ultimate regeneration of metals, but only after the earth has broken up and been dispersed as dust. In terms of human interest in resources on earth, the key process of regeneration of metals is geological (weathering, dispersion and re-accumulation). Figure 5.1 is a development of Figure 4.2 which illustrated timescales of accumulation of matter and energy. It can be seen in Figure 5.1 that there is a clear distinction between those resources which are regenerated in the relatively short timescales from seconds to years, and those which are regenerated over thousands to millions of years. Without human intervention this is what is happening in the physical world. This separation of timescale summarises the distinction between resources which have been traditionally referred to as "renewable" and "non-renewable". "Non-renewable" resources appear at the bottom of Figure 5.1 because their regeneration time is thousands of years or longer whilst "renewable" resources occur near the top of Figure 5.1 because their regeneration time is much shorter. For non-renewable resources, regeneration times are much greater than human timescales.

In terms of human perception, the timescales from seconds to years might be more appropriately termed "economic" and timescales from centuries to millions of years as "physical/natural". This would go some way towards explaining the different perceptions of the future held by natural scientists and economists, the former dealing in comparatively longer timescales and the latter relatively short ones. Humans tap into the flow of resources, sometimes depleting them where the rate of consumption is greater than the rate of resource regeneration. Clearly, if resources are regenerated over very long timescales (for example coal), then rates of exploitation which are faster than this, will deplete the accumulated stocks of resources in the system. Such resources have been described as "depletable" or "exhaustible" or "non-renewable" resources. They are, in fact, renewing but at rates which are so slow as to be meaningless when measured against human economic timescales, which can be identified as being from seconds to years. This perception of resources with a long regeneration time, as stocks, is perfectly understandable from the viewpoint of a single generation, or even several generations. To all intents and purposes coal is a stock of a resource. It is a low entropy accumulation of matter and energy which is useful to humans and which can be depleted in local areas and in totality, in the sense that the stock of the resource within the system can be used up before replacement accumulations can be regenerated.

There are other resources which lie in between the extremes of "non-renewable" resources and "renewable" resources. They are regenerated over timescales which were identified in Figure 5.1 as being from days to decades, and they fall clearly between two other groups of resources ("renewable" resources and "non-renewable" resources). The regeneration processes for such resources (biological and ecological) are comparable to human timescales, and they have been termed "renewable resources" in much literature. As explained elsewhere (Jowsey and Kellett, 1995; Jowsey, 1997), these resources have completely different physical and economic characteristics from other resources which are often included in the category of "renewable resources" i.e. those resources at the top of Figure 5.1 which are regenerated over much shorter timescales and which are, mainly, continuously available. The resources which arise from biological and ecological processes are animals, birds, fish, plants, etc., (collectively termed "biomass" in Figure 5.1). They are regenerated within timescales which are relevant to humans and to human exploitation. Their continued existence, however, is dependent on their being exploited in a "sustainable" way. It is possible for these resources to be over-exploited and then depleted as if they were a stock (Jowsey, 1998). Once the genetic material is lost, the stock becomes "extinct" which means that it is totally depleted and incapable of regeneration. These resources are renewable, but can also be depleted by exploitation if they are not managed carefully. They can continue to renew and continue to exist as a resource, if they are exploited at a rate which is slower than their renewal rate, that is, at a sustainable rate.

Traditional classification of resources considers reproducibility of the resource stock in terms of the extent to which a resource exhibits 'economically significant' rates of regeneration (Perman, Ma and McGilvray, 1996). This can be taken to mean that regeneration occurs within periods of time which are comparable to human lifespan. Where the rate of resource regeneration is economically relevant, resources are described as being renewable, and this term is collectively applied to hydro power, solar power, wave power, wind power, tidal power and biomass. Where the rate of resource regeneration is not economically significant, the term non-renewable is used, and this is applied to those resources which do not regenerate within periods of time comparable to human lifespan, but over thousands to millions of years, such as fossil fuels and metals.

5.2.3 Entropy and Resource Exploitation

The third critical feature of natural resource exploitation is entropy, which was related to the concept of quality introduced in Chapter 4. Entropy is the inexorable increase in disorder, which is taking place in the universe. The concept of entropy is central to the discipline of thermodynamics, which is the systematic study of the relationship between heat, work, energy and temperature. It is a fundamental part of all of the physical sciences. The First Law of Thermodynamics contends that energy and matter cannot be created or destroyed and this means that the physical processes of resource creation are cyclical (at least until the end of the universe). The thermodynamic principle of entropy, which comes from the Second Law of Thermodynamics, requires that chaos or "unavailability" is an ultimate tendency of the utilisation of specific materials. The Second Law of Thermodynamics contends that the entropy of an isolated system always increases. There are two aspects which define any given form of energy; its quantity and quality. It is the quantity of energy which is conserved; quality degrades. Entropy is the amount of energy not available for work, which is a relatively organised form of energy.

Whenever a unit of, say, fossil fuel is used, the entropy of the world increases as the low entropy coal, oil or natural gas is converted into high entropy, low-grade heat. No conversion from one form of energy to another is perfectly efficient and the consumption of energy is an irreversible process. The implication of the Second Law is that, without importation of new energy sources, a closed system must eventually use up its "available" energy. Since energy is necessary for life, life ceases when useable energy is exhausted. All processes which use natural resources are irreversible due to entropy. Minerals become too dispersed and mixed with impurities such that their re-use would be increasingly energy intensive. The entropy of the universe is increasing so that more and more energy becomes "unavailable" for conversion into mechanical work and, in this sense, the universe is "running down". As energy collapses into chaos, entropy increases. High quality energy is relatively more ordered energy which is in a state of low entropy. It may be highly localised, as in a lump of coal or a nucleus of an atom, or it may be energy that is present in the coherent motion of atoms, as in the flow of water. Because energy and matter cannot be destroyed, materials taken into the economic system from the environment have to either accumulate in the system or return to the environment as waste.

These considerations have important implications for resource exploitation, in that the use of a resource will not destroy or remove the energy and/or matter from the environment, although it will be transformed, and as a result of the Second Law of Thermodynamics, its entropy will increase. In using a resource, its entropy will increase because it will be dispersed and the energy/matter concentration declines and its quality is reduced. In all economic production processes, ordered, low entropy sources of energy are used up and high entropy waste heat is dissipated. If natural resources are left alone to naturally dissipate, the rate of change of entropy in the environment will be gradual. Rapid exploitation of natural resources in the economic process may lead to high rates of entropy change, greater than natural change, and this may become a significant environmental problem because of the inability of natural systems to absorb such rapid changes.

Natural processes are accompanied by an increase in the entropy of the universe corresponding to energy existing at ever-lower temperatures. If the unit of coal is not used by humans as fuel, it will gradually be eroded away and dissipated. The natural direction of change causes the quality of energy to decline and every action diminishes the quality of the energy of the universe.

> "Modern civilisation is living off the corruption of the stores of energy in the Universe. What we need to do is not to conserve energy, for Nature does that automatically, but to husband its quality. In other words, we have to find ways of furthering and maintaining our civilisation with a lower production of entropy: the conservation of quality is the essence of the problem and our duty toward the future."
> (Atkins, 1984).

Increasing entropy is related to increasing disorder among particles. The natural state of the universe is disorder and chaos. Where order and coherence arise, as in the accumulation of metal ores or the emergence of a plant from a seed, there is disequilibrium in a local part of the universe. Atoms are organised into a structure. This structure is driven by a flow of energy, which is dissipated. Once the energy flow ceases, the structure crumbles to dust or chaos. For people to live, they must convert energy into high entropy wastes, thus perpetuating the disequilibrium, which is their structure. People exploit high quality energy for the advantages it provides. In doing this, total entropy increases resulting, inevitably, in low quality energy, or waste heat. At the point where this energy conversion process can no longer continue, the human structure crumbles into dust. In physical terms, life forms are an unusual occurrence. It is a matter of common experience that disorder will tend to increase if things are left to themselves. Order can be created out of disorder, but it requires the expenditure of energy and so reduces the amount of useful energy available. Temporary and local decreases in entropy (increases in order) can be achieved, but the entropy of the whole eventually increases.

Stocks of resources can and do build up in the systems which resources flow through, and, indeed, this was identified as a defining characteristic of resources in Chapter 4.

Nevertheless, the stock eventually flows through the system in its inexorable dissipation and conversion from low entropy into high entropy matter and energy. It has already been explained that humans interfere with flows and stocks of natural resources when they utilise resources. They can tap into the current flows and/or draw down stocks, which have been accumulated by past imbalances between inflows and outflows. If humans exploit a flow of energy and/or matter, they intercept the flow between the natural input and output from the system. The natural output from a system will be in the form of gradual creation of high entropy matter and/or energy, such as low grade heat emissions. Interruption of this natural process may create problems as, for example, when large amounts of stocks of energy in the form of fossil fuels are used quickly in economic processes. In this situation, the increase in rate of change of entropy in a relatively short space of time may cause problems of pollution and may also disrupt the natural cycle of resource creation or regeneration.

Energy and matter are transformed in economic processes, from a state of easy availability (highly concentrated resources) into a state of non-availability (highly dispersed waste). The economic process is subject to the Second Law of Thermodynamics because it is not possible to recover completely the matter or energy involved in mechanical work or wasted in friction. Complete recycling is only physically possible if a further amount of energy is expended and the resulting increased rate of change of entropy would not be sustainable for the biosphere, because the resultant pollution would make biological and ecological systems unable to support life. All economic action, including recycling, therefore, devalues either energy or matter or both and leaves less energy or matter available for future generations. Resource depletion is irreversible and the Hotelling prediction of increasing resource prices would hold in the long-run (Hotelling, 1931). The observation of falling prices for "exhaustible" resources is, as described in Chapter 3, the result of new resource discoveries (which cannot go on forever), or temporary technology shifts. In reality, the increase in rate of change of entropy which accompanies resource exploitation is a cost which should be incorporated in the resource price, but which is often not recognised in the market.

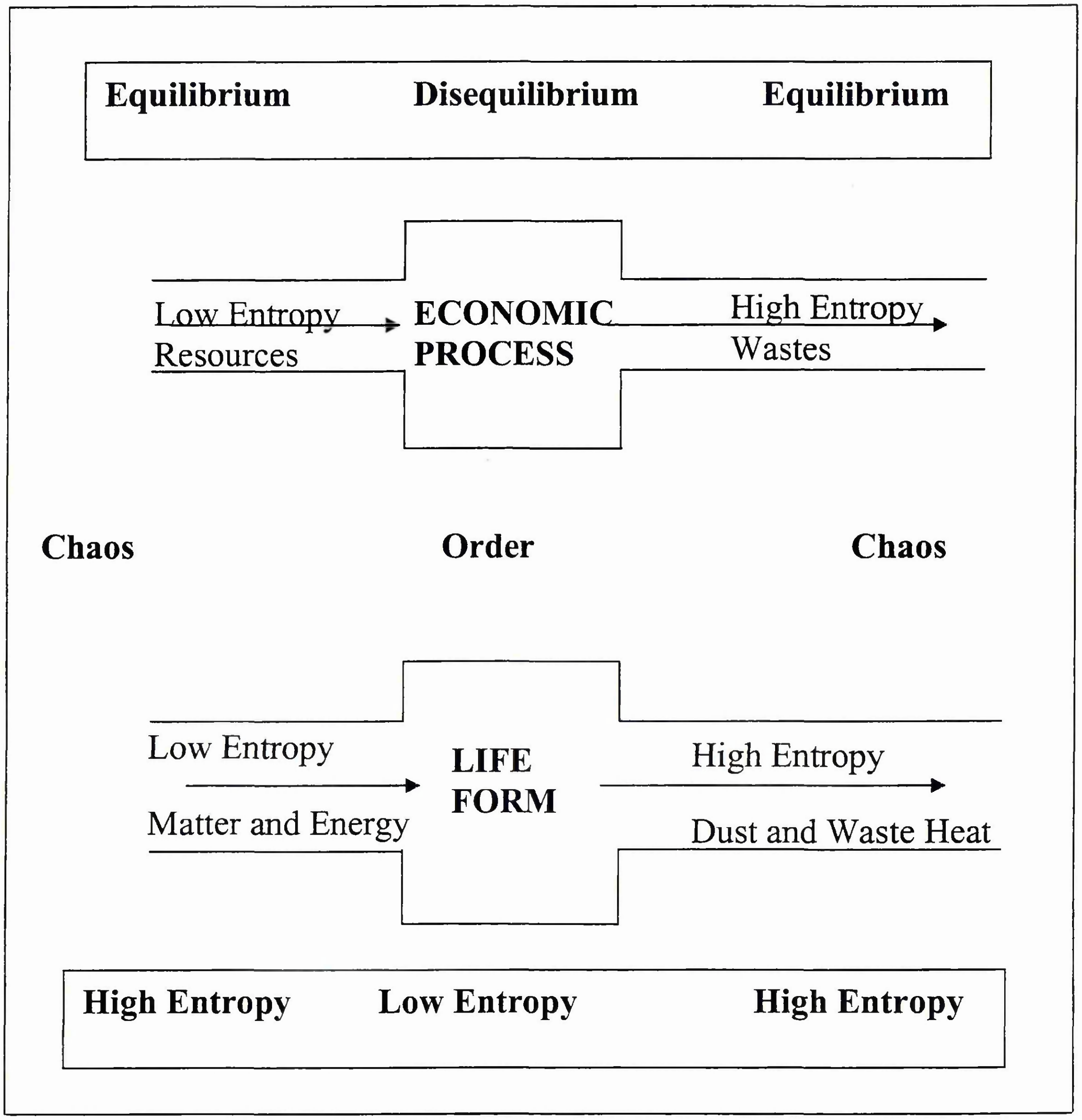
Energy can neither be created or destroyed, but it exists in many different forms, such as heat, chemical energy, electrical energy, etc. The earth can exchange energy, but very little matter, with the rest of the universe (exceptions are space dust and meteorites into the system, and atmospheric gases out of the system). Solar energy is the only real input to the earth's system from outside. In a closed system, the sum of energy, in all its forms, does not change with time; the form of energy changes, but the total amount is conserved. Every time the form of energy changes, the quality of energy is downgraded to a 'less useful' form. The earth can export high entropy heat in the form of radiation into space, but accumulation of heat is clearly a problem as is illustrated by global warming, which could be seen as a product of the economic system ignoring the concept of entropy.

5.2.4 Entropy and Economics

The concept of entropy encompasses energy, time and irreversibility, which are important concepts in environmental economics. In all economic production processes, ordered, low entropy sources of energy are used up and high-entropy waste heat is dissipated. Entropy can, therefore, play a central role in the integration of physical and economic theories of resources. It is central to the cyclical nature of resource creation in the physical world and it is important in the economic world in understanding the processes of resource depletion and waste assimilation. Developing the ideas introduced in Chapter 4, the similarity between physical and economic processes can be seen in Figure 5.2. In the upper part of Figure 5.2, the economic system has inputs of low entropy materials which are processed to provide goods and services, before high entropy wastes are returned to the environment in a low quality chaotic state. The order which is formed by the economic process interrupts the normal state of disequilibrium or chaos which would be the case in the natural world. The physical process which, for example, allows the creation of a biological life form is illustrated in the lower part of Figure 5.2. The life form is sustained by inputs of low entropy matter and energy, itself emitting high entropy dust and waste heat. The life form is a temporary disequilibrium or interruption in the inevitable progression of low entropy matter and energy to high entropy matter and energy. Disorganised (high entropy) matter and energy are ordered or organised into a life form which is a temporary state of order (low entropy), before the inevitable progression of the matter and energy to a state of disorder (high entropy).

No physical process is possible without energy, and all such processes relevant to the functioning of economics are of an irreversible nature because of the Second Law of Thermodynamics. The throughput flow begins with the extraction (depletion) of low entropy resources and ends with an equal quantity of higher entropy waste or pollution. There is irreversibility in the combustion of fossil fuels, destruction of the rain forest and extinction of species and other environmental-economic impacts, and so thermodynamics brings real, irreversible time into the analysis.

Figure 5.2 The Role of Entropy in Physical and Economic Systems



It has been argued (Daly 1974), that the throughput flow, viewed as the cost of maintaining stocks (of physical wealth and population), begins with the extraction (depletion) of low entropy resources at the input end, and terminates with an equal quantity of high entropy waste (pollution) at the other end. There is no alternative to increasing entropy in order to maintain the stocks of people and artefacts. In any isolated system entropy always increases or remains constant, it never decreases. Systems have a tendency to ever increasing disorder. The economic process transforms stocks of highly concentrated and easily available resources into products and wastes which contain the same material in lower concentration. For example, oil in high concentration or low entropy, serves as fuel, while one of the waste products from its combustion, carbon dioxide, is eventually evenly distributed throughout the atmosphere in a state of high entropy (Georgescu-Roegen, 1971). Stocks of resources are permanently reduced by economic action and at the same time the stock of wastes from the economic process is permanently increased. The physical process and the economic process are irreversible because of entropy. Nor does technology offer a solution to increasing entropy because all technologies obey the Laws of Thermodynamics (Daly, 1974).

Neoclassical economics does not regard time or entropy as a constraint to the economic process and Walras' general equilibrium analysis (Walras, 1874) assumes an open system where both energy and matter enter the economic process as inputs from the outside. Static analysis and dynamic analysis in neoclassical economics are dealt with in the same way – as a choice between two resources today, or one resource today and another tomorrow. In reality, the economic system is an open sub-system of the larger system of the earth (or the universe), which is ultimately a closed system. Neoclassical economics analyses static and equilibrium conditions whereas physical and economic systems are dynamic and in disequilibrium. Not until the 1970's did economists begin to realise the limitations which the Second Law of Thermodynamics imposes on economic production systems, when their attention was drawn first to natural resource scarcity and later to pollution problems (see, for example, Kneese, Ayres and d'Arge, 1970). The concept of entropy encompasses both resource depletion and waste assimilation and, therefore, provides a theoretical link between these two key problems of environmental economics.

5.2.5 Entropy and Pollution

Exploitation of resources is most rewarding for life forms or for economic agents if those resources are concentrated or accumulated in a small spatial area. The concentration provides higher quality energy and/or matter, which is more attractive to those exploiting it because less effort is required. For this reason high-grade metal ores are preferred to low grade ores, and coal is preferred to peat. The degree of concentration or accumulation is, therefore, a critical feature of resource exploitation. This concentration or accumulation has been shown to be the result of physical processes which are cyclical and continuous, and which arise from four fundamental forces. The existence of an accumulation of matter and/or energy has been shown to be a disequilibrium in the natural progression of entropy in the universe. Interfering with the natural rate of creation of entropy can have consequences – the creation of a large amount of high entropy (in the form of low grade heat emissions) in a relatively short space of time can destabilise the environment and cause adverse impacts. Examples of pollution arising from interference with the natural rate of creation of entropy are readily available. The inevitable creation of high entropy in the process of resource use is, therefore, also a critical consideration in resource exploitation.

Pollution may arise from concentrations of high entropy wastes which are still lower entropy than the surrounding environment. A pollutant requires a pathway (such as the atmosphere or water supply) to a target or receptor (Haigh, 1992). Exploitation of natural resources in large quantities creates pathways for pollution. If the pollutant reaches no target in damaging quantities, but is dispersed in the environment harmlessly, there is no pollution. Moreover, for economists, if the benefits of the economic process which creates the pollutant outweigh the costs, then pollution is justified. This means that there is an optimum level of pollution (Turner et al, 1994) and that zero pollution is not feasible as a policy objective because of the costs involved in reduction of waste outputs and in loss of the benefits derived from the goods being produced.

