PUBLIC POLICIES AGAINST GLOBAL WARMING

HANS-WERNER SINN

CESIFO WORKING PAPER NO. 2087
CATEGORY 8: RESOURCES AND ENVIRONMENT
AUGUST 2007

CESifo *Working Paper No. 2087*

PUBLIC POLICIES AGAINST GLOBAL WARMING

Abstract

Judged by the principle of intertemporal Pareto optimality, insecure property rights and the greenhouse effect both imply overly rapid extraction of fossil carbon resources. A gradual expansion of demand-reducing public policies – such as increasing ad-valorem taxes on carbon consumption or increasing subsidies for replacement technologies – may exacerbate the problem as it gives resource owners the incentive to avoid future price reductions by anticipating their sales. Useful policies instead involve sequestration, afforestation, stabilization of property rights and emissions trading. Among the public finance measures, constant unit carbon taxes and source taxes on capital income for resource owners stand out.

JEL Code: O13, Q32, Q54, H23

Keywords: global warming, carbon taxes, Pareto optimality.

Hans-Werner Sinn
Ifo Institute for Economic Research
at the University of Munich
Poschingerstr. 5
81679 Munich
Germany
sinn@ifo.de

August 2007

I wish to thank Max von Ehrlich for careful research assistance and Wolfgang Weber for an introduction to the laws of organic chemistry.

1. The greatest externality ever

There are only small amounts of carbon dioxide, CO_2, in the atmosphere, just about 0.04%. But this small amount is just right for us. Less would make the world too cool, and more would make it unpleasantly hot. Mankind has genetically been optimized and adapted to a situation that has prevailed with only little variation over millions of years.

The temperature of the Earth is the result of a delicate balance between the radiation received and remitted. In order for the Earth to maintain a given temperature, it needs to radiate as much energy back into space as it receives. The warmer the Earth is, the more energy it remits. If remittance is hampered by greenhouse gases, which absorb low-frequency emissions, but do not impede high frequency emissions, the Earth has to be warmer to nevertheless remit the energy it receives. Suppose the Earth's atmosphere consisted only of oxygen and nitrogen, which in reality make up 99% of it. Then a square meter of the Earth's surface would absorb, on average, 288 watts of energy, and the equilibrium temperature of the atmosphere that makes the Earth remit exactly these 288 watts would be -6°C. This would be way too cold for mankind to live there.[1] Fortunately, however, there are tiny quantities of greenhouse gases in the air, in particular 380 parts per million (ppm) of carbon dioxide[2], up to 0.02% of water vapor, and a few other, even rarer, though more effective, climate gases such as methane (1.8 ppm) or nitrous oxide (0.3 ppm). Taking other countervailing effects such as dust and clouds that cool the Earth into account, an equilibrium temperature of $+15^\circ$C follows, which is today's cozy average. The 21°C extra warmth relative to what would have prevailed without the greenhouse gases is just fine. Fortunately, the Earth does not have an atmosphere like Venus which consists predominantly of carbon dioxide. Venus has a temperature of 525°C. With that heat, there would be no life and no love on Earth.

Before the Industrial Revolution there were only 280 ppm carbon dioxide in the atmosphere, and the average temperature was about 14°C. The nearly one-degree increase to 15°C that we have seen in the meantime has not really been a problem. The 20 cm increase in the sea level that has resulted is tiny relative to the 5 m decline since the last warm period some 120,000 years ago, and even more so relative to the 100 m rise since the last ice age some 18,000 years ago.[3] But we are currently just at the beginning of a period of rapid change.

---

[1] See Houghton (2004, p. 15 n.).
[2] See Stern et al. (2006, p. III).
[3] See Houghton (2004, pp. 145–150).

Cautious “pre-Chinese” estimates predicted a doubling of the pre-industrial concentration of carbon dioxide in the atmosphere until 2050, i.e. an increase to 560 ppm. They also predicted an increase to 650 ppm by 2100 if business goes on as usual.[4] The more recent estimates published in the Stern Review[5] are more pessimistic. They suggest that a doubling of the pre-industrial CO_2 concentration could already take place up to 2035, and that by 2100 a value of about 900 ppm would be reached in a business-as-usual scenario. The estimated temperature increase, as measured from the pre-industrial level, resulting from the doubling of the pre-industrial concentration level is about 2°C or more. A partial melting of glaciers and polar caps as well as the thermal expansion of the sea water would increase the sea level by about another 20 cm. The 5°C increase that the Stern Review fears up to 2100 would increase the sea level by about one meter. If this does not sound much, note that a 5°C increase is about the increase in the world temperature since the last ice age and that a one meter rise in the sea level would flood more than one fifth of Bangladesh.[6] There are further dangers including more powerful and devastating tropical storms, the elimination of a substantial fraction of the world’s species, and droughts causing mass migrations toward more fertile countries and regions. Stern and his co-workers argue convincingly that temperature increases beyond 5°C would “take humans into unknown territory”.

Economists have challenged the Stern result that an increase by 5°C could cost mankind up to 7 trillion dollars in present value terms,[7] but whatever the true value is, the developments are alarming by all means. It is understandable that the Stern Review calls the carbon dioxide problem the “greatest and widest-ranging market failure ever seen”.

2. Carbon, carbon dioxide and public policy

Even before the Stern report fuelled a new public debate about the problem of global warming, most governments signing the Kyoto Protocol had taken action, subsidizing a wide variety of alternative technologies, including wind energy, water power stations, bio fuels, wood pellets, solar heating, photovoltaic panels and the like. High taxes on fuels have also given incentives to install better insulation of homes, mitigate the expansion of traffic and to build lighter cars empowered with hybrid engines or common-rail diesel engines. There is even a new interest in previously discarded nuclear technologies. The new EU system of

---

[4] See, e.g., Leggett, Pepper and Swart (1992).
[5] See Stern et al. (2006)
[6] See Muhtab (1998) and Houghton (2004, pp. 10 and 150-152 as well as figure 4.4.
[7] Nordhaus (2006), Tol and Yohe (2006), Byatt et al. (2006) and Carter et al. (2006).

CO_2 emissions trading has, moreover, induced business, in particular electricity producers and the chemical industry, to economize on their combustion processes.

All of this sounds encouraging in the efforts to overcome the world's greatest market failure and solve its largest public goods problem. The idea is that if one country or a group of countries cut their CO_2 emissions, aggregate emissions will be reduced by the same amount, and even if others do not follow, global warming will be mitigated at least somewhat. As described by the theory of privately provided public goods, the incentive to curtail emissions may not be enough from an efficiency perspective, but the situation is not hopeless.

Unfortunately, this view does not carry very far because it neglects the supply-side effects that result from the international and intertemporal linkages between the CO_2 emitters via the underlying energy markets. All the technological devices cited above are means to reduce the demand for fossil fuels. But what about the supply of energy? The public debate is silent about the supply side of the problem, and even the voluminous Stern Review mentions the energy markets only in passing (pp. 185, 318).

How the CO_2 concentration in the atmosphere changes depends on extraction, and extraction is the result of both demand and supply. Extracting the carbon from underground and accumulating it in the air as carbon dioxide is one economic act that cannot simply be separated. Ultimately, all the demand reducing measures will mitigate the problem of global warming only to the extent that they induce the oil sheiks and other owners of fossil fuel resources to keep the carbon underground.

Suppose for a moment the oil sheiks cannot be convinced, i.e. suppose the suppliers of carbon stubbornly follow their intended extraction plans whatever happens to the price of carbon. In this case, the demand reductions by one country or a group of countries will be useless. They will simply reduce the world energy price and induce other countries to increase their energy demand by exactly the same amount. The amount of carbon dioxide accumulated in the air will not change, and global warming will continue unchanged.

But is the link between the extraction of carbon and the production of carbon dioxide emissions really that strong? Would it not be possible for policy-makers to induce the production of technical devices that decouple the emission of CO_2 from the burning of carbon fuel by having more efficient combustion processes? Can't we continue to produce energy from burning carbon without pumping more CO_2 into the atmosphere? The answer is basically no, with only two exceptions, sequestration and afforestation, which will be discussed in section 6. The reason lies in the laws of chemistry. Fossil fuels basically consist of molecules that are composed of carbon and hydrogen. Oxidation generates usable energy, converting the carbon into carbon dioxide and the hydrogen into water. Coal consists predominantly of carbon.[8] In crude oils, every 5 to 9 carbon atoms bind one hydrogen atom. Methane has 4 hydrogen atoms for each carbon atom. Each hydrogen atom brings an energy of about 30% of the energy contained in a carbon atom.[9] Thus, for example, a molecule of methane generates 2.2 times the energy of a molecule of carbon while generating the same amount of carbon dioxide.[10] While the ratio of energy relative to carbon dioxide is best for methane and a bit better for oil than for coal, none of the fossil fuels can avoid the production of carbon dioxide. In fact, with all fossil fuels the ratio between the carbon burned and the amount of carbon dioxide produced is the same chemical constant.

There is of course the possibility of increasing the efficiency of combustion processes by avoiding a waste of oxidizable carbon or a waste of heat generated by oxidation, but this does not contradict this statement. The laws of chemistry imply that demand reducing measures will be unable to mitigate the greenhouse effect unless they succeed in also reducing carbon supply.

It is obvious what kind of reactions the demand reducing policies described above will have if the supply path for carbon remains unchanged. Genuine demand reducing measures such as insulating homes, building lighter cars, or reducing traffic will simply mean that domestic demand is replaced by foreign demand, which is stimulated through a decline in world energy prices relative to what they otherwise would be. Alternative methods of generating usable energy from wind, water, sunlight or biomasses may also depress the price of energy in the world markets and stimulate demand elsewhere, but if, as assumed, they do not affect the extraction path, the general equilibrium reaction of world energy markets must be such that the alternative energy produced simply is consumed in addition to the energy contained in fossil fuels. There is a contribution to economic growth and mankind's well being, but not towards a mitigation of the greenhouse effect. The same is true for measures that avoid the waste of heat or brake energy (hybrid cars). They generate more useful energy, but cannot reduce the consumption of carbon. Even the energy provided by nuclear power stations will come on top of the fossil energy rather than replacing it. And ironically, measures that improve the technical efficiency of combustion processes by avoiding the

[8] Lignite coal consists to about 70% of carbon and about 5.5% of hydrogen, anthracite consists to about 93% of carbon, 3% of hydrogen. The rest is oxygen, nitrogen and sulphur. See Dubbel (1990).

[9] The figure cited refers to net calorific value, which is gross calorific value net of unavoidable loss of energy because of the vaporization of the water generated.

[10] One of the implications of this difference is that one tonne of methane generates 1.8 times the energy of one tonne of coal while generating even less carbon dioxide (2.75 versus 3.7 tonnes).

emission of unburned fossil fuel components through chimneys or exhaust pipes, such as the use of hotter combustion processes in power plants or the common rail diesel technology, would increase the world-wide output of CO_2 and exacerbate the problem of global warming.

