Global warming: The neglected supply side[1]

1. Introduction

Since the publication of the Stern Review (2006), the problem of global warming has been put high on the political agenda. Tony Blair stressed the need for urgent action, it was the main theme during Germany's EU presidency in the first half of 2007, and the G8 Summit in Heiligendamm in June 2007 focused on it. The Bali conference in 2007 called for rapid action.

Indeed, the scientific evidence for an increase in the carbon dioxide (CO_2) content and a subsequent warming of the atmosphere is overwhelming. The facts are undeniable.

- From measuring the CO_2 content of air bubbles in ice cones drilled in Greenland and Antarctica one knows that it was 280 ppm (parts per million) before industrialisation, whereas now it is 380 ppm.
- Although 380 ppm is tiny, implying that less than 0.04 percent of the air is CO_2, the impact on average world temperature is enormous. If carbon dioxide and other, less important, greenhouse gases[2] were absent from the atmosphere, average temperature of the earth's surface would be – 6°C. With the greenhouse gases, the present average temperature is 15°C, about 21°C more than without them. Obviously, the temperature is extremely sensitive to even small variations in greenhouse gas concentration.
- Since pre-industrial times, average world temperature has increased by 0.8°C. The acceleration in recent decades has induced a rapid melting of Greenland ice and of glaciers. The northern polar cap has shrunk sufficiently to raise expectations that the Northwest Passage between the Atlantic and the Pacific will soon be navigable. The sea level has risen by 20 cm relative to pre-industrial times.

There is broad agreement among climate forecasters that with a business-as-usual scenario the temperature increase will be in the order of 3°C between 2035 and 2050 relative to pre-industrial times. The Stern Review fears a 5°C increase in a business-as-usual scenario by 2100. The authors of the review argue that 5°C is a threshold at which mankind will be entering "unknown territory". As a comparison, a 5°C increase is equivalent to the temperature increase since the last ice age, some 15,000 years ago. The costs in terms of floods, storms and countervailing investment in heat-protected dwellings and air-conditioning will be huge by all standards, whatever the assumptions of the forecasts are in detail. Migration waves from arid to fertile parts of the world could even threaten the political stability of the world. Thus, there is broad political agreement that policy measures against global warming are needed.

2. The current policies

A major policy move was the so-called Kyoto Protocol of 1997. The Protocol stipulates that the contracting parties (most of them industrialised countries) reduce their emissions of greenhouse gases in the commitment period 2008–2012 by 5.2 percent compared to the level of 1990.

The Protocol has been signed by 175 countries to date, but for most of the countries signing implied no costs, as emissions were not effectively constrained. Of the 175 countries, only 51 countries are required to reduce greenhouse gas emissions below levels specified for each of them in the treaty. The rules of the treaty effectively constrain only 29 percent of current worldwide emissions of carbon dioxide (CO_2).

Important countries like China and India signed, but are not constrained, and the US did not even ratify the contract. Australia, one of the largest polluters in per capita terms, initially did not ratify the contract

[1] This chapter closely follows the von Thünen Lecture given by Hans-Werner Sinn to the German *Verein für Socialpolitik,* October 2007, and is based on the theoretical foundations laid in his presidential address to the International Institute of Public Finance in August 2007. See Sinn (2007a, 2007b, 2007c).
[2] In particular, 0.02 percent water vapour, 1.8 ppm methane and 0.3 ppm nitrous oxide.

either but has recently signed documents to ratify it in Bali. The EU15 countries are among those effectively constrained by the Kyoto Protocol. They committed to reducing their CO_2 output by 8 percent by 2008–2012. They mutually agreed on an allocation plan distributing the required CO_2 reductions internally. Some countries have advanced substantially in fulfilling these requirements, others lag behind. In 2005, Germany, for example, had already accomplished nine tenths of its reduction target of 21 percent. Some of the Western European countries like France, Finland, Sweden and the UK are good performers too, whereas other countries are still amiss in living up to their commitments. Spain was allowed to increase its emissions by 15 percent but in fact had increased them by 52 percent by 2005; Ireland increased its emissions by 25 percent, although it was allowed to increase them only by 13 percent. In Portugal the actual increase is 40 percent, while the country's limit was set at 27 percent. Italy is obliged to cut its emissions by 6.5 percent but increased them by 12.5 percent instead. Austria promised to reduce its emissions by 13 percent but actually increased them by 18 percent.[3] To be sure, by the end of 2005, the non-complying countries still had up to seven further years to meet their targets. However, as two thirds of the adjustment period had already passed by then, it seems unlikely that the violators will still be able to comply. Hence, it must be feared that the treaty is not even working for the countries that signed and ratified it.