The group of resources at the top of the resource regeneration matrix in Figure 5.1 (hydro power, solar power, tidal power, wave power and wind power) are those which are least likely to create pollution problems. The use of these resources (with currently available technology) involves "tapping into" the flow of the resource in order to capture the energy it contains. There is an increase in the emission of high entropy, low quality wastes in doing so, because the concentrated flow of energy these resources provide will be dissipated and reduced in quality, albeit from a relatively high entropy starting point. Large amounts of high entropy wastes which could cause problems to life support systems will not be created, however, because the overall change in entropy is relatively small.

Those resources which arise from biological and ecological processes over months and years can create problems of high entropy wastes in local environments for short periods of time as they decompose. Natural dissipation of such high entropy wastes is efficient and part of the natural ecological process. Only where there is human interference with those ecological systems is there likely to be a problem with increased emissions or accumulations of high entropy wastes. This is evidenced by the lack of high entropy biomass "pollution" in the natural world.

The greatest interruption in the natural process of gradual degradation of matter and/or energy, and the creation of high entropy matter and/or energy comes from those resources at the bottom of the resource regeneration matrix (metals, fossil fuels, etc.). These resources store high quality, low entropy matter and/or energy for long periods of time. If left to natural processes they would eventually, over very long periods of time, dissipate into high entropy, low quality matter and energy. If, however, they are used intensively as a resource over a very short period of time, then the high entropy emissions of industrial production can accumulate in the atmosphere and cause problems such as air pollution. Other problems of a high entropy, pollution nature (such as water pollution by chemical wastes and land pollution by heavy metals created in industrial processes) will also arise from the rapid exploitation of such resources and the consequent disruption of the natural cycle.

The problem is not the *amount* of high entropy waste released, but the *rate* at which it is released. Human exploitation of resources increases the rate of creation of high entropy wastes. It is as if all that entropy should not be unleashed so quickly, because the system into which it is released cannot cope with it. The rate of change of entropy should be a crucial consideration of resource exploitation. Use of hydro power, solar power, tidal power, wave power and wind power causes a relatively small increase in rate of change of entropy. Use of biomass resources and fresh water causes a moderate increase in rate of change of entropy. Use of metals, fossil fuels and nuclear fuels causes a large increase in rate of change of entropy.

5.2.6 Measurement of Entropy

Essentially, the concentration or accumulation of energy and/or matter as a resource, is a temporary interruption in the inexorable increase of entropy in the universe. Just as an internal combustion engine can create low entropy work for a short time, by burning fossil fuels, but eventually returning high entropy exhaust emissions to the atmosphere, so all accumulations of matter and/or energy are available for exploitation rapidly, creating a sudden concentration of high entropy emissions, or they will gradually dissipate with a slow and gradual discharge of high entropy matter and/or energy into the environment. Rapid creation of high entropy emissions, faster than their natural creation, may well be a bigger problem than the depletion of resources, and evidence over the past thirty years seems to confirm this. The process of economic growth, interpreted currently as material growth, requires increases in material or energy inputs and outputs. Adequate environmental sink space (the capacity of the earth's environment to absorb waste materials) is just as important to the working of the global economy as is the continuing availability of low-entropy inputs.

The group of resources with very short regeneration timescales is also the group of resources which contribute least to increased rates of entropy change in the environment. Use of hydro power, solar power, tidal power, wave power and wind power will increase overall entropy in the environment because the concentrated flow of energy these resources provide will be dissipated and reduced in quality, but these resources are themselves already in a state of relatively high entropy. The flow of solar energy to earth is of extremely low intensity (approximately 1.36 kW/m^2 at the outer edge of the atmosphere and 1kW/ m^2 at the earth's surface). Its intensity is increased naturally if it is collected through the chemical energy of green plants, or via the hydrological cycle into river flow; but using solar power directly is difficult because it is so diffuse (Georgescu-Roegen, 1975). Wind power harnesses natural forces to drive turbines which generate electricity. The wind turbine blades concentrate the energy of the wind, but do not increase the rate of overall entropy change above what would be the case in the natural world. Hydro power on a small scale taps into the kinetic energy of flowing streams. Again, the energy is concentrated to drive turbines, but the increase in rate of entropy change in the environment is no greater than it would be if the streams were left to flow naturally. Large scale hydro power may have additional effects in that the collection of large amounts of water in reservoirs can cause methane gas, as plants which are flooded decompose. This decomposition will take place faster than it would in the natural world and so the rate of entropy change is increased, at least slightly. Wave power harnesses the kinetic energy of wave motion to generate electricity. As with wind power there is no increase in the rate of entropy change, over and above its rate of change in the natural world. The same can be deduced about tidal power, which uses tidal rise and fall to generate electricity. These energy sources will increase the rate of entropy change to some extent, however, because the capital equipment required to exploit them will use other resources which increase the rate of entropy change. The overall rate of change in entropy resulting from the exploitation of this group of resources is, however, relatively small.

Those resources which arise from biological and ecological processes over months and years can create problems of high entropy wastes in local environments as they decompose. Natural dissipation and assimilation of such high entropy wastes is efficient, however, and part of the natural ecological process. Only where there is human interference with those ecological systems is there likely to be a problem with increased emissions or accumulations of high entropy wastes (Jowsey, 2001b). Growing biomass to generate electricity is often claimed to be neutral in terms of the overall carbon-dioxide effect on the environment. This is because as the biomass grows it absorbs carbon-dioxide which is then released when the material is burnt to generate electricity. The process will increase the rate of entropy change, however, because nutrients will be taken from the soil and dispersed as low-grade heat. Moreover, biomass resources are themselves organised from relatively high entropy matter and energy in the environment. In order to preserve their temporary disequilibrium which is their ordered state, they consume low entropy matter and energy, increasing the rate of entropy change in the environment. Nevertheless, the rate of entropy change caused by biomass resource use can be accommodated by the natural environment.

In general, the entropy of a gaseous substance is greater than the entropy of the same substance in liquid form, and the entropy of a substance in liquid form is in turn greater than the entropy of the same substance in solid form. Using water as an example, ice has lower entropy than liquid water, which has lower entropy than steam or water vapour. Using material resources with high concentration in a way which disperses them increases the rate of entropy change in the environment. Converting fossil fuels into heat energy and gaseous emissions will cause rapid entropy change in terms of relative temperature change and relative concentration change as described above. Similarly using highly concentrated metals in economic processes will disperse them and lead to high rates of entropy change. The rate of release of high entropy matter and/or energy is increased most by exploitation of those resources which have the longest regeneration time. Metals, fossil fuels and non-metallic minerals store high quality, low entropy matter and/or energy over long periods of time before being dissipated slowly by natural processes. If, however, they are exploited over a very short period of time, then the high entropy emissions of low grade heat and other waste products can accumulate in the environment causing significant problems, sometimes even on a global scale. If the rate of release of high entropy wastes is rapidly increased, it can exceed the carrying capacity of the environment causing significant pollution problems.

Entropy change could be measured as resources are used by either measuring the proportionate change in temperature as an energy resource is used, or the proportionate change in concentration of matter as a resource consisting of matter is used. For an energy resource:

$$Et = \frac{T_2 - T_1}{T_1} \qquad \text{(Equation 5.5)}$$

where E_T is the proportionate change in temperature, which is a surrogate for entropy change as the resource is used and its original temperature T_1 changes to the new temperature T_2.

For a resource which is matter:

$$Ct = \frac{C2 - C1}{C1} \qquad \text{(Equation 5.6)}$$

where E_C is the proportionate change in concentration of matter, which is a surrogate for entropy change as the resource is used and its original concentration C_1 changes to a new concentration C_2. The greater the change in temperature or concentration as a natural resource is used, the greater the proportional entropy change. Rate of entropy change as a resource is exploited can be represented by the term $\Delta s/t_u$, where Δs equals change in entropy and t_u equals utilisation time, or time over which a resource is exploited. The term $\Delta s/t_u$ is a combination of physical and economic influences on natural resource exploitation. The critical physical consideration which needs to be taken into account as a natural resource is exploited, is the rate of change of entropy that results from that exploitation. This will be considered further in attempting to classify natural resources and in identifying the true costs of their exploitation.

6 ECONOMIC ASPECTS OF NATURAL RESOURCE EXPLOITATION

6.1 Accumulation and Concentration

It was established in Chapter 4 that accumulations of matter and energy are attractive to humans as natural resources. This is because the process of accumulation concentrates the quantity and quality of the resource, affecting the ease or difficulty of finding it (existence proving), making it easier to own or control (determining access to it), and making it easier to exploit (because for a concentrated resource, rate of supply relative to rate of consumption will be high). If the accumulation/resource is sufficiently concentrated in quantity and quality, then more return will come from its exploitation for a given amount of effort. This means that it is more likely to be economic to exploit. The degree of concentration or accumulation of a natural resource is, then, a key economic characteristic of natural resource exploitation.

Low entropy resources are concentrated accumulations of matter and/or energy, which are more readily exploited because they produce a greater return from a given level of effort or cost. "Non-renewable" resources are found in varying states of concentration/accumulation, but those which are exploited first and for the most profit, are those which are highly concentrated. High-grade mineral deposits are preferred to low-grade, and coal with a high calorific value is preferred to deposits with a low energy value, such as lignite. To an extent, the same principles apply to biomass and water; concentrated accumulations are more easily and profitably exploited. Fishing in densely populated fishing grounds is clearly preferred to fishing in less densely populated areas, and fast-growing trees will be planted to enable more concentrated harvesting of biomass. Those resources grouped together at the top of the resource regeneration matrix (Figure 5.1) are not concentrated or accumulated to the same extent as those towards the bottom. In essence they are flows of relatively high entropy resources.

6.2 Knowledge of Existence

The knowledge that a resource exists is also an important factor governing its exploitation. Technology plays an important role here in making it possible to find and to exploit an accumulation of matter and/or energy as a resource. Some accumulations may not be recognised as a resource until there is an advance in technology which may be driven by market forces. In his treatment of non-renewable resources, Hotelling did not consider the possibility of replacement of the resource by exploration for new sources (Hotelling, 1931). Instead, the resource was treated as a fixed stock. In fact, over much of the modern era, non-renewable resources have been discovered at faster rates than they have been depleted, which has made them appear more like renewable resources. The role of technology in exploiting resources is of fundamental importance to the economics of resources. As a particular resource becomes scarce, market forces should operate to raise its price. While it has been claimed that there is little evidence for this (Barnett and Morse, 1963; Barnett, 1979), experience following the oil price rise of 1973 would seem to corroborate this view. As oil was made artificially scarce by cuts in production by the Organisation of Petroleum Exporting Countries and its price rose, more effort was devoted to finding substitutes for it in certain uses. Technology provides the means to exploit new resources as they are discovered. As the world moves on, human knowledge is extended and technology improves, accumulations of matter and/or energy, which were previously overlooked as resources, may become "useful". Oil occurred in surface deposits in parts of the ancient world, such as modern day Iraq, but was regarded as a concentrated pollutant in that it had no use and was potentially harmful. In the same way barytes, which was once discarded from lead mines has now become a useful resource in the process of oil drilling. Knowledge of the existence of an accumulation and of its potential use as a resource is of obvious importance economically.

Clearly it is a pre-requisite of natural resource exploitation that knowledge of the existence of a resource must obtain before a resource can be exploited. The technology to enable that exploitation must also be available. There are many examples of potential resources which are not currently exploited because the technology to do so economically does not yet exist. In the past oil from beneath the sea-bed has been just such an example. Currently, it is well known that oil exists in shales in abundance, but it is not economic to exploit it because it involves crushing the rock itself and, with current technology, this is uneconomic. Similarly, gold exists in vast quantities in seawater, but it is so dispersed that it is not economic to exploit with current technology. Advancing technology thus provides a potential solution to the problem of resource depletion. If, as a resource is depleted its price rises, then more effort will be made to find new sources of supply and/or substitutes for it. More effort will be devoted to research and development in order to achieve this, and technology will advance as a result. For example, were the price of a barrel of oil to rise sufficiently, more effort would be put into research and development to extract oil at lower cost from oil shales. At some point in this process, extraction of oil from oil shales would become "economic". This is an illustration of market forces at work, and is the probable reason for the lack of evidence of natural resource price increase as described elsewhere and discussed more fully in Chapter 3.

6.3 Ownership and Access

Ownership of a resource (access to it and control of it) is also an important factor governing its exploitation. It was shown in Chapter 3 that open access to certain resources can lead to their over-exploitation and exhaustion. More concentrated resources, such as coal or oil deposits are more likely to be privately owned than less concentrated resources such as fish and wave power.

Ownership and control of natural resources is of obvious political and strategic importance, but it is also of fundamental economic significance. Where property rights for natural resources exist, the property owners have a powerful incentive to use those resources efficiently because a reduction in the value of the resources represents a personal loss. Optimum value from the resources will be obtained as a result. For "non-renewable" or "depletable" resources it can be shown that this results in optimum depletion of resources, and that the market mechanism conserves resources in a way which is optimal for society (Hotelling,1931). Where resources are not privately owned, they may be state-owned and controlled, or treated as common property, where the resources are jointly owned and managed by a specified group of co-owners, or there may be open-access to the resources. State ownership of property occurs to varying degrees in virtually all countries. Problems of efficiency and sustainability can arise in these situations because of incompetence on the part of bureaucrats and planners, or because the decision-makers have their own interests which diverge from the general interests of society. Common property resources may be governed by formal (legally enforced) or informal arrangements. Where the arrangements are informal, they are more likely to break down, especially in the face of increasing population pressure. Open-access to natural resources can lead to a "Tragedy of the Commons" (Hardin, 1968). Individuals who exploit the open-access resource have no incentive to protect the asset value of the resource by restricting their exploitation. Others would gain the benefits of an individual's conservation. Individuals have an incentive to maximise the use value of the resource (i.e. maximise current revenue from the use of the resource in the current time period) and to ignore the asset value because there is no incentive for conservation. This situation has been described elsewhere in relation to open-access fisheries (Jowsey, 1998).

6.4 Rate of Consumption Relative to Rate of Supply

Rate of consumption of a resource relative to its rate of supply is also a critical factor (possibly the most critical factor) affecting resource exploitation. Clearly for those resources created over geological ages, such as fossil fuels and metals, the rate of supply is very slow and the fact that they are a flow resource is of little relevance in terms of human needs. The rate of consumption of such resources is inevitably greater than their rate of regeneration (with any positive rate of use) and, as such, use of these "exhaustible" resources cannot be sustained in the long term. For those resources created as a result of biological and ecological processes, such as biomass, the rate of supply can be greater than or equal to the rate of consumption, but careful management of the resource is necessary for this to be the case (Jowsey, 1998). For resources at the top of the resource regeneration matrix, hydro power, solar power, tidal power, wave power and wind power, the rate of supply is greater than the rate of consumption.

The rate at which a natural resource can be supplied relative to the rate at which it is consumed is crucial to price determination in the economics of resources. As with all resources, scarcity leads to high prices, while abundance leads to lower prices. There are also implications for long-term economic growth in the relationship between rate of consumption and rate of supply (because, ultimately, economic growth may not be sustainable with high rates of consumption of certain resources). For the "non-renewable" resources which appear at the bottom of the resource regeneration matrix, the rate of supply is so low (over geological ages) that it is inevitable that the rate of consumption will be greater than the rate of supply. This is clearly not sustainable over the long run. For sustainability, the rate of consumption must be less than or equal to the rate of supply.

For those resources at the top of the resource regeneration matrix, such as solar power, the rate of consumption will be less than or equal to the rate of supply, (it cannot exceed supply) and there can be certainty that these resources will exist for a very long time into the future. As a result, use of these natural resources is much more "sustainable". For those resources in the middle of the resource regeneration matrix, biomass and water, the rate of consumption can be greater than the rate of supply, making extinction of the resource possible if the point is reached where stocks cannot recover. This is unsustainable and more likely to occur with open-access as discussed in Chapter 3. It is also possible with such resources, however, that the rate of consumption can be less than or equal to the rate of supply. Sustainable forestry and sustainable fishing operate on this principle.

The rate at which a natural resource is consumed compared to the rate at which it can be supplied is of obvious economic significance. The rate of consumption (r_c) depends on a number of factors including the state of the world economy and the availability of the technology necessary to enable exploitation. The rate of supply (r_s) is clearly dependent upon regeneration time and the availability of stocks of the resource where these are possible. For non-renewable resources with very long regeneration times the rate of regeneration is not economically significant. Rate of supply for these resources is entirely dependent on the availability of stocks, as expressed earlier in Equation 4.3. With any economically significant rate of consumption of a non-renewable resource, it is clear that stocks will be depleted and that eventually r_s must be less than r_c. This is not sustainable over the long run. For those resources which have been termed biomass resources here, if the rate of consumption is greater than the rate of supply, then extinction can occur; a point will be reached at which stocks cannot recover and the resource is then effectively a non-renewable one. For hydro power, solar power, tidal power, wave power and wind power, rate of consumption, r_c will be less than or equal to rate of supply, r_s (because it cannot exceed supply) and there will be certainty that these resources will exist in the future. For each of the three distinct types of resources which were identified in terms of regeneration time, it is possible to show a distinction in terms of rate of consumption relative to rate of supply.

To summarise, for non-renewable resources: $r_c > r_s$; for biomass resources: $r_c \leq r_s$ if the resource is carefully managed, or $r_c > r_s$ for a short period of time if there is over-exploitation (which is much more likely to occur with open access); and for hydro power, solar power, tidal power, wave power and wind power: $r_c \leq r_s$ in all circumstances. This might be expected given that r_s is not independent of regeneration time (indeed regeneration time is the main determinant of rate of supply where stocks are not available), but the relationship between rate of consumption and rate of supply provides further important evidence of a distinction between different types of natural resources.

6.5 Rate of Change of Entropy

The rate at which the exploitation of a natural resource increases rate of change in entropy of matter and energy was discussed in Chapter 4. This is also a key economic characteristic of natural resource exploitation, although this may not be recognised when the resource is exploited. If exploitation of a natural resource results in a rapid rate of entropy change (a rate significantly in excess of that which would occur in the natural dissipation of the resource), then the resultant high entropy matter and/or energy may exceed the carrying capacity of the environment. The resulting "pollution" may be a significant problem and is a cost of economic exploitation of natural resources which is often external to the market and may not even be recognised. Use of "non-renewable" resources, such as coal or oil, is likely to increase the rate of change of entropy, much more than use of resources such as solar power, or than use of biomass and water. This is because "non-renewable" resources are concentrated accumulations of low entropy resources which in a natural system would only slowly dissipate over a very long period of time. Exploitation by humans greatly speeds up the conversion from low entropy to high entropy matter and/or energy. This can have considerable consequences in the form of pollution, for economic and environmental/ecological systems. Use of biomass and water will increase the rate of change of high entropy matter and/or energy, but not by as much as the use of "non-renewable" resources. This is because the conversion of biomass (and possibly water) resources to high entropy matter and/or energy in a natural process is much faster anyway than the natural progression of non-renewable resources to a state of high entropy. Animal and plant lifespans are much shorter than the periods of time for which "non-renewable" resources exist in a state of low entropy. As a result, their use as a resource is unlikely to greatly increase the rate of release of high entropy matter and energy. This is not to deny, however, that irresponsible exploitation of such resources could have complex and possibly irreversible effects, which may ultimately result in accelerated release of large amounts of high entropy matter and/or energy. Destruction of tropical rainforests may prove to be an example of this. Use of resources such as solar and wind power is unlikely to increase greatly the rate of release of high entropy matter and energy. This is because they are already a relatively high entropy natural resource. As a result, significant pollution (which is widespread and long-lasting) is unlikely to result from their exploitation.

