RESEARCH PAPERS

from the Department of Social Sciences

Institut for Samfundsvidenskab og Erhvervsøkonomi

Research Paper no. 15/00

Critical Assumptions in Estimation of Non-Renewable Resource Capital Consumption

Anders Chr. Hansen

Roskilde University, Denmark

Research Paper no. 15/00

Critical Assumptions in Estimation of Non-Renewable Resource Capital Consumption

Anders Chr. Hansen

Roskilde University, Denmark

Research Papers from the Department of Social Sciences, Roskilde University, Denmark.

Working paper series

The Department of Social Sciences is one of the largest at Roskilde University with 43 permanent scientific personnel together with several Ph.Ds, and other teaching staff. Most of the academic personnel have a background in economics, political science or sociology. It is a general goal of our department and the rest of Roskilde University to foster interdisciplinary teaching and research. The later can be seen from the four main research lines of the department, namely:

- Changes in the welfare state in a national and international perspective.
- Public organisation and policy analysis.
- Innovation and technology development with special attention to service firms and information technologies.
- Institutions, actors and institutionalisation.

The Research Papers from the Department of Social Sciences are edited by Associate Professor Susana Borrás.

Please note that:
The papers are on a 'work in progress' form, which means that comments and criticisms in the form of feed-back are welcomed. For this purpose, the address(es) of the author(s) is specified on the title page. Readers must also be aware that the material of the working papers might be printed later in journals or other means of scientific publication in a revised version.

ISSN 1399-1396

Abstract

In this paper, the critical assumptions used when estimating non-renewable resource capital consumption are identified and discussed. The paper reviews an accounting approach, two user-cost approaches and a repurchase approach to estimation of non-renewable resource capital consumption. The latter is, however, not comparable to the other approaches since it is not intended to distribute the non-renewable resource rent over generations. The approaches are discussed from the perspective of investing the resource rent (Hartwick's rule). The difference between the accounting approach (Total Rent or net-price approach) and the user-cost approaches (Hotelling and Serafy approach) is found to be the intergenerational distribution ethics underlying these approaches. The two approaches give answers to different questions of how much investment is needed to pursue an intergenerational distribution ethics as to non-renewable resource rents. In the case of the accounting approach, a Golden Rule ethics (maximum constant future consumption) and in the case of the user-cost approaches, a Rawlsian ethics (constant consumption). The user-cost estimates are found to depend on assumptions of cost structure, time preference, and depletion profile. The time preference assumptions reflected in the rate of discounting and the depletion profile reflected in the discounting horison are found to be very critical assumptions. It is asserted that they are often more critical to the natural capital consumption estimate than the technological assumptions reflected in the cost elasticity. The consequences of using discounting methods with a more moderate discounting of the distant future as suggested in the theoretical literature are examined. Similarly the consequences of using more realistic assumptions of the resource depletion profile are examined. Finally the question of growth of non-renewable resources is discussed. It is concluded that capital gains and new discoveries are not substitutes to investments of the resource rent in an intergenerational distribution perspective while they can be in a shorter, but still long term growth perspective.

A partly overlapping paper is published as "Estimating Non-Renewable Resource Capital Consumption" in Mohan Munasinghe and Osvaldo Sunkel (eds.): "Sustainability of Long-Term Growth", 2000.

Keywords:

Natural capital, resource rent, green national accounting, user-cost, logarithmic discounting, Hartwick's rule.

Address for correspondence: anders@ruc.dk

Critical Assumptions in Estimation of Non-Renewable Resource Capital Consumption

By Anders Chr. Hansen, Roskilde University, Denmark

TABLE OF CONTENTS

Introduction

Natural capital consumption is a key concept in economic sustainability analysis. The background for the concept is that the sustainability principles require some welfare transfers to future generations. It is a key concept because the stocks of the economy mediate intergenerational welfare transfers. Natural capital consumption is the capital equivalent of the resources that are used up by the current generation and thus not available to future generations.

The problem related to consumption of mineral reserves (that are non-renewable) is that according to the intergenerational distribution ethics implied by the principles of sustainable development, they "belong" to all generations. Not only to the generation that actually consumes them. Yet, to be of any value at all they have to be consumed at some point of time.

On this background, a macroeconomic theoretical framework for analysis of these balances has evolved. Solow (1974) showed that it is possible to maintain a constant consumption level in an economy based on an exhaustible resource that is essential to production. Even if no further technological progress occurs. Hartwick (1977) transformed this analysis to a policy prescription, which has been known as the *Hartwick rule*. It prescribes investment of the current resource rent in reproducible capital as a condition for maintaining a constant consumption level, even after the resource has been exhausted. Subsequent contributions from Dixit et al. (1980) showed that a growth path with constant consumption is characterised by zero net investments. Asheim (1994) added that this does not lead to the conclusion that consumption is sustainable if the value of net investments is zero at a single point of time.

Moreover, since the relative shadow prices of natural and man-made capital change over an optimal path where man-made capital is substituted by natural capital, the current relative prices are not adequate for valuing natural capital consumption. Or put differently, as Heal (1997), the shadow prices of current natural capital consumption depend on the time preference reflected in the sustainability objective.

Dixit et al. (1980) and Hartwick (1990) extended the model to include renewable and environmental resources as well. This paper is, however, confined to the question of valuation of non-renewable resource use. This question is of great importance when the theoretical framework as described above should be transformed to numerical estimates of investment requirements.

The theme of this paper is the problems that arise when this theoretical framework is applied in empirical economic analysis. More precisely, it is the problems that are attached to the estimation of natural capital consumption.

The paper attempts to assess the relative importance of the different assumptions one has to make in this process. This is difficult because they are of widely differing nature. Some regard uncertainties about the future, some relates to technological or geological features like the input requirement and feasible depletion profiles. Still others concern time preference.

A number of alternative approaches have been suggested in the literature. I shall review them in turn and discuss their required assumptions. One approach is simply to define the resource rent as the value added that can not be ascribed to labour or man-made capital. This *accounting* approach was used to estimate natural capital consumption by Repetto et al. (1989). Two alternative *user-cost* approaches are based on the Hicksian notion of net-income. In this paper, they are termed the Hotelling approach and the Serafy approach. A special section is devoted to the analysis of the above mentioned time preference assumptions behind the user-cost approaches. Some suggestions of how to handle alternative time preference assumptions and their effects on the estimated natural capital consumption are presented. Finally, the question of growth of non-renewable resources and a *repurchase approach* to natural capital consumption is discussed.

The Total Rent Approach

The accounting approach to estimate resource rent can be named the *total rent approach*. If aggregate statistics are available, the non-renewable resource rent of the mineral extracting industry is simply

(1) $R = VA - (d+r)K - wL$,

where VA is value added of the mineral extraction industry, w is the wage rate, K the amount of capital, and L the amount of labour used in the industry. Information on the capital stock is assumed not to be included in the statistics. The logic is that if there are only three factors of production contributing to value added and if the contributions of labour and capital have been accounted for, then the residual must stem from the natural resource itself.

If aggregate statistics for the mineral extraction industry are not available the equivalent is the product of the physical amount of extraction and the *unit rent*. The unit rent can be defined as unit price, p_j, minus unit costs, ac_j, and is also referred to as the *net-price* (e.g., Landefeld and Hines, 1985; Repetto et al., 1989; BEA, 1994), the contribution of the average extracted mineral unit to national income.

Estimation of the unit rent requires data on average extraction costs, *ac*, for the jth firm:

(2) $ac_j = (TC_j + (d+r)K_j)/q_j$,

where TC_j is total exploration, development, and operating costs, K_j is the invested capital stock, d is the depreciation rate, r is the normal rate of return to capital (net of depreciation), and q_j is the quantity extracted.

For the industry, the total resource rent, R, is then

(3) $\quad R = \Sigma_j(p\text{-}ac_j)q_j,$

where p is the price of the mineral and ac_j the comparable average cost estimate, preferably including costs of transport to port as in World Bank (1998).

The assumptions one have to make about costs and prices in equations *(1)-(3)* are not critical. Prices, wages and labour data are typically readily available. Capital stocks must be assessed and normal returns to capital and depreciation estimated. The assumptions needed for that are, typically, of a trivial kind such as a depreciation rate.

The problem with this estimate is that it accounts all of the resource rent as consumption. According to this method, the rent as such is not consumable income. Only after it has been invested, the proceeds from the so accumulated capital stock are consumable. This is an implicit distribution ethics, which is as much in favour of future generations as possible. Thus it has resemblance to the Golden Rule ethics known from economic growth theory (Phelps 1961). That is, capital is accumulated as much as the future generations would prefer, which is all of the resource rent.

As numbers are easy to get at, the method has been used by, e.g., The World Bank (1998) and The Danish Economic Council (1998) in estimating natural capital consumption. However, in many countries such a strong preference for the consumption level of future generations is indeed a possible, but not a very plausible assumption. There is a lack of logic in the ethical premise that only the present generation is *not* entitled to consume some of the rent it gets from the natural resources.

There is a way to bring ethical consistency into the total rent approach. The ethical premise could be that the generations living at the present and all future generations are equally entitled to consuming the rent of the *extracted* non-renewable resource. In the following sections it will be clear, that it makes a considerable difference whether it is the current rent or the prospected rent from the entire depletion program that is to be shared by all generations. In the case where only the rent extracted in a given year is to be distributed evenly, the consumable share of the rent would equal the annual returns to it, invested as capital. The capital consumption estimate would then be the total rent multiplied by $(1+r)^{-1}$.

Still, this leaves an open question of why we should not care about rents that we expect to earn in, say, the next 10 years. Following even the modified golden investment rule a resource rich economy could produce increasing consumption opportunities over a decade or two that could be more beneficial if they were evened out. This brings in the notion of a user-cost to which we return in the following chapters.

The total resource rent can, however, serve as a *maximum* estimate of natural capital consumption like in Hansen (1995). If more than that is consumed, there is really reason for questioning the sustainability of the consumption level. If more than that is saved for the future and if the current total stock of man-made and natural capital is considered sufficient, there is not much reason to worry about the consumption opportunities generated by the total capital stock in the future.

The two user-cost approaches discussed in the following build on the total resource rent, but divide it in a share that is consumable income and a share that is natural capital consumption. They both derive these shares from a Hicksian concept of net-income, which implies an interpretation of sustainability as a future path characterised by a non-declining capital stock or consumption.

