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Public policies against global warming: a supply side approach

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Abstract The countries that have ratified the Kyoto Protocol have pledged to limit global warming by reducing the demand for fossil fuels. But what about supply? If suppliers do not react, demand reductions by a subset of countries are ineffective. They simply depress the world price of carbon and induce the environmental sinners to consume what the Kyoto countries have economized on. Even worse, if suppliers feel threatened by a gradual greening of economic policies in the Kyoto countries that would damage their future prices; they will extract their stocks more rapidly, thus accelerating global warming. The paper discusses the remaining policy options against global warming from an intertemporal supply-side perspective.

Keywords Global warming · Kyoto protocol · Carbon taxes

JEL Classification O13 · Q32 · Q54 · H23

1 The greatest externality ever

There is only a tiny amount of carbon dioxide, CO_2, in the atmosphere, not more than 0.04%. But this 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,

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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 200 ppm (=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°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.

Cautious "pre-Chinese" estimates predicted a doubling of the preindustrial concentration of carbon dioxide in the atmosphere until 2,050, i.e., an increase to 560 ppm. They also predicted an increase to 650 ppm by 2,100 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 preindustrial CO_2 concentration could already take place up to 2,035, and that by 2,100, 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 2,100 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]

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[1] See Houghton (2004, p. 15 n.).

[2] See Stern et al. (2006, p. III).

[3] See Houghton (2004, pp. 145–150).

[4] See, e.g., Leggett et al. (1992).

[5] See Stern et al. (2006).

[6] See Muhtab (1989) and Houghton (2004, pp. 10 and 150–152 as well as Fig. 4.4).

There are further dangers including more powerful and devastating tropical storms, the elimination of a substantial fraction of the world's species, and in particular, 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 any standard. 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 Review fueled 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 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? 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 (Stern et al. 2006, 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 analytically. Ultimately, all the demand reducing measures will mitigate the problem of global warming only to the extent that they

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[7] Nordhaus (2006), Tol and Yohe (2006), Byatt et al. (2006) and Carter et al. (2006).

induce the oil sheiks and other owners of fossil fuel resources to keep the carbon underground.

Suppose for a moment the oil sheiks (and other resource owners) 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 producer price of energy 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.

Contrary to the theory of privately provided public goods, the net provision to maintaining the environment is not only small, if one country or a group of countries reduce their demands, but zero. While the Kyoto countries put a contribution in the collection tray before leaving the church, the non-Kyoto countries and other sinners that follow behind not only make no charitable contribution at all, but take the money from the tray put there by the Kyoto countries.

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 Sect. 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.

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[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 Dubel (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).

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 toward 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 emission of carbon soot, i.e., 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 (a trivial truth that carmakers do not like to hear).

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 which together with other human causes, in particular deforestation, increased the carbon content of the atmosphere by about 200 Gt of carbon.[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 809 Gt of carbon in the atmosphere.[14] If the percentage of natural absorption is kept fixed, burning the reserves means that, roughly

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[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 (2005, 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 (2005). 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 5.137×10^{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 En-

speaking, another 400 Gt of carbon will enter the atmosphere, which would be an increase by about 50%, from 380 ppm to 570 ppm. According to the information given in the Introduction, this would likely increase the world temperature by more than 2°C above the preindustrial 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 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.

There is some hope that the actual increase of carbon dioxide will be somewhat less than this figure, as it may take a couple of hundreds of years to reach near total exhaustion of resources. Over such a long period of time, nature's absorption capacity is higher than the 55% assumed above, as different biological and geological absorption mechanisms come into play than in the short run. 55% is the figure relevant for a period of about 100 years. According to detailed climate projections done by Archer (2005), Archer and Brovkin (2006), and Hooss et al. (2001), the absorption percentage will increase over a period of 300 years to a maximum of 75% and will remain stable at that level practically forever, the average stay of a molecule of carbon dioxide in the air being in the range of 30,000 years. If we redo the calculations with 75% absorption, i.e., assume that a quarter of the emissions stay in the atmosphere, the stock of carbon dioxide in the atmosphere would increase from today's 809 Gt to 1800 Gt, or from 380 ppm to 845 ppm, again assuming the lower of the two reserve figures cited above. This would be close to the Stern estimate of 900 ppm for the year 2100 where, relative to preindustrial times, temperatures would go up by 5°C, which seems less horrifying than the 1,220 ppm, but still enough to cause serious concern.

The report of the Club of Rome (Meadows et al. 1972) and the oil crises of 1973/1974 and 1982 once nourished public fears about the limits to growth resulting from the foreseeable resource scarcity. Optimists 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, this optimism now is giving rise to the environmental pessimism that results from the above calculations. The perils of global warming could be large

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vironmental 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).

[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.

