Eric Neumayer

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Scarce or Abundant?

The Economics of Natural Resource Availability

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Eric Neumayer

Department of Geography and Environment, London School of Economics and Political Science, Houghton Street, London WC2A 2AE, United Kingdom

Email: e.neumayer@lse.ac.uk

Correspondence address: Same address.

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Abstract

Most natural resources that are used in production are non-renewable. When they become depleted they are lost for future use. Does it follow that the limited availability of natural resources will at some time in the future constrain economic growth as many environmentalists believe? While classical economists have shared the belief in limits to growth, the distinctive feature of modern neoclassical economics is its optimism about the availability of natural resoures. This survey suggests that resource optimism can be summarised in four propositions. First, a rise in the price of a resource leads to a substitution of this resource with another more abundant resource and to a substitution of products that are intensive in this resource. Second, a rise in the price of a resource leads to increased recycling of the resource and to the exploration and extraction of lower quality ores. Third, man-made capital can substitute for natural resources. Fourth, technical progress increases the efficiency of resource use and makes extraction of lower quality ores economical. In a critical analysis of these four propositions it is shown that while the conjecture that natural resources will never constrain future economic growth is logically conceivable, we do not and indeed cannot know whether it will be possible in practice to overcome any resource constraint.

1. Introduction

Modern concern that limited availability of natural resources will constrain the possibilities for consumption growth or, for that matter, even non-declining consumption dates back at least to Malthus (1798). He was convinced that the limitedness of land put an absolute scarcity constraint on food consumption growth. While population rose at a geometric rate, the production of food could only be expanded at an arithmetic rate, Malthus thought. Hence, he believed that population could grow only until the minimum subsistence level of per capita food consumption was transgressed and had to decline sharply afterwards — only to grow and hit the absolute scarcity constraint afterwards again in an apparently endless vicious circle. Later on, Jevons (1865) warned against a running out of coal as an energy resource and expressed concern about detrimental consequences of rising coal extraction costs on economic growth and the competitiveness of British industry.

We know by now, of course, that both had been wrong: population grew tremendously in the 19th century and, even more than 130 years after Jevons's alarm, worldwide proven reserves of coal in 1996 would last for another 224 years at current consumption rates (British Petroleum 1997, p. 30). Moreover, coal is not seen as an essential resource anymore. Malthus and Jevons committed mistakes other resource pessimists repeated later on. Malthus did not consider the power of technical progress and he was not aware of the fact that, as Ricardo (1817) first realised, land availability is more a question of relative as opposed to absolute scarcity, i.e. land is a heterogeneous resource and it is possible to get the same amount of nutrition out of an ever lower quality acre by investing increasing inputs. Jevons, for his part, underestimated the scope for exploration and finding new reserves of coal and neglected the powerful possibilities of substituting other energy resources for coal. One has to keep in mind, however, that concern about the availability of natural resources was deeply rooted in mainstream economic thinking by that time and many classical economists, most notably Mill (1862) and Ricardo (1817) shared the belief that the economy had to stop growing sooner or later due to a resource constraint (Barbier 1989, chapter 1). In those days economics had a reputation as a „dismal" science (Barnett and Morse 1963, p. 2).

It was not before the so-called marginal revolution and the rise of neoclassical economics at the turn of the century, mainly due to Marshall, Walras and Fisher, that concern about resource availability vanished. In its leading macroeconomic metaphor, the income-expenditure-cycle, the depletion of natural resources is non-existent in a seemingly endless circular exchange of labour which produces goods to receive income which is in turn exchanged for the produced goods. Reality seemed to buttress this new thinking: the economy kept on growing, especially in the 'golden years' after the Second World War and even if it did not, as in the Great Depression, the reasons were no longer sought in limited natural resources.

Concern about natural resource availability emerged again with the publication of the Club of Rome's 'Limits to growth'-report (Meadows et al. 1972). This concern became popular and widespread after the quadrupling of world oil prices, as OPEC first boycotted the U.S. and the Netherlands for their support of Israel in the Yom-Kippur-War in 1973 and soon learned to exercise leverage over the OECD-countries.[1] Meadows et al. prophesied that the exhaustion of essential mineral and energy resources would make economic growth infeasible some time in the next century. Therefore, a halt to economic growth and even an eventual economic contraction might be enforced through resource scarcity. Essentially the same message was echoed by the Global 2000 Report to the President of the U.S. in 1980 (Barney 1980) and twenty years after their first report Meadows et al. published an updated, but hardly revised restatement of their argument (Meadows et al. 1992).

Economists, contrary to the wider public, this time did not share the concern about resource availability. Only some 'outsiders', regarded as eccentrics by the mainstream economist community, had sympathy with the report's motivation and goal (Daly 1992, first published in 1977; Georgescu-Roegen 1971, 1975; Mishan 1974), without overlooking the criticisms that could be raised against it. In economic terms Meadows et al. were simply naive in extrapolating past trends without considering how technical progress and a change in relative prices can work to overcome apparent scarcity limits. This criticism was put forward vigorously in a fierce attack by neoclassical economists who rejected the report(s) as pure nonsense (Beckerman 1972, 1974; Solow 1974b; Nordhaus 1973, 1992). For them the depletion of non-renewable resources had to be tackled with traditional economic instruments and had to be taken on board by neoclassical economics (Solow 1974a,c, Dasgupta and Heal 1974, Stiglitz 1974) — but limits to growth due to resource constraints were a non-problem.

This resource optimism of neoclassical economics is mirrored in what has become known as a paradigm of sustainable development called 'weak sustainability' (Solow 1974a, 1993a, 1993b; Hartwick 1977, 1990). While being concerned about the welfare of future generations, this paradigm essentially assumes full substitutability of 'natural capital' in that the depletion of natural resources can be compensated via investments into other forms of capital. Indeed, the fact that weak sustainability shares the resource optimism of neoclassical economics should come as no surprise as it can be interpreted as an extension to traditional neoclassical welfare economics (see Neumayer 1999 for more detail).

So far, the pessimists have been wrong in their predictions. But one thing is also clear: to conclude that there is no reason whatsoever to worry is tantamount to committing the same mistake the pessimists are often guilty of — that is the mistake of extrapolating past trends. The future is something inherently uncertain and it is humans' curse (or relief, if you like) not to know with certainty what the future will bring. The past can be a bad guide into the future when circumstances are changing. That the alarmists have regularly and mistakenly cried 'wolf!' does not *a priori* imply that the woods are safe.

Are natural resources scarce or abundant? Will they ever constrain economic growth? Can they easily be substituted for by man-made capital and technical progress? These are the central questions addressed in this survey of the economics of natural resource availability. The distinctive feature of mainstream modern economic thinking is its optimism about the availability of natural resources. Simplifying somewhat, I would suggest that resource optimism can be summarised in the following four propositions:

The resource optimists' creed

If some resource A is becoming scarce in an economic sense[2] its price will rise which triggers the following four mutually non-exclusive effects:

a) Demand shifts away from resource A and another resource B becomes economical and substitutes for resource A. Similarly, demand shifts away from products that are intensive in resource A.
b) It becomes economical to explore and extract as well as recycle more of resource A. As a consequence, the price of resource A will decline again, thus signalling an ease in economic scarcity.
c) Man-made capital will substitute for resource A.
d) More effort is put into technical and scientific progress in order to reduce the necessary resource input per unit of output. Also technical and scientific progress make resource-extraction cheaper and thus the extraction of a resource's lower-quality ores economical. As a consequence prices will decline again, signalling an ease in economic scarcity.

If resource optimism is correct, then there is no need to worry about the doomsayer's prediction of a 'running out' of resources: Either the world will not be running out of the resource or it will not matter if it does since another resource or man-made capital will function as a substitute.

This survey critically examines each proposition of resource optimism. Section 2 examines the possibilities of substituting one natural resource through another one. Section 3 looks at the role prices play in making increased exploration, extraction of low-grade ores and recycling of resources economical. Section 4 analyses the substitution possibilities of resources through man-made capital. Section 5 examines how technical progress contributes to overcoming resource constraints. Section 6 concludes.

Note that this survey only addresses the scarcity of natural resources as an input into the production of consumption goods. It does not look at the role nature plays in absorbing pollution and waste and generating direct utility to individuals through environmental amenities. The two aspects are certainly linked due to the first law of thermodynamics (conservation of mass) which implies that no material can be destroyed, it can only be transformed into other material, waste or pollution. But whether or not binding constraints to economic activity are likely to arise from a scarcity of these 'ecological resources' is distinct from the availability of natural resources for production purposes and should best be left to a separate survey (see Neumayer 1998a, 1998b).

Also note that the availability of food resources is not surveyed here. Indeed, given the focus on natural resources used in the production of consumption goods, the survey mainly looks at non-renewable resources as these are by far more important for production purposes than renewable resources. For the German economy, e.g., Bringezu and Schütz (1996, p. 4) estimate that the ratio of non-renewable to renewable resource intake is 50:1 in terms of weight.

2. Substitution through other resources

Let us first look at proposition a) of resource optimism which essentially says that a resource B will substitute for resource A if the latter is running out either directly or indirectly as demand shifts away from consumption goods that are intensive in resource A towards goods that are intensive in some other resource B. If the proposition is correct, then there is no need to worry about the depletion of resource A and since A could be any resource, there is no need to worry about the depletion of any resource at all. The point is that the depletion of a resource does not matter economically if it is or becomes unnecessary for production. It was this Beckerman (1972, p. 337) had in mind when he commented rather cynically on the first „Limits to Growth"-report:

> Why should it matter all that much whether we do run out of some raw materials? After all (...) economic growth has managed to keep going up

> to now without any supplies at all of Beckermonium, a product named after my grandfather who failed to discover it in the nineteenth century.