The Hotelling Approach

Hotelling Rent

Hotelling (1931) showed that the rent of the marginal unit (the Hotelling or scarcity rent) is the key factor in mineral extraction decisions. The optimal scale of extraction at time t, q_t, is where the price, p (assumed to be constant over time) equals the sum of the marginal rent, h_t, and the marginal costs, $mc(q_t)$. Total Hotelling rent is then

(4) $R_{Ht}=[p - mc(q_t)]q_t$

Investing R_{Ht} leaves a share of the total resource rent to be consumed in the year of extraction while allowing future consumption to be at the same level. This sustainably consumable share is determined as the difference between the marginal and the average costs and it is in effect the infra marginal or Ricardian rent, R_R.

(5) $R_R=(mc - ac)q$

This approach has been strongly advocated and used by Hartwick (1989) and Hartwick and Hageman (1993). Hartwick and Hageman applied the method in estimating the depreciation of US oil reserves due to extraction for 1987.

Estimation of Marginal Costs

The definition of marginal costs is essential in this method since marginal cost estimates are used to reveal the marginal rent as it must be perceived by the competitive, unrestricted, and well-informed mineral extractor according to economic theory. The costs of oil-production include finding, (or exploration) costs, development (or drilling) costs, and operating costs. Further, the relevant cost concept for macroeconomic analysis is not the marginal cost concept relevant to the individual extractor. To the individual extractor, increasing marginal costs means that he is approaching the limits of his organisation and installed equipment. At the industry (or national) level and in a long-term perspective, the costs of producing more oil include exploration and development costs. That is, the relevant cost concept for the purpose of intertemporal income distribution analysis is long run industry costs.

These exploration and development costs can be compared with R&D costs in other industries. In most macro analysis of, for instance, productivity development it is neglected that factor inputs used for R&D should be related to future rather than current output. It does, however, not make a big difference when only a small fraction of the factors are for R&D. In the mineral extraction industry, however, finding and development costs are the dominating cost components (see, e.g., Adelman, 1986). The Danish Energy Agency (1998) estimates the total operating costs for North Sea oil and gas extraction in Denmark as amounting to DKr 36 billion (1997 prices) for the period 1963-97. This figure should be compared to development costs of DKr 60 billion and exploration costs of DKr 20 billion. Thus, there is a strong case for defining marginal costs in this kind of analysis, as the costs of increasing resource extraction in an industry-wide and long term perspective.

The literature provides two alternative ways to estimate marginal costs in this framework. One is simply to collect information on all types of costs and relate them to the relevant deposits. The other is to assume a cost function and then find plausible parameter values.

Adelman (1972, 1990) provides an extensive treatment of marginal costs in the oil industry using the more general concept of *incremental costs*. It is important to notice that the three types of oil production costs have very different time profiles. Converting them to comparable figures of costs per barrel requires significant adjustments for the time of extraction of each barrel. Adelman (1972) developed a comprehensive algorithm for making these adjustments at the industry level, integrating operating and finding costs into the typically most significant cost component, the development costs.

The most important adjustment was to take into account the time profile of reservoir depletion (represented by the output decline rate) and the discount rate. The latter is for finding and development costs heavily influenced by uncertainty premiums due to basic or scientific uncertainty and political instability in the host country.

The Adelman definition of incremental costs can be expressed as the per barrel capital costs of added reserves plus the operating costs.

The costs of the capital invested in finding and development are distributed on future outputs assuming that output is declining at a constant rate. This means that capital costs per barrel are increasing as the number of barrels becomes fewer and as the cumulated interest on the initial outlays grows. Exploration and development costs per barrel in a reservoir are adjusted by multiplying a present-barrel-equivalent-factor defined as the integral over the depletion period of a discount factor using the sum of the discount rate and the constant output decline rate as discount rate.

Operating costs are assumed to be constant over the depletion programme and thus increase per barrel of extracted oil as the production shrinks. On the other hand, the present value of the future operating costs is lower than the operating costs today. Adelman derives a *present barrel factor* that can be multiplied on initial operating costs to get an approximation to the present value of the operating costs per barrel in a reservoir.

These cost estimates are then added and related to the new reserves in order to get the incremental cost or marginal cost concept that is suitable for macro analysis.

Hartwick and Hageman (1993) used marginal costs estimates calculated by Adelman (1986) to estimate the marginal rent on oil extraction in USA in 1978. The result was in turn used to compute the oil capital consumption to 1.1% of conventionally defined NNP. Sustainable consumption if the consumption of oil capital was taken into account would accordingly be 1.1% lower than if it was not and the gross savings required for sustainable development would be accordingly higher.

The Hotelling rent is conceptually linked to income forgone in the future because of present extraction, which is convenient for analysis of intergenerational income distribution. Income foregone in the future is measured as

$$(6) \qquad (p-mc_T)(q_T),$$

where T is the final year of the extraction program. The marginal cost of the last unit extracted can be argued to be 0. Thus, the marginal rent of the last unit extracted equals p and the present value of this unit at time t equals

$$(7) \qquad p(1+r)^{-(T-t)},$$

where r is the rate of discount. Optimal resource extraction thus requires that *(6)* equals *(7)* and, consequently

$$(8) \quad mc_t = p[1-(1+r)^{(t-T)}] \, ,$$

where subscript t denotes that the marginal costs are attached to the optimally extracted quantity at time t.

On this background, we can estimate the Hotelling rent that would occur under conditions of perfect competition including perfect information.

Since we know that the total rent is the quantity extracted multiplied by the *net price*, we need a function linking average costs to marginal costs. Assume an iso-elastic cost function

$$(9) \quad C = \alpha q^{\beta}$$

This function has the convenient feature of $mc_t = (1+\beta)ac_r$. From this and equation *(8)*, we can derive a general expression for the share of capital consumption (i.e. total Hotelling rent) in total resource rent:

$$(10) \quad (p-mc_t)/(p-ac_t) = (p-mc_t) \, / \, [p-mc_t/(1+\beta)]$$

and by substituting *(9)* into *(10)*

$$(11) \quad (p-mc_t)/(p-ac_t) = (1+\beta)/[1+\beta(1+r)^{(T-t)}]$$

for any q_r.

What we get here is a distribution key between 0 and 1, dividing the total resource rent in a capital consumption share and a consumable share. The underlying ethics of doing this is that we neutralise the net income that would occur if we postponed the resource extraction of the current year to the final year of the extraction programme. The distribution key depends, however, of three parameters, which themselves reflect inter-temporal weights of income.

Vincent et al. (1997) derive in this way a Hotelling rent for oil extraction in Indonesia under the assumption of a secular decline in prices of –1.5% annually, a discount rate of 12.5%, and 2003 as the year of final exhaustion. A constant elasticity cost function with elasticity 2.865 was derived from these assumptions. But then again, the entire exercise reduces to determining a distribution key for the total resource rent between the present and the future. Choosing these figures - of which none are actually observed - means choosing the distribution key.

In the Vincent et al. study this distribution key was increasing from about 10% to about 100% during the projection period 1985-2003.

The distribution key reserves the thus computed theoretical infra marginal rent for present consumption and the required share of reinvestment as the Hotelling rent. If the Hotelling rent is reinvested, a permanent level of consumption based on resource rent and cumulated invested Hotelling rent in the past can be obtained. However, infra marginal and Hotelling rent are distinguished by the parameters chosen.

The cost elasticity is usually not an observable parameter, but it reflects scale economies. In the absence of a constant term, the cost curve is linear and mc and ac are constant when the cost elasticity is 1, increasing if lower and decreasing if higher. Since the major part of the costs are exploration and development costs, it is plausible that increasing returns to scale will be experienced in the development of extraction in an entirely new area with poor prior knowledge of the mineral structures. Learning about the geological structures from early exploration and development may enable the extractors to target their activities more precisely subsequently. In that case, however, the appropriate term will be dynamic economies of scale. In an area where the geological structures are relatively well known an assumption of decreasing returns to scale would probably be more reasonable than an assumption of increasing returns to scale.

Application of the Approach

The Hotelling approach rests on a number of strong assumptions of the behaviour and circumstances for dynamic optimisation in the resource extracting industries.

First, the link between present marginal rent and rent forgone in the future rests on assumptions of dynamically optimising extractors in a competitive environment with no tax distortions and perfect information. It is, however, not difficult to find examples of oil extraction that are motivated by governments desperately needing hard currency to keep the economy a float and the government in power. Such behaviour is not only found in unstable transition and developing economies. The strong government pressure put on Danish oil industry to intensify development of oil fields was also motivated by the foreign debt, which grew steadily from the early 60s to the late 80s. At the other extreme, the large OPEC producers are doing their best to keep oil supply at less than the competitive optimum levels.

Second, oil extraction is probably more characterised by uncertainties relating to scientific ignorance, political instability, and structural changes in the market than most other industries.

For instance, more political instability may lead to higher discount rates and thus higher capital costs and less capital consumption. This is very important for an analysis of optimal resource depletion but why should the political situation in a country at the end of the 20^{th} century have any consequences for the distribution of the natural resource rent over generations?

Using market rates of interest or recommended discount rates for public investments do not necessarily solve the problem. They are poor indicators for the willingness of the present generations to share wealth with future generations.[1]

The problem with the practical use of the Hotelling approach is that much of the data required must be assumed rather than observed. At best estimates can be derived from developing costs (Adelman 1986) or an assumed cost function (Vincent et al., 1997). In both cases it takes a number of rather strong assumptions. When we add to that, the assumptions required with respect to discount rates and future prices, the final result will be based on assumptions rather than observations to such an extent that decision makers may be reluctant to use it.

On the other hand, if marginal cost data could be observed, they would probably often reflect circumstances, which were in conflict with the assumptions referred to above. Thus, a computed Hotelling rent as a comparable reference measure might be more useful, than an observed one.

Contrary to the Hotelling approach, the Serafy approach and the repurchase approach avoid making assumptions about the extractors obeying the Hotelling rule. In addition to this, they intend to calculate natural capital consumption without depending on the marginal cost data, required by the Hotelling approach. Instead they imply other assumptions that are not less "heroic".

The Serafy Approach

The Inter-Generational Distribution Ethics

The second economic approach to estimate natural capital consumption was presented by Serafy (1989). In the literature, it is referred to as the *Serafy formula*. This approach solves the question of how to define a sustainable income stream from a given resource asset in a different way but with a quite similar outcome.