The bad performance is surprising insofar as there is a Compliance Committee that supervises the countries' efforts and that may even impose sanctions. It may require a non-complying country to reduce its emissions by a further 30 percent of its target deviation and it can suspend this country from making transfers under an emissions trading program.

Hopefully, the new emissions trading system introduced by the EU in 2005 will make a difference. The European Emissions Trading System covers energy producers and energy-intensive industries of the manufacturing sector such as the production and processing of ferrous metals or the mineral oil industry, in total about 45 percent of the EU's CO_2 emissions and about 30 percent of the EU's overall greenhouse gas emissions (European Commission 2005). Emissions from other sectors, private households and traffic are not included in the trading system, although they are noted in the Kyoto Protocol. At this stage it is difficult to evaluate the performance of the system, as there are no reliable data on the emissions before the introduction of the system. However, according to a statement by EU Commissioner Dimas, it can be assumed that CO_2 emissions decreased by a few percent in the first year of the new system.[4]

The EU system involves two trading periods. The first was from 2005 to 2007, the second is from 2008 to 2012. At the beginning of the second trading period the reduction targets for energy producers and energy-intensive industries will be tightened, and perhaps the EU will then be able to come closer to its target than now seems likely. In 2011, the European Commission plans to include air traffic in the emissions trading system.

Other EU measures to reduce CO_2 emissions include targets for renewable energy sources, research and development programmes and guidelines for taxing energy as well as sector-specific measures to be implemented by the member countries. EU guidelines were to induce member countries to levy taxes on energy consumption or introduce feed-in tariffs for alternative energy producers and quotas for renewable energy sources. The EU has set a binding target to have 20 percent of the EU's overall energy consumption coming from renewable energy sources by 2020. In 2005 this share amounted to 6.3 percent in the EU and to 4.7 percent in Germany. Some EU countries like Austria, Portugal and the Scandinavian countries have reached shares of more than 15 percent because of their large supplies of hydropower. In the UK, Ireland, the Netherlands and Belgium renewable energy sources have a share of less than 3 percent.

In addition, the EU countries are carrying out a number of voluntary measures that are designed to reduce CO_2 emissions or unintentionally have this implication. In 2005, France was generating 78 percent of its electricity from nuclear power, while the average of the EU25 countries is 31 percent. Other countries with a relatively high share of nuclear power in electricity generation are Lithuania at 72 percent, Belgium at 56 percent, Sweden at 47 percent, Germany at 26 percent and the UK at 20 percent.

In general, the measures implemented in the EU countries may be classified as in Table 5.1.

[3] European Environment Agency (2007).

[4] European Environment Agency (2007).

Table 5.1

Common EU policies against CO_2 output
- Direct fuel demand reductions Better insulation of homes, lighter cars and traffic reduction
- Green electricity Wind, water, sunlight, biomass or hybrid cars
- Nuclear energy Electricity and hydrogen technology
- Other green energy sources Pellet heating, bio diesel, heat pumps, solar heating, geothermal heat
- More efficient combustion Common rail diesel engines, optimized power plants

As most of these measures are discussed in great detail in the media, we forego repeating a discussion of their technical and economic effectiveness here. Two remarks are appropriate, however.