The main economic characteristics of natural resource exploitation can be summarised as their accumulation and concentration, knowledge of their existence, ownership of them and access to them, rate of consumption relative to rate of supply, and rate of change of entropy. In Chapter 5 the main physical aspects of natural resource exploitation were identified as their comparative rates of flow through systems, their comparative regeneration times, the extent to which their exploitation increases the rate of entropy change and, linked to that, the extent to which their exploitation causes pollution. Considering these physical and economic aspects of natural resource exploitation together may reconcile the differing views of resources held by natural scientists and economists and provide a basis for classification of natural resources in Chapter 7.

7 REAL COSTS OF NATURAL RESOURCES

Having determined the most important physical and economic characteristics of resources in Chapters 5 and 6, it is now necessary to bring them together and find a way to represent them adequately in natural resource theory. A meaningful and useful theory of resources should establish the real costs of resource use if they are to be exploited in the optimum way. Such real costs of resource use must be able to reconcile the physical and economic characteristics of natural resources. Unification of these physical and economic characteristics can be achieved by investigating what the true economic costs of natural resource use are. If such real costs of resource use can be formulated it should be possible to classify different natural resources according to these costs. In order to do this, it is necessary to consider the user costs of natural resources.

7.1 User Costs of Natural Resources

The concept of user costs first appears in the basis of the economics of non-renewable or depletable resources in the early 20th century (Gray, 1914 and Hotelling, 1931), although some of the principles can be traced back as far as Ricardo and even Adam Smith. For non-renewable or depletable resources, consuming a unit of the resource implies that the stock for future consumption is reduced forever. It was shown in Chapter 3 that even most depletable resources, such as fossil fuels, are regenerating, but from a human time perspective, at a rate which is, practically, zero. In his seminal work of 1931, Hotelling showed that if the resource stock is fixed, consumption of a unit of the resource in the present implies that there will be less of the resource in the future. In addition to conventional economic costs there is an additional cost which is the reduced level of future benefits due to fewer resources being available. This additional or opportunity cost of consumption has been given the name 'user cost' (see, for example, Bowers, 1997). In environmental economics, the concept has been confined to non-renewable resources, presumably on the basis that those resources considered 'renewable' do not have such costs.

Since each unit of a non-renewable resource can be consumed only once, the current rate of consumption influences future consumption and the life of the resource. The opportunity cost of current consumption includes the impact on future benefits (for consumers) and profits (for producers), which is the user cost. The effect of user cost on output, should it be taken into account, was illustrated earlier in Chapter 3. The profit maximising output of the exhaustible resource is reduced because consumption in the current period affects consumption in future periods and this imposes an additional opportunity cost or 'user cost' which, if it is taken into account, reduces current output to the optimum output or consumption for society. If the user cost is not taken into account, then the rate of resource consumption will be greater than the social optimum.

The concept of user cost is generally described in rather vague terms. This is usually achieved by using the concept of opportunity costs to represent the additional negative value on future consumption or production of use of a non-renewable resource (see, for example, Turner, Pearce and Bateman, 1994). User costs have also been used as the basis for calculation of depreciation in national accounting, adjusting Gross National Product to allow for resources which have been depleted (Repetto et al, 1987 and El Seraphy, 1989). It is possible to analyse user cost in more depth and to give it a basis in natural science. In doing so the case for applying the concept of user cost to all natural resources and not just to non-renewables can be made.

A User Cost Function could be formulated which encompasses the physical and economic characteristics of natural resources which were identified in Chapters 5 and 6. Rates of flow of resources and comparative timescales of regeneration can be encompassed in the single concept of regeneration time. Entropy has been shown to be both an important physical aspect of natural resources and a key economic aspect of their exploitation. Rate of supply of a resource relative to its rate of consumption is an important economic consideration of natural resource use. Accumulation and concentration of resources, knowledge of their existence, ownership of them and access to them are all related and can be considered to be components of the idea of access to resources. Such a User Cost Function would have the following form:

$U_c = f(r_c / r_s ; \Delta s / t_u ; t_r ; ac)$ (Equation 7.1)

where:

U_c = user cost;

r_c / r_s = ratio of the rate of consumption to the rate of supply;

Δs = relative rate of change in entropy;

t_u = the time over which a resource is used (utilisation time);

t_r = regeneration time;

ac = access to a resource.

The term r_c / r_s represents the ratio of the rate of consumption of a natural resource relative to the rate of its supply. This is a fundamental economic concept of cost and price determination in conventional economics, which is included here to represent the economic characteristics of resources considered in Chapter 6. The component of user cost, t_r, is the length of time it takes for a natural resource (not just non-renewable resources) to regenerate, and so resources with longer regeneration times will have higher user costs. As t_r increases, then user costs rise. The ratio r_c/r_s incorporates the regeneration time t_r because r_s, the rate of supply of a natural resource, is partly dependent on regeneration time and partly on the existence of stocks. This was shown in Chapter 4 (see Equation 4.4) where the total available matter and/or energy which constitutes natural resources was shown to equal the past net rate of input of energy and/or matter (past input – output) plus the current net rate of input of energy and/or matter (current input – output). In the long-run as stocks are depleted, regeneration time begins to dominate supply of resources. So:

$$r_c / r_s = \frac{r_c}{(q / t_r)}$$ (Equation 7.2)

where q represents quantity of the resource.

Hence, $r_c / r_s \alpha t_r$ (Equation 7.3)

Hence, regeneration time t_r is effectively represented in the User Cost Function by the term r_c / r_s and the User Cost Function simplifies to:

$$U_c = f(r_c / r_s ; \Delta s / t_u ; ac)$$ (Equation 7.4)

The second term in the modified User Cost Function, expressed by Equation 7.4 arises from the previous analysis of the physical characteristics of natural resources in Chapter 5. This is the rate of change of entropy involved in the use of natural resources which is denoted by $\Delta s/t_u$. If a resource is consumed today, then the rate of change of entropy in the environment is accelerated, relative to a situation where that resource is left to dissipate naturally. It was shown in Chapter 6 that there are differences in the rate of change of entropy between different types of natural resource, with the use of fossil fuels, metals and non-metallic minerals increasing the rate of entropy change in the environment more than the use of other natural resources. Use of biomass resources increases the rate of entropy change by less than use of fossil fuels, metals and non-metallic minerals, but by more than the use of hydro power, solar power, tidal power, wave power and wind power. This latter group of resources are already in a state of relatively high entropy and so their use as a resource increases the rate of change of entropy by less than other resources. Resources which more rapidly accelerate the rate of change of entropy when they are used will have higher user costs due to subsequent environmental impacts in the form of pollution.

The term ac which represents access to natural resources affects their rate of consumption r_c. As was shown in Chapter 6, the main impact of there being open access to natural resources is greater consumption and this affects the ratio r_c/r_s. A scale could be constructed to represent the degree of access to a resource which is available. The two extremes of the scale could be zero where there is closed access (a privately owned resource) and 1 where there is completely open access (such as fishing in international waters). Between the two extremes there would be intermediate positions where there are social and legal arrangements to limit access to natural resources. The exact nature of access to resources, however, depends on the social and legal arrangements which are in place and so access to natural resources depends on resource policies and management. These policies will determine how access affects the ratio r_c/r_s and this will be considered later in Chapter 8. For non-renewable resources, such as fossil fuels, and biomass resources with open access, it has been shown that $r_c > r_s$ or $r_c/r_s > 1$. In the User Cost Function the ratio of r_c/r_s would increase with the use of such resources and increasing this ratio would increase user costs. For carefully managed biomass resources, and for hydro power, solar power, tidal power, wave power and wind power where $r_c/r_s \leq 1$, user costs will be lower. So:

$r_c/r_s \;\alpha\; ac$ (Equation 7.5)

Hence, ac is accommodated in the term r_c / r_s and so the User Cost Function simplifies to:

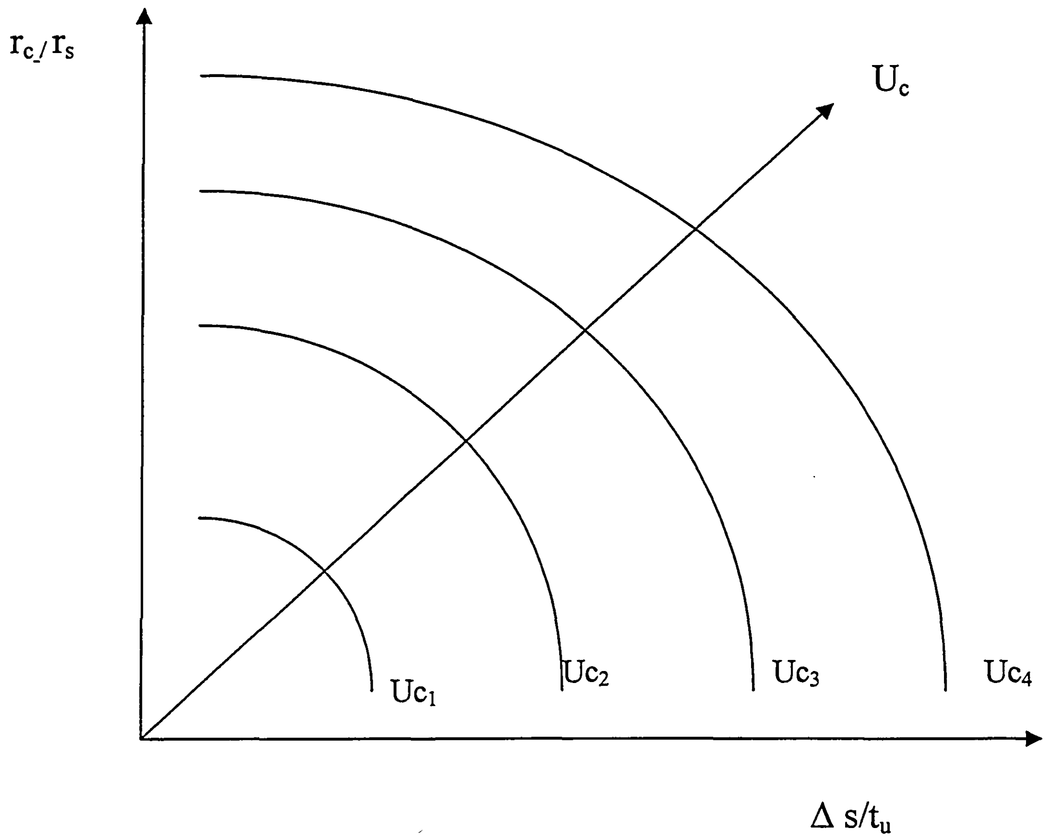
$U_c = f(r_c/r_s\,;\, \Delta s/ t_u)$ (Equation 7.6)

Equation 7.6 means that user costs for natural resources are dependent upon the ratio of the rate of consumption of a natural resource relative to the rate of its supply and the relative rate of change in entropy as a unit of the natural resource is used. These two terms encapsulate both the physical and the economic characteristics of natural resource creation and exploitation as described Chapters 5 and 6. The term r_c/r_s is a quantitative economic measure of resource availability, while the term $\Delta s/t_u$ is a qualitative physical measure of resource use. As such, r_c/r_s represents the relative quantity of a resource and $\Delta s/t_u$ represents its relative quality. In this way, the User Cost Function provides a basis for distinguishing between different resources, thereby creating the foundation for a systematic classification of all natural resources.

7.2 Classification of Natural Resources

User costs are related to r_c/r_s and $\Delta s/t_u$ by means of Equation 7.6. Various combinations of these particular factors can result in the same values of user cost. This implies that lines of equal user cost can be formulated as shown in Figure 7.1. As both r_c/r_s and $\Delta s/t_u$ increase, user costs increase with lines of equal but greater user costs, U_{c1}, U_{c2}, etc., expanding from the origin.

Figure 7.1 Lines of Equal User Costs

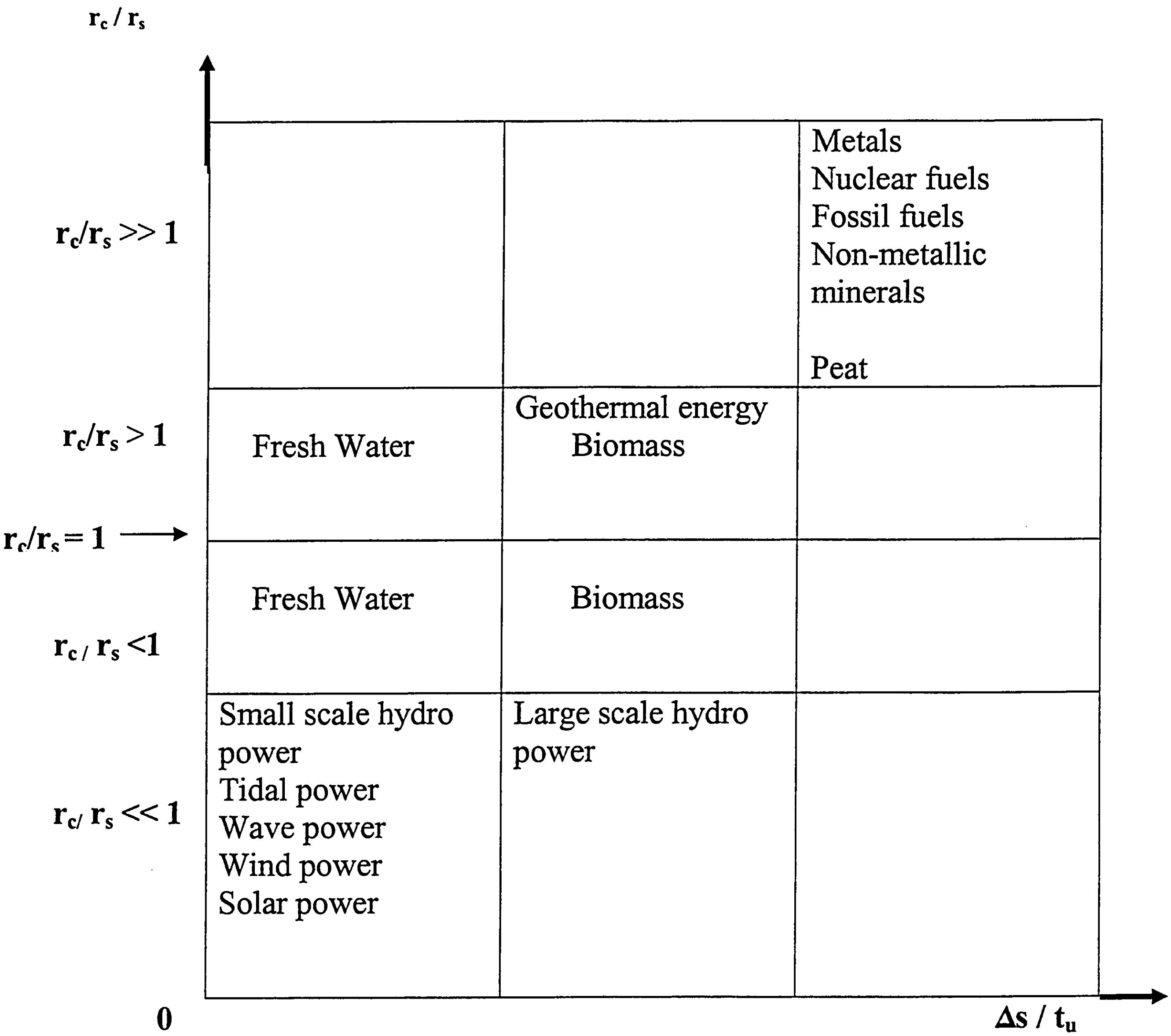


More than one type of natural resource could be on any one of these lines of equal user cost. So, for example, wave power and wind power are likely to be on a low user cost line because, in terms of the ratio of their rate of consumption relative to their rate of supply, and the relative rate of change in entropy as a unit of each natural resource is used, they are very similar. Natural gas and oil are likely to be on a high user cost line because they have similar (high) user costs. Consideration of the components of user costs reinforces the division of natural resources into three distinct groups. In terms of rate of consumption relative to rate of supply and rate of change of entropy in the environment, hydro power, solar power, tidal power, wave power and wind power are distinct from biomass resources which are, in turn, distinct from fossil fuels, metals and non-metallic minerals. User costs, as defined in the User Cost Function, are highest for the non-renewable resources and lowest for the resources in the group including solar power, with those resources which have collectively been termed biomass resources (although fresh water displays many of the same characteristics) having user costs which are between these extremes.

The two elements of the User Cost Function can now be used in a two dimensional diagram to show the distinctions between natural resources more clearly. In Figure 7.2, r_c/r_s is on the vertical axis while $\Delta s/t_u$ is on the horizontal axis. The non-renewable resources are at the higher end of the scales for both rate of change of entropy when they are used, and for rate of consumption relative to rate of supply. The biomass resources, which are potentially renewable if $r_c \leq r_s$, or depletable if $r_c > r_s$, are in the mid-range of both axes. Hydro power, solar power, tidal power, wave power and wind power are at the lower end of both axes because they cause the lowest rate of change of entropy when used, and because their rate of consumption is less than or equal to their rate of supply. Small scale hydro power causes a smaller rate of change of entropy than large scale hydro power (using dams which have considerable environmental effects) and so a distinction is made between the two. Geothermal energy is included in the analysis of Figure 7.2. It has a relatively high rate of consumption to rate of supply because its regeneration time is relatively long. This is because once the rocks providing this form of heat energy have cooled, they can take hundreds of years to re-heat. Use of geothermal energy, however, increases the rate of entropy change by less than the non-renewable resources and so it is in the mid-range of the entropy axis of Figure 7.2. Fresh water is included in the analysis of Figure 7.2 also. Fresh water resources can be considered potentially renewable if they are carefully managed, but they can be over-exploited in the same way as biomass resources. Rate of change of entropy with water use, however, is very low.

The formulation of user costs enables the division of natural resources into three distinct groups. Those with the lowest user costs can be described as 'continuous natural resources' or CNR encompassing hydro power, solar power, tidal power, wave power and wind power. Those with the highest user costs are the 'non-renewable resources', or NRR, of fossil fuels, metals and non-metallic minerals. Between the two extremes are fresh water, biomass and geothermal energy which have an intermediate level of user costs and can now be termed 'potentially renewable resources' or PRR, with user costs which are higher than for CNR, but lower than for NRR.