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 on the question as 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 despite various present value calculations, is the conceptual base of the Stern Review (Stern et al. 2006, especially 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 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 competitive 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 world price of carbon. If the resource owner extracts a unit today at time t and invests the cash flow in the capital market for one period the amount of money he will have is $P(t) - g(S(t))$ plus the return $i[P(t) - g(S(t))]$ where i is the rate of interest at which he can invest. If instead he postpones extraction, he will have $P(t) - g(S(t))$

plus the return $\dot{P}(t)$ which results from a potential increase in the price of carbon. Thus, he is indifferent between extracting now or a period later if

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

Equation (1) 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 (1931) condition that the percentage rate of price increase equal the rate of interest.[17]

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

$$Y = f(K, R, t), \tag{2}$$

where K is the stock of man-made capital, R is the flow of resource extraction and t is calendar time. As usual, it is assumed that $f_K > 0$, $f_{KK} < 0$, $f_R > 0$, $f_{RR} < 0$. The assumptions about the marginal product of the resource use R basically reflect the possibilities of reducing the demand for fossil fuels that were mentioned above, including a better insulation of homes, more sophisticated and energy efficient engines, solar energy, bio-fuels, and even nuclear power. All these technical possibilities of reducing the demand for fossil fuels are costly in the sense that they absorb parts of the economy's production capacity that otherwise would have been available for the production of consumption or investment goods. In line with this interpretation, f is defined as output net of the cost of saving energy or generating it from nonfossil sources. In a market economy, the technical possibilities to reduce the input of fossil fuels are activated endogenously via an increasing price P for fossil fuels. In addition, there may be exogenous technological progress that results in energy saving inventions that make it possible to reduce the consumption of fossil fuels while maintaining the production of consumption and investment goods. Such progress is captured by the time variable t and the assumption that $f_t \geq 0$.

Output (net of the cost of saving energy or generating it from nonfossil sources) can be used for consumption C, investment $\dot{K}$, and resource extraction:

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

As shown in Sinn's (1981) comment to Heal (1980), the model implies that it is impossible to increase consumption in one period without decreasing it in another if and only if

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

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[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.

which obviously is a condition for intertemporal Pareto optimality. Suppose society extracts a unit of carbon today and invests the additional output it generates for one period. After the period, it will then be able to consume the additional capital invested, $f_R - g(S)$, and the additional output produced by the extra capital, $f_K(f_R - g(S))$. Suppose alternatively, society postpones extraction by a period. In this case, it will be able to increase its consumption after the period by $f_R - g(S)$ plus the increase in the marginal product due to the larger scarcity of carbon, $\dot{f}_R$ (where f_R is the marginal product of carbon the period before). As both possibilities must generate, the same additional consumption when the extraction path is Pareto optimal, (4) results.

Equation (4) is a generalization of the Pareto 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 $f_R = P$, (4) obviously coincides with (1), demonstrating the efficiency of the market equilibrium.

Equation (4) describes an optimal portfolio mix between man-made and natural capital to be bequeathed to future generations. Given the consumption of the present generation, and hence given the overall volume of wealth that the present generation wants to bequeath to future generations, it defines a composition of this wealth in terms of man made capital above the ground and natural capital below the ground that maximizes the consumption of future generations. Equation (4) does not, however, indicate how much the present generation should bequeath and what level of consumption relative to the consumption of future generations would be efficient or fair.

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. The utilitarian specification common to many models 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.

Before we come to the normative question, let us first consider the positive side of the problem. 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 i:

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

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 (5) is

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

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 (1974b), Anand and Sen (2000), as well as Stern et al. (2006, especially annex to Chap. 2) have argued that the market solution cannot be accepted on ethical grounds because discounting future utility means discriminating against 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 1 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, (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, and it may have deep philosophical roots. Austrian economist Eugen von Böhm-Bawerk (1921), 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 reiterated that argument.

However, from the perspective of economic policy, this argument leads nowhere. If we mistrust the preferences of market agents and, therefore, bring in the government to intervene in the allocation decision, there will hardly be another outcome. After all, it is not the philosophers or economic thinkers that make collective policy decisions, but the current generation of voters themselves. The future generations under concern neither participate in today's market decisions nor in today's elections. 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 of markets and will, therefore, not take countervailing policy actions.

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

Of course, one could still maintain from a philosophical perspective that the current generations' 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, because he knows better how much weight should be given to the offspring than the parents themselves do. No indication is seen that parents are insufficiently altruistic toward their offspring and neither envisage future generations coming from Mars, and thus lacking a proper representation among the people living today, the argument is found totally unconvincing. (If anything, the distortion is likely to go in the wrong direction if governments are involved as the electorate probably has fewer children on average than wealth owners do.) If economics adopted the argument that people make a mistake when they discount the utility of future generations, it would leave the firm ground of methodological individualism and get stuck in the muddy waters of Nirvana ethics.

3.3 Insecure property rights

An argument that is not based on mistrust in people's preferences 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 et al. (1994). Various papers by Chichilnisky (1994, 2005) also were written with a similar, yet more general message.

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

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

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]

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

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). 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

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[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). Equation (7) can also be derived directly from (A.3) and (A.4) in the Appendix.

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 the custodians of substantial parts of mankind's fossil fuel resources, and as it now turns out, also of the world's atmosphere. It is they rather than the green policy-makers of the West who determine the speed of global warming. And if they feel insecure about how long they, their descendants, or members of their clans will be able to extract the resources they currently own, they could extract the resources more rapidly now and safeguard the proceeds in Swiss bank accounts.

How exactly political risk affects resource extraction is still subject to debate. On the basis 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 (2000, 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.

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[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.