The Hotelling as well as the Serafy approach attempts to estimate *user costs*. That is, in a dynamic perspective, the costs of using a good now rather than at a later point in time.

In this sense, both of the approaches are Hicksian, since the user cost is what is taken away from future consumption from the perspective of the present. The Serafy approach is also Hicksian in the sense that the idea of estimating the user cost by equalling the present value of a wasting asset by

[1] See, e.g., Lind and Schuler (1998).

the present value of an infinite annuity came from (Hicks [1939] 1946; 187). It differs from the Hotelling approach in assumptions of cost structure and of the extraction profile, but it has the same basic aim of defining a user cost.

The Serafy formula is inspired by the way Hicks suggested treating income generated from "the exploitation of a wasting asset" Hicks([1939] 1946; 187). He suggested equalling the present value of expected receipts from a "wasting asset" to the present value of a constant stream of receipts of an infinite asset. In this way the "true income" component of the former can be derived as the receipts from the equivalent infinite asset. An infinite asset could be thought of as a perpetuity, e.g., a bond of infinite duration, or as any capital stock that could infinitely provide a return to its owners. In this way the rent of a non-renewable resource can be distributed across all generations succeeding the one that actually exhausts it.

The underlying ethics is as in the Hotelling approach that present and future generations alike are entitled to an annual income of a constant value, and this income stream should be the maximum obtainable from a capital stock of the same value as the resource stock.

Serafy (1989) derived the formula using the present value at the beginning of the first period assuming that the income in each period was received at the beginning of each period. In the following exposition I shall assume that income is received at the end of each period.

The present value at the time of receiving the first rent from a non-renewable resource depleted by annually extracting an amount Q with the total resource rent $(p\text{-}ac)Q$ = R available at the end of each of the n periods[2] (including the present) can be formulated in discrete time as

$$(12) \quad R^* = R + R(1+r)^{-1} + R(1+r)^{-2} + ... + R(1+r)^{-(n-1)}$$

A more compact expression can be derived as the sum of a geometric progression. Multiplying by $(1+r)^{-1}$ gives

$$(13) \quad R^*(1+r)^{-1} = R(1+r)^{-1} + R(1+r)^{-2} + ... + R(1+r)^{-n}$$

and subtracting equation *(13)* from equation *(12)*

$$(14) \quad R^* - R^*(1+r)^{-1} = R(1 - (1+r)^{-n})$$

that can be rearranged to

$$(15) \quad R^* = R(1 - (1+r)^{-n}) / (1 - (1+r)^{-1})$$

[2] Serafy (1989) assumes that the resource rents occur at the beginning of each period and gets consequently (n+1) in the following expressions where n occurs.

Similarly, the present value of a constant and infinite stream of receipts of X can be formulated as

$$(16) \quad X^* = X/(1 - (1+r)^{-1}),$$

since the term $(1+r)^{-n}$ in equation *(11)* goes towards zero as n goes towards infinity[3].

The Distribution Key

The *true income* is obtained by equalling the two present values in equations *(15)* and *(16)* and solve for X.

$$R^* = X^* \Leftrightarrow R(1 - (1+r)^{-n}) / (1 - (1+r)^{-1}) = X / (1 - (1+r)^{-1})$$

$$(17) \quad \Leftrightarrow X = R(1 - (1+r)^{-n})$$

Equation *(17)* can be given a straightforward interpretation. Note that the present value of the resource stock was derived as a sum of a geometric progression. The only difference between equations *(12)* and *(13)* is that the entire depletion program is postponed one period expressed by multiplying every expression by $(1+r)^{-1}$. The true income in equation *(17)* is nothing but the difference between the present value of future rents in the reference case and the present value of the same future rents if they are postponed one period. This difference is equal to the loss of postponing the resource rent in the first period to the end of the depletion program. That would produce a loss of R in the first period and a gain of R in period $n+1$, but the present value of the latter would be only $R(1+r)^{-n}$.

The complement to the true income is the *non-renewable resource capital consumption*:

$$(18) \quad R - X = R(1+r)^{-n}$$

The interpretation of this expression is similarly the present value of the income forgone at the end of the depletion program by extracting the resource now. This definition of non-renewable resource capital consumption is fully in accordance with the Hotelling definition described in the above section on the Hotelling approach.

Rearranging equation *(18)* to express the share of capital consumption in the resource rent gives

$$(19) \quad 1 - X/R = (1+r)^{-n}$$

---

[3] Alternatively, equation (16) can be written as
$X^* = X(1+r)/r$
The reason why the right hand side is not just X/r is that the first period is not discounted because we calculate the present value at the time of receiving the first payments.

Serafy (1989) suggests that the remaining time span of the depletion program, *n*, can be approximated by dividing the extraction per year, *Q*, in the total stock, *S*.[4] Equation *(19)* then becomes

$$(20) \quad 1 - X/R = (1+r)^{-(S/Q)}$$

The resulting formula is very appealing since data are relatively easy to get and the result can be understood by intuition. It is simply the discount factor at the end of the extraction program. The capital that should replace the resource units extracted is the present value of the resource units, had they been kept in the ground to the end of the program.

Equations *(18)-(20),* however, state that any estimate, based on the El Serafy formula depends critically on two parameters: the time span of the depletion program and the rate of discount. Serafy (1989) also shows this with detailed tables. Additionally, rent (i.e., prices and costs) as well as the extraction rate is assumed to be constant throughout the depletion period. In the following sections, I shall review the role of these assumptions in turn.

Time Preference Structure

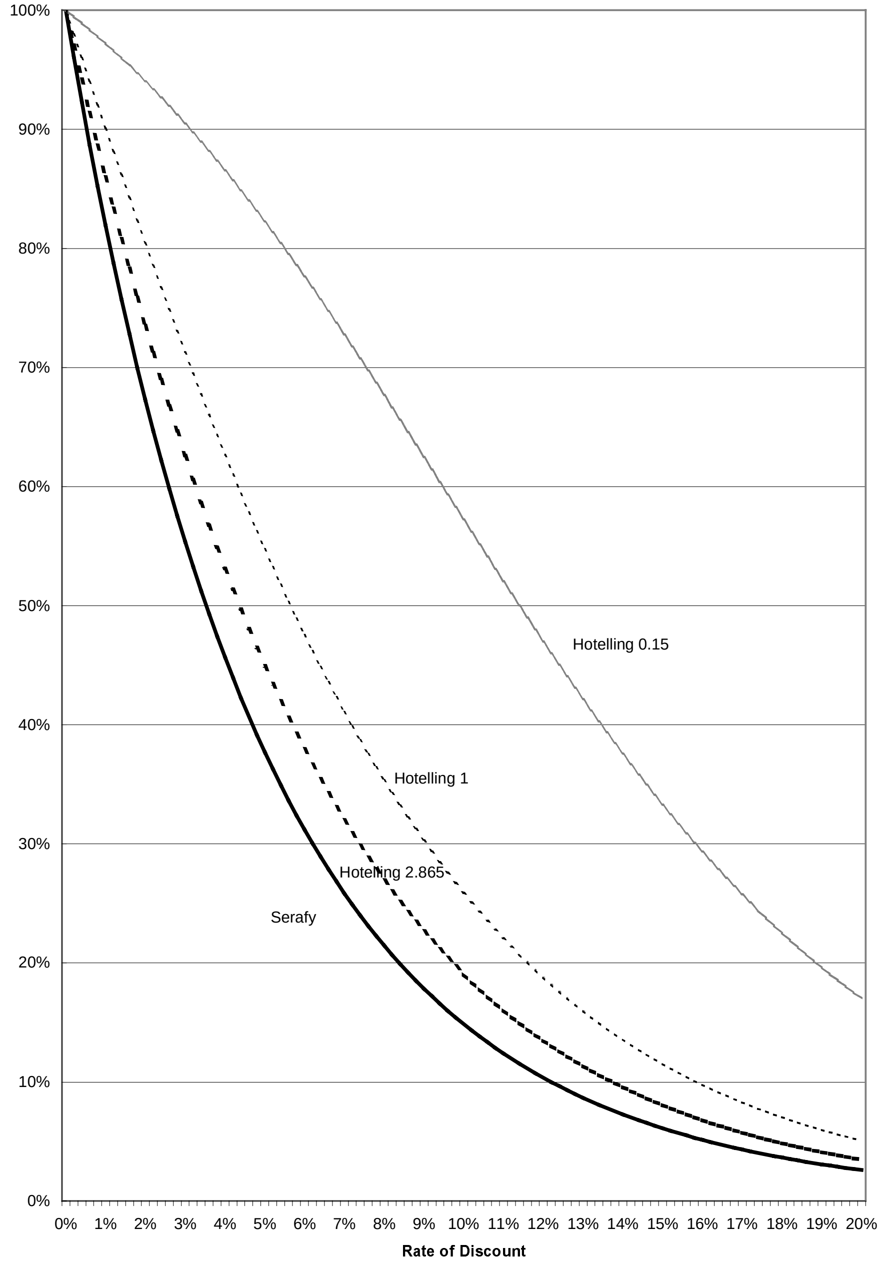
The Rate of Discount

As seen by equations *(11)* and *(19)* any user cost depends critically on the type and strength of time preference assumed and at which point in time, the alternative use is assumed to take place. This was also noted by Serafy (1989) and by Winter-Nelson (1996) who found that aggregate measures of rent from mineral extraction based on the El Serafy formula are very sensitive to the choice of discount rate. In fact, this is an understatement since the discount rate within a rather narrow range of values and given a realistic depletion period determines almost everything.

The figure below shows the Hotelling and Serafy distribution keys for the total resource rent from an extraction programme with 20 years to terminal time for varying rates of discount. The Hotelling curve is computed with an assumption of a cost elasticity of 2.865.

[4] *S* must be the stock at the beginning of each accounting period since we include the present period in the n period depletion program.

Figure 1: The Dependency of the Capital Consumption Share of Total Resource Rent on the Rate of Discount. T-t = 20, β = 0.15, 1, 2.865.



Source: Author's calculations

The diagram shows three curves based on the Hotelling approach differing by cost elasticities of 0.15, 1, and 2.865, respectively. Vincent and Rozali (1997) studying oil rent in Malaysia used the 0.15 elasticity. As noted above the character of the scale economies is reflected in whether the elasticity is below or above 1. The cost elasticity of 2.865 used by Vincent et al. (1997) for oil extraction in Indonesia is a representative of the class of decreasing returns cost functions, which is delimited by the Hotelling 1 curve and the Serafy curve.