How much carbon will end up in the air if all fossil fuels are burned? Are the stocks in the ground so limited that we do not have to be afraid or are they so big that measures to limit resource extraction are appropriate? A little back-of-the envelope calculation clarifies the dimensions of the problem. From the Industrial Revolution until the year 2000, humans burned about 300 Gt of carbon from fossil fuels.[11] The total reserves of oil, coal and methane that under present conditions seem worth extracting have been estimated to be in the range between 766 and 983 Gt of carbon, say about 900 Gt to take a number close to the average.[12] In the past, about 55% of the produced carbon dioxide was absorbed by land biomasses and the oceans (where 98% of carbon dioxide existing in the world is stored anyway).[13] Currently, (with the Stern figure of 380 ppm carbon dioxide) there are about 809 Gt of carbon in the atmosphere.[14] If the percentage of natural absorption is kept fixed, burning the reserves means that, roughly speaking, another 400 Gt of carbon will enter the atmosphere, which would be an increase by 49%, from 380 ppm to 566 ppm. According to the information given in the introduction, this would likely increase the world temperature by more than 2°C above the pre-industrial level.[15]

However, resources might be a better base for the calculation than reserves. Resources include stocks underground that under current energy prices and with current technologies are not worth extracting, but that could become profitable with higher prices. Estimates of the overall stocks of resources for oil, gas and coal in terms of carbon content range from 3,967 to

---

[11] Cf. World Energy Council (2000, p.149), between 1860 and 1998: 294 Gt of carbon. Marland et. al. (2005) between 1750 and 2004: 315 Gt. World Resource Institute (2005), between 1850 and 2000: 277 Gt of carbon. Note that the World Resource Institute reports CO_2 emissions which have to be multiplied by 12/44 to get carbon emissions (see IPCC 1996, p 1.8).

[12] World Resource Institute (2005): 862 Gt; World Energy Council (2000, p. 149): 983 Gt; calculations on basis of BP (2007, S. 6,22,32): 766 Gt; Calculations on basis of BGR (2007, S. 6 f..): 786 Gt. The carbon reserves consist to about 20–24 % of oil, 14-11 % of natural gas (methane) and 66–65 % of coal, calculated according to the proven reserves of BP (2007) and BGR (2007). Note that, for the reasons discussed above, the carbon shares cannot be equated with the energy shares.

[13] See Houghton (2004, p. 32).

[14]The stock of CO_2 in atmosphere is calculated using 5.137x10^18 kg as mass of the atmosphere, which translates to 1 ppm of CO_2 = 2.13 Gt of carbon (Trenberth 1981). For the early 1990s the UN Environmental Program (1998) estimated about 750 Gt Carbon in the atmosphere, for the year 2000 the CDIAC (2000) estimated 369 ppm and about 787 Gt of carbon in the atmosphere.

[15] Assuming that the other greenhouse gases remain constant, this would raise the concentration of GHG in the atmosphere to about 616 ppm. For this level of greenhouse gas concentration, the Stern Review assigns a chance of between 82% and 100% that the global temperature will increase by at least 2°C. See Stern et al. (2006, p. 195).

5,579 Gt.[16] If 45% of the lower of these two quantities enters the atmosphere, the stock of oxidized carbon existing there would increase from today's 809 Gt to 2,594 Gt, i.e. by 221%. The concentration of carbon dioxide in the atmosphere would accordingly increase from 380 ppm to about 1,220 ppm, far more than any model projections thus far have dared to predict.

The report of the Club of Rome (Meadows et al. 1972) and the oil crises of 1973/74 and 1982 once nourished public fears about the limits to growth resulting from the foreseeable resource scarcity. Market enthusiasts had countered these fears on the grounds that reserves tend to increase with exploration activities and that the explorable stocks underground would be much larger than Meadows et al. assumed. Ironically, these same enthusiasts now have to admit that their optimism is giving rise the environmental pessimism that results from the above calculations. The perils of global warming could be large enough to make everyone think back wishfully to the low estimates about remaining resources given by Meadows et al.

The calculations show that with regard to the use of fossil carbon, humans face an extremely difficult choice problem that involves the simultaneous reduction of the stock underground and accumulation of the stock above ground. The carbon problem is serious enough that the limited absorption capacity of the air may constrain resource extraction more than the scarcity of the resources itself. The economics of resource extraction may have to convert into an economics of waste accumulation.

From an economic perspective there are fundamental normative and positive aspects that center around the question to what extent market failures distort the extraction paths relative to the optimum and which policy instruments could possibly remedy them. The next two sections will go into this.

3. The nature of the market failure

If seen against the background of extracting fossil carbon from the ground, the market failure generated by CO_2 emissions has little in common with the static marginal externality model used in textbooks, which is also the conceptual center of the Stern report (2006, esp. pp. 24–28). To understand the market failure, an intertemporal analysis is needed that concentrates on the wealth society bequeaths to future generations. Society's bequest includes natural capital in the ground, man-made capital above ground and the industrial waste resulting from past extractions in the air. There are two basic choice problems involved. One is the optimal mix between man-made capital, the natural resource and the stock of waste. The other is the

[16] Cf. BGR (2005, p. 6 n.): 278 Gt of carbon from oil, 845 Gt of carbon from gas and 2,844 Gt of carbon from coal; World Energy Council (2000, p. 149): 426 Gt of carbon from oil, 534 Gt of carbon from gas and 4,618 Gt of carbon from coal.

overall wealth that society transfers to future generations. A crucial question is the extent to what market forces can be expected to find an appropriate solution to this double choice problem and, if markets fail, which kind of policy measures are appropriate to improve the intertemporal allocation of resources.

3.1 *Neoclassical optimism*

Let us approach this question stepwise and consider first the idealized neo-classical world of intertemporal resource allocation with exhaustible resources, abstracting from market failures in general and the problem of global warming in particular. Consider a representative resource owner who possesses a stock of the resource in situ, S, with different degrees of accessibility so that extraction costs can be written as $g(S)R$, $g'(S) < 0$, where $R = -\dot{S}$ is the current flow of extraction and g is the extraction cost per unit. The resource owner chooses his extraction path so as to maximize the present value of his cash flow $(P - g(S))R$ where P is the price of carbon and i the market rate of interest. If the resource owner extracts a unit today and invests the profit in the capital market he will earn a return of $i\,(P - g(S))$. If instead he postpones extraction, his return will be $\dot{P}$. Thus,

(1) $$i = \frac{\dot{P}}{P - g(S)}$$ (positive)

is a necessary condition for both an optimal extraction plan of the resource owner and a market equilibrium. In the special case where $g = 0$ this equation reduces to Hotelling's condition that the percentage rate of price increase equals the rate of interest.[17]

Because of the main theorem of welfare economics, the perfect market solution described by equation (1) must have its normative counterpart. Suppose output is given by the production function

(2) $$Y = f(K, R, t)$$

where K is the stock of man-made capital and t is calendar time. Output can be used for consumption of man-made goods C, investment of man-made goods $\dot{K}$, and resource

[17] Note also that the rule does not say that the price net of the marginal extraction cost rises at a rate equal to the market rate of interest, which would be the case with marginal extraction costs depending on the current flow of extraction rather than the stock not yet extracted. See Sinn (1981) for further details.

extraction:

(3) $$Y = C + \dot{K} + g(S)\,R \ .$$

Then, as shown in Sinn (1981), it is impossible to increase consumption in one period without decreasing it in another if, and only if,

(4) $$f_K = \frac{\dot{f}_R}{f_R - g(S)}$$ (normative; Pareto).

Equation (4) is a generalization of the efficiency condition of Solow (1974a) and Stiglitz (1974) for the extraction of depletable economic resources to the case of stock-dependent extraction costs. The Solow-Stiglitz condition refers to the special case where $g = 0$ and says that the extraction path be chosen such that the growth rate of the marginal product of the resource be equal to the marginal product of capital. With extraction costs this condition is modified such that the increase in the marginal product of the resource relative to the marginal product net of the extraction cost be equal to the marginal product of capital. As competitive markets imply that $f_K = i$ and $f_R = P$, equation (4) obviously coincides with equation (1), demonstrating the efficiency of the market equilibrium.

While equations (1) and (4) describe an optimal portfolio mix between man-made and natural capital to be bequeathed to future generations, they do not address the problem of how much wealth should and will be bequeathed. Answering this question is more problematic as it involves difficult intergenerational welfare judgments specifying the altruistic weight present generations are willing to give future generations. A common utilitarian specification uses an additively separable utility function of the type

$$\int_0^\infty N(t)\, U\big(c(t)\big)\, \mathrm{e}^{-\rho t}\, \mathrm{d}t$$

where N is the number of people in a dynasty, $c(t) = C(t)/N(t)$ is per capita consumption, U instantaneous utility and ρ is the rate of utility discount across and within generations.

If individuals have the possibility of investing their wealth at the going market rate of interest, they allocate their consumption across the generations such that they equate their rate of time preference to the market rate of interest:

(5) $\quad i = \rho + \eta \, \hat{c} \quad$ (positive, utilitarian).

Here the rate of time preference consists of the rate of utility discount ρ and the relative decline in marginal utility resulting from an increase in per capita consumption over time, $\eta \, \hat{c}$, where η is the absolute value of the elasticity of marginal utility.

The normative counterpart of equation (5) is

(6) $\quad f_K = \rho + \eta \, \hat{c} \quad$ (normative)

because a benevolent central planner who respects individual preferences would allocate consumption over time such that people's rate of time preference equals the return that a real investment is to be able to generate. Again, the market solution and the social planning solutions coincide.

3.2 *Nirvana ethics*

Many authors, notably Page (1977), Solow (1974 b), Anand and Sen (2000) as well as Stern et al. (2006, esp. annex to chapter 2) have argued that the market solution cannot be accepted on ethical grounds because discounting future utility means discriminating later generations relative to earlier ones. If anything, discounting could be justified by the probability of extinction for exogenous reasons, but the discount rate following from that argument is much smaller than the discount rates normally used, being in the order of one tenth of one percent.[18] Without discounting of utility, only technical progress that increases per capita consumption would in the long run be able to explain a positive rate of time preference from an ethical perspective, but as that rate would be much lower, equation (6) would imply a lower marginal product of capital. This would mean more capital accumulation and, because of (4), more resource conservation: The marginal product of the resource would have to rise at a lower speed, which requires a flatter extraction profile with a lower extraction volume in the present.

The argument is as old as the theory of interest. Eugen von Böhm-Bawerk (1888), who introduced the distinction between ρ and $\eta \, \hat{c}$ as the two main reasons for time preference, had already argued that people make a mistake when they underestimate future needs. Ramsey (1928, p. 543) and Pigou (1932, pp. 24–25) later repeated the argument.

[18] Stern et al. (2006, p. 47). The probability implies that mankind becomes extinct with a probability of 9.5% in one hundred years.

However, from the perspective of economic policy this argument leads nowhere, because it is not the philosophers who make collective policy decisions but the current generation of voters themselves. If the current generation discounts utility when they make their private intertemporal allocation decisions, they will elect politicians who do the same. These politicians will not find any mistakes in the intertemporal allocation pattern and will therefore not take countervailing policy actions.