Figure 7.2 Natural Resource Classification

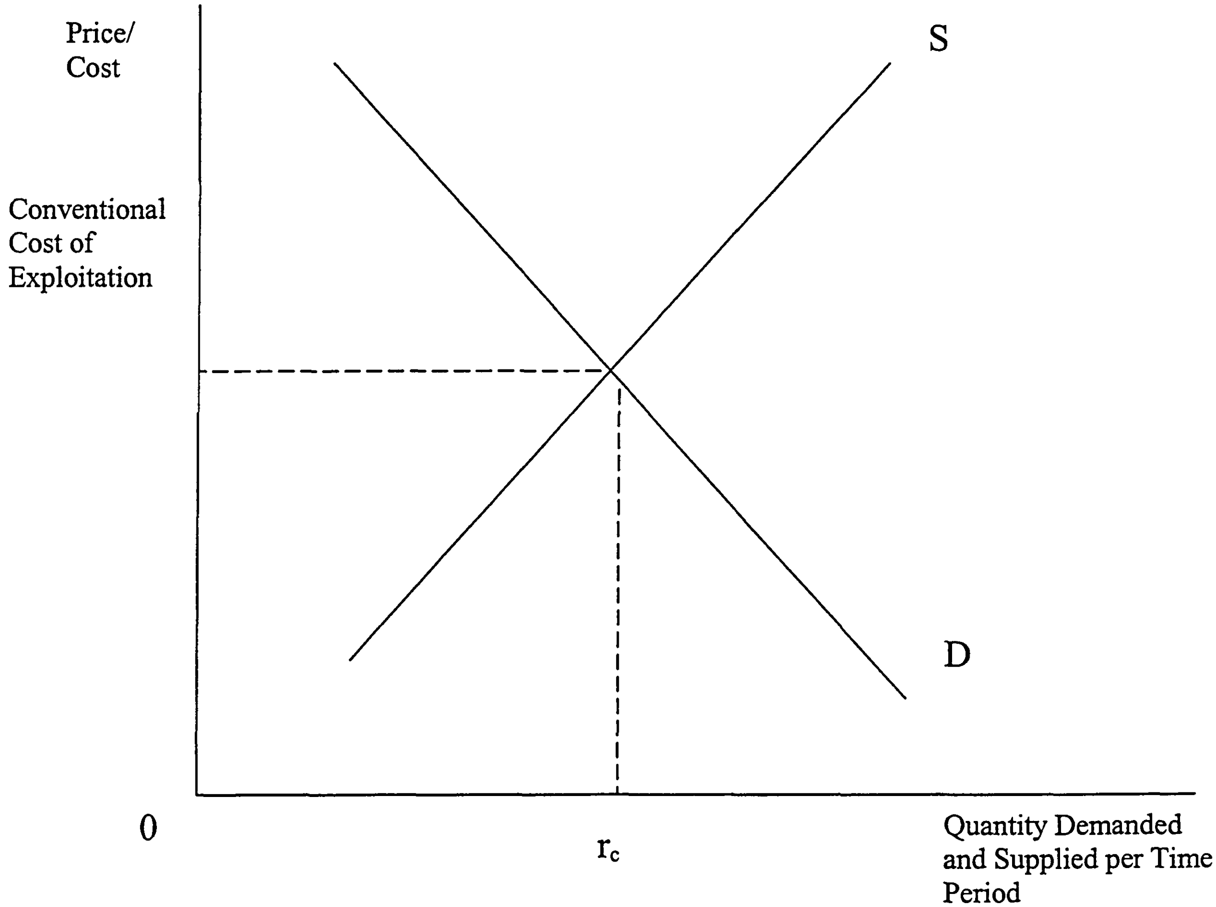


Natural resources can, then, be classified in terms of the relative rate of change of entropy and relative r_c/r_s and comparing these relative amounts shows order of magnitude differences in the extremes of resources (NRR and CNR). In general terms, CNR have the lowest user costs, PRR have intermediate levels of user costs and NRR have the highest levels of user costs. There may be more subtle differences in PRR resources requiring more accurate measurement of their user costs. In order to be more specific and to determine the exact positioning of each natural resource within these broad categories, it would be necessary to measure rate of entropy change as each resource is used (in the way that was described in Section 5.2.6) and to give detailed estimates of r_c/r_s.

It is possible (although unlikely) to exploit NRR very slowly, so that their utilisation rate t_u is no greater than the rate at which such resources are naturally dissipated. If this were to occur, then r_c could be less than r_s and the resource would move within the classification system, having lower user costs. The classification system is, therefore, fluid and resources can change position within it according to how they are managed/exploited. Peat is included separately in Figure 7.2, because it is an interesting example of a resource which could move within the classification system depending on how its exploitation is managed. It is possible for peat to be regenerated within economically significant timescales, and so if its exploitation is managed carefully, it could be considered a PRR and move down in Figure 7.2.

Conventional use of the concept of user costs of NRR suggests that user costs are simply an addition to conventional economic costs (Jowsey, 2002). In fact, as defined here, user costs incorporate all other costs, because they are represented in the term r_c/r_s. This is because the rate of consumption relative to rate of supply of a natural resource would be influenced by a change in the conventional costs of exploitation. For example, a rise in costs would change the ratio r_c/r_s because price would rise and resource consumption rates would fall. The market determines the rate of consumption of a natural resource, taking into account conventional costs via the supply curve. As a result, the quantity demanded and supplied per period of time is, in fact, rate of consumption r_c. This is illustrated in Figure 7.3. The concept of user costs brings together the physical and economic characteristics of natural resources which were analysed in Chapters 5 and 6. Consideration of relative user costs enables the classification of natural resources in three distinct groups of NRR, PRR and CNR. With detailed consideration and measurement of the elements of user costs it would be possible to further rank natural resources within these general groups in terms of the user costs of their exploitation.

Figure 7.3 Market Determination of Rate of Consumption



The issue of resource management is incorporated in both axes of Figure 7.2. Both r_c /r_s and Δs / t_u will be affected by the way in which a natural resource is exploited and managed. A management strategy for natural resources should emerge from consideration of their user costs and, in forming policy decisions for natural resource use, it should be determined what tools are available to allow consideration of user costs in resource utilisation policies. The elements of user costs encompass the two main problems of environmental economics, depletion and pollution. Policy for resource use should reflect these different elements of the user costs of natural resources. So resource use policy should discourage use of resources with high user costs and encourage use of resources with low user costs. Ways in which this can be done will be considered in Chapter 9.

8. GEOTHERMAL ENERGY CASE STUDY

8.1 Background

In Chapter 7 it was shown that user costs for natural resources are dependent upon the ratio of the rate of consumption of a natural resource relative to its rate of supply and the relative rate of change in entropy as a unit of the natural resource is used. In order to demonstrate the application of this theory in relation to a natural resource, it has been decided to investigate the case of geothermal energy. This involves attempting to derive the user cost function for an active geothermal field. Geothermal energy is a particularly interesting case study because the nature of this resource is such that it can move from being a renewable resource to being a non-renewable resource depending on the way that it is exploited. It is, therefore, possible for geothermal energy to change its location within the Natural Resource Classification diagram (see Figure 7.2 previously). A further reason for choosing to study geothermal energy is that there is a considerable amount of data available for this type of resource. Although much of this data are not in a readily usable form, suitable sources can be investigated and combined together to provide the information necessary to carry out this case study demonstration.

The term "geothermal energy" means the heat contained within the earth that can, or could, be recovered and exploited by humans. The thermal energy of the earth is enormous, in the order of 12.6 x 10^{30} MJ (Armstead, 1983), but only a fraction may be accessible for utilisation. Such utilisation depends, partly, on the geothermal gradient which expresses the increase in temperature with depth in the earth's crust. Down to the depths accessible by drilling, the average geothermal gradient is approximately 2.5-3.0 °C/100m. In many areas, however, the geothermal gradient is far from the average value. In areas with geologically 'young' sediments, the geothermal gradient may be as low as 1.0 °C/100m, while in some 'geothermal areas' the gradient may be more than 30.0 °C/100m (Dickson and Fanelli, 2003).

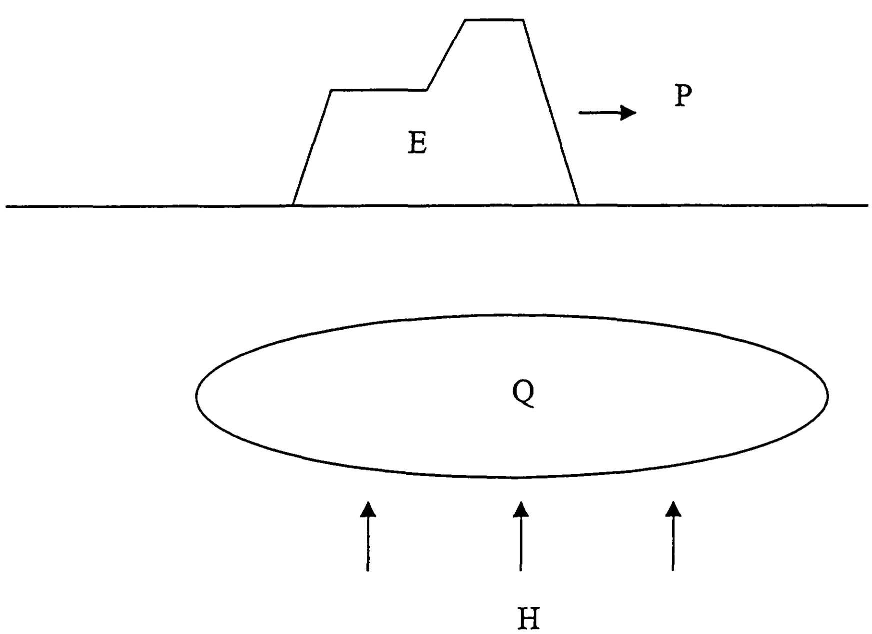
The first attempt at generating electricity from thermal steam was made at Lardarello in Italy in 1904. This was commercially successful and by 1942 the installed geothermal capacity was 127,650 kWe. The first geothermal wells in Japan were drilled at Beppu in 1919 and in the USA at the Geysers, California, in 1921. Many other countries have since developed geothermal power plants, including the Philippines, Mexico and Indonesia. Total world geothermal electricity capacity was 7,974 MWe in 2000 (Huttrer, 2001). Data on non-electric applications of geothermal energy, such as heat pumps, bathing and space heating, is less readily available but there are 58 countries reporting such usage (Lund and Freeston, 2001).

8.2 Derivation of the User Cost Function

The User Cost Function, as defined in Chapter 7, has two components: the depletion cost component (which is related to r_c/r_s); and the environmental cost component (related to $\Delta s/t_u$). Data are required on those aspects and subsequent costs which depend on the rate of consumption relative to the rate of supply of geothermal energy in a representative field, and on the rate of change of entropy (or environmental impact) as the resource is exploited. In order to investigate the derivation of the components of the User Cost Function for any geothermal field it is necessary to create a simple model of a geothermal system.

A geothermal system consists of three elements: a heat source, a reservoir and a fluid, which transfers the heat. The heat source could be magmatic intrusion to within 5-10 kilometres of the surface at very high temperatures (more than 600°C). Alternatively, it could be the earth's normal geothermal gradient. The reservoir is a volume of hot permeable rocks from which the circulating fluids extract heat. The fluid is water as liquid or vapour depending on its temperature and pressure. Fluid convection occurs as heated fluid of lower density rises in the geothermal system and is replaced by cooler fluid from the surface at the edges of the system. On this basis, a simple model of a geothermal system for electricity generation is modelled in Figure 8.1. In this model, there is a continuous flow of heat, H, from the geothermal source which has accumulated a quantity of heat, Q, in the geothermal reservoir. Wells have been drilled into this reservoir to provide steam for power plants which operate at a thermal efficiency, E, and have a total electricity output, P.

Figure 8.1 Simple Model of a Geothermal System.



$H =$ total natural heat flow through the geothermal reservoir (J/s)

$Q =$ total heat contained in the geothermal reservoir (J)

$P =$ total electrical power output of geothermal power plants (W)

$E =$ thermal efficiency of geothermal power plants (%)

8.2.1 Depletion Cost Component

The cost which would seem to be most directly associated with the depletion component of the User Cost Function is that of discovering and proving any given resource. This exploration cost is often not taken into account because it can be supported by subsidies and government funding which is not reflected in the actual price of the resource to eventual consumers. Hence, the cost, which must be spread over the total amount of the resource as it is exploited or depleted, is not taken into account within the normal market transaction. As such it is an example of market failure which, as defined previously in Chapter 7, is part of the User Cost Function of any resource.

The undiscounted unit cost of discovering and proving (exploration) a geothermal reservoir can be expressed as follows:

$$C_d = \frac{3.6 \times 10^6 \times K}{P \times t_u} \quad (\$/\text{kWh}) \qquad \text{(Equation 8.1)}$$

Where:

$C_d =$ undiscounted unit cost of discovering and proving the geothermal reservoir (\$/kWh);

$K =$ total cost of discovering and proving the geothermal reservoir (\$);

$P =$ total electrical power output of geothermal power plants (W);

$t_u =$ utilisation time of the geothermal reservoir (s)

The total electrical power output from the geothermal reservoir depends on the utilisation strategy and can be related to the rate of consumption of heat from the geothermal reservoir in the following way:

$$r_c = \frac{P}{E} \times 100 \quad \text{(W)} \qquad \text{(Equation 8.2)}$$

Where $r_c =$ rate of consumption of heat from the geothermal reservoir (J/s)

The rate of supply of heat from the geothermal reservoir is governed by the continuous heat flow from the geothermal source and the heat stored in the reservoir given by:

$$r_s = \frac{Q}{t_u} + H \quad (W) \qquad \text{(Equation 8.3)}$$

where:

r_s = rate of supply of heat from the geothermal reservoir (J/s);

Q = total heat contained in the geothermal reservoir (J);

H = total natural heat flow through the geothermal reservoir (J/s).

Depending on how the rate of consumption is chosen relative to the rate of supply, Equations 8.1 to 8.3 can be used to determine the utilisation time and the undiscounted unit exploration cost for the geothermal reservoir (or depletion component of the User Cost Function) for any given value of the total electrical power output of geothermal power plants.

If $r_c = r_s$, then $\frac{P}{E} \times 100 = \frac{Q}{t_u} + H$

So that: $$P = \frac{E}{100} \left(\frac{Q}{t_u} + H\right) \qquad \text{(Equation 8.4)}$$

and since $t_u = \infty$, then $$P = \frac{E \times H}{100} \qquad \text{(Equation 8.5)}$$

and $C_d = 0$ (Equation 8.6)

From Equation 8.4 it is possible to possible to determine the rate of exploitation of the geothermal field which will make it a renewable resource. Careful management of the field is necessary to ensure that this rate of exploitation is not exceeded. Exploitation of the resource at a greater rate than this will mean the geothermal reservoir is a non-renewable stock.

If $r_c > r_s$, then the utilisation time for the resource is given by:

$$t_u = \frac{E \times Q}{100 \times \left(P - \frac{E \times H}{100}\right)} \quad \text{(s)} \qquad \text{(Equation 8.7)}$$

and the unit cost of discovery is given by:

$$C_d = \frac{3.6 \times 10^8 \times K}{P \times E \times Q} \times \left(P - \frac{E \times H}{100}\right) \ (\$ / kWh) \qquad \text{(Equation 8.8)}$$

Equation 8.8 provides the means of determining the utilisation time of the natural resource (how long the geothermal reservoir will last) if the rate of consumption is greater than the rate of supply.

The application of Equations 8.1 to 8.8 for the derivation of the depletion component of the User Cost Function can be demonstrated using data obtained for the Geysers geothermal field in California, USA. This field was chosen as a basis for the case study because it is long-established, well-researched and has extensive published data available in English. Geophysical data have been used to evaluate the heat sources in the Geysers field (Stanley and Blakely, 1995). This suggested that the producing portion of the Geysers field cover a plan area which is approximately 22 km long by 7 km wide, giving a total plan area of 1.54×10^8 m^2. Geophysical measurements show that the unit rate of heat flow within the boundaries of this area is 0.336 W/m^2, indicating a total natural heat flow through the geothermal reservoir, H, of 5.2×10^7 J/s. A more recent analysis of the magma-hydrothermal history of the Geysers field (Norton and Hulen, 2001) estimates a plan area for the steam reservoir of approximately 1.0×10^8 m^2 and an average unit rate of heat flow of about 0.350 W/m^2. This results in a total natural heat flow through the geothermal reservoir, H, of 3.5×10^7 J/s. Due to the more recent data incorporated into this analysis, this estimate seems to be the most appropriate for use in this case study.

The geothermal reservoir in the Geysers field is located in a formation referred to as the felsite zone. This zone is roughly cylindrical with an approximate radius of 3.25 km and length of 22 km (Stanley and Blakely, 1995). This suggests a total volume for the reservoir of 7.3×10^{11} m^3. The amount of steam contained in the geothermal reservoir depends on the porosity of the rock. The average porosity of the felsite zone has been measured as 0.02 (Persoff and Hulen, 1999) so that the total quantity of steam in the Geysers field is estimated to be 1.46×10^{10} m^3. Since the average temperature of the Geysers field is 240°C (Stanley and Blakely, 1995) and the steam pressure is 3.3×10^6 Pa (Allis and Shook, 1999), standard tables give a saturated liquid density of 814 kg/m^3 and an enthalpy of 1.038×10^6 J/kg (Connel, 2003). This gives the total quantity of heat contained in the geothermal reservoir, Q, of 1.23×10^{19} J. This basic evaluation seems to under-estimate the total heat in the Geysers field when compared with other studies which range from 4.60×10^{19} J based on a steam reservoir volume of 9.0×10^{10} m^3 (Williams, 1992), and 5.90×10^9 J based on a steam reservoir volume of 1.0×10^{11} m^3 (Norton and Hulen, 2001). Assuming an average of this range gives a total quantity of heat contained in the geothermal reservoir, Q, of 5.25×10^{19} J for use in this case study.

Due to the nature of the heat source, the thermal efficiencies of geothermal power plants are often not stated. However, it is possible to estimate a typical value for the thermal efficiency of a geothermal power plant in the Geysers field. Although the temperature of the steam in the reservoir is 240°C (Stanley and Blakely, 1995), losses during extraction and collection reduce the inlet temperature of the steam in the condensing dry steam power plants in the Geysers field to between 169°C and 179°C (Mortimer, 1985). Assuming an average inlet temperature of 174°C and a condensing temperature of 30°C gives an estimated thermal efficiency of 32% based on the application of the Second Law of Thermodynamics to the Carnot cycle (Mandl, 1971). Since this is an idealised estimate and because some electrical losses will occur due to the need to remove non-condensible gases within the geothermal steam, an approximate value for the thermal efficiency of 30% is used in this case study.

Estimates for exploration costs of the Geysers geothermal field are difficult to establish. The various power plants on the field have been developed over a long period of time since 1962 and have at various times been subsidised by the state and federal governments. The World Bank estimates that exploration costs for a plant size of greater than 30 MW are between \$100 and \$200 per kW installed capacity for a high quality resource of greater than 100 °C (World Bank, 2003). Average plant size in the Geysers field is 71.43 MW (Ballantyne, 1991)). This gives exploration costs of between \$7,143,000 and \$14,286,000 per power plant. The mid-point of this range is \$10,714,500. The total number of power plants in the field in 1991 was 29, giving a total exploration cost of 29 x \$10,714,500 = \$310,720,500. This figure is likely to be a considerable underestimate, however, because since the 1960's several plants have ceased production and their exploration costs must also be considered and so an approximate figure for total exploration costs of \$500,000,000 would seem appropriate.