In this case, the capital consumption share of the receipts can vary from 100% if the discount rate is zero to practically nothing if the discount rate is 20. This is true for both of the approaches. Thus, they both reduce to the total resource rent if the rate of discount is zero.

Against this background the discount rates actually used in empirical studies are surprisingly poorly justified, if they are justified at all. Serafy (1989) recommends a 5% discount rate, with reference to what the classical economists called a natural rate of time preference. Bartelmus et al. (1993) used a 10% discount rate without explicit justification and so did Tongeren et al. (1993) in a similar study of Mexico and Castaneda (1997) in a study of Chile.

Vincent et al. (1997) provides some justification of their use of a discount rate of 12.5% for Indonesia, referring to the high social opportunity cost of capital and high social rate of time preference in fast-growing economies. Vincent and Rozali (1997) argue in a similar study of resource rents in Malaysia, that the rate of discount could be as much as 10%, which is between the opportunity cost of capital and the social rate of time preference in a fast-growing economy like Malaysia.

It is interesting to note that if decreasing returns to scale is considered the most realistic assumption, the choice of discount rate can be more important to the estimate than the choice of cost elasticity. The capital consumption estimate is more sensitive to the choice of discount rate within the 5-12.5% range than to the choice between the Serafy or the Hotelling approach irrespective of how much higher than 1, the cost elasticity is.

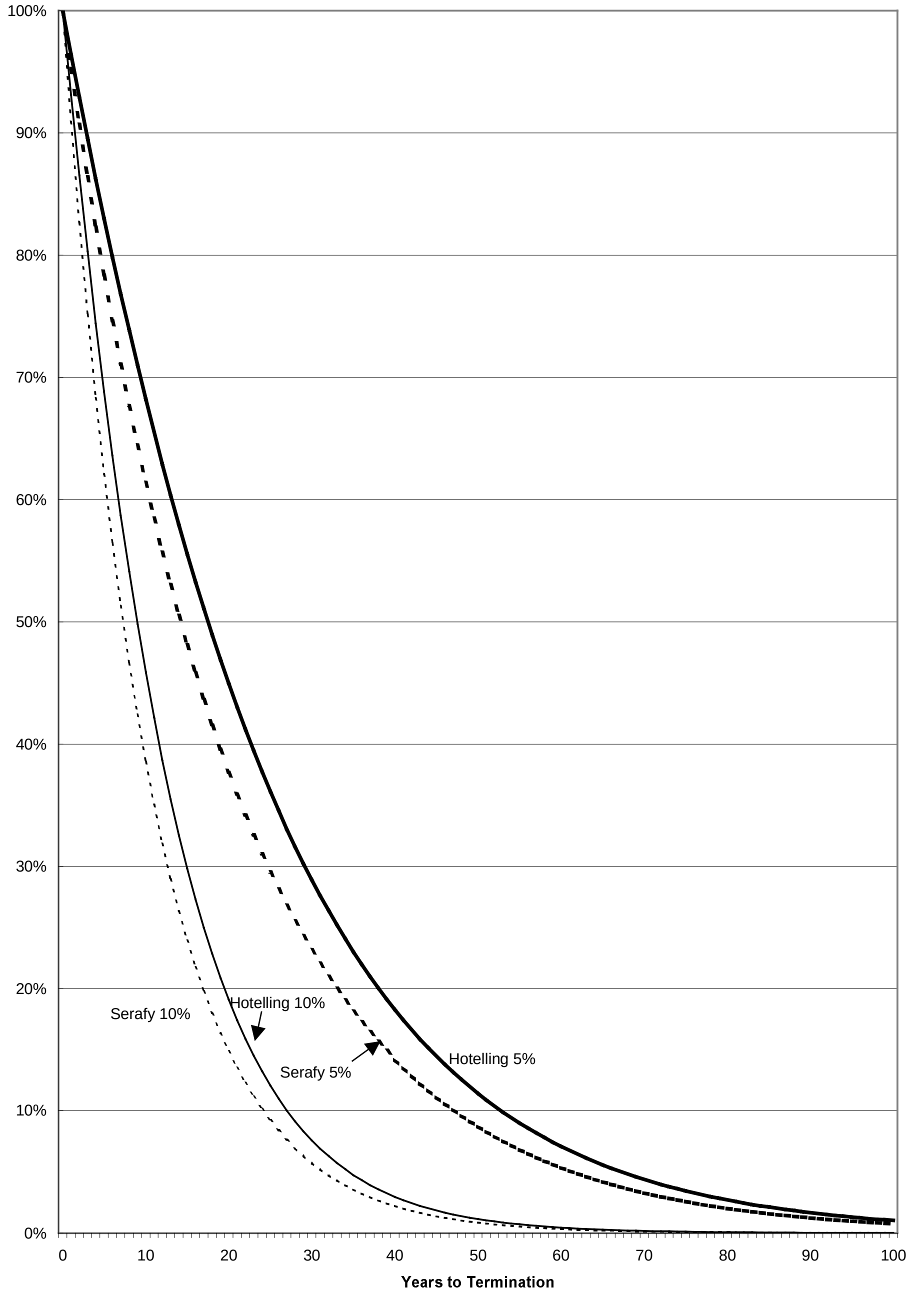
Of cause, the crucial role of the rate of discount declines as the extraction programme approaches termination. In the last year, there is no discounting at all.

The Discounting Horizon

It was shown above that the rate of discount is critical in determining the share of the total resource rent that is accounted for as natural capital consumption. Since the assumptions about the depletion program determine how many periods are discounted, these assumptions are as critical as the rate of discount itself.

The following diagram shows the relation between time to final exhaustion and the ratio of capital consumption to total resource rent. Two pairs of curves representing 5% and 10% discount rates respectively are shown.

Figure 2: The Dependency of the Capital Consumption Share of Total Resource Rent on the Time Distance to Final Exhaustion. R= 5%, 10%, β = 2.865.



Source: Author's calculations

Figure 2 shows that the time span of the depletion program plays an important role in both approaches because the estimated time to terminal extraction is the discounting horizon in both approaches. In any case, the capital consumption share will be 100% when the last resource unit is extracted. But how much, it will be in earlier stages of the extraction program, depends on the size of the resource stock.

Even if the difference between the estimates based on the Hotelling approach and the estimates based on the Serafy approach are small, they give rise to a puzzling question. How can a natural capital consumption estimate based on the smaller Hotelling rent come out as larger than an estimate based on the larger total rent? Both rent estimates are converted to capital consumption by discounting. It is difficult to give an economic explanation of this paradox, but the mathematics is clear. The Hotelling capital consumption share according to equation *(11)* is equal to $[(1+\beta)/[(1+\beta)(1+i)^{(T-t)}]$. Comparing this to equation *(20)* shows that the difference is that the latter is more cautiously discounted. Only part of the denominator in *(11)* is discounted.

In some studies, the Serafy approach yields higher estimates of capital consumption than the Hotelling approach. This is, however, not due to the basic properties of the two approaches, but to the discounting horizon given by the time distance to final exhaustion. As noted above, Serafy (1989) recommends estimating this period as the reserves-to-production ratio. This recommendation follows naturally from the assumption of a constant quantity of extraction. The logic of the Hotelling approach is, however, based on the time distance to *actual* terminal extraction. Extraction profiles normally do not follow a constant extraction path. Typically, extraction increases to its maximum and then declines gradually to terminal time. Thus, the time distance to actual terminal extraction may be more than twice as large as the reserves-to-production ratio.

The comparisons between estimates based on the two approaches also show that if it is realistic to assume decreasing returns to scale, the estimate may be *more sensitive to the choice of discount rate and discounting horizon than it is to the choice of cost elasticity*.

The importance of being aware of these proportions are emphasised by the results of theoretical research showing that the shadow prices on natural resources depend critically on the type and strength of time preferences (Howarth and Norgaard 1992; Asheim 1994; Heal 1997). Since user-costs and shadow prices are the same, I shall examine how alternative types of time preference can affect the user-cost.

In the following section, some of the problems involved in the choice of rate and horizon of discounting will be discussed.

The Arbitrary Element of the Discounting Horizon

The standard concept of recoverable reserves that is normally used is the proven reserves or the proven and probable reserves. Experience shows that discoveries of additional reserves and technically and economically induced increases in the recovery ratio leads to ultimately recoverable reserves that are larger than the at a given time known reserves – although this property cannot be maintained forever.

Additionally, the use of R/P[5] as the discounting horizon has the flaw that R/P is not an estimate of the remaining time to final exhaustion but should rather be interpreted as the inverse speed of exhaustion at the time it is estimated. This speed is not constant in any country, at least as far as fossil fuel reserves are concerned. IEA (1998) therefore uses the Hubbert curve as a general description of the depletion profile of a country's reserves. The Hubbert curve has a symmetric bell-shaped profile, which carries similarities with the Gaussian error or normal distribution function (Laherrère 1999). The symmetry question can be subject to discussion (IEA 1998; 97), but the general form of a gradual increase to a peak followed by a gradual decline fits fairly well with actual depletion profiles of given reserves.

The general description of the of the Hubbert curve is

$$(21) \quad q = 2q_m/(l+COSH(-b(T-t_m))),$$

where q is the annual production, q_m is the production at its maximum, T is time of final exhaustion, and t_m is the time of peak of the curve (Laherrère 1999).

Lahererre (1999) shows that this formula can be approximated to the identity

$$(22) \quad G = 0.8q_m c,$$

where G is the ultimately recoverable reserve and c is half the width of the curve at $q = 0.01q_m$. On this basis, a rule of thumb for estimating T can be derived by rearranging *(22)* and adding c to t_m.

$$(23) \quad T = t_m + 1.25G/q_m.$$

The Hubbert curve is definitely closer to the depletion profile of a typical oil reserve than a constant extraction assumption, but not necessarily the best approximation. There is no reason for not taking historical extraction data, geological knowledge of remaining reserves and the scarce data on costs and prices into account and adjust the predictions accordingly.

---

5 The notation of ratio of physical stocks and production now shifts from the previous "S/Q" to "R/P", which is standard in physical mineral reserve statistiscs.

When the estimate as shown above depends critically on the choice of discounting horizon, and this horizon is equalled with the time to final exhaustion, then the approximation of the final exhaustion with R/P is particularly harmful.