Of course, one could counter from a philosophical perspective that it would nevertheless be wrong to follow the current generations' preferences, because these preferences are wrong. However, that would be a dubious position, to say the least, because it would imply that parents do not take the needs of their children and further descendants into account and that a benevolent dictator, presumably advised by philosophers, is needed to enforce the lacking altruism. As I see no indication that parents might be insufficiently altruistic towards their offspring and neither envisage future generations coming from Mars and thus lacking a proper representation among the people living today, I find the argument totally unconvincing. If economics adopted it, it would leave the firm ground of methodological individualism and get stuck in the moody waters of Nirvana ethics.

3.3 *Insecure property rights*

An argument that is not based on mistrust in people's preference is based on the fact that resource owners often face insecure property rights and might therefore overextract. It was developed by Long (1975) and extended by Konrad, Olson and Schöb (1994). Various papers by Chichilnisky (1994, 2004) also were written with a similar, yet more general message, although these papers were not focusing on the intertemporal dimension of the problem.

Think of an oil sheik. The sheik feels insecure as to how long his dynasty will possess the oil underground, because he fears the risk of revolt and subsequent expropriation by a rival. Let

$$e^{-\pi t},\ \pi = const. > 0,$$

be the probability of survival of his or his heirs' ownership until time *t*, where π is the instantaneous expropriation probability. For a resource owner who maximizes the expected present value of his cash flow from resource extraction this effectively means that he discounts with $i+\pi$ rather than *i* alone. Hence (1) changes to[19]

[19] When the resource owner extracts the resource immediately and invests the cash flow in the capital market he has a return $i\,(P-g(S))$ as before, but when he keeps the resource in the ground, the expected return now is $\dot{P}-\pi\,(P-g(S))$. Equating these two expressions gives (7).

$$(7) \qquad i + \pi = \frac{\dot{P}}{P - g(S)} \qquad \text{(positive, insecure property rights).}$$

As the probability of being expropriated denotes a private, but not a social damage, the welfare optimum continues to be given by (4) and (6). As $i = f_K$ as before, equation (7) shows that for any given P the price path becomes steeper, which indicates overextraction and is a legitimization for conservative policy actions.

There is a similar implication for the extraction path if the property rights are improperly defined insofar as a multitude of firms extract from the same pool of oil or gas underground. The literature, including Khalatbari (1977), Kemp and Long (1980), McMillan and Sinn (1984) as well as Sinn (1982, 1984a), has demonstrated why the common pool problem implies overextraction and has discussed the possible policy remedies. The common pool problem was of major importance in the early years when the farmers of Texas detected they were sitting on a common pool of oil, and it therefore bears some responsibility for today's CO_2 problem. However, it seems that it has been largely solved by consolidating the oil fields or sharing arrangements between extracting firms.[20]

Unfortunately, the problem of insecure property rights has not gone away over time, and indeed it could be substantial, in particular in the case of oil and gas extraction. Think of Venezuela, the Arab countries, Iran or the former Soviet Union, where the political situation has been extremely insecure over the last decades and is likely to remain so in the future. It is estimated that in these countries there are between 70% and 80% of the world's oil and about three quarters of the world's gas reserves.[21] Thus people like Hugo Chávez, Saddam Hussein, Muammar al-Gaddafi, Mahmud Ahmadinejad, Mikhail Khodorkovsky or Roman Abramovich are or were the custodians of substantial parts of mankind's fossil fuel resources (and as it turns out now, also of the world's atmosphere). If such people feel insecure about for how long they, their descendants or members of their clans will be able to extract the resources they currently own, they better hurry up, extract the resources now and safeguard the proceeds on Swiss bank accounts.

How exactly political risk affects resource extraction is still subject to debate. On the basis

---

[20] The problem has regained its importance in the case of fossil water pools such as the Ogalalla aquifer beneath many Great Plain states in the US.

[21] BP (2007) reports that in 2006 Venezuela, the former Soviet Union and the Middle East (i.e. Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen and others) owned 79% of proven world oil reserves and 74% of proven gas reserves. For the same group of countries, EIA (2007) reports figures of 70% and 75%, respectively.

of a careful and extensive empirical study Bohn and Deacon (2000) showed that political risk may actually slow down extraction because it reduces the incentive to invest in exploration of new fields and in extraction technology. The authors construct a political risk index that explains ordinary investment well and then show that there is a negative correlation between this index and the speed of oil extraction. Interestingly enough, however, upon decomposition of the effects, Bohn and Deacon (pp. 476–477) also find that dictators tend to conserve the oil more than democracies do, while frequent coups or constitutional changes tend to speed up extraction. One interpretation of this result is that, while democracies offer more safety for outside investors and hence attract direct investment, they at the same time tend to challenge the property rights of the countries' existing clans, who would not have carried out ordinary investment but own the countries' natural resources. Democracy for these clans is a serious ownership risk, which gives them every reason to speed up extraction in a similar way as increasing political turmoil does. If this interpretation is correct, the result of Bohn and Deacon fully supports the view that increased ownership risk leads to overextraction.

3.4 *Global warming*

Let us now turn to global warming, the theme of this paper. What is the exact way in which this type of externality enters the positive and normative equations describing intertemporal allocation of resources? The answer to the first part of this question is obvious, as, by its very nature, the externality does not affect the conditions that characterize market behavior. Equations (2) or (6) respectively remain valid. The emissions of carbon dioxide are an externality par excellence as they distribute evenly around the globe, damaging air quality, the world's most precious public good.

The real question is how the normative conditions are affected. Assume, in line with what was discussed above, that the temperature on Earth is a monotonically increasing function of the stock of carbon dioxide in the air, that the stock of carbon dioxide in the air is a monotonically increasing function of stock emitted, and that the stock emitted is proportional to the stock of carbon extracted. To the extent that the temperature deviates from the pre-industrial level, it creates damages in terms of costs of dislocation, dyke building, air conditioning, reconstruction of buildings, agricultural damages and the like. As the damage or the necessary repair activities can be described as a loss of output, a reduced form of the aggregate production function with the damage from global warming is

(8) $$Y = f(K, R, S, t),$$

where the resource in situ, S, stands in for the environmental quality in the sense of carbon being absent from the air. With $f_S > 0,\ f_{SS} < 0,$ the normal properties of a production function can be assumed, which then also imply positive and increasing marginal damage from cumulative resource extraction. As shown in Sinn (2007) it follows from (8) and (3) that it is impossible to make one generation better off without making another one worse off, if and only if,

(9) $$f_K = \frac{\dot{f}_R + f_S}{f_R - g(S)}$$ (normative, with greenhouse effect).

Thus, (9) is a condition for intertemporal Pareto efficiency in the extraction of fossil fuels with stock-dependant damages from global warming, the analogue of equation (4) above.

Equation (9) shows that with global warming and hence $f_S > 0$, $\dot{f}_R$ must be smaller for any given time and any given values of *K, S* and *R.* Thus it demands a flatter extraction path with less extraction in the present, but a lower decline thereafter. The larger the damage from global warming is, the wiser it is to shift extraction to the future.

If compared with the market equation (7) two aspects are worth noting. One the one hand, because of global warming, $f_S > 0$, the relative increase in the cash flow per unit extracted resulting from postponing extraction should be less than the rate of interest:

$$i > \frac{\dot{P}}{P - g(S)}$$ (normative).

On the other, because of the risk of expropriation, $\pi > 0$, the relative increase in the cash flow per unit extracted resulting from postponing extraction is even greater than the rate of interest:

$$i < \frac{\dot{P}}{P - g(S)}$$ (positive).

The resource owners take a risk into account that they should not take into account, and they neglect a peril they should not neglect. For both reasons there is overextraction.

This result is in itself not surprising because it confirms the common belief that, because of global warming, the emissions of carbon dioxide should be reduced. Note, however, that it does not involve a value judgment that derives from considerations of inter-generation equity, fairness or sustainability, but follows merely from economic efficiency considerations.

Equation (9) describes an optimal composition in the wealth portfolio consisting of man-made capital, fossil fuels in situ and carbon waste in the atmosphere that society should bequeath to future generations whatever the size of the bequest is. Unfortunately, however, society does not obey this equation, leaving future generations too little fossil fuels relative to the capital it provides.

4. A simplified interpretation

To summarize the discussion up to this point a graphical presentation that uses a somewhat simplified version of the neo-classical production function may be useful. Assume that $F(K,R,S,t) = i\,K + \phi(R) + \psi(S)$ with $i = \text{const.}$ and otherwise the properties assumed above, i.e. $\phi' > 0$, $\phi'' < 0$ and $\psi' > 0$, $\psi'' < 0$. Let $P(R) = \phi'(R)$ denote the inverse demand function for carbon implied by this specification and assume that the price elasticity of demand, $-\varepsilon$, is a constant.

Let us demonstrate the extraction path in *R,S* space, following a method developed in Sinn (1982). The slope of the possible time paths in *R,S* space is given by

$$(10) \qquad \frac{\mathrm{d}R}{\mathrm{d}S} = \varepsilon\,\hat{P}$$

as $\mathrm{d}R/\mathrm{d}S = \dot{R}/\dot{S} = -\dot{R}/R = -(\hat{R}/\hat{P})\hat{P}$ and $\varepsilon = \hat{R}/\hat{P}$ by definition. Rearranging (7) and using (10) gives

$$(11) \qquad \frac{\mathrm{d}R}{\mathrm{d}S} = \varepsilon\,(i+\pi)\left(1 - \frac{g(S)}{P(R)}\right) \qquad \text{(positive).}$$

Equation (11) uniquely defines a slope for each point in *R,S* space and thus the set of possible paths compatible with the marginal conditions derived. Assume that $g(S)$ and $\psi'(S)$ are differentiable and bounded from above so that they cannot go to infinity as S goes to zero while, by the assumption of a constant ε, the price is unbounded as R goes to zero. As is shown in the appendix this ensures that the extraction paths will lead to the origin. Thus, in fact, (11) uniquely defines the equilibrium path itself.

Figure 1 depicts the equilibrium paths for three alternative specifications. The middle path is an example of a path that characterizes a market equilibrium where $\pi = 0$. As illustrated by the arrows, the economy follows this path as time proceeds. On the way, the stock and the current extraction volume, *S* and *R*, both dwindle to zero. The upper, steeper path characterizes the market equilibrium with insecure property rights, $\pi > 0$. It is obvious that it starts with higher extraction at $S = S_0$, the given initial stock. Note that, although on this path, extraction is higher than with secure property rights for any given value of the stock in situ, this does not mean that extraction is higher for all points in time. In fact, as the stock shrinks faster, there must be a finite point in time after which extraction is permanently lower than it otherwise would have been. The extraction path in a diagram showing time at the abscissa and extraction on the ordinate would also be steeper than in the case with secure property rights, and it would cut the latter once from above.