Conversely, the existence of a resource does not matter economically as long as it is without an economic use. As Ray (1984, p. 75) observes:

> All materials used by industry were 'new' at some point in history; they have become 'resources' as a result of scientific and technological advance discovering them and developing their use. Bauxite did not even have a name before it was discovered that it could be processed into a new metal: aluminium.

It is clear, that proposition a) taken to its logical limit only applies to resources B that are quasi-undepletable, be they renewable or non-renewable. An example of the former is renewable energy from solar influx that will provide its daily service for a very long time to come. An example of the latter is cold fusion, which is based on a non-renewable resource and which might provide services some time in the future at reasonable costs without an immediate or even intermediate risk of running out. These two examples make clear that ultimately resource B must be something close to a 'backstop technology', i.e. a resource that can provide services at constant marginal costs in infinite amount (Dasgupta and Heal 1974). If such a resource exists, then the economy can be saved from doomsday for an indefinite time (Prell 1996).

Is a backstop technology possible? Strictly speaking, neither of our two examples is really a backstop technology, because the amount of services potentially provided, although very huge indeed, is still finite. Presumably, there cannot be any backstop technology in the strict sense, because the first law of thermodynamics (conservation of mass) states that energy cannot be created anew and because the second law of thermodynamics states that entropy in a closed system is monotonically increasing over time, i.e. energy is used up and cannot be used over and over again (Söllner 1997, pp. 181, 183). For all human relevance the universe is a closed system. But note: it is the universe that is a closed system, not the earth itself which is an open system in the sense that it is getting a steady, constant, finite influx of energy from the sun. It is a closed system only in so far as it does not exchange matter with the outside. Georgescu-Roegen's (1975, p. 370) suggestion that every car built today implies 'fewer plowshares for some future generations, and implicitly, fewer future human beings, too' due to the laws of thermodynamics is *not* correct in a system that receives a steady, constant, finite influx of energy where it is not compelling that entropy permanently increases. [3]

Now, cold fusion may remain a natural scientist's dream forever, but solar energy comes close to a backstop technology for energy resources — at least in principle: the solar energy influx exceeds current total world energy demand at about three orders of magnitude (Norgaard 1986, p. 326). Whether this vast energy influx can be used at reasonable economic costs is less clear, however. Lensson and Flavin (1996, p. 772) optimistically suggest that, due to rapidly declining provision costs, solar and wind energy as well as geothermal technologies will become fully competitive to fossil energy resources in the near future. They believe that the current energy infrastructure which is mainly based on oil, gas and coal will be gradually replaced by an energy infrastructure based mainly on solar energy and other renewables and using hydrogen as the medium to transfer primary energy to final energy users. They project world primary energy use to rise by slightly less than 50% from 1990 to 2050 and project about half of this energy demand to be provided by renewables in 2050 and more than 85% in 2100 (Lensson and Flavin 1996, p. 775). Boyle (1993) from the energy policy and research unit of Greenpeace International provides a similar optimistic view.

A different picture is painted by Trainer (1995) who represents the opposite, pessimistic view. He believes that the prospects of renewable resources providing sufficient energy at reasonable economic costs are vastly over-estimated in neglecting difficulties of „conversions, storage and supply" of renewable resources „for high latitudes" (Trainer 1995, p. 1009). He suggests that if the world must depend on renewable energy resources only, then it „must be based on materially simple lifestyles, a high level of local economic self-sufficiency, and a steady-state or zero-growth economy" (Trainer 1995, p. 1025).

Which of the two projections will be closer to *future* reality, we do not know. Projections are highly dependent on prophesying the *future* development of scientific and technical progress, the *future* growth of the economies, populations and world energy demand, and on predicting *future* changes in energy and environmental policies. Beyond the very immediate time span, these projections *necessarily* become closer and closer to sophisticated guesses and speculations lacking a sound and reliable scientific basis. Mistakes in past projections represent a case in point: many reports in the early 1970s overestimated the amount of nuclear power the world would be using in the mid-1990s by a factor of six, while leading studies in the early 1980s overestimated the cost of a barrel of oil by almost a factor of five (Lenssen and Flavin 1996, p. 770). These flawed estimates should remind us that our ability to project world energy supply and its composition, world energy demand and prices is very limited indeed in the intermediate and distant future.

So far we have only dealt with energy resources. Whether solar energy and other renewable energy resources can substitute for nonrenwable non-energy resources is even less clear. Direct substitution possibilities might be low, but a backstop energy technology has another advantage as well: if it provides services at not too high costs it can boost the availability of other resources that can be extracted economically — at least if we assume that ever lower quality ores can be extracted with ever rising energy and other inputs and that the costs of extraction do not rise steeply and rapidly towards infinity. It was this that Adelman (1990, p. 1) referred to in stating that „the total mineral in the earth is an irrelevant non-binding constraint", for the question really is whether it will be possible or not to extract ever more resources from ever lower quality ores at reasonable economic costs. Energy is the one and only real limiting factor in the long run, because given enough energy there will always be enough natural non-energy resources extractable from the crust of the earth.

However, there does not seem to exist any serious study that has tried to compute the prospects of backstop technologies to substitute on a large scale for the depletion of non-energy resources in the long run or to facilitate the mining of resource ores of low concentration — which would be an overwhelming task and presumably therefore has not been attempted yet. What we have are more or less optimistic statements, but no comprehensive, detailed analysis — see, e.g., Gordon et al. (1987), Scott and Pearse (1992), Beckerman (1995) or Goeller and Zucker (1984, p. 456) who assure the reader that they

> ...believe that, with a few exceptions, the world contains plentiful retrievable resources that can supply mankind with the necessary materials for the very long term, and that these resources can probably be extracted and converted to useful forms indefinitely with acceptable environmental consequences and within the boundaries of foreseeable economic constraints.

3. The role of prices in overcoming resource constraints

Let us look at proposition b) now. It highlights more than any of the other three propositions the role resource prices play in overcoming resource constraints. Prices serve different functions in an economy, the most important being that they signal economic scarcity and that they act as a coordination mechanism pushing the economy towards efficiency and triggering technical progress. That the pessimists have persistently either ignored or downplayed the role that prices play in easing resource constraints, allowed a former economics professor of mine to make the ironic comment that the world has already run out of oil many times — apparently without any dramatic damage. It is utterly naive, as Meadows et al. (1972) and many others have done, to compare current amounts of resource use with current proven reserves and simply extrapolate from the past that hence the resource will be depleted in x years. For the gradual depletion of a resource affects its price which affects supply and demand to which the economy adapts permanently. This dynamic process makes mockery out of simple-minded static computations of a resource's remaining life-time.

The Hotelling (1931) rule highlights the role prices play in the economics of resource availability. The rule says that, under some restrictive assumptions (on which more will be said later on), the resource rent (that is the price of the resource for the marginal unit minus the marginal cost for extracting this unit) must in a perfectly competitive economy rise at a rate equal to the interest rate for a given stock of a non-renewable resource. The resource rent can be interpreted as the net marginal profit for the resource owner and is often called 'Hotelling rent'.

The intuitive reason why the rule must hold in a context of rational utility maximising agents is as follows: imagine otherwise, e.g., that the resource rent rose at a rate lower than the interest rate. Then it would pay the resource owner to liquidate more of the resource, deposit his receipts in a bank and earn interest on his account — which gives him a higher net rate of return than leaving the resource in the ground since by assumption resource rents rise at a lower rate than the interest rate. It would pay to liquidate more of the resource up until marginal extraction costs rise so much that the resource owner is just indifferent between extracting a marginal resource unit and leaving this unit in the ground. It might be profitable to even liquidate the whole resource stock! Now imagine instead that the resource rent rose at a higher rate than the interest rate. Then it would pay the resource owner to leave more of the resource in the ground in order to extract it later on, thus getting a higher net rate of return than if he had extracted the resource right now and had put the receipts in a bank account. The deeper reason why the Hotelling-rule must hold is that for the resource owner a stock of non-renewable resource is just another asset in his portfolio, so it has to earn an equal net rate of return as the other portfolio-assets do. Hence equilibrium is where resource rent rises at a rate equal to the interest rate.

That the resource rent rises at the interest rate holds true more generally, however, only in a setting of certainty about e.g. the size of the resource stock, the date of exhaustion, the existence and marginal costs of a backstop technology etc.[4] Deshmukh and Pliska (1985) show that the resource rent need not rise at the rate of interest if uncertainty is introduced. One important aspect is the exploration of new reserves. Pindyck (1978) is the seminal paper showing how prices (and resource rent) can fall over time as the exploration of new reserves increases the available resource stock. The resource rent is responsive to changes in the underlying economic scarcity of a resource which suggests resource rent to be a good indicator of economic scarcity (see Hartwick and Olewiler 1986; Perman, Ma and McGilvray 1996, pp. 154-159). The resource rent reflects the opportunity cost of current resource extraction, i.e. the trade-off between resource extraction now and resource extraction in the future. It is a measure of anticipated scarcity of the resource. Rising resource rents would indicate rising scarcity, whereas falling resource rents would indicate falling scarcity and no rise or fall would suggest no change in scarcity.