The use of R/P instead of a more realistic time distance to final exhaustion, thus causes an implicit systematic error in the estimates. It could be argued that a prediction of future depletion profiles always would be very uncertain, so one might as well use a rule of thumb. It is, however, not advisable to use a rule of thumb, that gives estimates that by a high degree of certainty not will be realised. A rule of thumb, which has a chance to hit the reality should be preferred.

It could also be argued that in an inter-generational distribution perspective, the choice of depletion profile does not matter. What matters is the transformation of the entire recoverable reserve to an equivalent stock of capital that can sustain a constant income stream. But it turns out that the assumption of depletion profile has a decisive impact on the income stream that can be sustained indefinitely from a given reserve.

Assume that there are two countries, A and B, which have identical economies and both posses a mineral reserve of 100 units. They both pursue the same intergenerational distribution objective reflected in their accounting of natural capital consumption using the Serafy approach. They differ only in their choice of depletion program. A exhausts its reserve over 10 years while B extends the program over 50 years. Assume that a resource rent of 1 is attached to each resource unit and the rate of discount is 3%.

With the Hicksian approach, the infinitely maintainable income from the reinvested resource rent is the returns to the accumulated stock of reproducible capital. The stock of accumulated capital after termination of the depletion program is the sum of the capital consumption shares of the annual resource rent equal to $R^*(1+r)^{-1}$. Inserting in *(15)* we get

$$(24)\quad R^*(1+r)^{-1} = R(1 - (1+r)^{-n})(1+r)^{-1} / (1 - (1+r)^{-1})$$

that can be rearranged to the permanent returns to the reproducible capital stock as

$$(25)\quad rR^*(1+r)^{-1} = (S/n)(1 - (1+r)^{-n})$$

The right hand side is not invariant for changes in n. S/n declines and $(1 - (1+r)^{-n})$ increases as n is increased, but not in the same proportions. That is, the permanently maintainable consumption level varies with n for a resource stock of a given size.

Inserting the values for country A and B yields a permanently maintainable income during as well as after the depletion program of 2.6 in country A and 1.5 in country B.

This difference in outcomes is a result of assumptions about the depletion program that are rather arbitrary in an intergenerational distribution context. It is hard to find any justification for dependency of the permanent income from the resource rent on the length of the depletion period.

Serafy (1989) also notes that the relation between S/Q and the capital consumption share also works the other way. The country that holds resource depletion (Q) back will have a larger true income share and a smaller capital consumption share. On face value it is true that this could serve as an incentive to conserve mineral resources, but as we have seen, it will in the long run be a disadvantage to future as well as present generations.

Alternative Solutions to the Discounting Problem

Atkinson et al. (1997) address the problem by showing that the share of capital consumption in the resource rent according to the Serafy formula differs considerably from country to country depending on the remaining reserve. Table 1 is reproduced from the article. It shows that a country like Iran with a reserve to production ratio (R/P) of 115 years would have only 3% of the total resource rent accounted for as natural capital consumption. UK with a R/P of 5 years would have 86% of the total resource rent accounted for as natural capital consumption. The table also includes comparable cost estimates, using the Hotelling approach with cost elasticities 1 and 2.865.

Table 1. Average Oil Capital Consumption in 1980-90 for selected oil producers. Estimated with a constant rate of discount 3% and R/P as discounting horizon using the Serafy and Hotelling estimation approaches. Per Cent of Total Resource Rent and in mio. US$ (1990).

(n=R/P)	Pro-duc-tion	Re-serves	R/P	Unit Rent *	Total Rent	Serafy		Hotelling 1		Hotelling 2.865	
	Mio t	*Mio t*		*US$/t*	*US$ mio*	*Pct*	*US$ mio*	*Pct*	*US$ mio*	*Pct*	*US$ mio*
Algeria	49	1800	37	125	6051	33%	2025	50%	3034	40%	2446
Congo	6	110	19	126	741	58%	427	73%	542	65%	480
Indonesia	70	726	10	86	6051	74%	4457	85%	5133	79%	4783
Iran	111	12700	115	159	17617	3%	597	7%	1155	5%	796
Mexico	130	6079	47	103	13451	25%	3387	40%	5412	31%	4200
Nigeria	75	2400	32	132	9861	39%	3825	56%	5511	46%	4544
UAE	73	1300	18	161	11668	59%	6868	74%	8646	66%	7686
United Kingdom	104	535	5	55	5727	86%	4919	92%	5292	89%	5105
Venezuela	100	8604	86	111	11142	8%	880	15%	1632	10%	1156

* These figures were derived from the data on "Total Rent" and "Production" in the source. For Congo the figure was replaced by a more realistic figure, since it seemed to be due to a printing error.
Source: Atkinson et al. (1997;82) and author's calculations.

The first column shows average production in 1980-90 while the second column shows the reserves. The third column shows the reserve-to-production ratio and the fourth the total rent per unit ("unit rent"). The Serafy and Hotelling estimates of natural capital consumption are calculated using equations *(20)* and *(11)*. They are presented both in percentage of total rent and in million US$ (1990-prices) and are calculated with a 3% rate of discount and R/P as discounting horizon.

The Serafy approach yields estimates of capital consumption shares between 3% and 86%. The corresponding Hotelling 1 estimates vary between 7% and 92%. Estimates based on other cost elasticities larger than 1 will be in between the corresponding estimates of these two columns.

Irrespective of approach the in some respects arbitrary choice of discounting horizon is responsible for most of the variation. One way to prevent this arbitrary element to become too dominant is to choose a low rate of discount. Atkinson et al. (1997) suggested this. There are, however, a number of alternatives.

One alternative could be to use a rate of discount that is constant in the near future and then gradually declining possibly to zero in the far future. This approach was suggested by Weitzman (1999). The logic of this approach is that the future may consist of several different scenarios with different rates of discount. The further we look into the future, the less weight is attached to the scenarios with high rates of discount since the present value of those will diminish rapidly. Ultimately, the scenario with the lowest rate of discount will represent the future. The problem in implementing this idea is that it is difficult to justify the level and time profile of the discount rate without having the plausible scenarios at hand. These scenarios would probably differ much from country to country.

Another alternative could be to discount only over the horizon of the present generations. There is not a clear-cut definition of this horizon. Demographically, the length of a generation could be defined as the median age of mothers giving birth to a child. The highest fertility rates are in most countries among women of age 25-29. In some countries, predominantly the formerly centrally planned economies, some Latin American, and a few African countries, the highest fertility rate is in the age of 20-24. In the table below, the horizon of a generation is taken to be 25 years. Note, however, that deriving the planning horizon from demographic data in this way is not the only way and not necessarily the best way to do it.

A third alternative could be to use the Chichilnisky (1996, 1997) sustainability criterion. According to this criterion, the social welfare function reflecting explicit concern for future generations is the weighted sum of the net present value of future welfare (normally discounted) and the undiscounted level of future welfare as time goes towards infinity. Heal (1997) shows that the shadow price of a resource unit will be higher under this criterion than under a utilitarian welfare function without the undiscounted component.

This is due to the different valuation of the far future. Maximisation of this function reflects a time preference profile where a share of future welfare is discounted and a share is not. The major problem in operationalising this idea is how to attach reasonable weights to the part of the welfare function that concerns welfare to the present generations and the part that concerns welfare to the future generations. Ultimately this decision must be based on intergenerational distribution ethics, but a starting point could be equal weights, *0.5/0.5*. The weighted discount factor would then be $0.5*(1+r)^{-n} + 0.5$.

Finally logarithmic discounting could be used. Logarithmic discounting reflects time preference where relative rather than absolute time distance is valued. The logarithmic discount factor would be n^{r}, where r is chosen higher than typical discount rates reflecting the extremely high time preference behind the interest rates on very short term markets.

The following table shows natural capital consumption under alternative time preference structures in percent of total resource rent and in millions US$ for the same countries as in table 1.

Table 2. Average Oil Capital Consumption in 1980-90 for selected oil producers. Estimated with non-constant discounting and R/P as discounting horizon using the Serafy estimation approach. Per Cent of Total Resource Rent and in mio. US$ (1990).

Serafy	**n = R/P**		**N=25 if R/P>25, otherwise n=R/P**		**Weighted discounting**		**Logarithmic discounting**	
	Pct	*US$ mio*	*Pct*	*US$ mio*	*Pct*	*US$ mio*	*Pct*	*US$ mio*
Algeria	33%	2025	48%	2890	67%	4038	58%	3520
Congo	58%	427	58%	427	79%	584	64%	478
Indonesia	74%	4457	74%	4457	87%	5254	70%	4262
Iran	3%	597	48%	8414	52%	9107	49%	8652
Mexico	25%	3387	48%	6424	63%	8419	56%	7558
Nigeria	39%	3825	48%	4710	69%	6843	59%	5862
UAE	59%	6868	59%	6868	79%	9268	65%	7568
United Kingdom	86%	4919	86%	4919	93%	5323	78%	4479
Venezuela	8%	880	48%	5321	54%	6011	51%	5713

Source as table 1.

The first pair of columns repeats the Serafy estimate with n = R/P from table 1. The second pair of columns shows the discount factor if the discounting horizon was set to 25 for countries with R/P higher than 25 and to R/P otherwise. The third set shows the weighted discount factor and the resulting natural capital consumption estimate. As noted above, the present and the future have been assigned equal weights. The fourth pair of columns shows the logarithmic discount factor and the corresponding natural capital consumption estimate. A discount rate of 15% has been used here whereas the other estimates were calculated with a 3% discount rate.

Each of the discounting approaches considerably reduces the variation caused by the assumed time distance to terminal extraction, but some of this variation remains. The lower boundary of the range of estimates has now been raised from 3% in the constant discounting case to 48%. This is the effect of giving more weight to future welfare than is the case with constant rate discounting. Non-constant discounting produces estimates of resource capital consumption in between the Total Rent approach with its inherent Golden Rule ethics and the user-cost approach with its inherent constant consumption level ethics.

Such estimates may be relevant whenever a country adopts targets for sustainable development that reflects such an intermediate position in intergenerational distribution. For instance, it is possible that developing countries and countries with economies in transition will find the constant consumption ethics too unambitious for their development strategy.

What happens if we substitute the R/P assumption of the depletion profile with the more realistic Hubbert curve assumption? Tables 3 show the effect on the user-cost estimates. The final exhaustion time, T, is derived from equation *(23)* using estimates of ultimately recoverable reserves and peak time and levels from Duncan and Youngquist (1998).