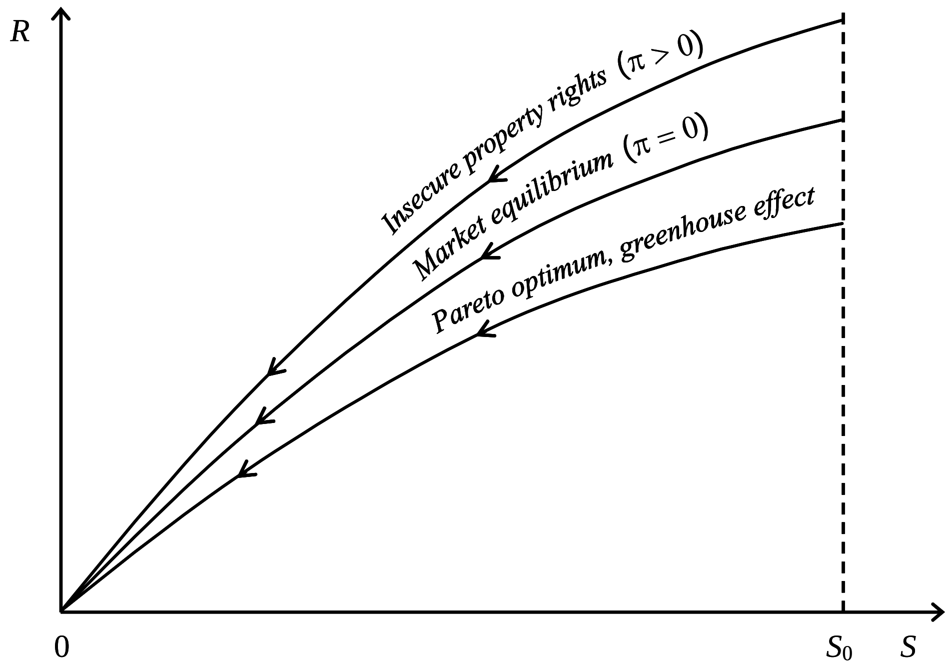

Figure 1: Efficient and actual time paths in the presence of global warming and stock dependent extraction costs

The middle path showing the market equilibrium with well defined property rights would be Pareto efficient if there were no greenhouse effect. However with the greenhouse effect another path is Pareto efficient. Its slope follows from (9) and (10) under the simplifying assumptions made:

(12) $$\frac{\mathrm{d}\,R}{\mathrm{d}\,S} = \varepsilon\left[i\left(1-\frac{g(S)}{P(R)}\right)-\frac{\psi'(S)}{P(R)}\right]$$ (normative, with greenhouse effect).

Equation (12) gives a lower slope for each point of the *R*,*S* diagram and hence a lower slope and position of the path leading to the origin, which, as is shown in the appendix, remains the target point as time approaches infinity also from an efficiency perspective. A comparison of the three paths shown reiterates the point made above that the insecurity of property rights implies a higher current extraction volume than in standard analysis while the extraction volume should, in fact, be lower because of the greenhouse effect.

5. Green policy paradoxes

Let us now return to the problem of public policy. It was shown in section 2 that the demand policies emphasized in the public debate are useless if the supply path of carbon is fixed. Alternative ways of generating energy, carbon taxes or attempts to reduce the energy intensity of economic activities are all futile if the sheiks do not participate in the game. One country's green policies just help the other country buy energy at lower prices, and the speed of global warming is unchanged.

While the assumption of exogenous supply was made for didactic reasons, it has more relevance for the resource problem than might appear at first glance for the simple reason that, apart from the extraction cost, fossil fuels need not be produced but are available at a given quantity in the Earth's crust as a gift of nature. To be sure, this still leaves room for supply reactions in the sense of tilting the time path of extraction. However, if firms react to a change in demand today by extracting less, they must extract more tomorrow, and vice versa. In light of the marginal conditions discussed in the previous two sections the policies needed are those that make the extraction path flatter, which implies less extraction in the present and more in the distant future.

It may in addition be useful to choose policies that reduce the exhaustible stock of resources in the very long run. However, the analysis of the positive and normative conditions for such policies involves detailed assumptions on the limiting properties of the production and extraction cost functions which, in principle, cannot be observed empirically in this historical phase of time. Under the simplified assumption of the previous section, that the functions giving the unit extraction cost and the marginal product of the resource in situ are differentiable and bounded from above as the stock in situ dwindles to zero while the resource price is unbounded, it would never be optimal to limit the exhaustible stock, but of course there are other possible assumptions, and nothing we know today would allow us to decide which ones are more realistic. Sound public policy against global warming should therefore focus on trying to flatten the time path of extraction rather than reducing the stock that will be exhausted as time goes to infinity. This is also advisable insofar as, for many years to come, the effects resulting from a policy of permanent exemption could easily be overcompensated by effects that operate via tilting the supply path.

If this postulate is accepted, most of the demand-reducing measures discussed in section 2 may not pass the test. While some of them may reduce the stock worth extracting as time goes to infinity, it is by no means obvious that they will tilt the time path of extraction in the right direction. The reason is that they exert two countervailing effects on the current extraction volume. On the one hand, they reduce the incentive to extract because they depress today's prices. On the other, they increase the incentive to extract because the anticipated demand and price decline that these policies generate in the future reduces the opportunity cost of the resource in situ. Unless it is demonstrated that the latter effect is dominated by the former, the policies cannot reasonably be proposed as a means to mitigate the greenhouse effect.

To be more concrete, let us begin the policy discussion with an analysis of tax systems. Consider first a cash flow tax to be paid by the resource owners. Such a tax will admittedly be hard to implement, but it is a good starting point for understanding the problem. The tax revenue equation for a cash flow tax is

(13) $$T = \tau\ Z\,, \quad Z \equiv \big(P - g(S)\big)R \qquad \text{(cash flow tax)}$$

where T is the tax revenue, τ the tax rate and Z is the cash flow. Let $\theta = 1 - \tau$ denote the tax factor. As is well known, a cash flow tax does not affect the extraction path, because choosing the extraction path so as to maximize the present value of θ times the cash flow stream is the same as choosing it so as to maximize θ times the present value of this stream, and maximizing a constant times the economic result of an action is the same as maximizing the result itself. See Brown (1948) for the general argument and Dasgupta and Heal (1979, ch. 12) as well as Sinn (1982, 1984 b) for its application to the taxation of exhaustible resource. A cash flow tax that is levied at a constant rate has the property of reducing the shadow price of the resource in situ exactly by the amount necessary to generate behavioral neutrality. It is the ideal example for a demonstration of the two countervailing effects.

Consider next an ad-valorem sales tax on the extraction of carbon. This tax differs from a cash flow tax only insofar as extraction costs are not tax exempt. Let a star indicate the ad-valorem tax. The tax drives a wedge between the consumer price P and the producer price, which is $\theta^* P$. An ad-valorem sales tax might also be difficult to implement. However, a consumption tax levied by the consuming countries would be possible, and according to one of the main theorems of public finance, it would have the same allocative effects as the sales tax.

If there are no, or only negligible, extraction costs, the consumption tax is as neutral as a cash flow tax, because it then *is* such a tax. As the stock of the resource that will be extracted in the long run is given, there will be no supply reactions at any point in time. The only effect the tax has is that it makes the producers of carbon poorer by effectively expropriating part of the available stock in situ.

If extraction costs are not negligible, the consumption tax loses its neutrality property. As the resource firm tries to maximize the present value of the cash flow stream $\theta^* RP - g(S)R$ which is equivalent to maximizing the present value of the stream $RP - (g(S)R/\theta^*)$ it is obvious that equation (7) changes to

$$(14) \qquad i + \pi = \frac{\dot{P}}{P - \frac{g(S)}{\theta^*}} \qquad \text{(constant ad-valorem tax)}$$

which implies that, with any given values of i, π and P, $\dot{P}$ is becoming smaller. Thus the extraction path becomes flatter and indeed more carbon is conserved. The flattening of the path means less extraction in the present and more in the distant future.

This seems to shed a rather favorable light on the basic policy conclusion of the Stern Review, that a world-wide tax on the consumption of carbon would mitigate the global warming problem. There are two important caveats, however. One is that the tax only operates via increasing the marginal extraction costs. As marginal extraction costs are likely to be only a small fraction of the price of the extracted resource, the effect on the extraction path may be tiny. For instance, the average production costs of crude oil amounted to only about 15% of the average spot price in 2006.[22] The second is the assumed constancy of the tax rate. What if environmentalist concerns become more and more popular so that resource owners expect that governments will increase the tax rate over time?

[22] Following Harks (2007) average production cost of crude oil amounted to about 10$ per barrel while the average spot price was about 65$ per barrel (see BP 2007).

The answer has been given in Sinn (1982) with an intertemporal optimization model describing the market reactions to a changing ad-valorem tax rate.[23] Here it may be enough to sketch the argument. To understand the implications of a changing tax rate, let us for a moment return to the cash flow tax, which coincides with the ad-valorem tax if extraction costs are absent. Assume that the tax factor changes at a constant rate $\hat{\theta}$:

$$(15) \qquad \theta(t) = \theta(0)\ \mathrm{e}^{\hat{\theta} t}, \quad \hat{\theta} = \text{const.}$$

As the resource owner maximizes the present value of his cash flow net of the tax relevant for the respective point in time, (15) together with the neutrality of a constant cash flow tax implies that he behaves as if he used a discount rate $i + \pi - \hat{\theta}$ instead of only $i + \pi$ as was assumed before. Thus, instead of (14), we get

$$(16) \qquad i + \pi - \hat{\theta} = \frac{\dot{P}}{P - g(S)} \qquad \text{(changing cash flow tax).}$$

Equation (16) shows that with a changing tax rate, the often appraised neutrality of a cash flow or consumption tax disappears, giving way to substantial intertemporal distortions.[24] With an increasing tax rate, i.e. with $\hat{\theta} < 0$, $\dot{P}$ would have to be higher, with any given P indicating steeper rather than flatter price and extraction paths with more extraction in the presence. Thus the problem of global warming is exacerbated rather than mitigated.

Unfortunately, this verdict transfers to the ad-valorem tax on the extraction volume if the transaction costs are negligible. When $g(S) = 0$, equation (16) equally applies to such a tax with $\hat{\theta} = \hat{\theta}*$.

If extraction costs are assumed, the problem of moving the economy in the wrong direction is mitigated, and with sufficiently strong extraction costs, current extraction may even move in the right direction. In general, as has been shown by Long and Sinn (1985), with or without extraction costs, the borderline case where taxation is neutral for the extraction path is characterized by an absolute tax wedge that increases at the rate of discount, i.e. in the current model at the rate $i + \pi$, so that the discounted revenue loss per unit of the extracted resource is

[23] As my paper was published in a German conference volume, it had no influence on the discussion of the same problem by Ulph and Ulph (1994) and Sinclair (1994). The German paper can be downloaded from the CESifo website: www.CESifo.de.

[24] For a closely related discussion of the intertemporal distortions resulting from a non-constant tax on ordinary consumption goods, see Howitt and Sinn (1989).

constant. As the absolute tax wedge with an ad-valorem tax is $\tau^* P$, it follows that the borderline case is characterized by

(17) $$\hat{\tau}^* + \hat{P} = i + \pi$$ (borderline case for ad-valorem consumption tax neutrality).

Faster increase of the tax wedge implies the resource firms anticipate extraction and a smaller increase implies they will postpone extraction. Using (7), condition (17) can easily be converted to

(18) $$\hat{\tau}^* = (i+\pi)\frac{g(S)}{P(R)}$$ (borderline case for ad-valorem consumption tax neutrality).