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 (1) and (7) 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 the stock emitted, and that the stock emitted is proportional to the stock of carbon extracted. A reduced form of the production function is

$$Y = f(K, R, S, t), \tag{8}$$

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. It is important to note that output as given by (8) not only is defined net of the endogenous cost of producing energy from nonfossil sources as was explained above, but also net of the damage from global warming. This damage can have a two-fold interpretation. It can be the direct damage in terms of a reduction of output available for consumption, investment, and extraction due to drought, floods, and other consequences of global warming. Alternatively, it can be interpreted as the cost of preventing or mitigating such damages such as the costs of dykes, irrigation, insulation, or air conditioning. The assumptions on the derivatives f_R and f_S reflect the increasing economic difficulties resulting from lowering the flow of carbon extraction and accumulating carbon in the atmosphere.

The inclusion of global warming in the production function changes the definition of intertemporal Pareto optimality in a nontrivial way. As is proved 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,

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

Equation (9) is a generalization of (4) (the modified Solow–Stiglitz efficiency condition) to the case of global warming.

A literal interpretation of (9) can be given as follows. Suppose society extracts a unit of carbon today and invests the additional output it generates for one period. After the period, it would be able to consume the additional capital invested, $f_R - g(S)$, and the additional output produced by the additional capital, $f_K(f_R - g(S))$, if there were no global warming. With global warming, consumption is lowered by f_S, the additional flow of damages the extracted stock of carbon causes. Suppose alternatively that society postpones extraction by a period. In this case, it will be able to increase its consumption after the period by $f_R - g(S)$ plus the increase in the marginal product due to the larger scarcity of carbon, $\dot{f}_R$. In a social optimum, the additional consumption resulting from both options is the same, and this implies (9).

Equation (9) has obvious implications for the speed of extraction, and hence global warming. As time proceeds, the stock of fossil carbon moves from underground to above ground, so S becomes smaller and the marginal flow of damages rises ($f_{SS} < 0$). Obviously, the marginal damage caused by the greenhouse effect, $f_S > 0$, implies that $\dot{f}_R$ has to be smaller for any given time and any given values of K, S, and R. Thus, a flatter extraction path with less extraction in the present and more in the future is required when the damage from global warming is taken into account. The larger the marginal damage is, the slower should be the speed of extraction, and hence the speed at which the earth warms up.

If compared with the market (7), two aspects should be noted. One the one hand, because of the damage from 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:

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

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 actually even greater than the rate of interest:

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

Thus, the two reasons for market failure are additive, working in the same direction. The resource owners take a risk into account that they should not take into account, and they neglect a peril that 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.

The problem is that society does not respect this rule. Given its current living standard, it would generate more long-term growth in consumption, and hence a higher living standard for future generations if it decided to invest less in man-made capital and instead leave a higher stock of fossil fuels (and a lower stock of carbon dioxide in the air) to future generations.

4 A simplified interpretation

To summarize and intensify 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 $F(K, R, S, t) = iK + \phi(R, t) + \psi(S)$ with $i = \text{const.}$ and otherwise the properties assumed above, i.e., $\phi_R > 0$, $\phi_{RR} < 0$ and $\psi' > 0$, $\psi'' < 0$. Here $\phi(R, t)$ is the partial production function of the carbon inputs and $\psi(S)$ denotes that part of output that is not needed for compensating for the damages of global warming. As explained, $\psi' > 0$ denotes the flow of marginal damage from the extracted stock of carbon. Let $P(R, t) = \phi_R(R, t)$ denote the inverse demand function for carbon implied by this specification with $P_R < 0$. Due to the definition of the production function as given above, the shape of this demand function reflects the technological substitution possibilities for fossil fuels (bio fuels, solar energy, nuclear power, etc.) that would endogenously be activated by higher carbon prices. Similarly, the time dependence of the inverse demand function captures the possibilities of exogenous technological progress that would shift the demand curve. Assume that $\partial P(R, t)/\partial t \leq 0$ for $t \leq T$, $P > 0$ for all $R > 0$, and $\partial P(R, t)/\partial t = 0$ for $t > T$ to allow for exogenous technological change in finite time. Assume, moreover, that the absolute value of the price elasticity of demand, $\varepsilon(R, t) = -\frac{\partial R}{\partial P}\frac{P}{R}$, unit extraction costs $g(S)$ and the flow of marginal damage from the extracted stock of carbon $\psi'(S)$ are bounded from above as R and/or S go to zero. Let all functions of the model be differentiable and well defined for nonzero values of their arguments. Under these specifications, the Appendix derives the essential properties of the extraction path in R, S space that will be discussed below.

For an easy graphical presentation of the possible time paths, let us simplify further by disregarding exogenous technological progress (i.e., the time dependence of the demand curve). Independent of calendar time, the slope of the possible time paths in R, S space is then uniquely given by

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

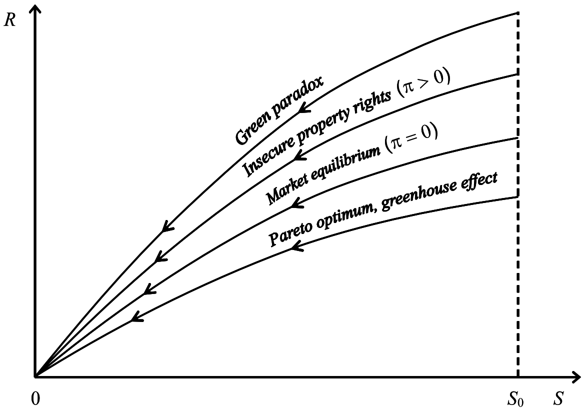
as $\mathrm{d}R/\mathrm{d}S = \dot{R}/\dot{S} = -\dot{R}/R = -(\hat{R}/\hat{P})\hat{P}$ and $\varepsilon = \hat{R}/\hat{P}$ by definition. Rearranging (7) and using (10) gives

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

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. As is shown in the Appendix, the extraction path will lead to the origin. Thus, in fact, (11) uniquely defines the equilibrium path itself.