Unfortunately, resource rent is not directly observable and hence inherently difficult to measure. This is the reason why attempts to empirically validate Hotelling's rule have resulted in contradictory conclusions — see e.g. Miller and Upton (1985) versus Farrow (1985) and Halvorsen and Smith (1991) who reject the Hotelling hypothesis (for an overview see Berck 1995). Mackellar and Vining (1989, p. 522f.) even suggest that due to

> ...changing unit extraction costs, producers' price expectations, imperfect competition, exploration, inefficient capital markets, durability and recycling of the resource in question, and so on, virtually any path of real re-

source prices over the last century could be judged consistent with the theory [of Hotelling].[5]

Note, however, that what Farrow (1985) and Halvorsen and Smith (1991) really reject is not the Hotelling-rule as such, which *must* hold in a context of rational utility maximisers, but the simplistic proposition that actual resource rent is rising at the interest rate. One has to keep in mind that the Hotelling-rule only holds true for some rather restrictive assumptions. Hartwick and Hagemann (1993, p. 222) have made this point clear:

> We can summarize Hotelling's rule this way: *if*, under quite restrictive assumptions regarding (a) mineral quality, (b) market uncertainty including stock size uncertainty, (c) agents' foresight, and (d) the functioning of futures markets, mineral stock owners are extracting at each date so as to maximize the discounted future profits from their mineral holding, *then* the rental earned on the marginal ton extracted will increase over time at the rate of interest. (...) Failure to demonstrate that 'rent rises at the rate of interest' might reflect the invalidity of any one of the assumptions on which this prediction is based. What such failure does not imply, however, is that mineral stock owners are not maximizing discounted future profits (that is, the current market value of the mineral deposit).

Because of the difficulties in measuring resource rent, studies of resource scarcity have come up with two alternative indicators: unit extraction costs, i.e. the value of factor inputs per unit of output of the resource-extracting industry, and relative resource prices, i.e. the ratio of a resource price index to an overall price index.

The relative resource price indicator is close to resource rent. It includes the current extraction cost plus the resource rent, that is the opportunity cost of current extraction. Its rationale is that with approximately constant marginal current extraction costs the change in the overall resource price is a good proxy to the change in the unobservable resource rent, so that with rising resource scarcity the overall resource price would rise relative to a suitably defined overall price index. Its chief advantage is that it is easily observable: „In today's closely integrated global marketplace, most natural resource commodities trade at a single, U.S. dollar-denominated price" (Mackellar and Vining 1989, p. 525). The rationale for using unit extraction costs instead is that if resource extraction is a Ricardian process, i.e. it starts from the high-quality ores and moves continually to the lower quality ores, then one would expect unit extraction costs to rise with rising resource scarcity. In a competitive context it is reasonable to presume that resource extraction broadly follows a Ricardian process for then „the market serves as a sensing-selective mechanism, scanning all deposits to take the cheapest increment or tranche into production" (Adelman 1990, p. 3). Unit extraction costs are less easy to observe, at least in highly integrated resource industries because then it becomes difficult to isolate resource extraction costs proper from other costs such as transportation and processing costs (Mackellar and Vining 1989, p. 519).

The classical study of resource scarcity is Barnett and Morse (1963). It examined unit extraction costs for the period 1870-1957 for agricultural, mineral and forest resources in the United States finding a general downward trend with the exception of forestry. Barnett (1979) and Johnson, Bell and Bennett (1980) updated the original study to the 1970s coming to the same principal conclusions of falling unit extraction costs which they interpreted as a decline in resource scarcity.

At the beginning of the eighties the studies undertaken by Slade (1982) and Hall and Hall (1984) shed some doubt on these findings. Slade (1982) examined relative resource prices for several mineral and energy resources finding evidence for 'U-shaped' price trends, i.e. after prices had fallen over a substantial period of time, they were then starting to rise. Slade (1982, p. 136) concluded that „if scarcity is measured by relative prices, the evidence indicates that non-renewable natural-resource commodities are becoming scarce“. Similarly Hall and Hall (1984, p. 363) found evidence for „measurable increasing scarcity of important natural resources“ in studying both unit extraction costs and relative resource prices for energy and forestry products in the United States. Both studies claimed that part of the rise in oil prices in the 1970s was due to rising scarcity and not simply an artefact of the exercise of market power by OPEC (Slade 1982, p. 136, Hall and Hall 1984, p. 373). More recent studies have mostly failed to support these findings of rising scarcity.[6] Slade (1988, p. 200) herself admitted that there was no statistically significant upward trend in resource prices and Slade (1992, p. 7) concluded that there is no evidence of an increase in unit extraction costs and that „when we consider a century of data, the most striking feature is the decline in the relative price of the majority of mineral commodities“. A recent study by Uri and Boyd (1995) equally failed to find any increase in unit extraction costs or relative resource prices for several mineral resources.

Can one conclude, therefore, that resources have not become more scarce in an economic sense over the past and will not become scarce in the future? There are two objections to doing so:

- As pointed out, empirical studies do not measure resource rent, the theoretically correct indicator, but a surrogate indicator. Unfortunately, the forward looking properties of the surrogate indicators are very poor. They can be very misleading, i.e. suggesting the opposite of the true underlying scarcity trend. What is more, they can be contradictory: Brown and Field (1978) detected a rising trend in the relative resource price of lumber while at the same time the unit cost was falling. Why is it that the indicators can be very misleading and contradictory?[7]

  Take unit extraction costs first. If the resource is becoming scarce, unit extraction costs will rise given that resource extraction follows a Ricardian process. However, improvements in the extraction technology countervail this effect and if technical change is sufficiently strong, unit extraction costs can *fall* in spite of *rising* future economic scarcity (Farzin 1995, p. 118). Unit extraction costs only measure the costs of extracting already discovered deposits but do not reflect the costs of future extraction (Fisher 1979, p. 257). It is a backward, not forward looking indicator. "The unit cost measure does not warn us of impending physical exhaustion" (Brown and Field 1979, p. 219). This is no mere theoretical possibility:

> In the 19th century, technical progress steadily reduced unit extraction cost in the U.S. lumber industry despite the fact that forest resources were disappearing at a rapid rate. The number of some whale species in the oceans has dwindled while superior hunting methods have steadily reduced unit extraction costs. (Mackellar and Vining 1989, p. 520).

Relative resource prices are in principle better suited to predict future resource scarcity, since expectations about the future should enter current prices. In the absence of a complete set of future markets, however, relative resource prices also fail to reflect future scarcity accurately. That is, relative resource prices are only an imperfect forward-looking indicator. To give an example: Farrow (1995) suggests that the market did not anticipate the end of hunting of passenger pigeons which became extinct "with hardly a ripple in its commercial price" (Brown and Field 1978, p. 241). More generally, often market prices do not or, rather, cannot take into account ecological thresholds and irreversibilities in depleting natural capital. Resource prices would be much higher if the environmental externalities were internalised.

Equally, they cannot work for resources that are characterised by open access.

Since resource prices are supposed to function as a proxy for the unobservable resource rent, problems arise if the link between the price and the rent is rather weak. This will be the case if, for example, substitution among other factor inputs in the processing of the resource is high, because then the price will rise less than the rent. Similarly, if the raw resource (e.g. bauxite) has a small share in the production costs of the final good (e.g. aluminium), then the price for the final good will be much more influenced by changes in other factor prices than by the resource rent. Another major problem is the selection of an appropriate deflator or numeraire to transform nominal into real resource prices. As Hartwick and Olewiler (1986, p. 148ff.) report from other studies, trends in resource prices can be quite divergent depending on which deflator — e.g. index of factor inputs, index of intermediate goods, index of final goods and services — is used.

The most fundamental objection against using relative resource prices as an indicator for resource scarcity was provided by Norgaard (1990, 1991). His argument is as follows: In an ideal system of complete markets, including futures and options markets, relative resource prices should reflect present and future scarcity accurately. The problem is that this full set of markets is not existent and that therefore traders in natural resource markets have to form their own expectations about scarcity and the future price paths. Since these traders are boundedly rational utility maximisers with imperfect information and imperfect foresight, they might well be badly informed about real resource scarcity. The same holds true if their only concern is over the next 5-10 years, as Aage (1984, p. 108) suspects, or the next 10-20 years, as Ray (1984, p. 76) suggests. But if that is the case, then

> ...the cost and price paths their decisions generate are as likely to reflect their ignorance as reality. To control for whether or not allocators are informed, however, we would have to know whether resources are scarce. Since this is the original question, the exercise is logically impossible. (Norgaard 1990, p. 19f.).

Inferring the real underlying scarcity trend from the time-series of the indicator is therefore flawed from the beginning. Norgaard (1991, p. 195) suggests that the only thing one can really test is whether or not allocators *believe* that a resource is scarce and not real scarcity.

- Past trends cannot be simply extrapolated into the future (and most definitely not into the far future). That the resource constraint is not binding yet, does not imply that it will not be so in due course. To give an example: The World Bank projects world output to rise at about 3.2% p.a. (World Bank 1992, p. 9), which means that it would already be about 3.5 times higher than present in 2030. It is not all that clear whether there are sufficient resources for such a tremendous growth of output. The point is that resource pessimists are concerned whether there will be enough resources to satisfy a demand that exceeds past levels of demand by orders of magnitude.