Using these figures for the Geysers geothermal field:

if $r_c \leq r_s$ $\quad$ $P = 1.05 \times 10^7$ J/s $= 1.05 \times 10^7$ W = 10.5 MW;

if $r_c > r_s$ and $P = 5 \times 10^7$ W , t_u = 12,644 years , $C_d = 9 \times 10^{-6}$ \$/kWh;

if $K = \$500 \times 10^6$, then:

Table 8.1 Variables for a Simple Model of the Geysers Geothermal Reservoir

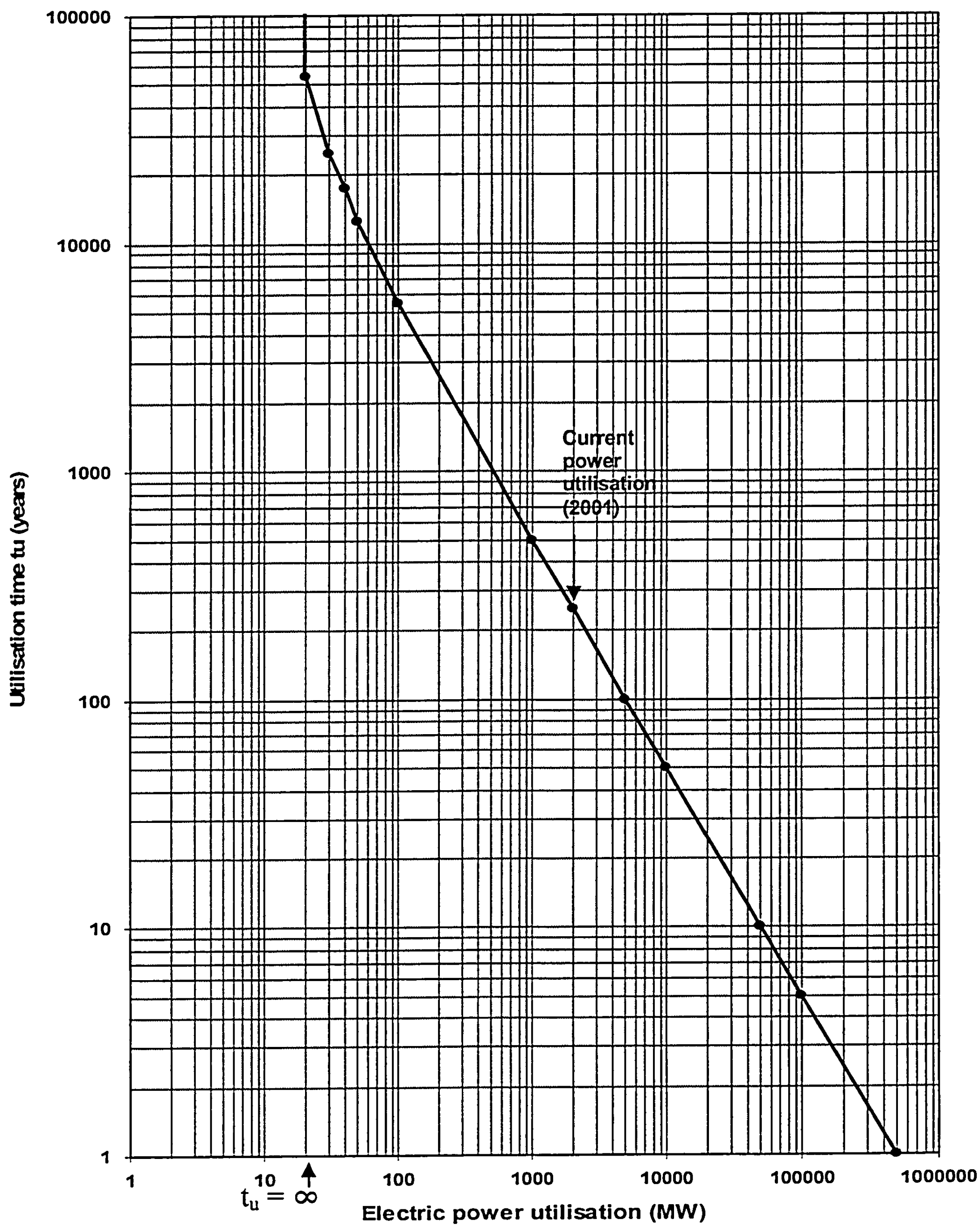
P (W)	(P- $\frac{E \times H}{100}$) (W)	t_u (s)	t_u (a)	C_d (C/kWh)
1.05×10^7 (10.5 MW)	0	∞	∞	0
5×10^7 (50 MW)	3.95×10^7	3.987×10^{11}	12,644	0.009
1×10^8 (100 MW)	8.95×10^7	1.760×10^{11}	5,580	0.010
1×10^9 (1000 MW)	9.895×10^8	1.592×10^{10}	505	0.013
2×10^9 (2000 MW)*	1.985×10^9	7.917×10^9	251	0.014
5×10^9 (5000 MW)	4.9895×10^9	3.157×10^9	100	0.014
1×10^{10} (10,000 MW)	9.9895×10^9	1.577×10^9	50	0.014
5×10^{10} (50,000 MW)	4.99895×10^{10}	3.151×10^8	10	0.014
1×10^{11} (100,000 MW)	9.99895×10^{10}	1.575×10^8	5	0.014
5×10^{11} (500,000 MW)	4.999895×10^{11}	3.150×10^7	1	0.014

*2001 capacity

The relationship between electric power utilisation and the utilisation time of the geothermal reservoir t_u is clear from these calculations. At a low rate of electric power production (<10.5 MW) t_u is infinite because $r_c < r_s$. At 10.5 MW $r_c = r_s$ and $t_u = \infty$. As the rate of electric power production from the geothermal reservoir increases, the utilisation time shortens because $r_c > r_s$: at 50MW it is 12,644 years, and at 50,000 MW it is just 10 years. At the 2001 rate of electric power production (2000MW) the utilisation time of the geothermal reservoir is 251 years. The relationship between electric power utilisation and utilisation time is shown in Figure 8.2. It can be seen from Figure 8.2 that at a rate of electric power utilisation of 10.5

MW, the utilisation time becomes infinity and the geothermal reservoir becomes a renewable resource. At electric power utilisation rates of more than 10.5 MW, however, where $r_c > r_s$, the trade off between electric power utilisation and utilisation time becomes linear.

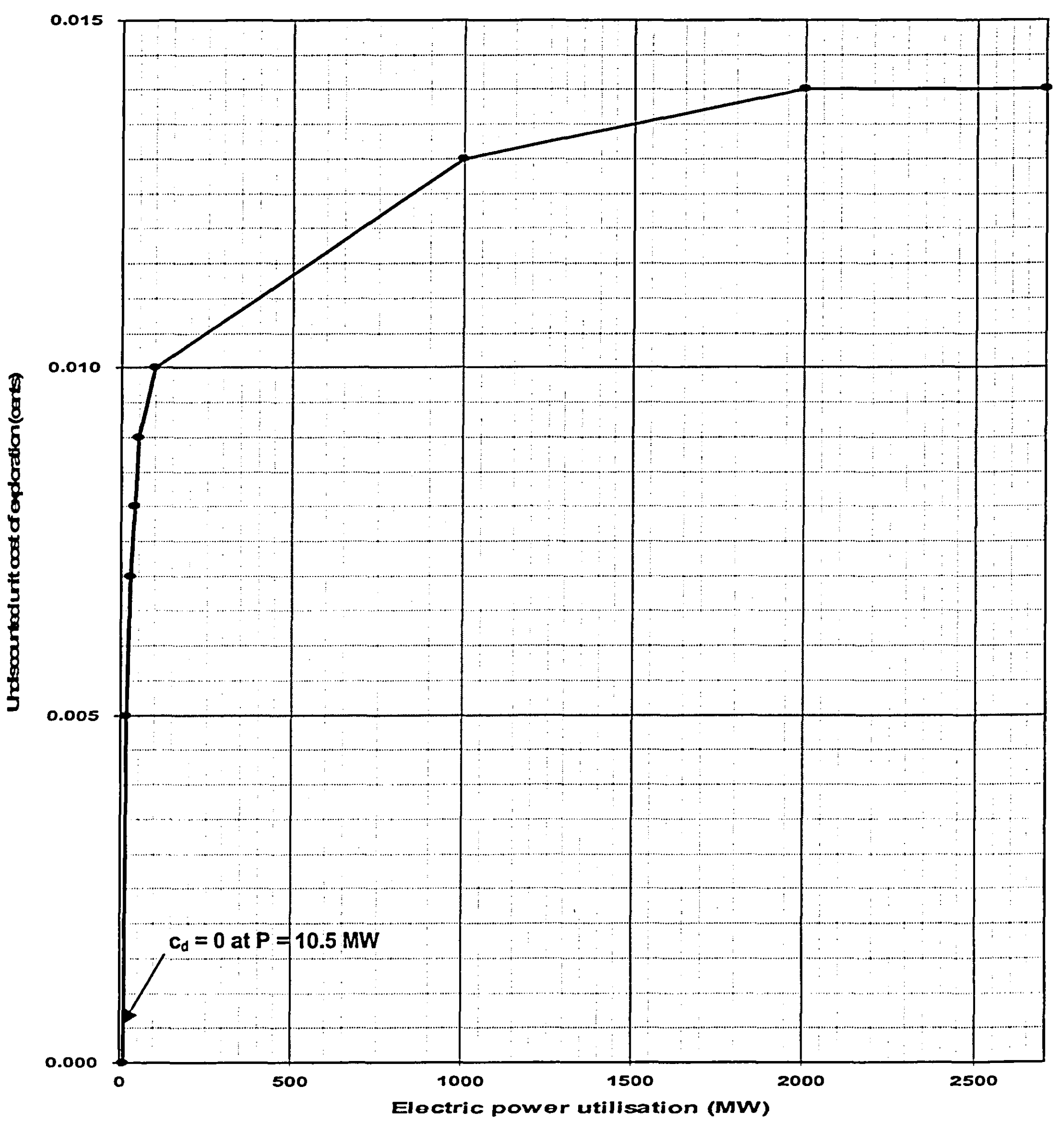
Figure 8.2 Relationship Between Electric Power Utilisation and Utilisation Time for a Simple Model of the Geysers Geothermal Reservoir



The linear trade-off between electric power output and utilisation time is clearly shown in Figure 8.2. At a power utilisation rate of 10.5 MW or less, utilisation time becomes infinite because $r_c \leq r_s$.

The relationship between the undiscounted unit cost of exploration and utilisation time is shown in Figure 8.3. It is zero at 10.5 MW because the exploration costs are spread across an infinite output ($r_c \leq r_s$ and so the geothermal reservoir is a renewable resource). As electric power utilisation increases and the geothermal resource becomes non-renewable, undiscounted unit costs of exploration rise steeply until the electric power utilisation reaches about 100 MW, thereafter flattening out to a constant value of 0.014 cents per kWh at an electric power utilisation of about 2000 MW.

Figure 8.3 Relationship Between the Undiscounted Unit Cost of Exploration and Utilisation Time for a Simple Model of the Geysers Geothermal Reservoir



The discounted unit cost of exploration can be related to the undiscounted unit cost of exploration through the discount factor, R, as follows:

$C_d' = R.Cd$ Equation 8.9

where $R = \dfrac{r(1+r)^{tu}}{(1+r)^{tu} - 1}$

r = fractional discount rate = 0.10; t_u = utilisation time (a)

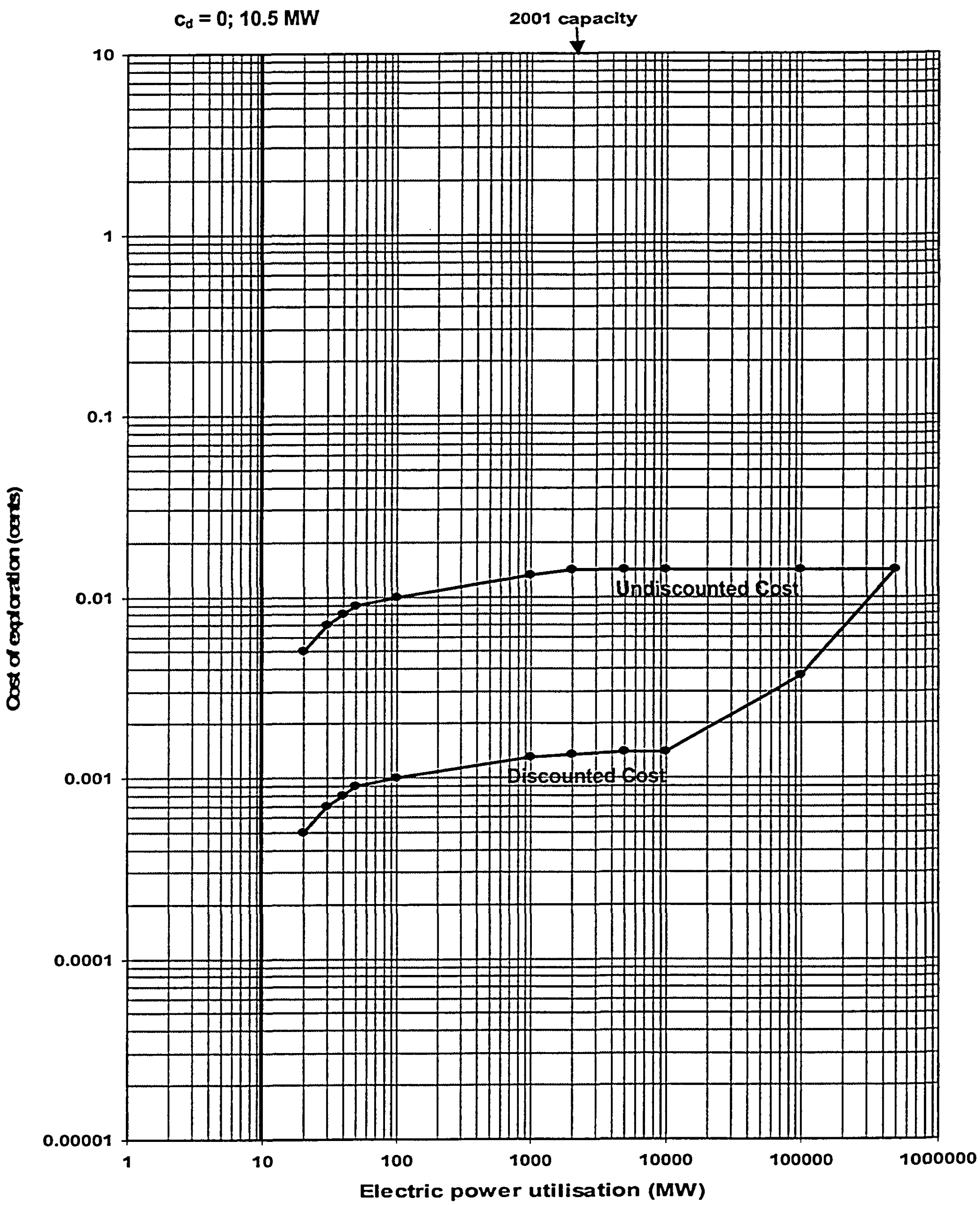
The relationship between the discounted unit cost of exploration (C_d') and electric power utilisation is shown in Table 8.2 and Figure 8.4.

Table 8.2 Relationship Between Discounted Unit Cost of Exploration and Electric Power Utilisation for a Simple Model of the Geysers Geothermal Field

P (W)	t_u (a)	R	C_d' (c / kWh)
1.05×10^7	∞	-	0
2.0×10^7	52,571	0.1	0.0005
3.0×10^7	25,612	0.1	0.0007
4.0×10^7	16,930	0.1	0.0008
5.0×10^7	12,644	0.1	0.0009
1.0×10^8	5,580	0.1	0.0010
1.0×10^9	505	0.1	0.0013
2.0×10^9	251	0.1	0.0014
5.0×10^9	100	0.1	0.0014
1.0×10^{10}	50	0.1	0.0014
1.0×10^{11}	5	0.26	0.0037
5.0×10^{11}	1	1.10	0.015

The discounted unit cost of exploration is zero at the sustainable rate of electric power production of 10.5 MW. As the rate of electric power production increases, so too do discounted unit costs of exploration, fairly steeply at first, then levelling off at electric power utilisation ranging between 2000 MW and 10000 MW and thereafter increasing to 0.015 cents per kWh. This can be compared with the current production cost of electric power from the Geysers geothermal reservoir of 4-8 cents per kWh. At current rates of production, the undiscounted cost of exploration is small, but the discounted cost is even smaller and it is unsurprising that depletion costs are not taken into account. Exploration costs are not significant here because the Geysers geothermal reservoir is such a large resource, but as the best resources are used they may become significant for smaller resources.

Figure 8.4 Relationship Between Discounted Unit Cost of Exploration and Electric Power Utilisation for a Simple Model of the Geysers Geothermal Field



Figures 8.3 and 8.4 are simplified due to the finite number of data points included - otherwise the curves would be smoother.

This proposition could be tested by further work using "idealised" geothermal fields. Further work could also be done to investigate the situation for depleteable resources such as coal, oil and natural gas and this will be addressed in the recommendations in Chapter 10.

8.2.2 Environmental Cost Component

Compared with electric power production from fossil fuel power plants, geothermal energy is relatively environmentally benign. It does have environmental impacts, however, which are normally in proportion to the scale of such exploitation (Lunis and Breckenridge, 1991). The external environmental cost of these impacts is represented in the User Cost Function by the term $\Delta s/t_u$. This rate of change of entropy is the relative change of temperature or concentration of the resource with time. If exploitation of the resource increases the rate of change of entropy over time relative to this change when the resource dissipates naturally, there will be adverse environmental consequences.

The cost of these environmental impacts is generally unpriced or external to the market. Cost benefit analysis is, therefore, necessary to estimate these costs and a variety of techniques, which were described in Chapter 2, are available to do this. In order to formulate the User Cost Function for environmental impacts of geothermal energy it is necessary to identify these impacts.

The environmental impact of geothermal energy production begins with the drilling phase. Access roads need to be constructed as does a drilling pad which will cover an area ranging from 300-500m^2 for a small rig of depth up to 700m, and 1200-1500m^2 for a depth of up to 2000m (Dickson and Fanelli, 2003). Surface morphology will be affected and there could be damage to plants and wildlife. In addition, undesirable gases may be discharged into the atmosphere and blowouts can pollute water courses. When drilling is completed these environmental impacts should cease. Construction of pipelines and utilisation plants will have similar impacts to the drilling phase, with additional impact on the landscape scenery (possibly including the elimination of hot springs and geysers which were tourist attractions).

During plant operation, if geothermal fluids are discharged into the environment, considerable damage can be done by the gases they contain which include carbon dioxide, hydrogen sulphide, ammonia, methane and trace amounts of other gases. In addition, dissolved substances in geothermal fluids, such as sodium chloride, boron, mercury and arsenic can lead to environmental damage. Thermal damage can result if the temperature of released fluids exceeds that of the natural environment and the extent of this damage can be difficult to assess because the plant and animal organisms that are most sensitive to temperature variations may underpin whole ecosystems. Most geothermal power plants attempt to keep the working geothermal fluids within a closed system that returns them to the original reservoir after useful energy has been extracted. Nevertheless, the process of venting steam that has reached excessive pressures and periodic equipment failures result in small amounts of geothermal fluids reaching the surface environment. These fluids are often acidic and can damage aquatic ecosystems and contaminate drinking water.

Air pollution, particularly from hydrogen sulphide, for which people have a low tolerance level can be ameliorated by various processes. Subsidence of the land surface can occur if large quantities of geothermal fluids are extracted, and small scale seismic events may be triggered. Finally, noise pollution can occur from the power plant, but this is unlikely to be a major problem.

The main environmental impacts of geothermal energy production can be summarised as follows:

- Carbon dioxide emissions
- Hydrogen sulphide emissions
- Ammonia emissions
- Methane emissions
- Geothermal fluid damage from dissolved substances
- Thermal damage from geothermal fluids

The environmental impact of carbon dioxide emissions from geothermal power plants is probably the most significant of these impacts and provide an important example of the derivation of the environmental cost component of the User Cost Function.

In Chapter 5 it was shown that entropy change might be determined by measuring the proportionate change in concentration of matter as a resource consisting of matter is used (see Equation 5.6).

If,

C_1 = concentration of carbon dioxide in the air due to natural emissions from an unutilised geothermal reservoir (%)

C_2 = concentration of carbon dioxide in the air from a utilised geothermal reservoir (%)

and, U_e = environmental cost component of the User Cost Function due to carbon dioxide emissions ($).

Then, $U_e \alpha \dfrac{(C_2 - C_1)}{C_1}$ Equation 8.10

$\dfrac{(C_2 - C_1)}{C_1}$ is the relative change in concentration of carbon dioxide in the air over the utilisation time of the geothermal reservoir.