Figure 1 depicts the equilibrium paths for four alternative specifications, where the highest path is irrelevant for the time being; it will be discussed in the next section only. Consider the second path from below first. It 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.

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



The second path from above 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 of carbon in situ. 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.)

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

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

Compared to the market equilibrium with well-defined property rights, (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 under consideration 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.

A generalization of the assumptions is possible. If we reintroduce the assumption that the demand function also depends on calendar time to include exogenous technological progress (in addition to the endogenous progress triggered by price changes that was already included), the shape of the three curves would in general be modified, and it would be possible to generate more erratic extraction profiles, including U-shaped profiles that may fit reality better. The relative positions of the paths would not be affected by this modification, and they would still lead to the origin due to the boundedness assumptions that were made above (see Appendix). Similarly, nothing fundamental would change if the separability assumptions concerning the production function, which were made for didactic purposes only, were given up. After all, the marginal conditions of the previous sections were all derived without these assumptions.

More fundamental modifications would result by giving up the boundedness assumptions. If, for example, the price elasticity of demand and the marginal extraction cost went to infinity (such that the price itself is bounded) as the extraction flow and the resource in situ approach zero, more complicated extraction patterns without terminal exhaustion could result from both a normative and a positive point of view. Mind, however, that the boundedness assumptions are perfectly compatible with the exogenous and endogenous development of replacement technologies and only exclude the invention of a truly *perfect* substitute that imposes a fixed upper bound on the price of carbon, which seems rather unlikely.

To be sure, substitutes will gain importance. Electricity can be produced from sunlight and nuclear power; hopefully one day even fusion power and its energy can be stored in the form of hydrogen. However, hydrogen cannot easily be transported in sufficient quantities and is, therefore, not a perfect substitute for fossil fuels. Under enormous pressure a given amount of hydrogen energy needs many times the space of carbon energy,[22] and even if hydrogen is cooled sufficiently to a liquid state, it needs four times the space of gasoline, not counting the voluminous and heavy cooling and storage devices. It is hard to imagine that helicopters and fighter planes will ever run on hydrogen or stop flying because they cannot. That is basically all that is needed to assume to satisfy the boundedness assumptions.

Admittedly, bio fuels could be perfect substitutes to fossil fuels. However, bio fuel will not impose a fixed upper bound on the price of fossil fuel, as the supply capacity for bio fuel is limited and its price will also rise. The space needed for growing the biomass competes with agricultural land for food production. In order to satisfy the energy demand for current worldwide transport alone (which itself is just one fifth of current world energy demand), an area of 1.4 giga hectares would be necessary, which is equal to the total agricultural area of the world (see International Energy Agency 2006b, p. 289). This shows that only tiny contributions to market supply will be possible when the political constraints are taken into account. The tortilla crisis of January 2007 in Mexico City gave a first impression of the likely political resistance that a policy of expanding bio fuel production will cause. The citizens of this world will never accept starvation while food is converted to fuel, and significant stocks of fossil fuels remain untouched in the ground.

In the light of these considerations, public policies that would limit the overall extraction and exempt part of the stock in situ permanently from extraction to mitigate the problem of global warming seem hardly defendable. By contrast, public policies against global warming that focus on postponing extraction receive a strong justification from the marginal conditions derived above. The rest of this paper will, therefore, focus on such policies.

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[22] If hydrogen is compressed at 200 bar, it needs 13 times the volume of gasoline per unit of energy. However, with such enormous compression, the hydrogen container would effectively be an explosive bomb.

5 Green policy paradoxes

Let us return to the debate of Sect. 2, where it was shown that the demand policies emphasized in the public debate are useless if the supply path of carbon is stable. 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 producer 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, and it is by no means obvious that the demand-reducing measures discussed in Sect. 2 will be able to tilt the extraction path in the right direction.

In light of the marginal conditions discussed in the previous two sections, the policies needed are those that make the extraction path flatter, i.e., they should induce resource owners to extract less in the present and foreseeable future and more in the distant future. Whether demand-reducing measures reach this goal is unclear because they exert two countervailing effects on the current extraction volume. On the one hand, they reduce the incentive to extract today because they depress today's prices. On the other, they increase the incentive to extract today 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 cash flow tax can be described by the equation

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

where T is the tax revenue, τ^* the tax rate, and Z the cash flow. Let $\theta^* \equiv 1 - \tau^*$ 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, Chap. 12) as well as Sinn (1982, 1984b) 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.

To get a heuristic intuition for this result, one may think of a pneumatic system of pipes connecting various pistons. If only one piston is pressed down, the others go up. If, however, all pistons are pressed equally, none of them moves. The cash flow tax is neutral because it exerts equal pressure at each point in time.