Table 3. Average Oil Capital Consumption in 1980-90 for selected oil producers. Estimated with a 3% rate of discount and time to final exhaustion (T-1985) as discounting horizon using the Serafy and the Hotelling estimation approach. Per Cent of Total Resource Rent and in mio. US$ (1990).

	R/P	**Peak Time**	**Peak Prd.**	**EUR**	**T**	**T-1985**	**Serafy**		**Hotelling 1**	
		Year	*Mio bl*	*Mio bl*			*%*	*US$ mio*	*%*	*US$ mio*
Algeria	37	2002	0.58	28.5	2063	78	10%	603	18%	1097
Congo	19	2003	0.11	3.6	2044	59	17%	130	30%	221
Indonesia	10	1977	0.62	38.1	2054	69	13%	787	23%	1393
Iran	115	1974	2.21	129.6	2047	62	16%	2819	28%	4860
Mexico	47	2001	1.32	56.6	2055	70	13%	1699	22%	3017
Nigeria	32	2004	0.96	48.8	2068	83	9%	848	16%	1562
UAE	18	2017	1.77	85.4	2077	92	7%	769	12%	1443
United Kingdom	5	1995	1.01	44.2	2050	65	15%	839	26%	1463
Venezuela	86	2005	1.47	115.1	2103	118	3%	341	6%	661

Source: Atkinson et al. (1997;82), Duncan and Youngquist (1978), and author's calculations.

The first column shows again the reserve-to-production ratio. The peak time, peak level, and estimated ultimately recoverable reserves *(EUR)* reported in the second to fourth columns are from Duncan And Youngquist (1998). Inserting these figures in equation *(23)* gives *T* and the distance from 1985 to *T* is given in the sixth column. These figures seem quite optimistic in the case of, e.g., UK, cf. the critical remarks to the Hubbert curve above.

The last two pairs of columns are the user-costs according to the Serafy approach and the Hotelling approach with a cost elasticity of 1. Again, other cost elasticities above 1, will produce estimates in the range between these two.

The estimates in table 3 are several orders of magnitudes smaller than the estimates in table 1. This shows that the choice of *n*, which has received very little attention and is rather poorly justified in many empirical studies, can be the most important choice in the estimation study.

The effect of applying the same depletion profile assumptions as in table 3 along with a time preference ordering that places more weight on future generations' well-being than constant rate discounting does, is shown in table 4. Here we only use the Hotelling approach since the logic of the

Serafy approach is built on the constant level of extraction assumption, while the logic of the Hotelling approach is in fully accordance with the Hubbert curve depletion profile.

Table 4. Average Oil Capital Consumption in 1980-90 for selected oil producers. Estimated with non-constant discounting and time to final exhaustion (T-1985) as discounting horizon using the Hotelling estimation approach. Per Cent of Total Resource Rent and in mio. US$ (1990).

	T-1985	**Logarithmic discounting 15%**		**Logarithmic discounting 25%**		**Weighted discounting 3%, Weights 0.5/0.5**	
		%	*US$ mio*	*%*	*US$ mio*	*%*	*US$ mio*
Algeria	78	68%	4141	50%	3047	31%	1858
Congo	59	70%	521	53%	393	46%	340
Indonesia	69	69%	4192	52%	3117	37%	2265
Iran	62	70%	12332	53%	9257	43%	7618
Mexico	70	69%	9304	51%	6911	37%	4928
Nigeria	83	68%	6708	50%	4908	27%	2697
UAE	92	67%	7856	49%	5696	22%	2568
United Kingdom	65	70%	3990	52%	2983	41%	2330
Venezuela	118	66%	7317	47%	5187	11%	1248

Source: As table 1.

Table 4 shows two variants of logarithmic discounting. One with 15% discount rate and one with 25% rate of discount. The weights and constant rate of discount in the weighted discounting case are the same as above. In all cases the discounting horizon is the same as in table 3.

Now the differences to the original user-cost estimates in table 1 are more mixed. This is because the range of discounting horizons have been narrowed down due to more realistic assumptions and because the future is not discounted as powerful as in the constant rate of discount case. It is interesting to note, that the combined effect of this is that all estimates of the capital consumption share with 15% logarithmic discounting are close to 70%, whereas raising the logarithmic discount rate to 25% produces estimates in the vicinity of 50%.

These methods could be useful in analyses of intergenerational distribution based on other ethical perspective than the constant-level-of-consumption and the corresponding user-cost approach (Serafy or Hotelling). If the analysis is concerned with the savings required when the future returns to capital are uncertain and may be lower in the far future, it is possible to reflect this assumption in one of the alternative discount factors

The use of non-constant discount allows applying the same intergenerational ethics in the allocation of non-resource income between consumption and savings as in the allocation of the total resource rent between consumption and savings. This could be relevant in countries that regard a constant level of consumption ethics as an inappropriate basis for the development strategy.

To be sure, the alternative estimates presented in the tables should not be interpreted as recommendations but as examples of how different preferences for the well-being of future generations that are reflected in the discounting horizon affects the natural capital consumption estimate.

The above estimates show that assumptions of time preference are crucial to the natural capital consumption estimates. Considerations of how to choose empirically founded parameters in the case of non-constant, unweighted discounting is, however, sparse. This is an important task for future research.

New Discoveries and Capital Gains as Substitutes for Investments

When a unit of non-renewable resource is extracted, it unquestionably reduces the stock of the resource available to future extraction correspondingly. But other actions may change the resource stock and its associated wealth as well. The discovery of new deposits. Lasting changes in future prices and costs. Reassessments of known deposits. How should such changes be accounted for in the non-renewable accounts? The central economic question is whether new discoveries, reassessments and changed expectations of prices and costs that increase the value of a country's mineral stocks can be a substitute for investing the resource rent.

One of the pioneering green national accounts studies by Repetto et al. (1989) focused at the changes in proven and probable reserves in the Indonesian economy. They obtained the result that mineral wealth actually increased at the same time as finite mineral stocks was consumed. This was in part due to the price increases of the two oil shocks, but also in part due to new discoveries. They did, however, not include these changes in their estimates of resource capital consumption.

Peskin (1989) argued that they should be included, although not using a single year's price estimate, which would cause significant fluctuations in the resource capital consumption estimate.

Hartwick and Hageman (1993) also recommended that resource capital consumption should be computed net of additions from new discoveries and price increases. That is, "growth" of non-renewable resources adds to national wealth and thus compensates for simultaneous consumption of them. Or, put in another way, the question is whether that kind of increases in mineral wealth can be a substitute for investing the resource rent.

USGS (2000) provides a useful systematic framework for defining the resource stock more exactly, which may help to clarify these considerations. The total stocks of petroleum and gas are defined as the sum of *identified* reserves (proven, probable, and possible), the expected *"growth"* of these due to better knowledge of their extent and improved extraction techniques, and the still *undiscovered* resources, expected to be discovered on the basis of general geological knowledge. The sum of these stock concepts and the cumulative production until now is the estimated ultimately recoverable reserves.

It is important to be conscious about which of these stock concepts the mineral reserve in question refers to. In an intergenerational distribution perspective, the reserves available to future extraction must be the relevant stock concept. Note that neither reassessment of existing deposits nor discovery of new deposits adds to the total stocks that are available for future extraction. These activities only reclassify already existing geological structures. Consequently they do not transfer wealth from the present to the future and they can not be a substitute for reinvesting the resource rent.

In an assessment of the strength of a particular economy for the next, say, 10 years, the identified reserves are the relevant concept. Reserves have to be identified before they can be extracted and within such a time perspective, the undiscovered reserves and expected "growth" of identified reserves may not be likely to appear.

In the user cost approaches, changes in the physical stock are automatically reflected in the discounting horizon. Higher estimates of the ultimately recoverable reserves or the reserves available for future extraction gives a longer horizon and thus a smaller user cost. In this way, these approaches reduce the investment requirements in the case of new discoveries even if the discoveries themselves are do not enter the accounts.

The question of reassessments of the value of mineral stocks due to changes in price or costs is more complicated. The short-term price volatility that can be observed in many mineral markets is mirrored in the unit rent due to the definition of the rent as a residual after deducting costs of labour and capital from the price or value. This complicates wealth accounting because prices affect not only the rent but also the value of the resource capital.

Technically, such problems can be remedied by using moving averages, but how should expectations of future price trends and changes in them enter the accounts?

Vincent et al. (1997) used a method of extending the Hotelling approach with resource revaluation. The calculation of the economic depreciation was improved by including the present value of anticipated price changes (calibrated with formerly realised prices). It was shown in a simplified model that investing the resource rent according to the Hotelling approach without taking account of future trends in prices was insufficient to keep the mineral wealth constant. The theoretical result was empirically demonstrated in the case of Indonesia. The conclusion was that Indonesia should have invested more than the Hotelling rent to offset the economic effects of declining oil prices after 1986. Capital gains and losses should be accounted for, but without confusing short-term volatility with long-term trends.

This point is probably justified in the case of Indonesia and also in the theoretical model used. The simplified model did, however describe an economy that did not consume oil but only exported it in exchange for consumer goods. If more realistic assumptions of domestic production of consumer goods and domestic consumption of oil were introduced into the model, the result could have been modified to some extent. The lower oil price did lower the rent in the resource extracting industry, but it must also have increased the consumable income in the other sectors of the economy. If the degree of self-sufficiency is exactly one, these two effects can net out and the capital gain (or loss) adds nothing to the consumption opportunities of the economy. Capital gains in the mining industry will be counter balanced by capital losses in the rest of the economy. If the country is a net-importer, the net-effect is negative. Only to the extent the country is a net exporter of the raw material in question, a capital gain will reflect a positive effect on consumption opportunities.

However, this latter conclusion overlooks the fact, that no country can be a net exporter of an exhaustible resource forever. The terms of trade improvement for a net-exporter of a non-renewable resource good must be transformed to a terms-of-trade worsening when the resource is so depleted that the country becomes a net-importer of the resource good. Therefore the net present value of the welfare change due to changes in resource price should be extended to infinity and include the welfare change following from using the resource as an input as well. The latter can be assumed to be capitalised in reproducible capital stocks. Then, the sign of the net present value of even a lasting price increase will depend on how heavily the future is discounted.