This condition confirms that, without extraction costs ($g(S) = 0$), a constant ad-valorem tax would be neutral: $\hat{\tau}^* = 0$. With extraction costs, P grows at a lower rate and thus tax neutrality is compatible with a rising ad-valorem tax rate. If the tax rate rises faster than in the borderline case, the extraction path will again become steeper, with more current extraction and faster global warming. As this case remains a plausible possibility if the unit extraction costs are small relative to price, I conclude that the risk that ad-valorem taxes on the emission of carbon dioxide are useless or even dangerous is far too large to justify their implementation.

To demonstrate the argument in *R,S* space use again the simplified model introduced in the previous section. To keep the formal expressions simple, return to the cash flow tax, but keep in mind that a cash flow tax with $\hat{\theta} < 0$ produces qualitatively the same result as an ad-valorem consumption tax with $\hat{\tau}^* > (i+\pi)g(S)/P(R)$: It follows from (10) and (16) that, instead of (11), we now have

(19) $$\frac{\mathrm{d}R}{\mathrm{d}S} = \varepsilon\,(i+\pi-\hat{\theta})\left(1-\frac{g(S)}{P(R)}\right)$$ (changing cash flow tax) .

The normative condition (12), in turn, remains of course valid.

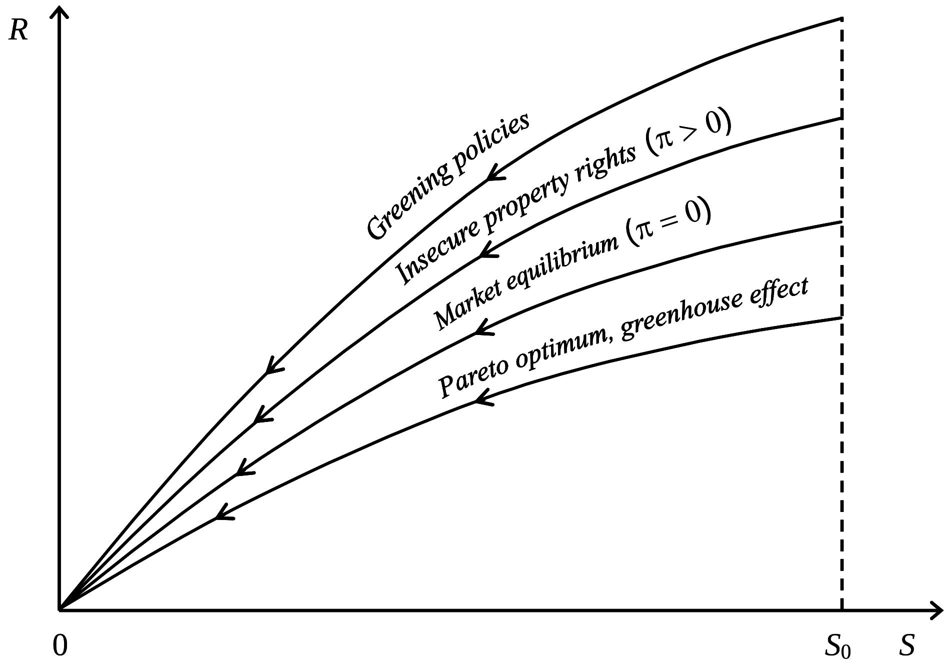

Figure 2: The green policy paradox

Figure (2) illustrates these results. The three lower paths are those shown in figure 1. The second path from below characterizes the market equilibrium with well-defined property rights and no government intervention $(\pi = \hat{\theta} = 0)$. The lowest path shows the Pareto optimum with the greenhouse effect. The second path from above characterizes the behavior of markets if property rights are insecure $(\pi > 0,\ \hat{\theta} = 0)$. Above this path is the path resulting from an increasing cash flow tax rate or an ad-valorem tax on the flow of extraction whose increase satisfies the condition $\hat{\tau}^* > (i+\pi)g(S)/P(R)$. It characterizes a green policy paradox insofar as the anticipation of a gradual greening of policy in the sense of an increasing cash flow or sufficiently increasing consumption tax rate will make the flow of current extraction even higher, and speed up global warming even more, than would be the case without government intervention.

Unfortunately, this result not only applies to an increasing tax rate but to the bulk of the green demand reducing policies discussed in section 2.

- Think of better insulation of homes, of lighter cars and of traffic reductions as examples of measures that directly reduce the demand for fossil fuels.
- Think of the generation of electricity from wind, water, sunlight, biomass or vehicle brakes (hybrid cars) as examples of green policy measures that reduce demand for

fossil fuels by providing non-fossil energy alternatives.

- Think of nuclear energy, nuclear fusion in particular, which, albeit not particularly green, also belong into this category. The electricity generated from nuclear energy could be used to produce hydrogen, which would facilitate storing and transportation of the energy provided.
- Think of pellet heating, bio diesel, heat pumps or solar heating as further examples of measures that reduce the demand for fossil fuels because the energy comes from other sources.
- Think of modern diesel engines and optimized power plants as examples of devices that reduce the demand for fossil fuels because they increase the technical efficiency of combustion processes.

All of these measures are currently intensely debated in the industrialized countries, and governments pour out subsidies to develop them further. As the world becomes warmer and more and more people accept and understand the mechanics of the greenhouse effect, public support for such measures will rise so that the demand reducing effect becomes stronger and stronger. This will have similar implications for the development of the prices resource owners will be able to charge as a general ad-valorem tax on carbon consumption that increases with the passage of time. Indeed it is straightforward to re-interpret the tax wedge $\tau * P$ assumed above as a demand wedge that pushes the demand curve prevailing at a particular point in time proportionately downward relative to the position that would have prevailed without the government policies that aim at reducing the production of carbon dioxide. $\theta * P$ in this case is the observable (consumer and producer) market price, and P is the price that would have prevailed without the demand reducing measures had the extraction flow been the same. It follows that the anticipation of a gradual greening of public policies that satisfies the condition $\hat{\tau}* > (i+\pi)g(S)/P(R)$ will give resource owners the incentive to anticipate the price dampening effect by selling more in the present and less in the future. The extraction path is shifted upward as is demonstrated in figure 2 by the move from the second highest to the highest curve, which, unfortunately, goes in the wrong direction exacerbating the double distortion that already results from insecure property rights and the greenhouse effect. The demand reducing measures of those countries for which the Kyoto Protocol involves binding constraints are not only useless, as was argued in section 2 under the hypothetical assumption of a constant supply path. What is more, they may even worsen the situation, because they induce the resource extracting countries to speed up their extraction.

The current price of carbon falls under these measures sufficiently to induce the unconstrained countries to buy so much more that the reduction in consumption of the constrained countries is overcompensated.

6. Useful policies against global warming

While ad-valorem carbon taxes and other demand reducing measures of the type emphasized by politicians and in the public debate may be useless or even dangerous, because they may cause countervailing supply reactions, the set of effective policies against global warming is not empty. This section discusses the remaining possibilities. Basically they consist of

- public finance measures to flatten the supply path
- safer property rights
- binding quantity constraints and
- technical means to decouple the accumulation of carbon dioxide from carbon consumption.

Let us look into these options.

6.1 *Public finance measures to flatten the supply path*

6.1.1 *Decreasing ad-valorem tax rate*

If an increasing ad-valorem tax rate tilts the supply path in the wrong direction, a declining one might do the job. Suppose therefore, the government started today with a high tax rate and announced that this tax rate would decline with the passage of time. In principle, such a policy would give the resource extractors the incentive to postpone extraction.[25]

This possibility can be understood by inspection of equation (16), which refers to a cash flow tax or, equivalently, to an ad-valorem tax when extraction costs are negligible. Obviously, when the tax rate declines such that $\hat{\theta} = \pi$ it is possible to compensate for the risk of expropriation. And when it declines faster such that $\hat{\theta} > \pi$ it is even possible to mitigate the distortion from the greenhouse effect, tilting the extraction path in the direction of the lowest path in figures 1 and 2, which satisfies the Pareto conditions (9) and (12).

Although the policy of reducing the ad-valorem tax rate is a theoretical possibility, it would not be very practicable. One problem is that it would lead to a negative tax rate in finite

[25] A detailed formal analysis can be found in Sinn (1982) and Long and Sinn (1985). See also Sinclair (1994) and Ulph and Ulph (1994) who independently found the same result. There is a box on this issue in the Stern Review (Stern et al. 2006, p. 318) which alludes to the latter three authors. However, the box remains isolated in the Stern report and has no visible influence on the course of the analysis.

time so that the government would have to effectively subsidize resource consumption.[26] Another problem is that the government may not be able to credibly commit to gradually cutting taxes on carbon consumption. Rising environmental concern of the public will make a policy of gradually reducing the tax rate hard to implement, regardless of what was initially announced.

6.1.2 *A unit tax on carbon consumption*

A better possibility to achieve a similar result is the introduction of a constant unit tax on carbon extraction, which perhaps could be more credibly defended. As I showed in Sinn (1982) and as follows from the more general theorem of Long and Sinn (1985), a unit tax would slow down extraction. The absolute tax wedge it implies is a constant and thus the unit tax satisfies the Long–Sinn theorem according to which extraction is slowed down if the discounted tax wedge declines with the passage of time. Admittedly, in theory, a unit tax could also be perverted into a global warming device by increasing its rate sufficiently fast. However, in comparison to an ad-valorem tax on resource consumption, a unit tax is much more “distant” from the borderline condition to which the theorem of Long and Sinn refers. So the danger that a further greening of tax policy would tilt the extraction path in the wrong direction is much smaller.

A unit tax on carbon consumption would, in principle, do the job the Stern Review expected from carbon taxation. Note, however, that it would not slow down global warming because it internalizes a marginal externality of similar size but because its present value declines with the passage of time. There is no similarity between the static argument used in the Stern Review and the dynamic forces set in motion by the tax.

Of course, even the unit tax on carbon extraction needs to be uniform world wide, because, if not, the non-taxing countries could free ride on the price dampening effect the tax creates, consuming more than they otherwise would have done in the present and in the future.

6.1.3 *Subsidizing the stock in situ*

A more direct way to internalize the negative externality exerted by the accumulated stock of carbon dioxide or, equivalently, the positive externality generated by the stock of carbon in situ, f_S, would be to subsidize the stock in situ. If, say, the consuming countries decided to pay each year a fee of size $f_S S$ to the resource owners to keep their proven stocks

[26] The problem could be avoided by imposing a lower bound for the tax rate. Starting with a sufficiently high tax rate one could approach the optimal path as close as one wishes. A proof can be found in Sinn (1982, esp. pp. 95–98).

underground, the externality would effectively be internalized and, provided there are no other distortions, market forces would satisfy the normative equation (9) for a Pareto optimal extraction path in the presence of global warming.

As much as this is a theoretical possibility, from a political perspective it would be an impossible proposal. No one will succeed in convincing those countries that already suffer from high oil prices to bribe the oil sheiks to cut their oil supply and charge even higher prices than they do anyway.

6.1.4 *Taxing capital income*

As the problem of overextraction implies a wrongly composed portfolio of man-made and natural capital, the portfolio composition can be improved by taxing the returns to man-made capital, while leaving the capital gains of the resource owners untaxed, and indeed, to a first order of approximation, this is the situation prevailing in the world.