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 τ be the tax rate applied to the consumer price P and let $\theta \equiv 1 - \tau$ denote the respective tax factor such that the producer price $\underline{P}$ is given by $\underline{P} = \theta P$. 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 ad valorem 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 ad valorem tax loses its neutrality property, because it basically is a cash flow tax plus a tax on extraction costs. As the cash-flow component of this tax is neutral, it has the same behavioral implications as a proportional increase in extraction costs. To derive the formal condition for a market equilibrium, note that maximizing the present value of the cash flow stream $\theta RP - g(S)R$ is equivalent to maximizing the present value of the stream $RP - (g(S)R/\theta)$. It is obvious that (7) now changes to[23]

$$i + \pi = \frac{\dot{P}}{P - \frac{g(S)}{\theta}} \quad \text{(constant ad valorem tax)}, \tag{14}$$

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, as is desired.

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.[24] 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?

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[23] Equations (14) and (16) can also be derived formally from (A.3) and (A.4) in the Appendix.

[24] Following Harks (2007), the 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).

To understand what happens, let us first reconsider the cash flow tax. Suppose the tax factor changes at a constant rate $\hat{\theta}^*$ such that

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

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 (according to which $\theta^*(0)$ drops out of the optimization problem) 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), one gets

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

Equation (16) shows that with a changing cash flow tax rate, the often appraised neutrality of a cash flow or consumption tax disappears, giving way to substantial intertemporal distortions. 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 when the tax rate increases over time.

Obviously, this verdict transfers to the ad valorem tax on the extraction volume if the transaction costs are negligible because, in this case, the two taxes are undistinguishable. When $g(S) = 0$, (16) equally applies to such a tax with $\hat{\theta} = \hat{\theta}^*$. As was shown by Sinn (1982) and other authors, an ad valorem sales tax whose rate increases over time accelerates the extraction of fossil fuels when extraction costs are absent.[25] 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 constant over time. As the absolute tax wedge with an ad valorem tax based on the consumer price P is τP, it follows that the borderline case is characterized by

$$\hat{\tau} + \hat{P} = i + \pi \quad \text{(borderline case for ad valorem tax neutrality)} \tag{17}$$

for all points in time where $\hat{P}$ is the growth rate of the consumer price that would have prevailed without the policy change (and will still prevail in the case of neutral taxation). Faster increase of the tax wedge implies that the resource firms anticipate extraction, and a smaller increase implies that they will postpone extraction. As is shown in the Appendix, by using (7), condition (17) can be converted to

$$\hat{\tau} = i + \pi \frac{g(\tilde{S})}{P(\tilde{R}, t)} \quad \text{(borderline case for ad valorem tax neutrality)} \tag{18}$$

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[25] Cf. also Long and Sinn (1985), Ulph and Ulph (1994), and Sinclair (1994). For a closely related discussion of the intertemporal distortions resulting from a non-constant tax on ordinary consumption goods, see also Howitt and Sinn (1989).

for all t where $\tilde{R}$ and $\tilde{S}$ denote the time paths of R and S that would have prevailed without taxation (and will prevail despite taxation). Thus, the ad valorem tax does not change the speed of global warming when it grows at a (time-dependent) rate that, at each point in time, is given by the product of the discount rate and the cost share in the resource owners' sales revenue before the imposition of the tax.[26]

This condition confirms that without extraction costs ($g(S) = 0$) a constant ad valorem tax would be neutral: $\hat{\tau} = 0$. With extraction costs, i.e., $g(S) > 0$, 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 the cost share times, the discount rate, the rate of return from keeping the resource in situ exceeds the rate of return from extracting the resource and investing the proceeds in the capital market. Thus, the resource owners will anticipate extraction to make the price path sufficiently steep to compensate for the rising tax rate. Global warming will accelerate.

This possibility is called the green paradox, because it shows that good intentions do not always breed good deeds. Environmentalists often argue that carbon taxes are needed to reduce the demand for carbon and slow down global warming, and they advocate increasing the tax rate over time so as to give the economy time to adjust and fight global warming more aggressively as it evolves and damages increase. The green paradox implies that such a policy is likely to backfire and create even more harm for the environment by speeding up global warming.

To demonstrate the green paradox in R, S space, we return to the case of the cash flow tax and abstract from exogenous technological progress such that $P(R,t)$ reduces to $P(R)$, keeping in mind that a cash flow tax with $\hat{\theta}^* < 0$ produces qualitatively the same result as an ad valorem consumption tax with $\hat{\tau} > (i+\pi)g(\tilde{S})/P(\tilde{R})$: It follows from (10) and (16) that instead of (11), we now have

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

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

Figure 1 above illustrates the green paradox. As explained, 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 $\hat{\tau} > (i+\pi)g(\tilde{S})/P(\tilde{R},t)$. It characterizes the green paradox.

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[26] Note that the formulation refers to an ad valorem tax on the consumer price P and the cost share in the resource owners' sales revenues gross of the tax burden τP. An equivalent formulation that refers to the proportional price wedge $\underline{\tau}$ expressed in terms of the producer price $\underline{P} \equiv P\theta$ can easily be derived if it is noted that the Long–Sinn theorem implies that similar to (17), $\hat{\underline{\tau}} + \hat{\underline{P}} = i + \pi$. Solving (A.13) from the Appendix for $\hat{\underline{P}}$ and inserting the result into this equation yields $\hat{\underline{\tau}} = (i+\pi)g(\tilde{S})/\underline{P}$. Thus, with regard to the producer price wedge, tax neutrality prevails if this wedge rises at a rate given by the product of the discount rate and the cost share in the after-tax sales revenue. Of course, the two formulations are fully equivalent.

Unfortunately, the green paradox not only applies to an increasing tax rate, but may also be relevant for the bulk of the green demand reducing policies discussed in Sect. 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.