In practice, the environmental cost component of the User Cost Function will depend on the actual change in the amount of carbon dioxide in the air. If Q_{c1} is the original amount of carbon dioxide in the air due to natural emissions from an unutilised geothermal reservoir, then the actual amount of carbon dioxide in the air from a utilised geothermal reservoir is:

$\dfrac{(C_2 - C_1)}{C_1} \times Q_{c1}$ Equation 8.11

If Q_a is the amount of air affected by carbon dioxide emissions, then by definition,

$C_1 = \dfrac{Q_{c1}}{Q_a} \times 100\%$ Equation 8.12

Substituting this gives $(C_2 - C_1) \times \dfrac{Q_{c1}}{100} \times \dfrac{Q_a}{Q_{c1}}$

$= \dfrac{(C_2 - C_1)}{100} \times Q_a$ Equation 8.13

If $C_2 >> C_1$ then $\dfrac{(C_2 - C_1)}{100} \times Q_a$ becomes $\dfrac{C_2 \times Q_a}{100}$ Equation 8.14

By similarity, $U_e \propto \frac{(C_2 - C_1)}{C_1}$ becomes $U_e \propto \frac{C_2 \times Q_a}{100}$ Equation 8.15

If q_{c2} equals the carbon dioxide emissions per unit of electricity generated by the geothermal field, then

$$q_{c2} = \frac{C_2 \times Q_a}{100 \times P \times t_u} \times 1000 \times 60 \times 60 \quad (g\ CO_2/kWh) \qquad \text{Equation 8.16}$$

$$\text{Or, } q_{c2} = \frac{3.6 \times 10^6}{P \times t_u} \times \frac{(C_2 \times Q_a)}{100} \quad (g\ CO_2/kWh) \qquad \text{Equation 8.17}$$

where, P = total electric power output of the geothermal reservoir (W)

t_u = utilisation time of the geothermal reservoir (s)

$$\text{Hence, } Ue = \frac{P \times tu \times q_{c2}}{3.6 \times 10^6} \qquad \text{Equation 8.18}$$

If the external cost of the environmental impact of carbon dioxide emissions is p_e ($/gCO₂), then the actual form of the environmental cost component of the User Cost Function for carbon dioxide emissions can be given as

$$p_e \times U_e = p_e \times \frac{P \times t_u \times q_{c2}}{3.6 \times 10^6} \quad (\$) \qquad \text{Equation 8.19}$$

This gives the total cost of the carbon dioxide emissions from the geothermal field. However, in order to determine the undiscounted unit costs of the environmental impact of carbon dioxide emissions from the geothermal field, C_e, total costs must be divided by electricity output,

$$C_e = \frac{p_e \times U_e}{P \times t_u} \times 3.6 \times 10^6 \quad (\$/kWh) \qquad \text{Equation 8.20}$$

Substituting for Ue gives

$$C_e = p_e \times q_{c2} \qquad (\$/kWh) \qquad \text{Equation 8.21}$$

Carbon dioxide emissions to the earth's atmosphere would be increased beyond their natural level by the use of geothermal energy to produce electricity. If left in a natural state the rate of release of carbon dioxide from the geothermal reservoir would be very slow. While this is a significantly lower amount than that of fossil fuel power plants, it will still contribute to global warming effects and this contribution must be evaluated. Impacts of global warming include sea level rise, an increase in precipitation intensity, more severe droughts and floods in some places and effects on species (Ekins and Barker, 2001). Global valuation of environmental impacts is fraught with difficulty. Cultural, social, ethical, philosophical and economic aspects of impact values vary widely both temporally and spatially, raising numerous fundamental valuation issues (Rothman, 2000). For example, even allowing for variations in national income and ability to pay, Bangladeshis may value differing economic effects differently from North Americans according to their priorities and level of information.

Estimates of total damages from carbon emissions focus primarily on high-income countries where the impacts of global warming are expected to be relatively less costly than those of the developing world. For example, Nordhaus (1994) and Cline (1992) estimate the annual costs to the USA of a 3°C warming to be \$70billion and \$75 billion respectively, or roughly 1 per cent of total USA output. According to the IPCC, however, global damages may approximate 2-3 per cent of global output with higher losses as a percentage of GDP experienced by the developing countries (IPCC, 1995). As a result, there is a large degree of uncertainty over the cost of damage per tonne of carbon equivalent. A large part of the uncertainty about the marginal costs of carbon emissions is due to the choice of discount rate (Tol,1999). The possible range of estimates of damage costs per tonne of carbon is from £30 to £120 (approximately \$45 to \$180) with the UK Department of Environment, Food and Rural Affairs suggesting £70 (\$105) per tonne as the social cost of carbon (Clarkson and Deyes, 2002). This amount represents a political perspective rather than the entire range put forward by academics which will be considered here.

The cost of carbon dioxide emissions from the Geysers field can be calculated using this information. It has been suggested that geothermal energy generally results in lower greenhouse gas emissions than fossil fuel energy production (Dickson and Fanelli, 2003). Fossil fuel energy production results in 1042 grams/kWh of carbon dioxide emissions from coal fired plants. Carbon dioxide emissions from the Geysers elecric power production can be calculated from data on the range of non-condensible gas content which is <0.3% to 1% (Mortimer, 1985). Carbon dioxide is approximately 70 % of the non-condensible gases and the estimated steam consumption rate for condensing plants is approximately 8 kg/hr/kWnet = 8kg/kWh. This gives an apparent upper limit to carbon dioxide emissions of 56 grams CO_2/kWh

Accepting a lower estimate figure for Geysers carbon dioxide emissions of 0.48g/kWh from the latest generation of Geysers power plants (Reed and Renner, 1995) gives a full range of 0.48g/kWh to 56g/kWh. Using the range of emissions 0.48 - 56 grams per kWh and a damage cost per tonne of \$45-180 results in \$45-180 x 10^{-6} per gram of carbon dioxide. Multiplying this by the range of emissions gives 45-180 x 10^{-6} x 0.48-56 \$/kWh = 0.0000216 cents per kWh to 0.01008 cents per kWh which is a range of at least 2 orders of magnitude. Hence, even with a well-researched pollutant such as carbon dioxide, there is a considerable degree of uncertainty with the user cost component of environmental impact. It can be seen that this is partly due to the monetisation process and continuing disagreement over the price/cost of the impact of carbon dioxide emissions. Obviously, this will have to be reduced before more reliable estimates of the user cost component of this environmental impact can be derived.

A similar process of derivation to the one used here for carbon dioxide can be followed for other environmental impacts. There will, however, be even more uncertainty over the price/cost of these impacts as they are less well-researched than those of carbon dioxide. The analysis here demonstrates the derivation and application of a process to cost/price the environmental impact of carbon dioxide emissions, but it also shows that agreed values of the prices of specific environmental impacts are needed to obtain the complete environmental cost component of the User Cost Function. Although this is beyond the scope of current work, this suggests significant recommendations for further work.

9 POLICIES FOR THE SUSTAINABLE MANAGEMENT OF RESOURCES

9.1 Sustainable Management of Resources

Natural resource policies play a significant part in the wider debate about what constitutes 'sustainable development'. Resource constraints on growth and development have been analysed by various authors (for example, Hotelling, 1931; Meadows et al, 1972; Daly, 1991). The new environmentalism which arose in the 1960's recognised resource constraints and the limits to the carrying capacity of the environment (Boulding, 1966). This is, in fact, a recognition that the consequences of the physical characteristics of natural resources must be accommodated in the economic process. Additionally, the scale and rate of throughput of matter and/or energy are subject to an entropy constraint because increasing the rate of entropy change in the environment means increasing pollution problems. The environmental economic problem is that the market is unable to recognise this constraint and so unrestricted growth may be 'unsustainable'. Indeed, there is no agreement about what exactly constitutes sustainable development, or if it is, in fact, attainable. There are numerous published definitions of the term, including more than 50 in one source (Pezzey, 1989). Hence, only a brief review of the salient points of the sustainability debate will be considered here.

Accepting the most widely used definition of sustainable development, expressed in the so-called Brundtland Report, which is: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987), the central concerns are of intragenerational and intergenerational equity. Intragenerational equity means fairness to all members of the current generation and encompasses ideals such as the elimination of world poverty and hunger, and ensuring that pollution does not damage the well-being of current populations. Intergenerational equity means fairness to members of future generations by ensuring that activities undertaken in the present do not compromise their living standards. The principle of intergenerational equity is a key feature of sustainability, but it may be compromised by the way in which economists treat the future. Economic analysis assumes that a given unit of benefit or cost matters more if it is experienced now than if it occurs in the future (Pearce and Turner, 1990). One reason for this is that people have impatience or 'time preference' for benefits in the present, rather than at some future date. Another reason is that capital is productive and so £100's worth of resources now will generate more than £100's worth of resources in the future. In order to take into account time preference and the productivity of capital, economists 'discount' future costs and benefits so that their value in the present is lower. One important result of discounting is to discriminate against future generations because their costs and benefits are reduced in value relative to those in the present. This has implications for intergenerational equity. Consequently, discounting is considered in more detail in Section 9.3.

In terms of natural resources, sustainability requires that successive generations face no greater constraints on the use of natural resources than are experienced by the current generation. This may seem impossible given that some natural resources are effectively non-renewable and thus depleted with use. If any of these resources are used by the present generation, then they are unavailable for future generations. The problem is to maintain productive or consumption potential over time, and literature on this has concentrated on arguments about whether natural capital (of which natural resources are an important part) can be substituted by man-made assets to leave a constant capital stock (Solow, 1986,1991; Costanza and Daly, 1992). In order to ensure that the productive capacity of future generations is not impaired by depletion of natural resources, a strategy for sustainable use of resources is required.

It has been demonstrated in Chapters 5 and 6 that there are a number of factors which influence natural resource exploitation. In addition to depletion, there is the pollution caused by use of resources in economic processes which is at least equally important. These factors influence the true economic cost (the user cost) of natural resources. The user cost of all natural resources (not just NRR) depends on the rate of change of entropy as they are used, and their rate of consumption relative to rate of supply. The User Cost Function derived in Chapter 7 incorporates the most important problems of environmental economics: depletion of natural resources and pollution of the environment. Reducing user costs would reduce depletion and reduce pollution. Since all natural resources (not just non-renewables) have user costs, policy for sustainable management of resources should aim to recognise and incorporate user costs of natural resource use in the economy. Policies for sustainable management of resources should mitigate against exploitation of those natural resources with the highest user costs and should promote exploitation of those resources with the lowest user costs. If these objectives can be achieved, the twin environmental economics problems of depletion and pollution can be addressed in a coherent and logical manner.

It has been argued that improvements must be made in the extraction and use of non-renewable resources so that the economically efficient level of stocks is maintained as a constant (Bowers, 1997). Furthermore, it has been proposed that this condition can be met by technical progress in the following four areas:

- improvements in efficiency in primary use;
- efficiency in recycling;
- efficiency in extraction;
- replacement of non-renewable resources by renewable alternatives.

Each of these would reduce user costs of natural resource exploitation. Improvements in efficiency in primary use would reduce the rate of consumption relative to rate of supply, and is likely to reduce the rate of change of entropy because more goods or services or energy would be extracted from each unit of resource, thereby reducing overall consumption of primary resources (although the final effect will be circumstance specific). A United Kingdom government report recommended improving resource productivity to help deliver sustainable prosperity (UK Government Performance and Innovation Unit, 2001). Greater efficiency in recycling and extraction would have the same impacts and would also, therefore, reduce overall user costs. Replacement of non-renewables by renewable alternatives, is likely to reduce user costs in terms of both rate of consumption relative to rate of supply, and in terms of rate of change of entropy, but care must be exercised to ensure that the renewable replacement is not over exploited, to the point where its continuing availability is threatened. The general presumption by Bowers that replacement of non-renewable resources by renewable alternatives is desirable, does not recognise the difference between CNR renewables and PRR renewables. It is possible that the user costs of a PRR are greater than the user costs of the NRR being replaced, in which case the change would not lead to more sustainable natural resource use. Replacement of NRR by CNR would, however, lead to a more sustainable resource position.

Policy for sustainable management of resources should, therefore, promote these four areas, in effect extending the life of NRR by implementing the first three conditions, in order to buy time to achieve the replacement of NRR by CNR. This suggests a basis for policy-making in relation to the depletion of natural resources, that is, a depletion policy.

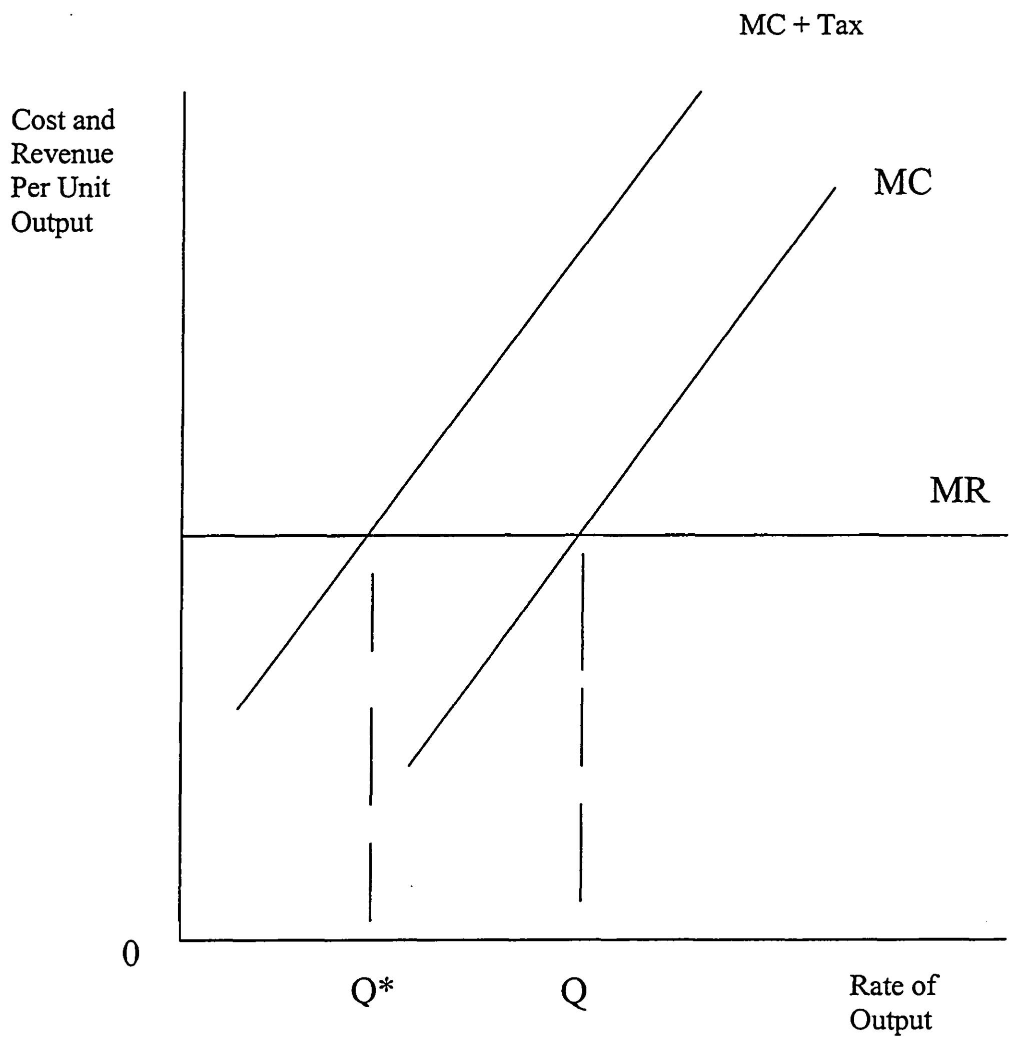
9.2 Existing Natural Resource Policies

A variety of interventions by governments around the world apply to the use of natural resources. Indeed, free markets in natural resources must be considered to be the exception. Intervention takes a multitude of different forms. Among them are interest rates, taxation, subsidies, anti-trust legislation and pollution controls. Natural resource policies are based on such forms of intervention and they can be considered for each of the different types of resource identified in Chapter 7 in turn. For NRR, such as the products of the mining, petroleum and natural gas industries, the fact that they can be extracted only once influences policies which govern their management. Governments often recognise the short-term nature of the benefits of such resources and implement policies to try to maximise or prolong them. Even where governments do not deliberately intervene in the production and consumption decisions for such resources, they have an influence via their interest rate policy. This is because the economics of extraction must take forgone future net benefits into account. The opportunity cost or user cost of current extraction includes the impact on future profits. For NRR production, the revenue from current extraction should be high enough to cover the marginal extraction cost as well as the marginal user cost. This is known as the Hotelling Principle (Gray,1914; Hotelling, 1931). For extraction to be justified, the market price of the resource net of extraction cost must rise in line with the market rate of interest. If prices are rising at a rate which is less than the rate of interest, then it is optimal for resource owners to extract all of the resource in the present and invest the proceeds. If resource prices are rising at a rate which is greater than the rate of interest, then it is optimal to leave the resource in the ground. For optimal extraction/depletion, therefore, it is necessary for resource prices to rise at a rate equal to the rate of interest. Government policies which affect interest rates thus affect extraction rates for NRR.

Changes in interest rates will affect the price-output path of an extractive industry because the decision to extract in the present and invest the proceeds in interest-bearing securities will be affected. A higher interest rate means higher returns on alternative projects to the NRR project and, to compensate, production must be shifted to the present. The proceeds can then be invested at the higher interest rate and so time to depletion of the resource is shortened. If the interest rate falls, the stock of the resource is now a more attractive asset and current production will be cut so that the time to depletion will be extended. In practice, governments' or central banks' changes to interest rates are extremely unlikely to be made in order to influence the rate of consumption of natural resources (although this could be the case for a country which was heavily dependent on natural resources for economic growth). They are much more likely to be made in order to influence economic activity or inflation in an economy. Moreover, interest rates can go up and down considerably in a short space of time and it is unrealistic to expect an automatic response by resource owners to each change (Kula, 1994). As a result the impact of interest rate policy on natural resource exploitation becomes arbitrary and without purpose.

Taxation can affect utilisation policies of NRR industries in many different ways. In most cases, taxes raise costs of extractive industries and this will reduce output. This is illustrated in Figure 9.1. In Figure 9.1, output is set at Q where profits are maximised because marginal cost (MC) equals marginal revenue (MR). The imposition of a tax per unit of the resource extracted raises marginal costs to MC+Tax, and the profit-maximising output falls to Q*. Different types of tax, other than a unit tax, will shift the MC curve in different ways, but the basic principle remains the same – that costs will be raised and the profit-maximising output will fall.