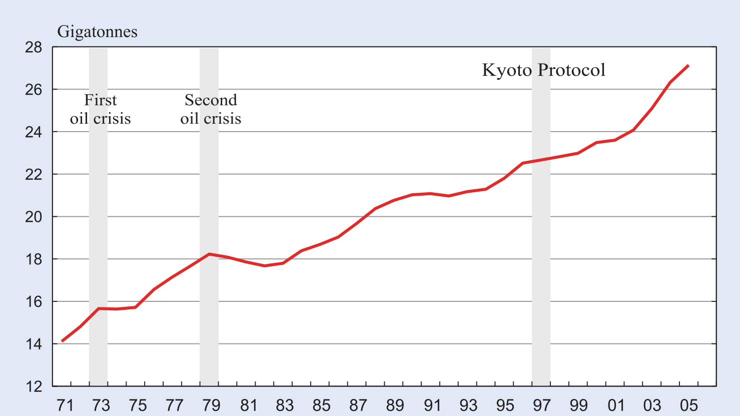
First, the policy measures do not include sequestration and afforestation. We will argue below that these are two particularly effective measures that deserve more attention than they have received thus far.

Second, all measures listed in Table 5.1 are similar in the sense that they want to solve the CO_2 problem by reducing the demand for fossil fuels. Better insulation, lighter cars and a reduction of traffic diminish demand directly. Producing electricity from wind, water, biomass or sunlight means using a replacement technology to produce energy which also reduces the demand for fossil fuels. The hybrid car belongs to this category because it transforms brake energy into electricity. Nuclear energy from splitting atoms is the most important replacement technology in use today, and perhaps one day nuclear fusion reactors will be available. Nuclear energy can be transported via the grids, but it could also be used in vehicles if the electricity is converted to hydrogen, which is a storage device rather than an energy source of its own. Green, non-energy sources like pellet heating, bio diesel, heat pumps, solar heating and geothermal heat are already frequently used in Europe due to high subsidies paid.

Finally, there are ways to improve the efficiency of combustion processes by avoiding the waste of unburned fuels such as power stations with finer coal powder and common rail diesel engines. They also reduce the demand for fossil fuels.

The measures taken to reduce the demand for fossil fuels and the emissions of carbon dioxide stand in striking contrast to the development of actual emission figures. As Figure 5.1 shows, worldwide emissions of carbon dioxide have continued to grow even after the Kyoto protocol was signed. There is not even a dent in the curve. If anything, emissions have accelerated in recent years. This poses a puzzle for economic theory and raises doubts about the efficacy of the demand-policies taken thus far. The subsequent sections will explain how we believe the puzzle can be solved and what type of policy conclusions follow.

Figure 5.1



Note: Emissions are measured according to the IPCC sectoral approach.
Source: IEA (2007).

3. The missing supply side

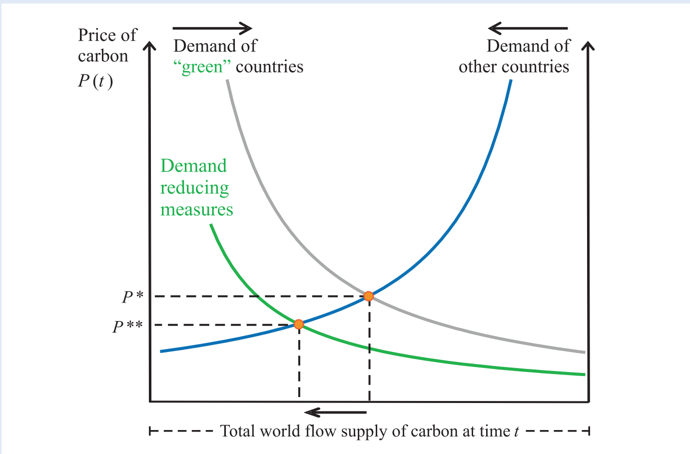
The rationale behind the demand policies is that they contribute to providing a global public good. If only a few "green" countries reduced their CO_2 exhaust, there would be less CO_2 in the air, the temperature of the atmosphere would remain lower, and some of the costs of global warming could be avoided. All countries would benefit from the actions of the green countries. To be sure, it would be better if all countries reduced their demand, but even if only a few countries do, global warming is at least mitigated somewhat.