As explained above, some or all of these measures will be endogenously induced by the price mechanism, and in addition to mere consumption restraint and personal sacrifices, they are behind the price elasticity of demand as measured by ε in the above equations. However, these measures may be further strengthened by discretionary government interventions in the form of subsidies for replacement technologies, quantity constraints, or moral suasion. In fact, as the world becomes warmer and more and more people become afraid of the greenhouse effect, public support for such measures will rise so that the demand-reducing effect caused by government interventions is likely to become stronger and stronger.

The policies will induce downward shifts of the carbon demand curve $P(R,t)$ at each point in time relative to the position that this curve otherwise would have obtained. Let $\tau(R,t)$ denote the function describing the relative vertical downward shifts of the carbon demand curve at alternative points in time. Then $\tau(\tilde{R},t)$ is the relative price wedge at time t caused by the policies as measured at the old extraction path, i.e., the path that would have resulted without government actions. Accordingly, $\theta(\tilde{R},t)P(\tilde{R},t)$ is the new time path of the producer price, given the old extraction path, where $\theta(\tilde{R},t) \equiv 1-\tau(\tilde{R},t)$. It is obvious that (18) will in this case remain perfectly valid as a neutrality condition which ensures that the extraction path will not, in fact, react.

If, however, resource owners anticipate that $\hat{\tau}(\tilde{R},t) \geq (i+\pi)g(\tilde{S})/P(\tilde{R},t)$ with strict inequality at least for some nondegenerate range of time, they will try to anticipate the price dampening effect by selling more in the present and less in the future until a new intertemporal equilibrium is reached where the modified Hotelling rule (7) again is satisfied. The extraction path in R, S space is shifted upward as is demonstrated in Fig. 1 by the move from the second highest to the highest curve. Unfortunately, this shift goes in the wrong direction, exacerbating the double distortion that already results from insecure property rights and the greenhouse effect. There is another green paradox in that a gradually greening demand policy speeds up global warming.

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.[27] Similarly, governments could promote demand-reducing measures and impose tight constraints on demand in the present and near future, but relax these measures gradually over time so as to reduce the relative price wedge caused by the policy intervention.

This possibility can be understood by inspection of (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 Fig. 1, 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 time so that the government would have to effectively subsidize resource

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[27] A detailed formal analysis can be found in Sinn (1982) and Long and Sinn (1985). See also, Sinclair (1994) and Ulph and Ulph (1994). 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 Review and has no visible influence on the course of the analysis.

consumption.[28] 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. This will be true in particular for other demand-reducing government policies from which a withdrawal cannot credibly be announced.

6.1.2 A unit tax on carbon consumption

A better way to achieve a similar result is the introduction of a constant unit tax on carbon extraction, which perhaps could be more credibly defended. As was shown 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 implied 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.

A time-invariant unit tax on carbon consumption would, in principle, be able to do the job expected from it in the Stern Review. Unfortunately, however, even when it levies a unit tax the government cannot commit to keeping the tax rate constant. If the tax rate increases sufficiently fast, it could mimic an ad valorem tax that rises faster than what the neutrality condition (18) requires. The only hope is that in comparison to an ad valorem tax on resource consumption, a unit tax is sufficiently "distant" from this condition to make a slow-down in global warming more likely.

The theoretically correct value of the unit tax that would internalize the marginal externalities from global warming would have to be equal to the present value of the flow of damages it causes, f_S, calculated at each point in time from this point to infinity. However, as the stock of extracted carbon in the air is accumulated with the passage of time creating an increasing flow of marginal damages that does not follow any simple growth pattern, it will be extremely difficult to calculate its present value for each consecutive point in time. Formulations of the sort f_S/i to express the present value of this flow are illustrative, but definitely wrong, missing the essentials of the problem, as f_S is far from being a constant. It is difficult to design a Pigovian tax on flows when the marginal damage results from a stock.

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 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 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. Even this would be difficult though, as both f_S and S change over time.

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[28] 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, especially pp. 95–98).

Apart from that, paying a subsidy for the stock in situ would be a politically 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. To a first order of approximation, this is indeed 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 τ_i, the market equilibrium is given by

$$i(1-\tau_i) = \frac{\dot{P}}{P - g(S)}. \tag{20}$$

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

$$\tau_i = \frac{f_S}{i(P(R) - g(S))} \quad \text{(Pareto efficient capital income tax rate)}, \tag{21}$$

where of course $P = f_R$ and $i = f_K$ must be assumed so as to depict competitive markets.

Admittedly, it would not be easy to calculate such a tax in practice either. However, the attractive feature of this tax is that it would more reliably tilt the extraction path in the right direction, slowing down global warming, than a tax on the flow of carbon consumption could ever do. A tax on the flow of carbon consumption exerts its influence on the extraction path through its change over time rather than its level. If it increases only a little or shrinks, it slows down global warming, but when it increases quickly, it accelerates global warming. Slight mistakes in assessing the time change of this tax could cause a policy disaster. By contrast, a source tax on capital income always produces a qualitatively correct change in the intertemporal allocation pattern, whatever its exact time path is because it is the level of the tax rate rather than its change over time that determines the extraction path.