Figure 9.1 <u>The Effects of a Rise in Per Unit Taxes on Output</u>

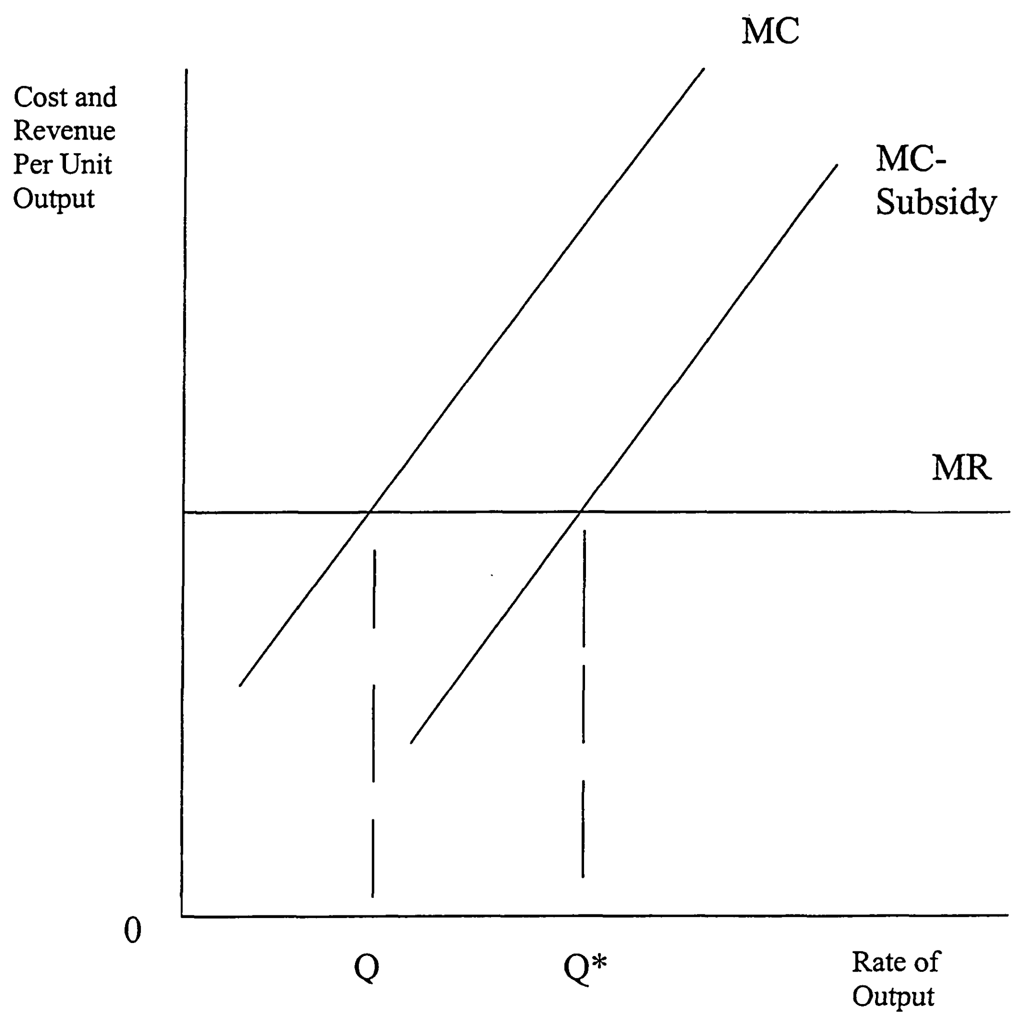


There are a variety of different taxes which are applied to NRR, including excise duties, ad valorem taxes, profits taxes, severance taxes and property taxes. Excise duties are taxes per unit of output and have the effect described in Figure 9.1 above. They may also encourage resource owners to defer production/extraction so that tax liabilities can be postponed. Ad valorem taxes or royalties are applied to resources in relation to their prices. They have a similar effect to that of excise duties, but the temptation to defer tax liabilities will not be as strong, because delaying extraction will raise future prices leading to a greater tax liability. In terms of Figure 9.1, the gap between the MC curve and the MC+Tax curve widens, so that as the MR curve rises (with price increasing), the output fall is greater. Profits taxes or rent taxes will have no direct effect on the extraction decision of the resource owner because there is no change in the rate of extraction over time that can offset the decline in the present value of the resource resulting from the tax. The government will simply collect some of the rent or surplus, and production will continue in the same way as before the tax. However, there may be indirect effects of such taxes which ultimately result in a reduction in the present rate of extraction. One possible effect may be that resource owners defer production in the hope that a more favourable political regime is elected. Profits taxes may have additional effects on development of new mines/oil fields in that removal of economic rent (surplus) by taxation will discourage resource owners from new developments. Obviously, such a situation will increase time to depletion of the resource.

Severance taxes are levied in many parts of the United States of America (USA). They are levied on minerals as they are extracted. They have the advantage that, as well as redirecting investment into less resource-consuming technologies, they promote recycling, and as a result, they reduce the rate of resource throughput. States having severance taxes argue that the revenues compensate current citizens for environmental damage caused by the extraction and compensate future generations for the loss of the resource by financing public investments (which reflects the natural capital debate mentioned in Section 9.1). Significant severance taxes would lead to a bias for resource conservation and could be used as an environmental premium to be paid to protect the interests of future generations. Severance taxes are generally very low, however, and not levied on all minerals (Tietenberg, 1996). For recyclable minerals, they could encourage recycling by raising the costs of primary production, but they are not levied in all States and may only shift primary production from one State to another (or even to other countries). Property taxes are an exception because they have different effects to other forms of tax in that they may shorten time to depletion. This is because they are normally applied in relation to the value of the property held, and since this value increases over time at the market rate of interest, an annual tax on resource value will increase tax paid, the longer the resource is owned. To avoid paying this tax in future periods, the current rate of extraction could be increased. Most economies rely on income taxes, sales taxes and profits taxes to finance government activity. Often resource use is either not taxed at all or taxed at a very low rate with the consequence that the relative price of resources relative to wages is lower than it otherwise would be (Young, 1992). As a result of the general failure to tax resources at the point of use or extraction, there is an incentive to develop resource-consuming, rather than resource-saving technologies.

Subsidies to NRR have the effect of increasing current production and decreasing time to depletion. Such subsidies can take various forms, including tax-breaks to allow for the fact that the resource is being used up (depletion allowances, which are commonly used in the oil industry of the USA), the payment of transport costs to overseas markets by governments in need of foreign currency for exports and favourable tax treatment of developers of mines/oil fields in order to encourage them to provide the necessary investment and technology for exploitation. The general effect of subsidies is illustrated in Figure 9.2. In Figure 9.2 marginal costs are reduced by the amount of the subsidy per unit of output and as a consequence the profit-maximising output, where marginal cost equals marginal revenue, is increased from Q to Q*. As well as increasing current extraction rates and shortening times to depletion, subsidies have distorting effects in the market, one of which may be to suppress production in other parts of the world, preventing developing countries from improving resource management practices. This may infringe the principle of intragenerational equity. A necessary condition for sustainable resource use and investment is that no resource use or development should be subsidised (Young, 1992).

Figure 9.2 The Effects of a Subsidy on Output



Anti-trust legislation to promote competition may have the effect of increasing rates of consumption of natural resources. This is because monopolists tend to restrict output and raise prices compared to those that would prevail under competition. The effect of monopoly is, then, to increase the life of the resource and aid conservation (although they may have undesirable effects in other, non-resource areas). Pollution controls are likely to reduce the rate of consumption of natural resources. Government standard setting to reduce pollution requires firms to reduce emissions of pollutants. This may be possible by installing 'clean-up' technology, such as sulphur scrubbing equipment at coal-fired power stations. If such equipment is prohibitively expensive, however, then the only way to comply with the legislation (and avoid the penalties for exceeding emissions standards) may be to reduce output. This reduction in output in turn reduces the consumption of natural resources as inputs.

For PRR, there are also various government interventions in countries around the world (Jowsey, 2002). The problem for these resources is to maintain an efficient, sustainable flow by constraining the harvest strategy so that the expected long-run harvest rate is no more than the expected long-run regeneration rate. Policies for PRR, such as fish and forests, usually attempt conservation, often by trying to ameliorate the effects of over-exploitation which may arise because of open-access (Jowsey, 1998). Among the many interventions by governments (and inter-governmental agreements) are quotas on fishing catches, restrictions on exploitation of whales, fish and forests and market-based incentives to preserve the asset value of PRR, such as individual transferable quotas (which are tradeable permits to exploit, used, for example, in New Zealand fisheries and in kangaroo harvesting in New South Wales, Australia).

Where taxation is applied to PRR, the impact on resource use is essentially the same as for NRR. A tax per ton harvested is equivalent to an increase in costs and a smaller harvest will result. Site use taxes, or license fees, as applied when land is brought into forestry use, increase set up costs and will increase the interval between planting and harvesting, and less wood per unit time will be harvested (Hartwick and Olewiler, 1986). Profits taxes will not affect current production or harvesting of PRR, but, as with NRR, future developments may be affected (less planting of forests, less investment in fishing boats, etc.).

For CNR, many governments around the world have attempted to promote their use by subsidies to production or by favourable tax treatment. An example is the United Kingdom (UK) government's Non-Fossil Fuel Obligation (NFFO) which provided a subsidy paid for by the Fossil Fuel Levy (between 0.3 and 2 per cent on the price of electricity generated from fossil fuels). Originally intended to raise funds to support the nuclear power industry, these measures have also been used to subsidise 'renewables'. The NFFO has been replaced by the Renewable Energy Obligation which has set a target for commercial energy providers of 10% renewable energy production by 2010, backed up by fines for non-compliance. Despite these subsidies and regulations, production of energy from renewable sources is still very limited in the UK.

The various measures outlined here which have been used to conserve both NRR and PRR, and sometimes to promote CNR, are ad hoc measures applied to specific resources which have varying degrees of success and which do not together constitute a coherent policy for sustainable management of all resources. As outlined in Section 9.1, such a policy should mitigate against those natural resources with the highest user costs and should promote those resources with the lowest user costs in order to effectively counter the twin environmental problems of depletion and pollution which threaten sustainable development. The various interventions described above tend to be applied in response to specific circumstances, political, economic, social and environmental, with little thought being given to the overall sustainability of policy. There is, therefore, a case for a more coherent basis for policy in relation to the use of natural resources, which should rest on the application of the User Cost Function as defined previously in Equation 7.6, because this represents the true economic and environmental cost to society of natural resource use.

9.3 Future Natural Resource Policy

If a monetary value of user costs can be determined, then policies could be devised which internalise the user costs which are currently external to the market. For example, a tax could be applied in line with that value. The valuation of user costs was demonstrated in Chapter 8. Accurate measurement of the constituent parts of user costs, r_c/r_s and $\Delta s/t_u$, derived in the way demonstrated in Chapter 8, is difficult principally because of the uncertainty associated with valuation of environmental impacts. It was shown in Chapter 7 that user costs are related to regeneration time through the parameter r_c/r_s . So the longer the regeneration time the greater the user costs. In terms of regeneration time, the relative orders of magnitude between different types of natural resources would be considerable. Regeneration times for representative resources were specified in Chapter 5. CNR take up to 10^5 seconds to regenerate whereas PRR take up to 10^8 seconds to regenerate, which is one thousand times as long. Furthermore, NRR take up to 10^{13} seconds to regenerate, which is one hundred thousand times as long as PRR (Jowsey, 2001b). Orders of magnitude for user costs based linearly on regeneration times alone could result in very great differences in user costs of different resources. However, although the user cost is proportional to regeneration time, this is only part of the User Cost Function. The other part is the rate of change of entropy. It could be inferred that the rate of entropy change involved in resource use is a more important component of user costs than regeneration time, because in the past thirty years it has become apparent that pollution problems are more urgent than the problems of depletion. As a result the temptation to attach values to user costs which are related solely to regeneration times of resources has been resisted here.

The approach demonstrated in Chapter 8, where the depletion cost component of the User Cost Function is related to exploration costs, might be problematic in policy terms if such costs are not internalised or are not incorporated because of tax breaks and subsidies. Hence, an alternative (simpler) approach may be needed. It might be possible to use a surrogate for r_c/r_s if resource users such as power station operators were made to sign contracts guaranteeing the fuel supply for the life of the project. So, if a gas power station has an expected life of 30 years, contracts for the supply of gas over 30 years would have to be signed in advance. The effect of the contracts on the price of gas could then be observed and used as a surrogate for r_c/r_s. It could, of course, be argued that such regulation is in itself more sustainable than the current situation because the contracts guarantee the power supply for some time into the future, and they are likely to drive up prices of NRR relative to CNR, because there is certainty of future availability of CNR and so their 'price' (based on costs of production) would not be affected. This is still a relatively short term policy, however, if the average life of a power station is the length of time used. Such a policy would also be difficult to apply to PRR because for many of these resources the size of the stock is not known (because of the difficulties involved in finding fish, for example) and problems of stock management of PRR would lead to a great deal of uncertainty about future supplies.

Attributing monetary value to rate of change of entropy is possible as was demonstrated in the case of carbon dioxide emissions from the Geysers geothermal reservoir in Chapter 8. Using costs of pollution (external environmental costs) as a proxy for rate of change of entropy is possible, but very often such costs are not measured (it is not possible to monetise everything) and where they are measured the valuation methods of cost-benefit analysis are used because actual market values cannot be observed. Establishing a market value for the environmental impact of increased rate of entropy change is not straightforward because no market currently exists for the environmental amenity affected.

An informal order of user costs might be inferred from the natural resource classification diagram. Without ascribing a numerical scale to the boxes in this diagram, presented earlier in Chapter 7, it can be seen that CNR have the lowest user costs (their user costs are not zero, however, because they involve use of other types of resources in order to utilise them, thereby increasing the rate of entropy change). PRR which are not being consumed at a rate which is greater than their rate of supply ($r_c/r_s \leq 1$) have the next highest user costs. Next are PRR which are being consumed at a rate which is greater than their rate of supply ($r_c/r_s > 1$). Finally, NRR have the highest user costs. The magnitude of the increase in user costs from one type of resource to another is not as important as recognition of the relative differences in user costs of natural resources. Appropriate natural resource policies would recognise the increasing user costs of resources from bottom left to top right of the natural resource classification diagram. Policy for sustainable management of resources should encourage use of those resources with the lowest user costs, and discourage use of those with the highest user costs.

It is now necessary to consider how such a policy might be applied in practice. Extensions and revisions of current natural resource policies are, of course, possible. In the context of national and international energy policies, taxes could rise in line with user costs and make NRR more expensive relative to PRR, which in turn could be more expensive relative to CNR. Taxes could be applied to resources in accordance with their relative user costs. Such a taxation regime could advantage those resources with the lowest user costs. The problem of how to apply such taxes in practice is considerable, however, since the question of appropriate units is difficult. Taxes per unit resource and severance taxes would not be appropriate because of the heterogeneous nature of natural resources. Ad valorem taxes may be more appropriate because they can be applied according to the price of each natural resource. Ideally, the magnitude of the relative taxes should be in proportion to relative magnitude of user costs. Ad valorem taxes could be applied in line with the user costs of resource use, the percentage tax applied by value increasing in four steps from CNR to NRR. Profits or rent taxes could be applied to resource users in line with the user costs of the resources involved and this would be appropriate in the private sector. For projects and economic activities where profits are not made, such as those in the public sector, however, there remains a problem if the profits are not transparent. Subsidising resources or resource projects with low user costs is also possible, but the question of how much to subsidise and in what units is difficult to resolve. Subsidising by units of energy output may be appropriate for power generation schemes, as has been done with NFFO contracts. The decision on level of subsidy is difficult, however, and likely to be arbitrary, and for resource schemes which are not associated with power generation, there is no obvious mechanism for application.

At this point it is appropriate to note that investment decisions for projects are normally based on discounted cash flow analysis and discount rates are important in this. The effect of changes in interest rates on depletion of natural resources was explained in Section 9.2. Interest rates reflect the rate at which wealth can be traded across time. The existence of interest rates is the basic justification for discounting. If £100 were invested now at an annual rate of 10% it will be worth £110 in one year's time. Conversely, £110 received in one year's time is worth £100 or 110 /(1+0.1) now. The discount rate is simply the compound interest rate used in reverse. It is possible to calculate the present value of future amounts using the general formula for present value which is:

$$PV = X / (1+i)^t \qquad \text{(Equation 9.1)}$$

where PV is the present value, X is the benefit or cost to be received in year t, and i is the discount rate. Equation 9.1 shows that the present value of a given sum payable in the future will be smaller the more distant the payment date and the higher the rate of interest or discount rate. This procedure for finding present value of a future benefit or cost is known as discounting. The rationale for a positive discount rate was briefly outlined in Section 9.1. The discount rate is the opportunity cost of capital. For private industrialists, there are two possible sources of finance for a project: savings, in which case the opportunity cost is the rate of return which could be made by lending the savings; or borrowing, in which case the opportunity cost is the rate of interest to be paid on the borrowing.

There are two methodological bases for calculating the social discount rate (the discount rate that should be used by society, rather than private investors). The first is the social opportunity cost (SOC) which is related to the marginal productivity of capital which represents the opportunity cost of capital (the rate of return which society could obtain from the next best investment project). This has been taken to be in the range of 6 to 8% in the United Kingdom (Pearce and Ulph, 1995) which is in line with average rates of return in all sectors of the economy (Kula, 1994). The second method is based on people's time preference for consumption now in the form of the rate of interest necessary to induce them to save. This is the social rate of time preference (SRTP). For society, since consumption can be expected to rise over time with per capita income, an extra unit of consumption in a later period will be worth less than an extra unit of consumption in the near future. This principle is known as 'diminishing marginal utility of consumption'. Values derived for the SRTP rate tend to be lower than for the SOC rate and typically 2 to 4 % (Kula, 1994).

Discount rates which are applied to project evaluations are often simply based on market rates of interest and very often the same rates are applied to projects of entirely different nature. Economists tend to use relatively high discount rates because they are uncertain about future income streams. In practice, the discount rates which are used tend to be set at the level of long-term interest on government bonds plus a risk premium. But few markets exist for assets with maturities exceeding thirty years, making the interest rate beyond that horizon highly uncertain (Newell and Pizer, 2002). Yet discounting is one of the most fundamental factors affecting policy decisions about resources (Kula, 1994). Investment projects which impose high costs in the future, or after a long delay, but have lower capital costs now, or in the near future, will be favoured over investment projects which have high returns, but occurring in the long term, combined with high capital costs now (Livingstone and Tribe, 1995). In NRR projects, the discount rate determines the price/output path for the extractive industry (Jowsey, 1997). In fisheries, the discount rate means the owner of the resource faces an intertemporal trade off such that any positive discount rate implies a larger harvest now and a smaller one in subsequent years. Forestry projects, with long time lags to harvest are extremely sensitive to the magnitude of the discount rate and it is one of the crucial variables determining the optimum tree cutting age (Jowsey, 1998).

Discounting has been the backbone of all time-dependent social theories in economics during the last 60 years or so (Kula, 1997), and yet discounting discriminates against future generations because it diminishes the importance of costs and benefits the further into the future they are received. The higher the discount rate, the lower the importance attached to the future and the less likely it is that resources will be conserved. This is the case when considering discount rates generally – higher rates attach less value to future costs and benefits. A positive discount rate is thought to discriminate against people in the future which infringes the intergenerational element of sustainability. Decisions concerning whether to undertake projects with long-term benefits (such as growing oak trees) or with long-term costs (such as storage of nuclear waste) may rest on the choice of discount rate. The further into the future the benefits or costs occur, the lower will be their present value. As the discount rate is increased, this time bias increases.

Interest rates affect the rate at which natural resources are used up – the higher the interest rate, the faster resources are likely to be depleted. This result is from earlier work on such resources which was considered in some depth in Chapter 3. This basically states that resource prices must rise at a rate equal to the interest rate, and if the interest rate rises then current extraction of resources must increase in order that their prices rise at a faster rate also. The same principle, in fact, applies to resources such as fish, as was shown in Chapter 3. This principle can be seen intuitively if the decision to extract/exploit or leave the resource as an asset is considered. If the resource is conserved, then its value rises as prices rise. If the resource is extracted/exploited in the present, then the proceeds can be invested at the prevailing interest rate. The higher the interest rate, the greater is the opportunity cost of any decision not to extract/exploit the resource. In this way, high interest rates lead to a more rapid depletion of the natural resource stock.