The discount rate itself is derived from expectations of the growth prospects of the economy. Thus, if a future rising price trend affects future growth negatively, it should be reflected in a lower rate of discount. This will in the user cost methods to some extend offset the effect of the initial increase in unit rent on the consumable resource rent.

In sum, capital gains and additions to reserves are not substitutes for investing resource rents if the investment requirements in an intergenerational perspective are considered. In a shorter perspective, e.g., 10 years, which normally is considered “long term” in economic policy, capital gains and physical additions to reserves can, however, be crucial for an assessment of the economy and its investments requirements.

A Repurchase or Physical Approach

A more direct approach has been discussed in the Danish debate (Mortensen and Larsen, 1994; The Danish Economic Council, 1998). According to this approach, sustainable use of fossil energy requires compensating investments in renewable energy capacity, joule by joule. In this way, the future generations are secured a potential energy supply equal to the potential supply prior to extraction. Thus it can be seen as an approach of valuing resource consumption at repurchase prices (in a wide sense) or as a physical approach of valuing resource consumption at prices that can sustain the physical properties (e.g., energy supply) of the initial resource stock.

This approach implies a final strategic goal of expanding the renewable energy sector to a level that corresponds to the energy content in the exploitable reserves at the time of introducing this principle. This type of strategy can be named a conversion strategy since it is aimed at converting the energy generation capacity of a country from fossil fuel based to renewable source based technologies. In this sense, it is a "strong" sustainability approach, targeting at a certain energy producing capacity rather than at a certain stock of general capital.

In its original form, the repurchase approach has a major drawback, which was pointed out by The Danish Economic Council (1998). If the future renewable energy capacity should be determined by the oil reserves that are exploited at present, most of the future renewable energy capacity would be installed in the now oil producing countries. This would not be recommendable since renewable energy production is typically most economic when it is close to where the energy is used.

If the strategic target instead was an energy generating capacity corresponding to some share of future energy consumption, we would solve the problem of location, but the investment obligations would still be attached to a conversion program rather than to the current resource exhaustion. Thus it would make little sense to let the resource rent from current oil and gas extraction govern the size and the speed of the program. It would be more economic to let markets allocate capital to the program according to a credible future demand for renewable energy. This is in fact what the Danish renewable energy strategy does. If the pace of the program should be tied up upon the current extraction of fossil fuels, disregarding efficiency considerations, it would probably be more costly.

If the approach is modified so that the expansion of the renewable energy sector is independent of the current energy consumption, we are back in a scenario where such a long-term investment program must be balanced against other long term goals of society.

Summary and Conclusions

This paper has reviewed a number of alternative methods for estimating non-renewable resource capital consumption. The purpose was to explore the assumptions one has to make when using the one or the other method.

The fundamental choice is the intergenerational distribution ethics behind the estimation approach. The Total Rent or net-price approach gives the answer to the question of how much of the resource rent should be reinvested if all resource rent belongs to the future. This would be the case if a Golden Rule ethics was pursued. A modified Golden Rule ethics, resting on the premise that the annually extracted rent should be equally distributed between the present and the future generations, was discussed. Even in this case, the ethics is weak since the answer would exclude the entitlement of the present generation to allocate its future consumption optimally.

The user-cost approaches give the answer to the question of how much of the resource rent should be reinvested if a constant consumption level should be maintained from the current year and infinitely, that is, also after the reserves have been ultimately depleted. This approach assumes traditionally in the empirical studies a constant rate of returns to capital.

Some intermediate approaches give the answer to the question of how much of the resource rent should be reinvested if the future returns to capital are increasingly uncertain or, put in another way, if our time preference includes specific preferences for the welfare of future generations.

The importance of knowing which question we are seeking the answer to cannot be exaggerated. A series of examples shows that the differences in estimates based on different approaches are considerable. The most critical assumptions are those of time preference, depletion horizon, and costs.

The table below summarises the share of total rent that should be accounted for as capital consumption according to the different approaches.

Table 5. Summary of capital consumption share in total rent according to the different estimation methods.

	Capital consumption share in total rent
Hotelling with observed mc	$(p-mc_t)/(p-ac_t)$
Hotelling with assumed mc	$(1+\beta)/[1+\beta(1+r)^n]$
Serafy	$(1+r)^{-n}$
Weighted discounting	$\omega(1+r)^{-n} + (1-\omega)$
Logarithmic discounting	n^r

Key parameters:

p Price

ac Unit costs (average costs)

β Cost elasticity

r The rate of discount

n Time to terminal extraction

ω The weights given to the present and the distant generations

The critical assumptions attached to these parameters are:

p: Price taking optimal depletion behaviour. The Hotelling with observed *mc* interprets the difference between the price and the observed marginal costs as the Hotelling rent. Hotelling with assumed mc calculates the Hotelling rent as it would have been if there had been price taking optimal depletion behaviour and the cost structure was as assumed.

ac: The assumptions are standard national accounting assumptions.

β: For the Hotelling approach with assumed *mc*, the technological assumptions are comprised in the cost elasticity. Even if scale economies are not found plausible, the choice of β may have a non-trivial effect on the capital consumption estimate.

r: The choice of the rate of discount over a plausible range of values may have an even larger effect on the estimate. The user cost approaches normally assumes time preference and future certainty of capital returns consistent with a constant rate of discount. A declining rate of discount (here logarithmic discounting) can reflect a deeper concern for the wellbeing of future generations and/or uncertainty about future growth.

ω: Weighted discounting is an alternative or additional way to reflect such assumptions. Declining discount rates and a constant weight to the distant future yields considerably higher capital consumption estimates than comparable constant discount rates.

n: The assumptions of the remaining depletion profile and extent falls in two main categories:

1. Constant extraction path: $n = S/Q$ (or R/P)

2. Hubbert curve extraction path: $n = t_m + 1.25G/q_m - t$

Constant extraction can be assumed for any of the approaches, while Hubbert curve extraction requires a reformulation of the Serafy formula.

The widely used practice of estimating the time to terminal extraction by the reserves-to-production ratio is criticised for being arbitrary. As an alternative, the Hubbert curve is suggested, but it is emphasised that it should be adjusted by information on past and planned extraction activities and developments in costs and prices. The choice between these two assumptions of depletion programmes was the most critical in the shown estimates.

The combined use of the Hubbert curve and non-constant discounting produced a remarkable uniformity of the share of natural capital consumption in resource rent. For example, using logarithmic 15% discounting yields capital consumption shares in the vicinity of 50% for all the countries studied.

A repurchase approach for estimation of non-renewable resource capital consumption was also discussed. It was concluded that it gave the answer to an entirely different question. The question of how much of the national income should be invested in renewable energy to replace the fossil fuel extracted. The question the energy planning authorities would like an answer to is, however, how much of the future energy consumption should be provided for by renewable energy sources at different points of time considering the costs of this energy and supply security, it provides. Former mineral wealth is irrelevant to this question. Thus, it is the right answer to the wrong question.

The question of how changes in mineral wealth enter the accounts is discussed. It is concluded that reassessments and discoveries that leave the ultimately economically recoverable reserves unchanged are irrelevant to intergenerational distribution analysis. For assessment of the background for economic policy in the near future, say 5 to 20 years, this information can nevertheless be of great importance.

The results demonstrate that natural capital consumption estimates are far from as robust as their conventional national accounts counterparts. They rest on a number of ethical premises as well as technical and scientific assumptions that are non-trivial. Thus, the credibility of the estimates can be improved by devoting much more effort to thoroughly justification of the assumptions and to alternative calculations based on alternative assumptions. This is particularly important for the success of the efforts to extend the use of such capital consumption estimates in macroeconomic sustainability analysis.

LITERATURE

Adelman, M.A. (1972): *The World Petroleum Market.* Resources for the Future. John Hopkins University Press.

Adelman, M.A. (1986): *Scarcity and World Oil Prices.* Review of Economics and Statistics **68**:387-97.

Adelman, M.A. (1990): *Mineral Depletion, With Special Reference to Petroleum.* Review of Economics and Statistics **72**(1):1-10.

Ahmad, J.A., S.E. Serafy, and E. Lutz (eds.) (1989): *Environmental Accounting for Sustainable Development.* The World Bank, Washington D.C.

Arrow KJ, Cline WR, Mäler K-G, Munasinghe M, Squitieri R, Stiglitz JE (1996): *Intertemporal Equity, Discounting, and Economic Efficiency.* In Bruce JP, Lee H, Haites EF (eds.): *Climate Change 1995. Economic and Social Dimensions of Climate Change.* Cambridge University Press. 125-44.

Asheim, G. (1994): *Net National Product as an Indicator of Sustainabillity.* Scandinavian Journal of Economics, 96, 357-65.

Atkinson, G, R Dubourg, K Hamilton, M Munasinghe, D Pearce, C Young: *Measuring Sustainable Development. Macroeconomics and the Environment.* Edward Elgar 1997.

Bartelmus, P., E. Lutz, and S. Schweinfest (1993): *Integrated Environmental and Economic Accounting: A Case Study for Papua New Guinea.* In Lutz (1993) 108-54.

BEA, Bureau of Economic Accounting (1994): *Accounting for Mineral Resources: Issues and BEA's Initial Estimates.* Survey of Current Business, April 1994. 50-72.

Brekke, KA (1997): *Hicksian Income from Resource Extraction in an Open Economy.* Land Economics **73**(4): 516-27.

Castaneda, B.E. (1997): *An Index of Sustainable Economic Welfare (ISEW) for Chile.* University of Maryland, Institute for Ecological Economics.

Chichilnisky, G. (1996): *An axiomatic approach to sustainable development.* Social choice and welfare 1996; 13(2): 231-57.

Chichilnisky, G. (1997): *What is Sustainable Development?* Land Economics, vol. 73, no. 4, 467-91.

Daly, H. and J.B. Cobb, JR. (1989): *For the Common Good.* Boston.

Danish Energy Agency (Energistyrelsen) (1998): *Oil and Gas Production in Denmark 1997*. (English version). May, 1998.

Dixit, A., P. Hammond, and M. Hoel (1980): *On Hartwick's Rule for Regular Maximin Paths of Capital Accumulation and Resource Depletion*. Review of Economic Studies (1980) XLVII, 551-556.

Dubourg, W.R. and D.W. Pearce (1994): *Paradigms for Environmental Choice: Sustainability versus Optimality*. Paper presented at the International Symposium on Models of Sustainable Development, Paris, March 16-18, 1994.