So far, reserves of both energy and non-energy resources have by and large persistently been rising over time. Figures 1 and 2 show the trend in world oil and gas reserves, respectively, together with their static reserves index, that is the current reserves to current production ratio in years. For both oil and gas both absolute reserves and the static reserves to production ratio are much higher than in 1965 (oil) or 1970 (gas), respectively. Figure 3 presents the exponential reserve index for major energy and non-energy resources in 1970 and 1992, respectively. The exponential reserve index states how long current reserves would last if future consumption were to *grow* at current rates of growth.[8] It shows that even the exponential reserve index has increased over the last 25 years in most cases or has only slightly decreased.[9] But surely, there is no guarantee that this fortunate trend will continue into the future, especially as output and possibly resource input might be growing very fast, as the group of nearly industrialised countries becomes larger and larger and continues to catch up with the high-income countries.

Source: British Petroleum (various years).

Figure 1. Word oil reserves.

Source: British Petroleum (various years).

Figure 2. World natural gas reserves.

Source: Meadows et al. (1972), WRI (1996-97), British Petroleum (various years).

Figure 3. Exponential reserve index for major resources.

What about the prospects of recycling, that proposition b) also refers to? These prospects are limited as well. Strictly speaking, given a backstop energy technology, the second law of thermodynamics imposes no physical constraint on the possibilities of recycling material. In principle, given an unlimited supply of energy, all material could be recycled — a fact that follows directly from the first law of thermodynamics (conservation of mass) and that was denied by Georgescu-Roegen first, but later on accepted (Georgescu-Roegen 1986, p. 11). However, there is an economic constraint since, for many materials, the costs of recycling material are likely to become prohibitively high as the recycling rate tends towards 100 per cent. Recycling can ease a resource constraint for some time, but it cannot overcome it in the end. For a detailed discussion of the physical principles governing the possibilities of recycling material see Georgescu-Roegen (1986), Biancardi et al. (1993, 1996), Khalil (1994), Kummel (1994), Mansson (1994), and Converse (1996).

4. Substitution through man-made capital

Let us turn to proposition c) now. Evidently, proposition a) cannot be a satisfactory solution, if there is no backstop technology that can substitute for all economically relevant resources and substituting them by renewable resources is either infeasible or would hugely overstretch their regenerative capacity.[10] Equally, proposition b) cannot be a satisfactory solution if we take on a very long-run perspective, because in the end a non-renewable resource is just that: non-renewable and it will be depleted in some finite time.[11] The resource might still be substituted with man-made capital then. But can man-made capital substitute for an ever diminishing resource stock?[12] The answer is yes under some restrictive assumptions, as proven by Solow (1974a) and Dasgupta and Heal (1979).[13]

Dasgupta and Heal (1979) examine under which conditions a non-renewable resource is essential and when it is inessential, where an essential resource is defined as a resource for which „feasible consumption must necessarily decline to zero in the long run" (p. 199). To make analysis possible they have to assume some sort of production function and they take the Constant-Elasticity-of-Substitution (CES) production function for reasons of simplicity. Since they assume that labour is constant, one can as well normalise it to one and suppress it and put only man-made capital K and resource input R as arguments into the function. Hence the constant elasticity of substitution refers to the elasticity of substitution between reproducible man-made capital and the non-renewable resource. Let us call this elasticity σ. The CES-function can be represented as follows:

$$F(t)=\left\{ \alpha K(t)^{(\sigma-1)/\sigma}+\beta R(t)^{(\sigma-1)/\sigma}+(1-\alpha-\beta)\right\}^{\sigma/(\sigma-1)}$$

where F is produced output and $\alpha, \beta > 0$, $\alpha+\beta < 1$, and

$$\sigma = \frac{d\ln(K/R)}{d\ln\left|MRS_{K,R}\right|}, \;\Rightarrow\; \sigma \geq 0.$$[14]

where MRS is the marginal rate of substitution between K and R:

$$MRS_{K,R} = \frac{dK}{dR} = -\frac{\partial F/\partial R}{\partial F/\partial K} = \frac{P_R}{P_K}$$

and P_K, P_R is the price of the man-made capital factor and of the resource factor, respectively. The higher is σ, the better can resources be substituted by man-made capital. There are three cases to distinguish: First, $\sigma > 1$; second, $\sigma = 1$ and third, $\sigma < 1$.

The first case is trivial and therefore uninteresting. To see this, note that with $\sigma > 1$ all exponents become greater than zero and since resources enter the production function only in an additive way they are inessential. However, for the same reason it is possible to have $F(K,0) > 0$, i.e. production without any input of resources, which contradicts the first law of thermodynamics. That something can be produced without any resource input is a physical impossibility. $\sigma > 1$ can therefore be dismissed.

The third case is uninteresting as well. Note that for this case the average product of the resource, *F/R*, is

$$F(t)\big/R(t) = \left\{ \alpha\left(\frac{R(t)}{K(t)}\right)^{(1-\sigma)/\sigma} + \beta + (1-\alpha-\beta)R(t)^{(1-\sigma)/\sigma} \right\}^{\sigma/(\sigma-1)}$$

and it is bounded above as the resource becomes depleted, because as $R \rightarrow 0$, *F/R* becomes

$$\lim_{R\rightarrow 0} F(t)\big/R(t) = \beta^{\sigma/(\sigma-1)}$$

With a finite resource stock and no technical progress, the boundedness of the average product *F/R* implies that total output is finite so that output must decline to zero as time goes to infinity. In the limit with $\sigma = 0$ the CES-function degenerates into a so-called Leontief production function of the form *F(K,R) = min(vK,wR)* with *v*>0, *w*>0, which means that all substitution possibilities are ruled out and we reached perfect complementarity (Varian 1992, p. 20).

Remains the second case. With $\sigma = 1$ the CES function collapses into the Cobb-Douglas production function of the following form (Chiang 1984, pp. 428ff.):

$$F(t) = K(t)^{\alpha} \cdot R(t)^{\beta}$$

It is apparent, that the resource is not trivially inessential since without resources (R = 0) no production is possible, i.e. F = 0. However, dividing F by R and taking the partial derivative of F with respect to R shows that

$$F/R = \frac{K^{\alpha}}{R^{(1-\beta)}} \text{ and } \partial F/\partial R = \beta \left(F/R\right) ,$$

so for $\sigma = 1$ both the average (F/R) and marginal product ($\partial F/\partial R$) of the resource are unbounded and both F/R and $\partial F/\partial R \rightarrow \infty$ as $R \rightarrow 0$. This combination ensures that the case $\sigma = 1$ is non-trivial: It is not overtly clear whether the resource is essential or not. Dasgupta and Heal (1979, p. 200-205) prove that it is not if $\alpha > \beta$, that is if the elasticity of output with respect to man-made capital is higher than the elasticity of output with respect to the non-renewable resource. There is no direct intuition for this result beyond the mathematical necessity. However, since in a competitive economy these elasticities are equal to the share of total income going to the factors man-made capital and resources, respectively (Euler's theorem), Dasgupta and Heal (1979, p. 200) circumscribe the condition $\alpha > \beta$ with the condition that man-made capital is „sufficiently important in production". Solow (1974a, p. 39), Hartwick (1977, p. 974) and Dasgupta and Heal (1979, p. 205) suggest that man-made capital's share is as much as four times higher than the share of resources, so that resources are not essential for the Cobb-Douglas case.[15]

There are several objections that can be raised against being optimistic as a consequence of this analysis, however:

1) The first objection is that we do not know whether σ is greater than, equal to or smaller than 1. There are econometric studies mainly on the relationship between man-made capital and energy.[16] Table 1 summarises the findings of several studies. It is important to note that the reported values are not the σ's as defined above, but so-called 'Allen partial elasticity of substitution' values, *σ(AES)*, with

$$\sigma(AES) = \frac{\partial ln\,K}{\partial ln\,P_E} \Big/ M_E$$

where P_E is the price of energy and M_E is the share of energy in total production costs. *σ(AES)* is not bounded below by zero and its values are not directly transferable into values of σ. However, negative values of *σ(AES)* signal complementarity between man-made capital and energy and the more negative is *σ(AES)* the higher is the complementarity. Vice versa for positive values of *σ(AES)* which signal substitutability (Allen 1938, p. 509).