At individual project level, however, when different discount rates can be applied, high rates have a different effect. All other things being equal, a project will have a lower net present value if a high discount rate is used in its appraisal. Existing use of discount rates in individual natural resource projects looks at the costs and benefits over time of each project and calculates present value using the formula:

$$PV = \sum(B_t - C_t) /(1+i)^t - K \qquad \text{(Equation 9.2)}$$

where $\sum(B_t - C_t)$ is the sum of benefits minus costs for each year (t) of the project, K is the capital sum which must be invested at the beginning of the project and $(1+i)^t$ is the discount factor. If a number of projects are being considered, they can be ranked in order of net present value and the project with the greatest net present value can be chosen for implementation.

It is appropriate to use discount rates as the policy mechanism to achieve sustainable resource use. This is because both elements of user costs incorporate time; regeneration time is part of rate of supply (r_s) and utilisation time (t_u) is part of the rate of change of entropy ($\Delta s/t_u$); and discount rates are a mechanism for comparing monetary values over time. The impact of the discount rate increases as the length of time involved in each project increases, so that, for example, a project involving nuclear resources with effects lasting very long periods of time would be more affected by the application of the discount rate than a natural gas project with effects lasting thirty or forty years. As a result, it is appropriate to use discount rates as the arbiter of regeneration time and utilisation time. A straightforward method of applying the principle of user costs in practice could involve the application of differential discount rates to different resources and resource projects. It is possible to apply different discount rates to projects involving natural resources with different user costs. It is also appropriate to use differential discount rates to achieve sustainable resource use. This is because, over time, differences in costs and revenues of projects would be magnified due to the nature of discount rates having greater impact over longer time periods. The nature of Equations 9.1 and 9.2 leads to this impact.

This can be illustrated using an example of a project present value calculation. Suppose that a project has revenues of £1million per annum and costs of £500,000 per annum. Capital costs of setting up the project are £1 million. If the project runs for 10 years, then the undiscounted value of the project is £4 million. If the project runs for 20 years, then its undiscounted value is £9 million which is 225 per cent greater. It is now necessary to investigate the effects of discounting on the present value of the future income streams from the project. Using Equation 9.2 and a discount rate of 10 per cent per annum gives a present value for the project of £2,379,507 after 10 years. After 20 years, however, the present value with the same discount rate is £3,682,450, which is only 155 per cent greater.

Accepting the rationale (of time preference and productivity of capital) for a positive discount rate, a low positive rate could be set for projects involving resources with the lowest user costs. Higher rates could then be set for individual projects involving resources with higher user costs. The choice of the lower rate for projects involving CNR must then be made. Lower rates have been applied to forestry projects in the UK and water projects in the USA where the projects have been deemed to carry positive external benefits. In 1986, the US Congressional Budget Office required the general use of a 2% discount rate, roughly equal to the real cost of borrowing on world markets (Perman, Ma and McGilvray, 1996). Discount rates which are used by economists have been based on long-term interest rates on government bonds as one measure of the cost of capital, adjusted by a risk premium (Tietenberg, 1996). Rates of up to 20 per cent have resulted, but a rate as high as this is extreme and would prohibit all but the most profitable projects (the present value of £1million pounds to be received in 20 years time is only £26, 084 if the discount rate is 20 per cent). It has already been suggested that the SOC rate could be as high as 8 per cent, while the SRTP rate could be as low as 2 per cent. Accordingly, it might be appropriate to set discount rates for CNR projects at 2 per cent; for PRR projects where $r_c/r_s \leq 1$, at 4 per cent; for PRR projects where $r_c / r_s > 1$ at 6 per cent; and for NRR projects, at 8 per cent. It may be appropriate to reinforce the more sustainable nature of CNR and PRR where $r_c/r_s \leq 1$ by setting their discount rates at 2 per cent and 3 per cent respectively, while PRR where $r_c / r_s > 1$ have a discount rate of 7 per cent and NRR of 8 per cent. The gap from 3 to 7 per cent would then emphasise the difference in types of natural resource in terms of their long-run sustainability. These rates are less extreme than the market influenced rates often currently used in investment projects, but will still make a significant difference to present value calculations over time, and the longer the period of time the bigger the difference made.

A differential discount rate regime would clearly advantage projects involving resources with lower user costs. The actual discount rates used could be greater or less than those suggested here, but the effects will be the same as long as the relative magnitudes of the rates vary with user costs. Differential discount rates based on the user costs of natural resource projects could easily be implemented in public policy decisions (by government decree), provided that there is widespread knowledge of the rules for classifying resources, and this would be a major step on the way to sustainable resource management. Transmitting those rates into private sector decisions may be more difficult. Legislation to try to impose certain levels of interest rates and discount rates on private sector decisions would be very difficult to enforce. However, in Germany, Federal governments enforce the use of standard discount rates in the evaluation of renewable energy projects. They can do this because there is a government subsidy involved. Providing government finance at low rates for (private sector) projects involving resources with low user costs would reinforce the public sector policy. Further research is necessary into ways of encouraging or enforcing a more sustainable discount rate policy in the private sector. For sustainable management of resources, the policies should be applied globally.

Because the impact of discount rate use in investment decisions is magnified over time, there would be an inbuilt mechanism in the use of differential discount rates applied to resources with different user costs which would lead to greater sustainability of natural resource use. It may well be possible to derive the actual discount rates to be applied to CNR, PRR and NRR by more accurate measurement of the terms in the User Cost Function. It is possible, however, to make natural resource use more sustainable simply by ensuring that the discount rate applied to NRR projects is greater than the discount rate applied to PRR projects, which is in turn greater than the discount rate applied to CNR projects. This Chapter has provided a basis for the use of differential discount rates in accordance with relative user costs of natural resources in order to manage those resources in a sustainable way. Natural resource policies which incorporate the theory of user costs of resources will be more sustainable than the current worldwide pragmatic resource policies which have no real foundation in natural science and economics.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Summary of Conclusions

It was shown in Chapter 2 that environmental policies do not adequately address the issues of pollution and waste and resource depletion. Furthermore, the thorough review of natural resource economics literature, undertaken in Chapter 3, has shown that conventional classification of resources as 'renewable' or 'non-renewable' is inadequate. The group of resources generally described as renewable includes at least two types of resources which have quite different characteristics. The 'biological' renewables encompass fish, forests, animals, plants and biomass, generally. Other non-biological flow resources, such as hydro, solar, tidal, wave and wind power have different physical and economic characteristics. These differences are not adequately treated in existing literature about the economics of resources, although they are sometimes mentioned (see, for example, Rees, 1985; Tietenberg, 1996). Economic theories of resources are, therefore, neither rigorous or complete. There is a need for a theory which can explain the production and consumption economics of all natural resources and which can cope with the transition of a resource from one category to another. Explanation of the economics of all natural resources is required in order to understand fully the implications and consequences of their use in the economic process.

The way that Neoclassical economics assumes perpetual growth with no limits to resource inputs or outputs to the production process has meant that there is no concept of 'irreversibility' in its assumption of constant economic growth. Even after the introduction of the 'materials balance' approach to resource use in the 1970's, the basic theories of 'renewable' and 'non-renewable' resources were not really challenged. This approach did focus attention on the link between resource consumption and the production of pollution and led to recognition that the Laws of Thermodynamics govern that link. The concept of entropy from thermodynamics provides a way of measuring the quality of natural resources and a means of understanding the irreversible nature of environmental and resource processes. No physical process is possible without energy, and all such processes relevant to the functioning of economics are of an irreversible nature because of the Second Law of Thermodynamics. Resource utilisation begins with the extraction (depletion) of low entropy resources and ends with an equal quantity of high entropy waste or pollution. There is irreversibility in the combustion of fossil fuels, destruction of the rain forest and extinction of species and other environmental-economic impacts, and so thermodynamics brings real, irreversible time into the analysis. Accordingly, a new unifying theory of natural resources should reconcile the views of natural scientists and economists.

The Laws of Thermodynamics were shown to dominate the creation processes of natural resources in Chapter 4. The physical processes which influence the creation and accumulation of matter and energy were found to be cyclical in nature. The processes are cyclical because of the First Law of Thermodynamics which contends that energy and matter cannot be created or destroyed. For energy, however, the Second Law of Thermodynamics means that entropy increases and as a result energy can not be recycled without a reduction in its quality. This means that there will be continuous cycling of energy/matter flows with gradual dissipation/degradation. The concept of resources as a flow was clearly established in Chapter 4 and the role of entropy in the resource creation process was identified and explained. Timescales of resource accumulation and the possibility of stocks accumulating were identified as critical factors affecting the creation and availability of resources. In terms of human perception, the timescales from seconds to years might be more appropriately termed "economic" and timescales from centuries to millions of years as "physical/natural". This would go some way towards explaining the different perceptions of the future held by natural scientists and economists, the former dealing in comparatively longer timescales and the latter relatively short ones.

The physical characteristics of resource flow and resource regeneration time are important in determining the uses to which natural resources can be put by humans and, indeed, the way that they are used. Humans tap into the flow of resources, sometimes depleting them where the rate of consumption is greater than the rate of resource regeneration. Clearly, if resources are regenerated over very long timescales (for example coal), then rates of exploitation which are faster than this will deplete the accumulated stocks of resources in the system. Such resources have been described as "depletable" or "exhaustible" or "non-renewable" resources. They are, in fact, renewing but at rates which are so slow as to be meaningless when measured against human economic timescales. This perception of resources with a long regeneration time as stocks is perfectly understandable from the viewpoint of a single generation, or even several generations. To all intents and purposes coal is a stock of a resource. There are other resources which lie in between the extremes of "non-renewable" resources and "renewable" flow resources. The regeneration processes for such resources (biological and ecological) are comparable to human timescales, and they have been termed "renewable resources" in much literature. These resources have completely different physical and economic characteristics from other resources which are often included in the category of "renewable resources" which are regenerated over much shorter timescales and which are, mainly, continuously available. The resources which arise from biological and ecological processes are animals, birds, fish, plants, etc., (collectively termed "biomass"). They are regenerated within timescales which are relevant to humans and to human exploitation. Their continued existence, however, is dependent on their being exploited in a "sustainable" way. It is possible for these resources to be over-exploited and then depleted as if they were a stock. Once the genetic material is lost, the stock becomes "extinct" which means that it is totally depleted and incapable of regeneration. These resources are renewable, but can also be depleted by exploitation if they are not managed carefully. They can continue to renew and continue to exist as a resource, if they are exploited at a rate which is slower than their renewal rate, that is, at a sustainable rate.

The explicit link between entropy and pollution was established in Chapter 5. The problem is not the *amount* of high entropy waste released, but the *rate* at which it is released. Human exploitation of resources increases the rate of creation of high entropy wastes. It is as if all that entropy should not be unleashed so quickly, because the system into which it is released cannot cope with it. The pollution absorption rate or carrying capacity of the environmental system can be exceeded if the rate of high entropy release is too rapid. The rate of change of entropy is, therefore, identified as a crucial consideration of resource exploitation. Use of hydro, solar, tidal, wave and wind power causes a relatively small increase in rate of change of entropy. Use of biomass resources and fresh water causes a moderate increase in rate of change of entropy. Use of metals, fossil fuels and nuclear fuels causes a large increase in rate of change of entropy.

In Chapter 6 the key economic characteristics of natural resource exploitation were determined. These are:

- the degree of accumulation and concentration of energy and matter
- knowledge of its existence
- ownership and access
- rate of consumption relative to rate of supply, and
- rate of change of entropy during exploitation.

The physical and economic characteristics of natural resources were analysed together in Chapter 7 in order to identify the real costs of natural resource exploitation and then to classify natural resources. A User Cost Function was formulated which encapsulated the physical and economic characteristics of resources previously identified. The User Cost Function was found to depend upon the ratio of the rate of consumption of a natural resource relative to the rate of its supply (r_c/r_s) and the relative rate of change in entropy ($\Delta s/t_u$) as a unit of the natural resource is used. These two terms encapsulate both the physical and the economic characteristics of natural resource creation and exploitation as described Chapters 5 and 6. The term r_c/r_s is a quantitative economic measure of resource availability, while the term $\Delta s/t_u$ is a qualitative physical measure of resource use. As such, r_c/r_s represents the relative quantity of a resource and $\Delta s/t_u$ represents its relative quality. In this way, the User Cost Function provides a basis for distinguishing between different resources, thereby creating the foundation for a systematic classification of all natural resources.

The formulation of user costs enables the division of natural resources into three distinct groups. Those with the lowest user costs can be described as 'continuous natural resources' or CNR including hydro, solar, tidal, wave and wind power. Those with the highest user costs are the 'non-renewable resources', or NRR, of fossil fuels, metals and non-metallic minerals. Between the two extremes are fresh water, biomass and geothermal energy which have an intermediate level of user costs and can be termed 'potentially renewable resources' or PRR, with user costs which are higher than for CNR, but lower than for NRR.

In Chapter 8, the User Cost Function was investigated via a case study of geothermal energy using data from the Geysers geothermal reservoir in California, USA. The depletion component of the User Cost Function ($r_c<r_s$) was calculated in order to determine utilisation time for the Geysers geothermal reservoir and the exploration cost per unit of electric power produced. It was shown that at levels of electric power utilisation of 10.5 MW or less, the geothermal resource can be exploited indefinitely because the rate of consumption is less than the rate of supply ($r_c<r_s$). At higher levels of electric power utilisation there is a linear relationship between electric power utilisation and the utilisation time of the resource, meaning a trade-off between higher rates of power output and how long the resource will last. At current rates of exploitation (2000 MW) the geothermal resource is projected to last for 251 years. The depletion cost component, represented by exploration costs per kWh, were found to be zero when electric power utilisation is 10.5 MW or less (because they are spread across an infinite range of output). For higher rates of power utilisation, they vary from 0.0005 cents per kWh to 0.015 cents per kWh, which is a very small amount in comparison to the production cost of 4 to 8 cents per kWh. This is because this particular resource is so large. Exploration costs can be expected to become more significant as such resources become more difficult to find. The results from calculating r_c/r_s for the Geysers geothermal reservoir show clearly that this type of resource can move from being a renewable resource to being a non-renewable resource if the rate of electric power utilisation is increased to more

than 10.5 MW. At rates of power generation of less than 10.5 MW the Geysers reservoir can be exploited indefinitely as a sustainable renewable resource.

The environmental cost component of the User Cost Function was also investigated in the case study in Chapter 8. Environmental costs arising from the increased rate of entropy release were identified and, using the example of carbon dioxide, a relationship was derived which is based on the amount of carbon dioxide emitted per unit of electricity generated and the price of carbon dioxide as an environmental pollutant. The environmental costs of carbon dioxide emissions were calculated for the Geysers geothermal reservoir and found to range between 0.0000216 cents per kWh and 0.01008 cents per kWh depending on the figures for carbon dioxide emissions and damage costs per tonne of carbon dioxide which are used. There is considerable uncertainty and lack of agreement over the estimates of damage costs of carbon dioxide, although there is considerable literature on this subject. Since there is even less understanding of such 'prices' for other pollutants, even greater uncertainty is likely to attach to the other environmental costs of geothermal energy.

The case study demonstrates that the depletion cost component of the User Cost Function can be calculated and can be use to predict utilisation time for a natural resource. In the case of the Geysers geothermal reservoir it was shown that the resource can be renewable or non-renewable, depending on the rate of electric power utilisation. The environmental cost component can also be calculated, but there is a great deal of difficulty because the costs must be calculated using the complex methods of cost benefit analysis and, even in the well-researched case of damage from carbon dioxide emissions, there is a wide range of costs.

In Chapter 9, the relationship between natural resource utilisation and sustainable development was investigated. It was shown that reducing user costs would reduce depletion rates and reduce pollution. Since all natural resources (not just non-renewables) have user costs, policy for sustainable management of resources should aim to recognise and incorporate user costs of natural resource use in the economy. Policies for sustainable management of resources should mitigate against exploitation of those natural resources with the highest user costs and should promote exploitation of those resources with the lowest user costs. If these objectives can be achieved, the twin environmental economics problems of depletion and pollution can be addressed in a coherent and logical manner.

Existing natural resource policies were also investigated in Chapter 9. The various interventions tend to be applied in response to specific circumstances, political, economic, social and environmental, with little thought being given to the overall sustainability of policy. There is, therefore, a case for a more coherent basis for policy in relation to the use of natural resources, which should rest on the application of the User Cost Function because this represents the real economic and environmental cost to society of natural resource use. Consequently, future natural resource policy was also suggested in Chapter 9. The difficulties of monetary valuation of user costs were acknowledged and possible surrogates in the form of resource price contracts and pollution costs were suggested. However, it was proposed that the most appropriate policy for sustainable management of resources should encourage use of those resources with the lowest user costs, and discourage use of those with the highest user costs, by using differential discount rates to evaluate natural resource projects. It was suggested that this would achieve sustainable resource use because, over time, differences in costs and revenues of projects will be magnified as a result of differential discount rates having greater impact over longer time periods. There would be an inbuilt mechanism in the use of differential discount rates applied to resources with different user costs which would lead to greater sustainability of natural resource use.

Natural resource use could be made more sustainable simply by ensuring that the discount rate applied to NRR projects is greater than the discount rate applied to PRR projects, which is in turn greater than the discount rate applied to CNR projects. Policy to implement the theory of user costs could take a variety of forms, but the adoption of differential discount rates in the evaluation of natural resource projects is the most likely to achieve a sustainable outcome because the effect of discount rates is magnified over time. In summary, the theory of user costs as described here provides an explicit set of criteria for classifying resources into three distinct groups based on clear natural science and economics foundations. Practical policies for the sustainable management of natural resources based on this theory will optimise depletion policy and reduce pollution.

10.2 Recommendations for Further Work

Analysis of the physical and economic characteristics of natural resources has enabled their classification as NRR, PRR or CNR according to the magnitude of their user costs. More detailed analysis of user costs would enable classification according to user costs within these three categories. This would involve an economic study of the rate of consumption of different natural resources relative to their rate of supply or regeneration to determine the depletion cost component of the User Cost Function in a way that has been demonstrated for the Geysers geothermal reservoir in Chapter 8. Measurement of the rate of change of entropy as resources are utilised should be undertaken in studies that identify and value the environmental costs of increased rate of release of high entropy in a way that has been explored for carbon dioxide emissions in Chapter 8. If applied thoroughly to a range of resources, such detailed work will enable more rigid and detailed classification of resources within the three categories of NRR, PRR and CNR.

Further work on exploration costs could use idealised geothermal fields to determine their significance for smaller geothermal resources than the Geysers field. Similarly, the significance of exploration costs for NRR such as coal, oil and natural gas could be examined. Further work in the implementation of natural resource policies is also desirable. More detailed measurement and specification of the User Cost Function would provide more precise classification of the different types of natural resource. It may then be possible to formulate a policy based on resource contracts for long periods of time in order to make resource utilisation more sustainable, as suggested briefly in Chapter 9. Such contracts might be particularly suitable to ensure more sustainable power generation, but this outcome would require detailed trials of resource contracts as a policy mechanism in order to test their effectiveness.

Application of differential discount rates to natural resource projects in accordance with the theory of user costs should be undertaken for a range of different projects in order that the efficacy of the proposal can be judged. Over a period of time and a range of projects, more projects involving resources with lower user costs should be undertaken relative to those with higher user costs and this would be a more sustainable outcome. Once the effectiveness of the policy proposal has been established, methods of transmitting the differential discount rates (based on user costs) into private sector projects require investigation. Legislation could be necessary to achieve this, and a case for this would need to be made. The fact that current global levels and methods of natural resource utilisation are unsustainable is well established (WWF, 2002). The importance of the further work recommended here is that it should provide more evidence of the real costs of resource use and of the effectiveness of policies to make economic development more sustainable.

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