How the taxation of interest income affects the equilibrium path follows from an extension of (7). Abstract from insecure property rights such that $\pi = 0$. When interest income is taxed at the rate $\tilde{\tau}$, the market equilibrium is given by

(20) $$i\,(1-\tilde{\tau}) = \frac{\dot{P}}{P-g(S)}\ .$$

A comparison with (9) shows that, with any given *i*, this condition implies the same development of the price path as would be Pareto optimal if

(21) $$\tilde{\tau} = \frac{f_S}{i\,\left(P(R)-g(S)\right)}$$ (Pareto efficient capital income tax rate).

While this seems an attractive solution at first glance, a qualification is appropriate insofar as interest income taxation drives down the speed of capital accumulation so that, eventually, the tax may simply increase the gross interest rate, leaving the net-of-tax interest rate constant. Thus the speed of global warming may not be affected much while too little man-made capital is handed over to future generations if judged by intertemporal utility comparisons such as those in equations (5) and (6). For these reasons, global warming cannot really be used to legitimate capital income taxation.

However, given that there is capital income taxation and given that only a fraction of the world's financial saving comes from the resource owners, two conclusions seem plausible. First, governments should not, for symmetry reasons, tax the income from resource ownership in the same way they tax capital income. Second, they should make every attempt to tax the capital income earned by resource owners in the international markets in a similar way they tax capital income by other people. Thus the international community of countries could try to close the tax havens existing in the world and make sure that all interest income is subjected to a minimum source tax. This would make it a little less attractive for the sheiks to convert their in situ resources into Swiss bank accounts.

6.2 *Safer property rights*

A more straightforward method to make Swiss bank accounts less attractive is securing the property rights of the resource owners. If the transitional expropriation probability π is set equal to zero, one of the main reasons for overextraction would be eliminated. As shown by (7), the extraction path would become flatter, such that the speed of global warming declines. While this in itself would not be enough to reach the Pareto optimum as described by (9), it might be a big move in the right direction.

Again, unfortunately, the theoretical solution is more straightforward than its practical implementation. The Iraq war tells a painful lesson in this regard. Despite all the resources the war has consumed it seems, if anything, that it has made the property rights for the resource owners of that country more unstable. In view of the perils of global warming it might have been better to support and stabilize the regime of Saddam Hussein and all the other resource owning dictators of the world rather than threatening them with democracy, but of course there were other considerations involved.

6.3 *Quantity constraints and emissions trading*

The difficulty with the public finance solution to the problem of global warming suggested by the Stern Review is that it is of a static nature while the problem is intrinsically dynamic. It is impossible to find the appropriate level of the carbon tax that Stern et al. are seeking because it is the change of that tax rather than the level that matters.

The difficulty can be avoided by not speculating about the economy's quantity reactions to price signals but by controlling the quantities themselves, the alternative to carbon taxation that the Stern report suggests. This can best be done with systems of emissions license trading such as those existing in the US and Europe, and it is the approach of the Kyoto Protocol. In principle it will work, because the aggregate extraction path itself is controlled by political decisions, while the market only has the task of allocating the necessary restraint in carbon consumption efficiently among firms and countries.

With quantity constraints on CO_2 production, the governments of the consumption countries effectively create a world-wide monopsony for carbon that cuts demand and depresses the producer price of carbon at the same time. As this creates a monopsony profit at the expense of the resource extracting countries and mitigates the problem of global warming in addition, there is every reason to participate.

But of course, there are downsides to this solution. One is X-inefficiency. Giving the intertemporal allocation task to governments does not automatically ensure that the Pareto efficient extraction path will be pursued. As governments lack the knowledge necessary to define the optimal time path of carbon emissions, the best society can hope for is a rough approximation to the optimum. Still, the perils of global warming are potentially so large and the market failure is so obvious that vigorous action is urgently needed.

Another is the completeness of the trading system. If it does not incorporate all important countries of the world, it may be useless or even counterproductive in the same sense as other demand reducing measures are that gain strength with the passage of time. The trading system reduces the demand of the participating countries and hence depresses the world market price at which the non-participating countries can buy the carbon. If the quantity constraints are gradually tightened such that, given the old supply path, the discounted market price of carbon would decline with the passage of time, the theorem of Long and Sinn (1985) applies according to which resource extractors would react by making the supply path steeper, thus exacerbating the problem of global warming. Because of the increase in current supply, the current world market price would decline so much that the extra demand of the non-participating countries would overcompensate the demand restraint of the participating countries.

The Kyoto Protocol constrains only a minority of countries. The countries that ratified the Protocol and face binding constraints consume just 29%[27] of annual carbon supply. India and China signed, but are not constrained, and many countries including the USA and Australia did not sign. Unless these countries participate, nothing is gained. The efforts of the EU, which has promised in the Kyoto Protocol to reduce its production of carbon dioxide

[27] CO_2 emission data for 2004 from IEA World Energy Survey (2006). The countries constrained by the Kyoto Protocol include the EU–27 (which contributed 15% of world CO_2 emissions), Canada (2%), Iceland (0.008%), Japan (4.6%), New Zealand (0.12%), Norway (0.14%), Russia (5.7%) and the Ukraine (1.1%). The USA contributed 21.8%, China 17.8%, Australia 1.3% and India 4.1% of world CO_2 emissions in 2004.

(including carbon equivalents of other greenhouse gases) from 1990 to 2008–2012 by 8%,[28] simply subsidize an even faster resource intensive growth process in China and make Americans drive even more SUVs and mega-trucks than they would have done anyway.

Nevertheless, Kyoto is a good start because it did show that world wide cooperative agreements are possible. Integrating, the four big countries mentioned would mean that another 45% of carbon consumption, in total three quarters of world consumption, would be captured. This share in itself would be substantial, and the hope that the remaining quarter could also be disciplined by political means would be justified.

6.4 *Sequestration and afforestation*

As was mentioned in section 2, sequestration and afforestation are exceptions to the rule that carbon extraction is proportional to the accumulation of CO_2 in the atmosphere. Thus they offer a unique opportunity to cut the problematic link between the carbon extracted and the carbon dioxide accumulated in the atmosphere on which this paper has focused.

Consider sequestration first. If the CO_2 originating from combustion were pumped back into the Earth's soil and stored underground, it could not pollute the air and hence could not contribute to global warming.

While this option sounds promising at first glance, closer scrutiny shows the practical limitations of sequestration.

- A substantial fraction of the carbon extracted comes from strip mining and does not leave any suitable storage space in the ground.
- The volume of CO_2 that would have to be stored is truly gigantic, much greater than the volume of fossil fuel burned. One cubic meter of anthracite (1.35 tons) generates about 4 tons of CO_2, which in liquid form (55 bar, 20°C) has a volume of 5.4 m^3. Similarly, one cubic meter of crude oil generates 3.6 $m^{3.}$ of carbon dioxide, and one cubic meter of liquid methane generates 1.6 $m^{3.}$ of carbon dioxide.[29]
- Storage is not risk-free because CO_2 is a heavy gas that would stay close to the surface and crowd out oxygen once released.
- Storage absorbs a substantial part of the energy produced.[30]

[28] Press release of the European Union as of March 4th 2002, MEMO/02/46.
[29] For those calculations I use a specific weight for liquid carbon dioxide of 0.74 t/m^3, a specific weight for coal of 1.35 t/m^3, a specific weight for oil of 0.85 t/m^3 and for liquid natural gas of 0.48 t/m^3.
[30] To produce a given amount of electricity currently a power station needs about 30% more coal if the carbon dioxide is to be stored underground. See Kleinknecht (2007).

Taking these difficulties into account it must be feared that sequestration will not make but a dent in the global warming process. Nevertheless, it is worth trying, and there is every reason for governments to use the funds currently misspent as subsidies for windmills, photovoltaic energy, bio diesel and the like for sequestration.

The second exception is afforestation. Because trees grow tall, they are able to store substantial amounts of biomass on the ground, more than other plants. As biomass is largely reduced carbon, generated by photosynthesis from water and CO_2, trees purify the atmosphere from the most important greenhouse gas.

Unfortunately, currently the world is far from the point were afforestation could reduce the greenhouse gases, as, on the contrary, the stock of forests is declining rapidly. It is estimated that net-deforestation each year destroys an area one and a half times the size of Ireland and oxidizes an amount of carbon greater than the combustion of fossil fuels by all traffic in the world, generating about 18% of total greenhouse gas emissions.[31]

This nonsense can certainly be avoided. Led by the UN, the countries of this world should try to reach agreements to protect their forests and stop the deforestation process immediately. Moreover the rich countries should be able to bribe the developing and emerging countries where most of the forests are located into active afforestation programs.

7. Concluding remarks

The Stern Review has triggered off a major debate on the problem of global warming, similar to the debate the Meadows report once induced with regard to the limited availability of natural resources. Surprisingly, however, there have been few attempts to reconcile these two debates. Neither in the public discourse nor in the Stern Review do exhaustible resources play any major role. The Stern Review mentions the issue, but only in passing, without ever trying to merge the two themes. In fact, however, the economics of climate change and the economics of exhaustible resources could not be more closely intertwined, for in essence the problem of global warming is the problem of gradually transporting the available stock of carbon from underground into the atmosphere, with useful oxidization on the way.

Markets unfortunately are unable to find the optimal path for this double stock-adjustment problem. Insecure property rights of resource owners and the externality of global warming distort the private incentives, leading both to overextraction relative to the criterion of intertemporal Pareto optimality.

Politicians seek to solve the problem by a myriad of measures aimed at reducing

[31] See Houghton (2004, p. 250 n.) and Stern et al. (2006, p. xxv).-

CO_2 emissions, which are, in fact, measures to reduce carbon demand, ranging from taxes on fossil fuel consumption to the development of alternative energy sources. However, these measures will not mitigate the problem of global warming, as they are unlikely to flatten the carbon supply path that wealth maximizing resource owners choose. If the measures reduce the price path of carbon that would result from a given extraction path such that the discounted value of the price reduction is constant for all points in time, resource owners will not react, and the extraction path will indeed remain unchanged. The current world price of carbon must fall sufficiently in this case to induce so much more carbon consumption by other consumers of carbon that the net effect on global warming is nil. If the measures reduce the discounted value of the carbon price in the future more than in the present, the problem of global warming will even be exacerbated, because resource owners will have an incentive to anticipate the price cuts by extracting the carbon earlier.

Useful policy measures that mitigate the problem of global warming must succeed in flattening the carbon supply path in the world energy markets. Among the public finance measures, unit taxes on carbon extraction and source taxes on capital income are feasible policy options that satisfy this requirement. A complete world-wide system of emissions trading that effectively combines the consuming countries to a monopsony would be able to enforce a more conservative carbon consumption path while in addition providing these countries with monopsony rents. Where possible, a stabilization of property rights in the resource extracting countries could also be tried to strengthen the conservation motive. Particular emphasis could be given to measures that try to decouple carbon extraction from the accumulation of carbon in the atmosphere. Sequestration is useful but difficult due to the gigantic quantities involved. Measures to stop the rapid deforestation of the world are particularly urgent and feasible.

References

Anand, S. and A. Sen (2000), "Human Development and Economic Sustainability," *World Development* 28, pp. 2029-2049.

Böhm-Bawerk, E. von (1888), Kapital und Kapitalzins, Part II, Positive Theorie des Kapitales, 4th Edition, Vol 1, Gustav Fischer: Jena, 1921.