Table 1. Estimates of the Capital-Energy Allen partial Elasticity of Substitution

σ(AES)	***Sample***	***Type of data***	***Source***
- 1.39	U.S.	1947-71 time-series	Hudson and Jorgenson (1974)
- 3.22	U.S.	1947-71 time-series	Berndt and Wood (1975)
1.07 / 1.03	U.S./9 OECD-countries	1955-69 cross-section	Griffin and Gregory (1976)
1.22	7 OECD-countries	1963-74 time-series	Özatalay et al. (1979)
- 2.32	Netherlands	1950-76 time-series	Magnus (1979)
0.36 – 1.77	10 OECD-countries	1963-73 time-series	Pindyck (1979)
- 3.8	U.S.	1971 cross-section	Field and Grebenstein(1980)
2.26	Australia	1946-1975 time-series	Turnovsky et al. (1982)
- 1.35	U.S.	1971-76 cross-section	Prywes (1986)
2.17	Taiwan	1956-71 time-series	Chang (1994)

Table 1 shows extreme variance in results ranging from complementarity to substitutability. There is much dispute about possible explanations for these „notably contradictory“ (Solow 1987, p. 605) findings, without a resolution.[17] Some argue that time-series econometric studies are likely to find complementarity, whereas cross-section analyses are likely to find substitutability between energy and man-made capital (Griffin 1981, pp. 71-74). This is because relative factor price variations tend to be much more pronounced cross-sectionally than over time within one country. If these relative price differentials have been existent for a long time, cross-section studies are likely to find long-run equilibrium effects and in the long-run we would always expect higher substitutability between factors than in the short run. Looking at table 1 shows, however, that some studies do not fit this explanation. At best, it can therefore only be part of the story. Another explanation offered by Berndt and Wood (1979, pp. 349f.) is that studies that find substitutability usually tend to include only three factors (labour, man-made capital and energy) in the production function, whereas studies that find complementarity include materials as a fourth factor. But, again, there are some studies using four inputs and still finding substitutability between capital and energy (e.g. Turnovsky et al. 1982). A third reason for the differing results is given by Solow (1987) and Chichilnisky and Heal (1993). They develop models in which different countries can exhibit either substitutability or complementarity between energy and man-made capital in spite of having the same physical production function. These differences can occur because of differences in energy prices and differences in energy demand conditions. Overall, it has to be said that a satisfactory explanation for the variance in results from econometric studies has not been found yet and that we do not have a reliable answer on the question whether energy and man-made capital are substitutes or complements. Hence it is not possible to conclude that resources in reality are inessential.

2) The second objection is that we cannot rule out the possibility that σ becomes smaller than 1 as more and more of the resource is used up. That is, σ is not constant over time, but itself a function of time, i.e. $\sigma = \sigma(t)$. Dasgupta and Heal assume a CES production function for simplicity, but there is no reason to expect that in reality the elasticity of substitution between man-made capital and resources is constant over time. As Dasgupta and Heal (1979, p. 207) admit themselves, constancy might be a flawed assumption as the resource is run down and the ratio of man-made capital to resources becomes very high. Especially in that phase even assuming $\sigma = 1$ might contradict physical laws since it assumes that F/R and $\partial F/\partial R \to \infty$ as $R \to 0$, i.e. the average product and the marginal product of the resource tend toward infinity as the resource stock tends to zero.

3) The third objection applies the same kind of argument to the share of man-made capital and the resource-share of total income. There is no reason to expect that in reality those shares remain constant as the stock of resource tends toward depletion (Slade 1987, p. 351). That is, α and β are not constant over time, but themselves functions of time, i.e. $\alpha = \alpha(t)$ and $\beta = \beta(t)$. Hence, even if σ was constantly equal to 1 throughout, the elasticity of output with respect to the resource (β) might supersede the elasticity of output with respect to man-made capital (α) after which the resource will become essential.

4) The fourth objection is that the dichotomy of man-made capital versus resources is an artificial and flawed one since man-made capital consists partly of resources. Victor (1991) looks at the properties of a Cobb-Douglas production function if it is assumed that man-made capital is itself produced from man-made capital, resources and labour:

Let the production function F be of the form[18]

(1) $F = K^c R^d L^e$, with $c,d,e > 0$ and $c+d+e = 1$

Now let the production function for producing man-made capital goods be of the form

(2) $K = K^p R^q L^s$, with $p, q, s > 0$ and $p+q+s = 1$

Solving (2) for K gives

(3) $K = R^{(\frac{q}{1-p})} L^{(\frac{s}{1-p})}$

Substituting (3) into (1) and re-arranging we arrive at

$$F = R^{(\frac{c \cdot q}{1-p}+d)} L^{(\frac{c \cdot s}{1-p}+e)}$$

It is obvious that man-made capital cannot infinitely substitute for an ever declining resource stock anymore. Of course, resources might still be substituted for by an ever increasing labour input; but in contrast to man-made capital, labour is not a factor that can be increased indefinitely since labour is supplied by human beings who, by the way, also consume natural resources. That is, in effect, given that resources are needed for the production of man-made capital goods, resources become essential for production even for the Cobb-Douglas case: Man-made capital cannot infinitely substitute for vanishing resources.

5. The role of technical progress in overcoming resource constraints

Let us finally turn to proposition d). Technical progress can be divided into what is known as 'resource-augmenting' technical progress and what I call 'augmenting resource' technical progress for lack of a *terminus technicus*. Resource-augmenting technical progress increases the efficiency of natural resource use and means that ever more output can be produced from a given amount of natural resources or that for a given output ever less resource-input is needed, respectively.[19] 'Augmenting resource' technical progress reduces resource extraction costs which means that lower-quality ores of a resource become economical to extract. This implies that the economically relevant resource stock *increases* although the total physical stock of a finite non-renewable resource cannot be increased, of course. It is this Baumol (1986) had in mind when he spoke misleadingly of „the possibility of continuing expansion of finite resources". Note that this conjecture does not contradict the laws of thermodynamics, as Young (1991) erroneously suggested.

In some sense technical progress is the strongest proposition of the resource optimists. Let us turn to resource-augmenting technical progress first. If there is permanent resource augmenting technical progress, that is, if a unit of output can be produced with ever declining resource inputs, then the resource is inessential even if substitution possibilities between man-made capital and resources are nil (Dasgupta and Heal 1979, p. 207). The same holds true as Stiglitz (1974) proves for so-called Hicks-neutral technical progress, that is technical progress that cannot be attributed to a production factor, given

- that the production function is Cobb-Douglas, i.e. $\sigma = 1$,
- that m/β is sufficiently large, where m is the rate of Hicks-neutral technical progress and β is the income share of the resource, so that m/β can be loosely[20] interpreted as the rate of resource-augmenting technical progress (Toman, Pezzey and Krautkraemer 1995, p. 145).

However, whether permanent resource augmenting technical progress is possible, especially in the limit as resource stocks go down, is unclear. Ayres and Miller (1980) and Gross and Veendorp (1990) suggest that assuming so contradicts the first law of thermodynamics (conservation of mass). There are likely to be limits to increasing efficiency. While it might be possible to reduce the required resource input per unit of output significantly for many resources, permanent efficiency increases face technical difficulties and would be prohibitively costly to achieve.

Unfortunately, it is rather difficult to measure resource-augmenting technical progress. Take energy use as an example. Often one finds figures of energy intensity which is declining over time.[21] See figure 4 which shows the time trend in energy intensity for the world and for OECD-countries.

Sources: Primary Energy Input: British Petroleum (various years), GDP: World Bank (1991, 1995) and IMF (1997)

Figure 4. Energy consumption and energy intensity.

Energy intensity is the ratio of energy input expressed in physical terms to the value of economic output, usually GDP.[22] The problem with this measurement is that it does not directly measure changes in the technical energy efficiency of production which is what we are looking for when we want to measure resource-augmenting technical progress. A decline in the energy intensity of an economy can come about for a number of reasons other than technical progress itself, e.g. because of a change in the sectoral structure of the economy, because of substitution of labour or man-made capital for energy, because of a change in the energy input mix towards energy sources which can provide more useful work per unit of heat etc. (Patterson 1996, p. 381, Kaufmann 1992). Reliable evidence on this point is hard to get. Kaufmann (1992) claims that his more complex econometric testing approach refutes earlier evidence from simpler regression models, e.g. Howarth (1991), which found technical progress to be a statistically significant and important contributor to the decline in energy intensity. Kaufmann (1992, p. 54), on the contrary, suggests „that most of the changes are associated with shifts in the types of energies used and the types of goods and services consumed and produced". Equally inconclusive is the situation for non-energy resources. Slade (1987, p. 351) cites evidence that suggests that technical progress has been resource-saving in some sectors but resource-using in others.

Another caveat in inferring conclusions from looking at resource augmenting technical progress is that even if resource intensities are falling over time, *absolute* resource consumption may well rise if the rate of consumption growth is higher than the rate of resource augmenting technical progress. Looking again at figure 4 shows that while energy intensities have fallen over time both worldwide and for the OECD-countries, consumption of primary energy has continuously risen due to tremendous population and output growth.[23] In fact, the two are even more closely related: Resource augmenting technical progress reduces the implicit price of energy, thus making production cheaper, boosting production and favouring the substitution of energy for other factors of production, which in return implies, *ceteris paribus*, an increased demand for energy. Khazzoom (1987) and Brookes (1990, 1992) believe that this 'rebound'-effect will in most cases be strong enough to lead to a *net* increase in energy use. Howarth (1997, p. 8) has shown, however, that this conjecture will only hold true under the conditions that „(i) energy accounts for a large fraction of the total cost of energy services and (ii) the production of energy services constitutes a substantial fraction of economic activity". He finds that neither of these conditions is empirically plausible.

Let us turn to 'augmenting resource' technical progress now. Slade's (1982) and Berck and Roberts's (1996) model show how improvements in the resource extraction technology can lead to a persistent downward trend in unit extraction costs and real resource prices over quite a long time span although the total resource stock becomes physically smaller.

Technical progress can boost the economically relevant resource stock and ease the resource constraint over a significant time span. However, whether there will be and can be permanent and at best exponential technical progress is unclear, of course. That there has been enormous technical progress in the past is beyond doubt, but there is no assurance that there will also be permanent technical progress in the future. As Lecomber (1975, p. 45) has put it: „The central feature of technical advance is indeed its uncertainty". It all boils down to whether you believe strongly in technical progress or not. To get a flavour of the resource optimists' faith, it is worth quoting Beckerman (1972, p. 338) at some length here:

> In fact, given the natural concentrations of the key metals in the Earth's crust as indicated by a large number of random samples the total natural occurrence of most metals in the top mile of the Earth's crust has been estimated to be about a million times as great as present known reserves. Since the latter amount to about a hundred years' supplies this means we have enough to last about one hundred million years. Even though it may be impossible at present to mine to a depth of one mile at every point in the Earth's crust, by the time we reach the year A.D. 100,000,000 I am sure we will think up something. If the idea that actual reserves might be a million times currently proved reserves seems unbelievable it should be borne in mind that existing proved reserves are probably about a million times as big as those known in the days of Pericles.