Duncan R.C. and W. Youngquist (1998): *The World Petroleum Life-Cycle*. Paper Presented at the PTTC Workshop "OPEC Oil Pricing and Independent Oil Producers" October 22, 1998.

Ewers, H.-J., H.D. Brabander, H.-M. Brechtel, M. Both, E. Hayessen, B. Mohring, M. Moog, W. Nohl and U. Richter (1986): *Zur monetaren Bewertung von Umweltschaden. Methodische Untersuchung am Beispiel der Waldschaden*. Umweltbundesamt, Berichte 4/86, Erich Schmidt Verlag, Berlin.

Hansen, A.C. (1995): *Bæredygtig opsparing og dansk økonomi*. In P. Lübcke (ed.): *Miljøet, markedet og velfærdsstaten*. Copenhagen.

Hartwick, J.M. (1977): *Intergenerational Equity and the Investing of Rents from Exhaustible Resources*. The American Economic Review, vol. 67, no 5, 972-974.

Hartwick, J.M. (1990): *Natural Resources, National Accounting and Economic Depreciation*. Journal of Public Economics 43 (1990) 291-304, North-Holland.

Hartwick, J.M. (1989): *I. NNP and Economic Depreciation of Natural Resource Stocks* and *II. The Non-renewable Resource Exploring-Extracting Firm and the r% rule*. Discussion Paper #741. Department of Economics, Queen's University, Kingston, Ontario, Canada.

Hartwick, J.M. (1993): *Forestry Economics, Deforestation, and National Accounting* In Lutz (1993) op.cit.: 289-314.

Hartwick J.M. and A. Hageman (1993): *Economic Depreciation of Mineral Stocks and the Contribution of El Serafy*. In Lutz (1993) op.cit.: 211-35.

Heal, G. (1997): *Valuing the future. Economic Theory and Sustainability.*

Hicks JR ([1939]1946): *Value and capital: an inquiry into some fundamental principles of economic theory*

Hotelling, H. (1931): *The Economics of Exhaustible Resources*. Journal of Political Economy 39:137-75.

Howarth, R.B. and R.B. Norgaard (1992): *Environmental Valuation under Sustainable Development*. The American Economic Review, May 92, 82, 2, 473-77.

IEA (International Energy Agency) (1997): *Energy technologies for the 21st* *century*. OECD, Paris.

IEA (International Energy Agency) (1998): *World Energy Outlook 1998*. OECD, Paris.

Keynes JM (1936): *The General Theory of Employment, Interest, and Money*. MaCMillan, London.

Laherrère, J.H. (1999): *World oil supply. What goes up must come down – but when will it peak?* Oil and Gas Journal. Feb. 1. 1999.

Laherrère, J.H. (2000): *Learn strengths, weaknesses to understand Hubbert curve*. Oil and Gas Journal. Apr. 17. 2000.

Landefeld, J.S. and J.R. Hines (1985): *National Accounting for Non-renewable Natural Resources in the Mineral extraction Industries*. Review of Income and Wealth, Vol. 31, No. 1 (March): 1-20.

Lind, R.C. and R.E. Schuler (1998): *Equity and Discounting in Climate-Change Decisions*. In W.D. Nordhaus (ed.): Economics and Policy Issues in Climate Change. Resources for the Future: 59-103.

Lutz, E. (ed.) (1993): *Toward Improved Accounting for the Environment*. The World Bank, Washington D.C.

Marshall, A. (1893): *On Rent*. Economic Journal, vol. 3, 1893.

Mortensen, J.B. and A. Larsen (1994): *Rates of Substitution, Sustainability and the Energy Sector*. Paper presented to the conference Governing Our Environment, Copenhagen, November 1994.

OECD (1989): *Environmental Policy Benefits: Monetary Evaluation*. Paris.

Pearce, D. and G. Atkinson (1992): *Are National Economies Sustainable? Measuring Sustainable Development*. CSERGE Working Paper GEC 92-11. London.

Peskin, H.M. (1989): *Accounting for Natural Resource Depletion and Degradation in Developing Countries*. The World Bank. Environment Department Working Paper No. 13.

Phelps E. (1961): *The Golden Rule of Accumulation: A Fable for Growthmen*. American Economic Review 1961; **51**: 638-43.

Proops, J.L.R. and G. Atkinson (1994): *A Practical Sustainability Criterion When There is International Trade*. Paper presented at the International Symposium on Models of Sustainable Development, Paris, March 16-18, 1994.

Repetto, R., W. Magrath, M. Wells, C. Beer, and F. Rossini (1989): *Wasting Assets. Natural Resources in the National Income Accounts*. Washington D.C., World Resources Institute.

Repetto, R., W. Cruz with R. Solozano, R. de Camino, R. Woodward, J. Tosi, V. Watson, A. Vasquez, C. Villalobos, and J. Jimenez (1991): *Accounts Overdue: Matural Resource Depreciation in Costa Rica* Washington D.C.: World Resources Institute.

Schulz, W. (1985): *Der monetare Wert besserer Luft.* Europaische Hochschulschriften, Peter Lang, Frankfurt am Main / Bern / New York.

Serafy, S.E. (1989): *The Proper Calculation of Income from Depletable Natural Resources.* In Ahmad (1989): 10-18.

Solow, RM (1974): *Intergenerational Equity and Exhaustible Resources.* Review of Economic Studies, 41, 29-45.

Stahmer, C. and Seifert E.K. (1994): *Valuation Concepts for Calculating "green GNP": Complementary not exclusive.* Paper presented at the International Symposium on Models of Sustainable Development, Paris, March 16-18, 1994.

Statistisk Sentralbyrå (1993): *Natural Resources and the Environment* 1992. Reports from the Central Bureau of Statistics, 93/1A. Oslo.

The Danish Economic Council (Det Økonomiske Råd) (1998): *Dansk økonomi, efterår 1998.*

Tongeren, J.v., S. Schweinfest, E. Lutz, M.G. Luna, and G. Martin (1993): *Integrated Environmental and Economic Accounting A Case Study for Mexico.* In Lutz (1993) op.cit.: 85-107.

USGS (U.S. Geological Survey) (2000): ***U.S. Geological Survey World Petroleum Assessment 2000 – Description and Results.***

Vincent, J.R. and Rozali M.A. (1997):*Environment and Development in a Resource Rich Country.*

Vincent, J.R., T. Panayoyou, and J.M. Hartwick (1997): *Resource Depletion and Sustainability in Small Open Economies.* Journal of environmental Economics and management **33**, 274-286.

Weitzman, M.L. (1998): Why the Far-Distant Future Should be Discounted at its Lowest Possible Rate. *Journal of Environmental Economics And Management* **36**:201-208.

Wicke, L. (1993): *Umweltökonomie.* 4. Auflage. Verlag Franz Vahlen, Munchen.

Winter-Nelson, A. (1996): *Discount rates, natural resources, and the measurement of aggregate economic growth in Africa.* Ecological Economics, **17** (1), 21-32.

World Bank (1997): *Expanding the Measure of Wealth. Indicators of Environmentally Sustainable Development.*

World Bank (1998): *Genuine Savings Rates in Developing Countries.*

World Resources Institute (1991): *Accounts Overdue: Natural Resource Depreciation in Costa Rica. A Joint Study by the Tropical Science Center, Costa Rica and the World Resources Institute.* WRI Publications Brief, December 1991. Washington D.C.

RESEARCH PAPERS from the Department of Social Science

To obtain a copy:

The papers can be downloaded free from the following address:

http://www.ssc.ruc.dk/

Paper-ready copies can also be obtained at a price of 40 DKK

Request and order for paper-ready copies can be made to the following address:

Secretary Janni Villadsen

Department of Social Sciences

Roskilde University

P.O box 260

4000 Roskilde

Phone +45 4674 2597

Fax + 45 4674 3080

Research Paper no. 1/99

Jesper Jespersen, Jørgen Birk Mortensen and Rasmus Rummel:
Bæredygtig energianvendelse og økonomisk vækst 'Hvad skal der til? – Hvad koster det? '
Nogle konsekvensberegninger gennemført ved hjælp af Makro og miljømodellerne Adam og Emma.

Research Paper no. 2/99

Jakob Torfing:
Velfærdstatens ideologisering

Research Paper no. 3/99

Eva Sørensen:
Democratic governance and the changing role of users of public services

Research Paper no. 4/99

Gunnar Skogmar:
The United States, Euratom and European Integration 1955-1957.

Research Paper no. 5/99

Peter Bogason:
Public Administration and the Unspeakable:
American Postmodernism as an Academic Trail of the 1990s.

Research Paper no. 6/99

Susana Borrás
The Cognitive Turn(s) in EU Studies

Research Paper no. 7/99

Helle Sundgaard Andersen, Lotte Jensen, Birgit Jæger, Karina Sehested, Eva Sørensen
Roles in transition! Politicians and Administrators between hierarchy and network.

Research Paper no. 8/99

Catharina Juul Kristensen & Søren Voxted
Hvorfor tager faglærte ufaglært arbejde?

Research Paper no. 1/00

Birgit Jæger
SCOT in Action

Research Paper no. 2/00

Leopold Galicki
Det Sociologiske Værksted

Research Paper no. 3/00

Anders Mathiesen
Nyliberalismen – og de ´stærke´ ledere

Research Paper no. 4/00

Eva Sørensen & Jacob Torfing
Kompetenceudvikling i Danmark

Research Paper no. 5/00

Susana Borrás
Science, technology and innovation in European Politics

Research Paper no. 6/00

Lars A. Engberg
Social housing in Denmark

Research Paper no. 7/00

John Andersen
Køn, klasse og ligestilling

Research Paper no. 8/00

Anne Reff Pedersen, Svend Bayer og Nina Middelboe
En præsentation af KIT
- At arbejde med kvalitative interview via lyd

Research Paper no. 9/00

Povl A. Hansen och Göran Serin
Industrins teknologistruktur i Öresundsregionen

Research Paper no 10/00

Jesper Jespersen
ØMUéns politiske økonomi

Research Paper no 11/00

Jesper Jespersen
Makroøkonomisk teori og ØMUén

Research Paper no 12/00

Lars Fuglsang
Three perspectives in science, technology and society studies (STS) in the policy context

Research Paper no 13/00

Jacob Torfing
Velfærdsstatens diskursivitet

Research Paper no 14/00

Christel Stormhøj
Feminist politics after poststructuralism