Bohn, H. and R. T. Deacon (2000), "Ownership Risk, Investment and the Use of Natural Resources," *American Economic Review* 90, pp. 526-549.Hotelling, H. (1931), "The Economics of Exhaustible Resources," *Journal of Political Economy* 39, pp. 137-175,

Brown E.C. (1948), "Business Income Taxation and Investment Incentives," in: L.A. Metzler, E.D. Domar et al., eds., *Income, Employment and Public Policy*, Essays in Honor of A. H. Hansen, W.W. Norton & Co: New York, pp. 300-316.

Byatt, I., I. Castles, I. M. Goklany, D. Henderson, N. Lawson, R. McKitrick, J. Morris, A Peacock, C. Robinson and R. Sidelsky (2006), "The Stern-Review: A Dual Critique. Part II: Economic Aspects," *World Economics* 7, pp. 199–232.

Carter, R. M., C. R. de Freitas, I. M. Goklany, D. Holland and R. S. Lindzen (2006), "The Stern-Review: A Dual Critique. Part I: The Science," *World Economics* 7, pp. 167–98.

Chichilnisky, G. (1994), "North-South Trade and the Global Environment," *American Economic Review* 84, pp. 851-874.

Chichilnisky, G. (2005), "The Kyoto Protocol: Property Rights and Efficiency of Markets for Environmental Services," in: S. Kant and R. A. Berry, *Institutions, Sustainability and Natural Resources*, Springer: Dordrecht NL, pp. 141-154.

Dasgupta. P. and G. Heal (1979), *Economic Theory and Exhaustible Resources*, Cambridge University Press: Cambridge, London, New York etc.

Houghton, J. (2004), *Global Warming*, third edition, Cambridge University Press, Cambridge UK.

Houghton, J. T., L. G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (1996), eds., *Climate Change 1995; The Science of Climate Change*, Cambridge University Press, Cambridge UK.

Howitt, P. and H.-W. Sinn, "Gradual Reforms of Capital Income Taxation," *American Economic Review* 79, 1989, pp. 106-124.

Kemp, M.C. and N.V. Long (1980), "Resource Extraction under Conditions of Common Access," in M.C. Kemp and N. V. Long, eds., *Exhaustible Resources, Ooptimality, and Trade*, North- Holland Publ. Co.: Amsterdam, pp. 127-135.

Khalatbari, F. (1977), "Market Imperfections and the Optimum Rate of Depletion of Natural Resources," *Economica* 44, pp. 409-414.

Konrad, K., T.E. Olson and R. Schöb (1994), "Resource Extraction and the Threat of Possible Expropriation: The Role of Swiss Bank Accounts," *Journal of Environmental Economics and Management* 26, pp. 149-162.

Long, N. V. (1975), "Resource Extraction under the Uncertainty about Possible Nationalization," *Journal of Economic Theory* 10, pp. 42-53.

Long, N. V. and H.-W. Sinn, "Suprise Price Shifts, Tax Changes and the Supply Behaviour of Resource Extracting Firms," *Australian Economic Papers* 24, 1985, pp. 278-289

Leggett, J., W.J. Pepper and R. J. Swart (1992), „Emission Scenarios for the IPPCC: An Update," in: J. T. Houghton, B. A. Callender and S. K. Varney, *Climate Change 1992: The Supplementary Report to the IPCC Assessments*, Cambridge University Press: Cambridge UK, pp. 69-95.

McMillan, J. and H.W. Sinn (1984), "Oligopolistic Extraction of a Common Property Resource: Dynamic Equilibria," in: M.C. Kemp and N.V. Long, eds., *Essays in the Economics of Exhaustible Resources*, North Holland Publ. Co.: Amsterdam and New York, pp. 199-214.

Meadows, D.H., D. L. Meadows, J. Randers and W.W. Behrens (1972), *The Limits to Gowth*, Universe Books, New York.

Muhtab, F.U. (1989), *Effect of Climate Change and Sea Level Rise on Bangladesh*, Commonwealth Secretariat: London.

Nordhaus, W.D. (2006), "The Stern Review on the Economics of Climate Change," NBER Working Paper No. W12741.

Page, T. (1977), *Conservation and Economic Efficiency. An Approach to Materials Policy*, John Hopkins University Press, Baltimore MD.

Pigou, A. C. (1932), *The Economics of Welfare*, 4th ed., Macmillan: London.

Ramsey, F. P. (1928), "A Mathematical Theory of Saving," *Economic Journal* 38, pp. 543-559.

Sinclair, P. J. N. (1994), "On the Optimum Trend of Fossil Fuel Taxation," *Oxford Economic Papers* 46, pp. 869-877.

Sinn, H.-W. (1981), "Stock Dependent Extraction Costs and the Technological Efficiency of Resource Depletion," *Zeitschrift für Wirtschafts- und Sozialwissenschaften* 101, pp. 507-517.

Sinn, H.-W. (1982), "Absatzsteuern, Ölförderung und das Allmendeproblem," in: H. Siebert, ed., *Reaktionen auf Energiepreisänderungen*, Lang: Frankfurt and Berne, pp. 83-103.

Sinn, H.-W. (1984a), "Common Property Resources, Storage Facilities and Ownership Structures: A Cournot Model of the Oil Market," *Economica* 51, pp. 235-252.

Sinn, H.-W. (1984b), "Optimal Resource Taxation," in: D. W. Pearce, H. Siebert and I.

Walter, *Risk and the Political Economy of Resource Development*, McMillan Press: London, pp. 197-204.

Sinn, H.-W. (2007), "Pareto Optimality in the Extraction of Fossil Fuels and the Greenhouse Effect," CESifo Working Paper No. 2083, August 2007.

Solow, R.M. (1974a), "Intergeneration Equity and Exhaustible Resources," *Review of Economic Studies* 41, Symposium on the Economics of Exhaustible Resources, pp. 29-45.

Solow, R.M. (1974b), "The Economics of Resources or the Resources of Economics," *American Economic Review* 64, pp. 1-14.

Stern, N., S. Peters, V. Bakhshi, A. Bowen, C. Cameron, S. Catovsky, D. Crane, S. Cruickshank, S. Dietz, N. Edmonson, S.-L. Garbett, L. Hamid, G. Hoffman, D. Ingram, B. Jones, N. Patmore, H. Radcliffe, R. Sathiyarajah, M. Stock, C. Taylor, T. Vernon, H. Wanjie and D. Zenghelis (2006), *Stern Review: The Economics of Climate Change*, HM Treasury, London.

Stiglitz, J.E. (1974), "Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths," *Review of Economics Studies* 41, Symposium on the Economics of Exhaustible Resources, pp. 123-137.

Tol, R.S.J., and G.W. Yohe, „A Review of the Stern Review," *World Economics* 7, pp. 233-251.

Trenberth, K. (1981), "Seasonal Variations in Global Sea-Level Pressure and the Total Mass of the Atmosphere," *Journal of Geophysical Research – Oceans and Atmospheres* 86, pp. 5238-5246.

Ulph, A. and D. Ulph (1994), "The Optimal Time Path of a Carbon Tax," *Oxford Economic Papers* 46, pp. 857–868.

Technical Sources

BGR (2007), *Reserves, Resources and Availability of Energy Resources*, Federal Institute for Geosciences and Natural Resources (BGR) self-published, Hannover, available at: www.bgr.bund.de.

BP (2007), *BP Statistical Review of World Energy*, BP self-published: London, available at: www.bp.com/statisticalreview.

CDIAC (2000), *Global Carbon Cycle 1992-1997*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Tennesse, available at: http://cdiac.ornl.gov/pns/faq.html. BGR (2007)

Dubel (1990), *Taschenbuch für den Maschinenbau*, 17th edition, Springer-Verlag, Berlin, Heidelberg and New York.

EIA (2006), Performance Profiles of Major Energy Producers 2005, Energy Information Administration – Official Energy Statistics from the U.S. Government, Washington DC, available at: http://www.eia.doe.gov/.

Harks, E. (2007), *Der globale Ölmarkt – Herausforderungen und Handlungsoptionen für Deutschland*, SWP-Studie 2007/S11, Stiftung Wissenschaft und Politik - Deutsches Institut für Internationale Politik und Sicherheit, Berlin.

IPCC (1996), *Guidelines for National Greenhouse Inventories Workbook*, Volume 2, IPCC, New York. available at: http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Kleinknecht, K. (2007), "Unser Freund, das Atom," *Frankfurter Allgemeine Zeitung*, March, 6th 2007.

Marland, G., T.A. Boden, and R. J. Andres (2005), "Global, Regional, and National Fossil Fuel CO2 Emissions," in *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. Available online at: http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm.

UN Environmental Program (1998), Introduction to Climate Change, Grid Arendal, available at: http://www.grida.no/climate/vital/intro.htm

World Energy Council (2000), *World Energy Assessment: Energy and the Challenge of Sustainability*, United Nations Development Programme, New York.

World Resource Institute (2006), Climate Analysis Indicators Tool (CAIT), on-line database version 3.0., World Resources Institute, Washington DC, available at: http://cait.wri.org.

Appendix

This appendix proves that under the assumptions made the extraction paths in the positive and normative variants of the model converge to the origin of the *R*,*S* diagram used in figure 1 and 2. For brevity, only the basic variants without the taxes are considered here. The extension to the taxes considered is straightforward.

Positive model

Using the simplified specification of the model of section 4, the resource owner's problem can be written as

(A1) $$\max_{\{R\}} \int_0^\infty \left[P(u)\, R(u) - g\left(S(u)\right) R(u) \right] \mathrm{e}^{-(i+\pi)u} \, \mathrm{d}u \, .$$
$$\text{s. t. } \dot{S} = -R \, ,$$
$$S(0) = S_0 \; .$$

Here it is assumed that the representative resource owner behaves competitively, taking the price path as given although, in the aggregate, $P = P(R)$ with the assumed properties.

The Hamiltonian for this problem is

(A2) $$H = PR - g(S)R - \lambda R \; .$$

The necessary conditions for an optimum are the stationary optimality condition

(A3) $$P - g(S) = \lambda \quad ,$$

the canonical equation

(A4) $$\hat{\lambda} - \frac{g'(S)R}{\lambda} = i + \pi$$

and the transversality condition

(A5) $$\lim_{t \to \infty} S(t)\ \lambda(t)\ \mathrm{e}^{-(i+\pi)t} = 0 .$$

As shown in the text, the slope of the possible paths in *R,S* space is given by equation (11) which has been derived from condition (7). Note that this condition can also be derived from (A3) and (A4) if (A3) is differentiated with respect to time. Consider first paths satisfying the slope condition that enter the ordinate above the origin. These paths are not feasible as the stock of the resource becomes zero in finite time so that the necessary marginal conditions can no longer be satisfied. Next consider the feasible paths (satisfying the slope condition) entering the abscissa. Because of the assumed constancy of the price elasticity of demand and the boundedness of $g(S)$, equation (3) implies that $\lambda \to \infty$ as $R \to 0$. Assuming that $g(S)$ is differentiable, the second term in equation (A4) vanishes as $R \to 0$ and hence $\hat{\lambda}$ converges to $i+\pi$ as t goes to infinity. This means that $\lambda(t)\ \mathrm{e}^{-(i+\pi)t}$ does not converge to zero as time goes to infinity so that the transversality condition can only be satisfied if *S* goes to zero, q.e.d.