This argument cannot be used to defend interest income taxation as such for the world due to the well-known intertemporal distortions it causes. However, that is not the issue. Given that there is already capital income taxation for normal investors and given that only a fraction of the world's financial saving comes from resource owners, there is every reason to advise governments to discriminate against ordinary capital income earned by resource owners to make it more attractive from them to keep their wealth underground. To be more specific, the international community of countries could try to close the tax havens existing in the world and make sure that all interest income earned 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.

Closing the tax havens is difficult, but not impossible. Before the world perishes from global warming, it might wish to send a few war ships to the Bahamas and similar tax oases to make them comply.

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. Their analysis exceeds the scope of this paper and the expertise of its author.

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.

In theory, 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 Review suggests. This can best be done with a complete system of emissions license trading such as those existing in the US and Europe than spans the world and incorporates all countries. This is the approach of the Kyoto Protocol. In principle, it might 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, there is every reason for the consumer countries to pursue it.

The big problem is the completeness of the trading system. The Kyoto Protocol constrains only a minority of countries. The countries that ratified the Protocol and face binding constraints consume just 29%[29] of annual carbon supply. India and China signed and ratified, but are not constrained, and the US signed, but did not ratify up to this writing. Many countries did not cooperate at all. The unilateral efforts of the EU, which has promised in the Kyoto Protocol to reduce its production of carbon dioxide (including carbon equivalents of other greenhouse gases) from 1990 to 2008–2012 by 8%,[30] thus far have not even caused a dent in the time path of world carbon extraction.

It was argued above in Sect. 2 that the demand restraint by the Kyoto countries would be useless if the supply path chosen by resource owners remained unaffected, because the world price of carbon would fall sufficiently to induce other countries to absorb the quantities not demanded by the Kyoto countries. According to the subsequent discussion of this paper, even this view turned out to be overly optimistic. As the quantity constraints of the Kyoto countries become stricter and more countries participate, the relative price wedge in the world carbon market measured at the old supply path increases, and if it increases sufficiently fast to satisfy the condition $\hat{\tau} > (i+\pi)g(\tilde{S})/P(\tilde{R},t)$, resource owners will react by anticipating their extraction. The resource owners will sell more carbon in the present and near future, despite the demand constraints, because they expect even more demand constraints in the future. They act like a farmer who harvests in a drizzle because he expects a downpour.

While these implications are disquieting, the good thing about the Kyoto Protocol is that it did show that world-wide cooperative agreements are possible. Integrating the three big countries mentioned and Australia, which recently announced that it wants to sign, 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 there could be hope that the remaining quarter could also be disciplined by political means. If the world acts quickly, before the resource owners have time to react, it might be possible to establish a world-wide trading system without loopholes.

The major difficulty will be convincing those countries that are resource consumers and resource owners alike. They are likely to object to establishing an emissions trading system that basically means partial expropriation of the existing stocks in situ and to undercut the demand constraints that other countries impose by trying to attract economic activities to their countries.

Moreover, of course, world-wide quantity constraints administered by a central body like the UN would basically mean a central planning solution with all the horrors and shortcomings history has shown such a solution would cause. The choice between the horrors of global warming and the horrors of central planning will not be easy to make.

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[29] CO_2 emission data for 2004 from IEA World Energy Survey (2006a). 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 US contributed 21.8%, China 17.8%, Australia 1.3%, and India 4.1% of world CO_2 emissions in 2004.

[30] Press release of the European Union as of March 4, 2002, MEMO/02/46.

6.4 Sequestration and afforestation

As was mentioned in Sect. 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.[31]
- 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.[32]

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 where 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.[33]

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

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[31] For those calculations, a specific weight for liquid carbon dioxide of 0.74 t/m^3 is used, 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.

[32] 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).

[33] See Houghton (2004, p. 250 n.) and Stern et al. (2006, p. XXV).

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 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. There is a green paradox.

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, time-invariant 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 into 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.

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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 Fig. 1. For brevity, only the basic variants without the taxes are considered here. The extension to the taxes considered is straightforward.

Positive model

Consider the simplified specification of the model of Sect. 4 and assume that there is a cash flow tax and ad valorem sales tax (or relative vertical demand wedge) whose respective tax factors at time t are given by $\theta^*(t) = \theta^*(0)\,\mathrm{e}^{\hat{\theta}^* t}$ and $\theta(t)$ where $\hat{\theta}^*$ is a constant. Let $i + \pi > \hat{\theta}^* > c$ as well as $i + \pi > \hat{\theta} > c$ where $c = \text{const.} < 0$, assuming $\theta^*(0), \theta(0) > 0$. The resource owner's problem can be written as

$$\begin{aligned} &\max_{\{R\}} && \int_0^\infty \theta^*(0)\big[\theta(u)P(u)R(u) - g\big(S(u)\big)R(u)\big]\mathrm{e}^{-(i+\pi-\hat{\theta}^*)u}\,\mathrm{d}u \\ &\text{s.t.} && \dot{S} = -R, \\ & && S(0) = S_0. \end{aligned} \tag{A.1}$$

It is assumed that the representative resource owner behaves competitively, taking the price path as well as the time paths of the tax rates as given, notwithstanding the fact that in the aggregate the price level, and possibly even the relative price edge caused by demand policies, in addition, depend on the extraction volume: $P = P(R,t)$ and $\tau = \tau(R,t)$ with $\theta \equiv 1 - \tau(R,t)$ (c.f. the derivation of the neutrality condition below).