6. Conclusion

It is important to note that the power of the resource optimists’ creed stems from the fact that not all four propositions need to hold true in isolation, but that any one of them or some combination thereof is already sufficient to save the economy from doomsday. What makes an analysis of these propositions difficult is that they are not amenable for refutation since they ultimately rest on basic beliefs about future substitution possibilities or technical progress. Resource optimism has powerful theoretical arguments as well as strong evidence up to now in favour. But as this survey of the economics of natural resource availability has made clear, whether the propositions of resource optimism will hold true for the future as well is a different matter. These propositions are surely logically conceivable, but whether they are possible in practice and likely to occur, we do not know. The only thing we do know is that they are *not* certain.

The world economy has so far exhibited a most remarkable capability to overcome resource constraints. Resources that were feared to become scarce at one time, often turned out to be abundantly available only a few years later. This gives reason to hope. And yet there are good reasons to be cautious as well: Never can there be any guarantee that the fortunate experiences of the past will replicate in the future. This holds especially true in times of rapid change as ours. Whether the limited availability of natural resources will ever constrain economic growth, we simply do not know. As Lecomber (1975, p. 42) has written as long ago as 1975:

> Everything hinges on the rate of technical progress and possibilities of substitution. This is perhaps the main issue that separates resource optimists and resource pessimists. The optimist believes in the power of human inventiveness to solve whatever problems are thrown in its way, as apparently it has done in the past. The pessimist questions the success of these past technical solutions and fears that future problems may be more intractable.

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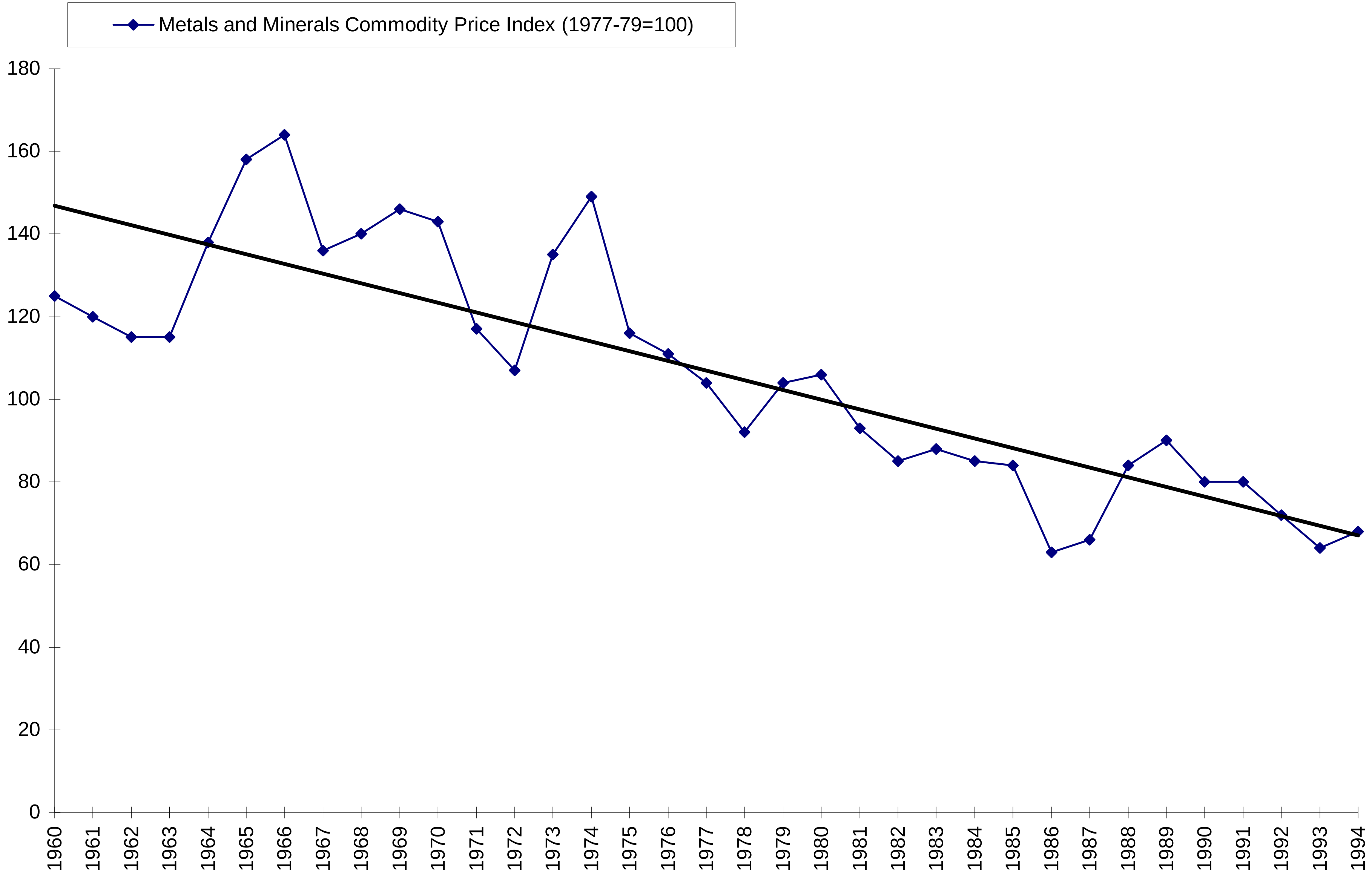

FIGURE 1 (Eric Neumayer)

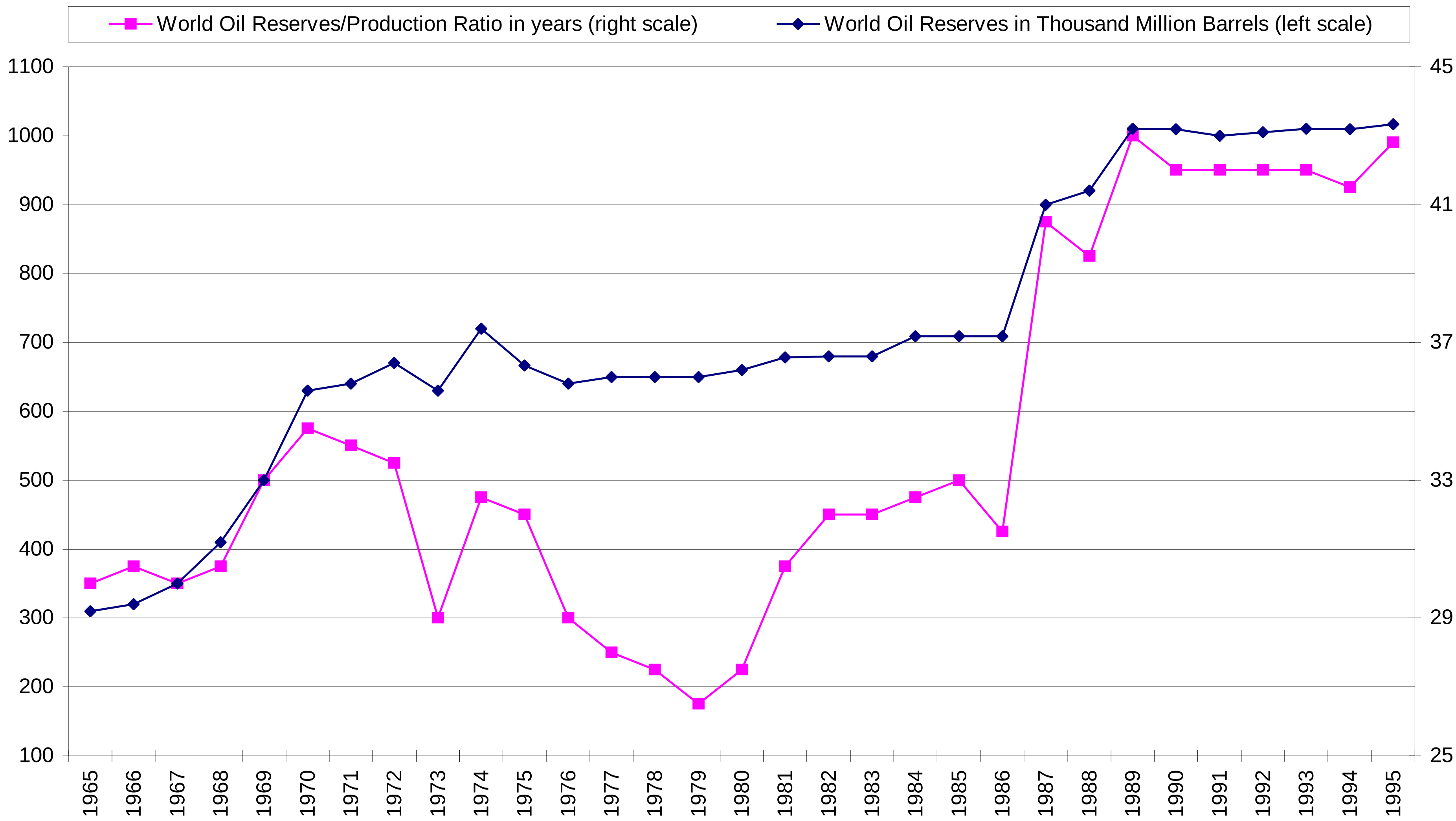

FIGURE 2 (Eric Neumayer)