Normative model

The crucial marginal condition for the normative variant of the model has been derived directly from the postulate of Pareto optimality in Sinn (2007). In addition to that marginal condition, a transversality condition has to hold that can be derived from the social planner's goal

(A6) $$\max_{\{R\}} \int_0^{\infty} \left[\phi\big(R(u)\big) + \psi\big(S(u)\big) - g\big(S(u)\big) R(u) \right] \mathrm{e}^{-iu}\, \mathrm{d}u .$$
$$\text{s. t. } \dot{S} = -R ,$$
$$S(0) = S_0 .$$

The Hamiltonian for this problem is

(A7) $$H = \phi(R) + \psi(S) - g(S)R - \lambda R \quad .$$

The necessary conditions for an optimum are the stationary optimality condition

(A8) $$\phi'(R) - g(S) = \lambda \quad ,$$

the canonical equation

(A9) $$\hat{\lambda} - \frac{g'(S)R - \psi'(S)}{\lambda} = i$$

and the transversality condition

(A10) $$\lim_{t \to \infty} S(t)\ \lambda(t)\ \mathrm{e}^{-it} = 0\ .$$

The slopes of possible paths in R,S space are given by condition (9). Note that differentiating (A8) with respect to time and inserting the result into (A9) also gives this condition.

Paths that reach the ordinate above the origin once again are not feasible since they end in finite time and make it impossible to satisfy the marginal conditions thereafter. Moreover, it follows from (A8) that λ goes to infinity as R approaches zero. Differentiability of $g(S)$ and the assumption that $\psi'(S)$ is bounded from above imply that $\hat{\lambda}$ approaches i as time goes to infinity which in turn implies that the transversality condition (A10) can only be met as S goes to zero as time goes to infinity, q.e.d.

Thus it has been shown that, despite global warming and stock dependent extraction costs, the assumptions about the limiting properties of extraction and production functions made in the text imply that no part of the stock in situ will and should be permanently excluded from extraction.

CESifo Working Paper Series

for full list see www.cesifo-group.org/wp
(address: Poschingerstr. 5, 81679 Munich, Germany, office@cesifo.de)

2024 Erkki Koskela and Ronnie Schöb, Tax Progression under Collective Wage Bargaining and Individual Effort Determination, June 2007

2025 Jay Pil Choi and Marcel Thum, The Economics of Politically Connected Firms, June 2007

2026 Jukka Pirttilä and Roope Uusitalo, Leaky Bucket in the Real World: Estimating Inequality Aversion Using Survey Data, June 2007

2027 Ruslan Lukach, Peter M. Kort and Joseph Plasmans, Strategic R&D with Knowledge Spillovers and Endogenous Time to Complete, June 2007

2028 Jarko Fidrmuc, Neil Foster and Johann Scharler, Labour Market Rigidities, Financial Integration and International Risk Sharing in the OECD, June 2007

2029 Bernardina Algieri and Thierry Bracke, Patterns of Current Account Adjustment – Insights from Past Experience, June 2007

2030 Robert Dur and Hein Roelfsema, Social Exchange and Common Agency in Organizations, June 2007

2031 Alexander Libman and Lars P. Feld, Strategic Tax Collection and Fiscal Decentralisation: The Case of Russia, June 2007

2032 Øystein Foros, Hans Jarle Kind and Greg Shaffer, Resale Price Maintenance and Restrictions on Dominant Firm and Industry-Wide Adoption, June 2007

2033 Jan K. Brueckner and Kurt Van Dender, Atomistic Congestion Tolls at Concentrated Airports? Seeking a Unified View in the Internalization Debate, June 2007

2034 Viet Do and Ngo Van Long, International Outsourcing under Monopolistic Competition: Winners and Losers, June 2007

2035 Nadia Fiorino and Roberto Ricciuti, Determinants of Direct Democracy, June 2007

2036 Burkhard Heer and Alfred Maussner, Inflation and Output Dynamics in a Model with Labor Market Search and Capital Accumulation, June 2007

2037 Konstantinos Angelopoulos, Jim Malley and Apostolis Philippopoulos, Public Education Expenditure, Growth and Welfare, June 2007

2038 Maarten Bosker, Steven Brakman, Harry Garretsen and Marc Schramm, Adding Geography to the New Economic Geography, June 2007

2039 Steffen Henzel, Oliver Hülsewig, Eric Mayer and Timo Wollmershäuser, The Price Puzzle Revisited: Can the Cost Channel Explain a Rise in Inflation after a Monetary Policy Shock?, July 2007

2040 Rosario Crinò, Service Offshoring and White-Collar Employment, July 2007

2041 Carsten Hefeker and Michael Neugart, Labor Market Regulation and the Legal System, July 2007

2042 Bart Cockx and Muriel Dejemeppe, Is the Notification of Monitoring a Threat to the Unemployed? A Regression Discontinuity Approach, July 2007

2043 Alfons J. Weichenrieder, Profit Shifting in the EU: Evidence from Germany, July 2007

2044 Annika Alexius and Bertil Holmlund, Monetary Policy and Swedish Unemployment Fluctuations, July 2007

2045 Axel Dreher, Jan-Egbert Sturm and Jakob de Haan, Does High Inflation Cause Central Bankers to Lose their Job? Evidence Based on a New Data Set, July 2007

2046 Guglielmo Maria Caporale and Luis A. Gil-Alana, Long Run and Cyclical Dynamics in the US Stock Market, July 2007

2047 Alessandro Balestrino, It is a Theft but not a Crime, July 2007

2048 Daniel Becker and Michael Rauscher, Fiscal Competition in Space and Time: An Endogenous-Growth Approach, July 2007

2049 Yannis M. Ioannides, Henry G. Overman, Esteban Rossi-Hansberg and Kurt Schmidheiny, The Effect of Information and Communication Technologies on Urban Structure, July 2007

2050 Hans-Werner Sinn, Please Bring me the New York Times – On the European Roots of Richard Abel Musgrave, July 2007

2051 Gunther Schnabl and Christian Danne, A Role Model for China? Exchange Rate Flexibility and Monetary Policy in Japan, July 2007

2052 Joseph Plasmans, Jorge Fornero and Tomasz Michalak, A Microfounded Sectoral Model for Open Economies, July 2007

2053 Vesa Kanniainen and Panu Poutvaara, Imperfect Transmission of Tacit Knowledge and other Barriers to Entrepreneurship, July 2007

2054 Marko Koethenbuerger, Federal Tax-Transfer Policy and Intergovernmental Pre-Commitment, July 2007

2055 Hendrik Jürges and Kerstin Schneider, What Can Go Wrong Will Go Wrong: Birthday Effects and Early Tracking in the German School System, July 2007

2056 Bahram Pesaran and M. Hashem Pesaran, Modelling Volatilities and Conditional Correlations in Futures Markets with a Multivariate t Distribution, July 2007

2057 Walter H. Fisher and Christian Keuschnigg, Pension Reform and Labor Market Incentives, July 2007

2058 Martin Altemeyer-Bartscher, Dirk T. G. Rübbelke and Eytan Sheshinski, Policies to Internalize Reciprocal International Spillovers, July 2007

2059 Kurt R. Brekke, Astrid L. Grasdal and Tor Helge Holmås, Regulation and Pricing of Pharmaceuticals: Reference Pricing or Price Cap Regulation?, July 2007

2060 Tigran Poghosyan and Jakob de Haan, Interest Rate Linkages in EMU Countries: A Rolling Threshold Vector Error-Correction Approach, July 2007

2061 Robert Dur and Klaas Staal, Local Public Good Provision, Municipal Consolidation, and National Transfers, July 2007

2062 Helge Berger and Anika Holler, What Determines Fiscal Policy? Evidence from German States, July 2007

2063 Ernesto Reuben and Arno Riedl, Public Goods Provision and Sanctioning in Privileged Groups, July 2007

2064 Jan Hanousek, Dana Hajkova and Randall K. Filer, A Rise by Any Other Name? Sensitivity of Growth Regressions to Data Source, July 2007

2065 Yin-Wong Cheung and Xing Wang Qian, Hoarding of International Reserves: Mrs Machlup's Wardrobe and the Joneses, July 2007

2066 Sheilagh Ogilvie, 'Whatever Is, Is Right'?, Economic Institutions in Pre-Industrial Europe (Tawney Lecture 2006), August 2007

2067 Floriana Cerniglia and Laura Pagani, The European Union and the Member States: Which Level of Government Should Do what? An Empirical Analysis of Europeans' Preferences, August 2007

2068 Alessandro Balestrino and Cinzia Ciardi, Social Norms, Cognitive Dissonance and the Timing of Marriage, August 2007

2069 Massimo Bordignon, Exit and Voice. Yardstick versus Fiscal Competition across Governments, August 2007

2070 Emily Blanchard and Gerald Willmann, Political Stasis or Protectionist Rut? Policy Mechanisms for Trade Reform in a Democracy, August 2007

2071 Maarten Bosker and Harry Garretsen, Trade Costs, Market Access and Economic Geography: Why the Empirical Specification of Trade Costs Matters, August 2007

2072 Marco Runkel and Guttorm Schjelderup, The Choice of Apportionment Factors under Formula Apportionment, August 2007

2073 Jay Pil Choi, Tying in Two-Sided Markets with Multi-Homing, August 2007

2074 Marcella Nicolini, Institutions and Offshoring Decision, August 2007

2075 Rainer Niemann, The Impact of Tax Uncertainty on Irreversible Investment, August 2007

2076 Nikitas Konstantinidis, Gradualism and Uncertainty in International Union Formation, August 2007

2077 Maria Bas and Ivan Ledezma, Market Access and the Evolution of within Plant Productivity in Chile, August 2007

2078 Friedrich Breyer and Stefan Hupfeld, On the Fairness of Early Retirement Provisions, August 2007

2079 Scott Alan Carson, Black and White Labor Market Outcomes in the 19^{th} Century American South, August 2007

2080 Christian Bauer, Paul De Grauwe and Stefan Reitz, Exchange Rates Dynamics in a Target Zone – A Heterogeneous Expectations Approach, August 2007

2081 Ana Rute Cardoso, Miguel Portela, Carla Sá and Fernando Alexandre, Demand for Higher Education Programs: The Impact of the Bologna Process, August 2007

2082 Christian Hopp and Axel Dreher, Do Differences in Institutional and Legal Environments Explain Cross-Country Variations in IPO Underpricing?, August 2007

2083 Hans-Werner Sinn, Pareto Optimality in the Extraction of Fossil Fuels and the Greenhouse Effect: A Note, August 2007

2084 Robert Fenge, Maximilian von Ehrlich and Matthias Wrede, Fiscal Competition, Convergence and Agglomeration, August 2007

2085 Volker Nitsch, Die Another Day: Duration in German Import Trade, August 2007

2086 Kam Ki Tang and Jie Zhang, Morbidity, Mortality, Health Expenditures and Annuitization, August 2007

2087 Hans-Werner Sinn, Public Policies against Global Warming, August 2007