The current value Hamiltonian for this problem is

$$H = \theta^*(0)\big[\theta P R - g(S)R\big] - \lambda R. \tag{A.2}$$

The necessary conditions for an optimum are the stationary optimality condition

$$\theta^*(0)\big[\theta P - g(S)\big] = \lambda, \tag{A.3}$$

the canonical equation

$$\hat{\lambda} - \frac{\theta^*(0)g'(S)R}{\lambda} = i + \pi - \hat{\theta}^*, \tag{A.4}$$

and the transversality condition

$$\lim_{t\to\infty} \theta^*(0)S(t)\lambda(t)\mathrm{e}^{-(i+\pi-\hat{\theta}^*)t} = 0. \tag{A.5}$$

The slope of the possible paths in R, S space can be derived from (A.3) and (A.4) if (A.3) is differentiated with respect to time and the assumption made in the text that $P = P(R, t)$ with $\partial P/\partial t \leq 0$ for $t \leq T$, $P > 0$ for $R > 0$ and $\partial P/\partial t = 0$ for $t > T$ is respected. Consider first paths on which R is bounded away from zero as time goes to infinity. 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 paths on which S is bounded away from zero as time goes to infinity while R converges to zero. Because of the assumed boundedness of the price elasticity of demand $\varepsilon(R)$, the unit extraction cost $g(S)$ and the growth rates of the tax factors $\hat{\theta}^*$ and $\hat{\theta}$ (A.3) implies that $\lambda \to \infty$ as $R \to 0$. As $g(S)$ is differentiable, the second term in (A.4) vanishes as $R \to 0$, and hence $\hat{\lambda}$ converges to $i + \pi - \hat{\theta}^*$ as $R \to 0$. This means that $\lambda(t)\mathrm{e}^{-(i+\pi-\hat{\theta}^*)t}$ 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) without reference to formal dynamic optimization techniques. In addition to that marginal condition, a transversality condition has to hold that can be derived from the social planner's goal

$$\begin{aligned} \max_{\{R\}} \quad & \int_0^\infty \big[\phi\big(R(u), u\big) + \psi\big(S(u)\big) - g\big(S(u)\big)R(u)\big]\mathrm{e}^{-iu}\,\mathrm{d}u \\ \text{s.t.} \quad & \dot{S} = -R, \\ & S(0) = S_0. \end{aligned} \tag{A.6}$$

The current value Hamiltonian for time t of this problem is

$$H = \phi(R, t) + \psi(S) - g(S)R - \lambda R. \tag{A.7}$$

The necessary conditions for an optimum are the stationary optimality condition

$$\phi_R(R, t) - g(S) = \lambda, \tag{A.8}$$

the canonical equation

$$\hat{\lambda} - \frac{g'(S)R - \psi'(S)}{\lambda} = i \tag{A.9}$$

and the transversality condition

$$\lim_{t\to\infty} S(t)\lambda(t)\mathrm{e}^{-it} = 0. \tag{A.10}$$

The possible paths in R, S space follow from (A.8) and (A.9). 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 (A.8) and the boundedness assumptions for $\varepsilon(R)$ and $g(S)$ 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 (A.10) can only be met as S goes to zero when time goes to infinity, q.e.d.

Thus, it has been shown that despite global warming and stock-dependent extraction costs as well as endogenous and exogenous arrivals of replacement technologies, 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.

Derivation of (18)

Let

$$\underline{P} = P(1-\tau) \tag{A.11}$$

denote the producer price such that

$$\dot{\underline{P}} = \dot{P}(1-\tau) - \dot{\tau}P. \tag{A.12}$$

Note that the arbitrage argument used to derive (7) applied to the producer rather than the consumer price such that

$$i + \pi = \frac{\dot{\underline{P}}}{\underline{P} - g(S)}. \tag{A.13}$$

Using (A.11) and (A.12), (A.13) becomes

$$i + \pi = \frac{\dot{P}(1-\tau) - \dot{\tau}P}{P(1-\tau) - g(S)}. \tag{A.14}$$

After some algebraic transformations, this yields

$$\hat{P} = (i+\pi)\left(1 - \frac{g(S)}{P(1-\tau^*)}\right) + \hat{\tau}\frac{\tau}{1-\tau}. \tag{A.15}$$

Substitute the left-hand side of this equation for $\hat{P}$ in (17) and note that the neutrality condition is derived for the old extraction path before the policy change as characterized by the time paths $\tilde{R}$ and $\tilde{S}$. Then (A.15) becomes

$$\hat{\tau} = (i+\pi)\frac{g(\tilde{S})}{P(\tilde{R},t)} \quad \text{(borderline case for ad valorem tax neutrality).} \tag{A.17}$$

Moreover, it follows from (17) and the logic of the above derivations that τ may depend on the flow of extraction R in addition to calendar time such that $\tau = \tau(R,t)$. In (A.17), $\hat{\tau}$ can, therefore, be replaced with $\hat{\tau}(\tilde{R},t)$, where

$$\hat{\tau}(\tilde{R},t) \equiv \frac{\frac{\partial\tau}{\partial\tilde{R}}\frac{\partial\tilde{R}}{\partial t} + \frac{\partial\tau}{\partial t}}{\tau(\tilde{R},t)}. \tag{A.18}$$

This formulation is useful if the tax wedge is re-interpreted as a perturbation caused by demand reducing policies where it cannot, in general, be assumed that the demand curve will be shifted downward proportionally at a given point in time as would be the case with an ad valorem tax rate.

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