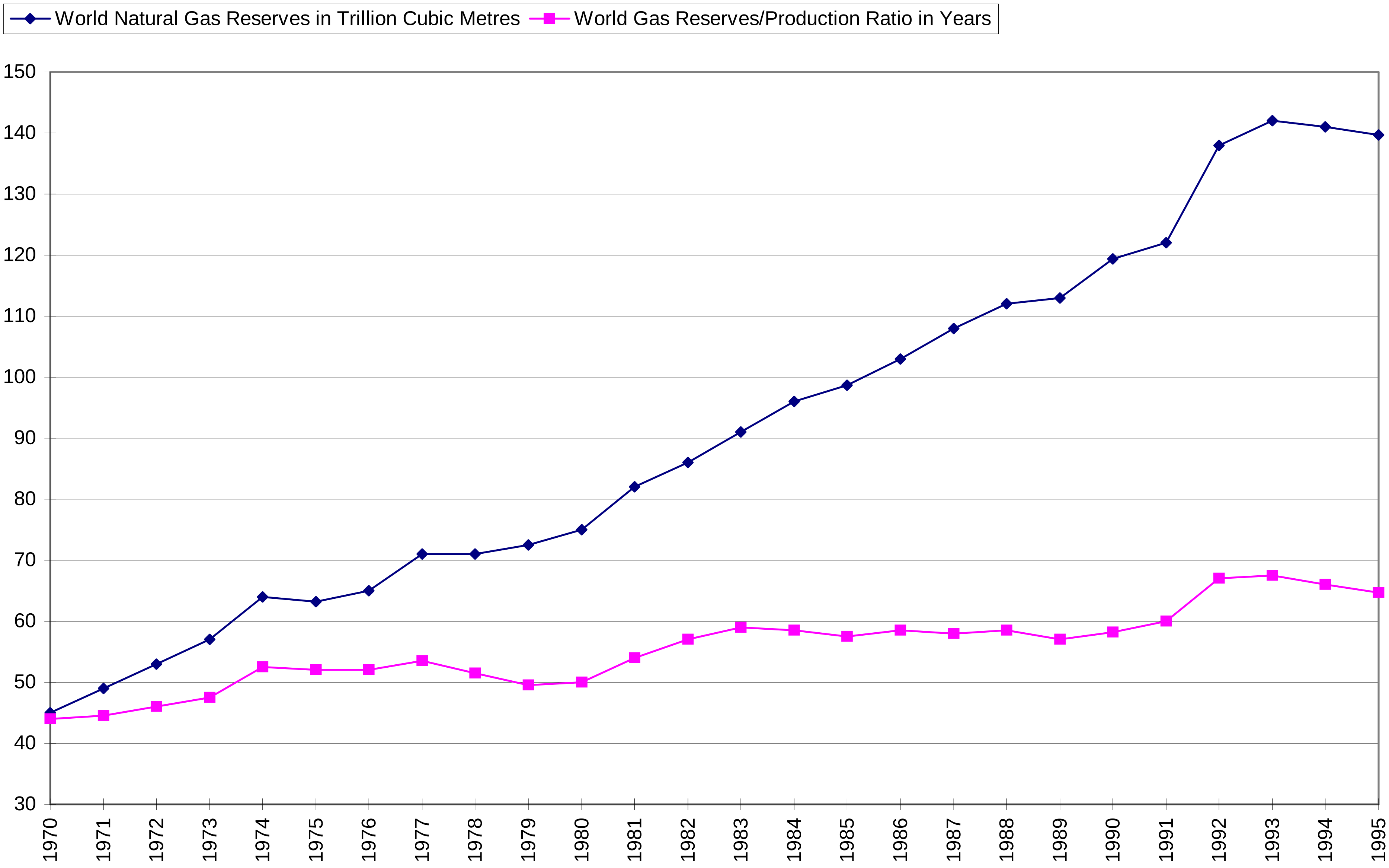

FIGURE 3 (Eric Neumayer)

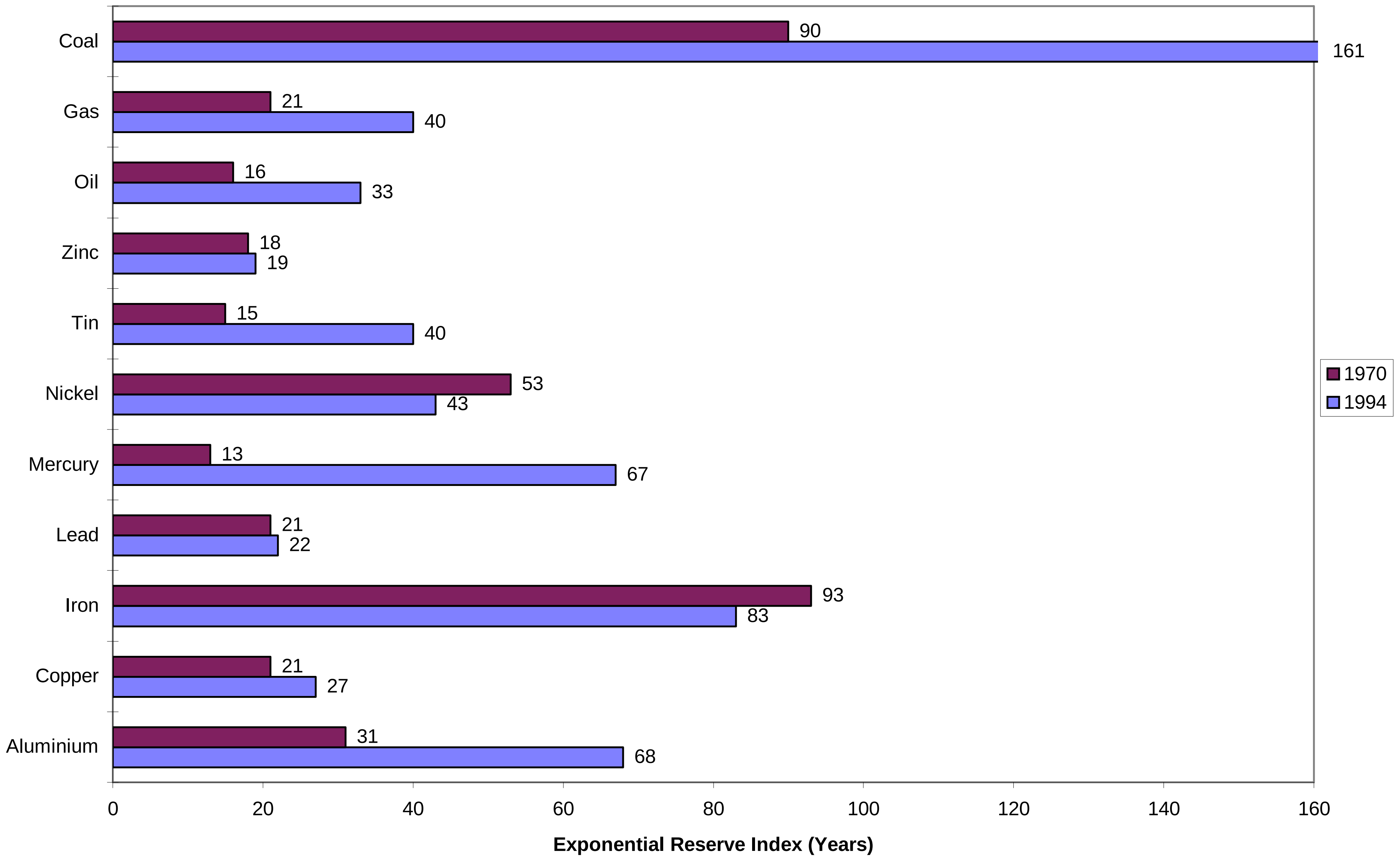

FIGURE 4 (Eric Neumayer)

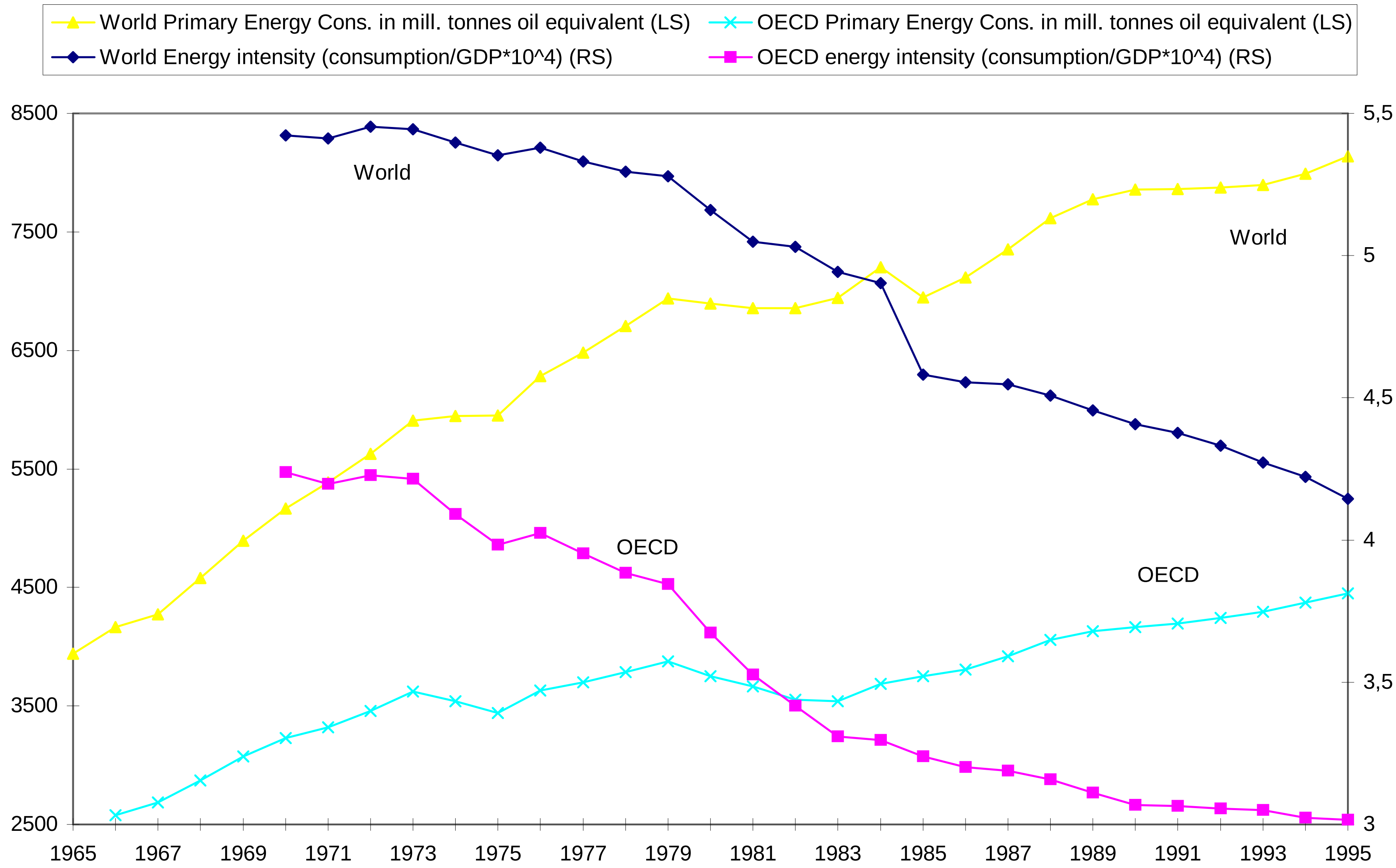

FIGURE 5 (Eric Neumayer)

ENDNOTES

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[1] However, the rise in oil prices was clearly linked to the exercise of market power by OPEC and not to dramatically rising natural scarcity, although there is some evidence that prices had started rising before 1973 (Slade 1982, p. 136). For a history of world oil prices see Adelman (1995).

[2] Some natural resources are scarce on this world in a physical sense. If they have no productive use, nobody cares about this scarcity, however. Scarcity in an economic sense I define to be excess demand for the resource at a given price.

[3] Of course, Georgescu-Roegen was not so naive as to overlook the fact that the earth is not a closed system. He merely claimed that using solar energy needs more non-solar energy input than is gained in energy eventually (Georgescu-Roegen 1986, p. 23). While this might be true for the present, there is absolutely no reason to expect that this has to be true in the future as well.

[4] It also holds for uncertainty if agents form rational expectations and there is a complete set of contingent forward markets. Neither is very realistic. See Graham-Tomasi, Runge and Hyde (1986).

[5] On this, see also Swierzbinski and Mendelsohn (1989) who explain the apparent contradictory results as follows: Miller and Upton (1985) demonstrate that stockholders use the Hotelling-rule at each moment of time to forecast the value of their stocks. That time-trend tests of the Hotelling-rule (e.g. Farrow 1985 and Halvorsen and Smith 1991) have generally failed to support the rule is due to the fact that because of dynamic uncertainty and consistent updating in information the true mean rate of change in the resource price persistently deviates from the deterministic Hotelling-rule.

[6] A recent study of Moazzami and Anderson (1994) finds empirical support for Slade's (1982) 'U-shaped' price trend hypothesis, however.

[7] See Farzin (1995) for a more detailed and technical analysis.

[8] The exponential reserve index is computed as $ln(r \cdot s+1)/r$, where r is the average rate of consumption growth and s is the static reserve index (see Meadows et al. 1972, p. 68). For 1970, I have computed the average annual growth rate over the time period 1965-1970 and for 1994 the average annual growth rate over the time period 1985-1994 in order to average out coincidental annual fluctuations in consumption growth in the years for which the exponential reserve index is computed.

[9] In addition, as Ray (1984, p. 76) observes, in continents other than Europe and Northern America, „large areas (...), even parts that have been geologically classified as probably rich in minerals (...), have been no more than partially explored".

[10] It also has to be taken into account that the growing of renewable resources has its ecological price in the form of fertiliser and pesticide use as well as soil erosion.

[11] Although if we take on an even longer time perspective, fossil fuels will become renewed again, albeit at such a slow rate that this renewal is of no plausible relevance to humankind.

[12] Daly (1994, p. 25) tries to refute the possibility of substituting man-made capital for natural capital (here: natural resources) with a general argument: „One way to make an argument is to assume the opposite and show that it is absurd. If man-made capital were a near perfect substitute for natural capital, then natural capital would be a near perfect substitute for man-made capital. But if so, there would have been no reason to accumulate man-made capital in the first place, since we were endowed by nature with a near perfect substitute." Daly's argument is incorrect, however. It says that if A is a near perfect substitute for B, then B must be a near perfect substitute for A. But the conclusion does not follow from the premise. A might have some additional desirable properties that B does not have: For some production purposes A and B are almost near perfect substitutes with almost linear isoquants. But for other purposes, A has some desirable properties that B does not have. Hence, A can substitute for the totality of B, but not vice versa. Hence, there is reason to accumulate A and substitute for B.

[13] An important assumption is that there is no depreciation of man-made capital. As Dasgupta and Heal (1979, p. 226) indicate, the basic results would go through as well with capital depreciation as long as capital depreciates at less than an exponential rate. Note also that technical progress which Dasgupta and Heal exclude could counteract exponential capital depreciation. On this, see the discussion in section 5.

[14] Note that σ is bounded below by zero. With $\sigma = 0$, capital and resources are already perfect complements. A negative elasticity of substitution ($\sigma < 0$) is not possible.

[15] Slade (1987, p. 351) reports values that suggest that man-made capital's share and the resources' share are approximately equal. However, this is a misunderstanding. Berndt and Wood (1975), on which Slade based her values, included intermediate goods in the production function. Those intermediate goods do not fall from heaven and presumably the share of man-made capital in those intermediate goods is higher than the share of resources, so that the ultimate share of man-made capital is still considerably higher than that of resources, thus reconciling the reported values with those of Solow (1974a), Hartwick (1977) and Dasgupta and Heal (1979).

[16] In one of the rare attempts to estimate elasticities of substitution for non-energy resources, Brown and Field (1979, p. 241) found high elasticities of substitution for steel, copper, pulp and paper through man-made capital and labour. Deadman and Turner (1988, p. 91) present qualitative evidence for low elasticities of substitution for Beryllium, Titanium and Germanium.

[17] See Berndt and Field (1981), Chichilnisky and Heal (1993), Prywes (1986), Solow (1987) and Chang (1994).

[18] Note that here labour is not assumed to be constant and therefore enters the production function explicitly.

[19] Resource augmenting technical progress is technical progress that can be attributed to the production factor natural resources. It is to be distinguished from technical progress that augments other factors of production such as labour augmenting technical progress and from so-called Hicks-neutral technical progress that cannot be attributed to any single production factor.

[20] 'Loosely' because formally it is not possible for the Cobb-Douglas production function to distinguish pure capital- from resource-augmenting technical progress.

[21] Energy intensity generally falls also cross-sectionally with rising incomes. There is an important caveat, however. To compare energy intensity cross-sectionally, the GDP of each country has to be converted from the local currency into a common denominator, usually into US$. Until recently, it was common to use official exchange rates. Now, however, the United Nations and the International Monetary Fund pay more attention to the purchasing power of currencies and have published GDP-figures measured in purchasing power parity. According to Khatib (1995, Table 1, p. 728) GDP in purchasing power parity is reasonably close to GDP as conventionally measured in the OECD-countries. For developing, and Eastern European countries as well as countries of the former Soviet Union, however, GDP is often 200% or even more higher if expressed in purchasing power parity than conventionally reported. China's GDP, e.g., rises from 415 to 2,257 billion US$. Not surprisingly, Khatib finds that the energy intensity in developing countries drops significantly when GDP is calculated in purchasing power parity. The same is to be expected for resource intensities other than energy.

[22] This is the most often used measure for energy intensity. For other, more contested concepts of measuring energy efficiency see Patterson (1996).

[23] Recent evidence even seems to suggest that resource intensity might revert to rise again at high levels of income. De Bruyn and Opschoor (1997, p. 266) found evidence for developed countries showing their aggregate consumption of materials, energy and transport „again increasing faster than GDP“ in the late 1980s and early 1990s after more than a decade of delinking resource consumption from economic growth.