Unfortunately, this rationale is incomplete to say the least, because it neglects crucial links between the green countries and other countries via the underlying energy markets. The amount of CO_2 emitted into the air depends on the carbon consumption of the green countries, on the carbon consumption of nongreen countries and on the supply of the extracting countries. Only if world wide supply is very price-elastic, such that suppliers are willing to follow demand at minimal price changes, is the assumption correct that demand changes of green countries translate directly into changes in CO_2 emissions. If supply is not very price-elastic, things are different.

Suppose, to illustrate the problem, that world supply of fossil fuels does not react to price changes. In that case, the green countries' demand restraint is useless. The restraint will depress the world market price of carbon sufficiently to induce other consumer countries to consume so much more carbon that the overall output of CO_2 remains unchanged. If this case prevailed, the demand restraint of the EU countries would simply subsidise Americans to enable them to drive even bigger SUVs and the Chinese to finance a further acceleration of their CO_2-intensive growth process. The contribution to slowing down the pace of global warming would be nil. Figure 5.2 illustrates this case.

The distance between the two vertical lines marks the world flow supply of carbon in a particular year *t*. Assume for the sake of argument that it does not react to price changes. This assumption will be removed further below. From left to right, the diagram measures the demand of the green countries and from right to left the demand of the other countries. The demand reduction by the green countries depresses the world price of carbon from *P** to *P*** and reallocates the given supply from the green countries to other countries as is shown by the arrow below the diagram.

Figure 5.2



Source: Sinn (2007c).

When carbon supply is price-inelastic, there are other implications for environmental policy that are worth noting:

- The use of alternative energy sources, such as electricity from wind, water, sunlight or nuclear power, does not mitigate global warming but simply increases world energy consumption.
- The production of bio diesel, ethanol or wood pellets will likewise increase energy consumption. In addition, it will exacerbate the problem of global warming to the extent that it implies the conversion of forests so that the average stock of cut wood in buildings or living wood in trees is reduced. (Note that wood, in whatever form, is a store of carbon as long as the wood is not degrading.) If the production of bio fuel does not imply the conversion of forest land but the conversion of land used for food production, it will increase food prices. The net effect on carbon dioxide in the atmosphere will be zero in this case. Likewise the net effect will be zero if bio-energy is produced from material that otherwise would be wasted, degrading by oxidation.[5]
- Improvements in combustion processes that do not involve the reduction of the waste of heat but operate via a more complete combustion of fossil fuels, such as using finer coal powder for power stations or the common rail diesel technology, will increase CO_2 output and increase global warming. (Improvements reducing the waste of heat such as those resulting from a better motor management are CO_2 neutral in the aggregate.)

Although all of this is only a thought experiment, it demonstrates how futile it is to carry out demand policies without knowing how they affect supply. To predict the effects on global warming, it is essential to understand the supply side of the world energy market. Only to the extent that demand policies succeed in inducing the owners of carbon to keep their stocks underground will they be able to mitigate the problem of

[5] If degrading occurs without oxidation such that methane is produced and evaporates to the atmosphere, the production of bio fuel can slow down global warming as methane is six times as dangerous a greenhouse gas as carbon dioxide over a period of 500 years and 25 times as dangerous over a period of 100 years. See IPCC (2007), p. 33.

global warming. This trivial fact has often been overlooked in the public and scientific debates of the problem.

4. The supply potential

To understand supply, it is useful to first focus on the available and exploitable stocks of reduced carbon in the ground, for these stocks are the source of the CO_2 problem. Reduced carbon that can be used for combustion (oxidation) is contained in coal, oil and methane. Combustion combines the carbon with oxygen to produce CO_2. Burning one tonne of carbon generates 3.6 tonnes of CO_2. Carbon occurs normally in conjunction with other elements, in particular hydrogen as so-called hydrocarbons. Hydrogen can also be burned and contributes to the energy content of fossil fuels. As hydrogen turns to water upon combustion, it is harmless for the environment. The larger the hydrogen content of the fuel, the lower is the CO_2 output per unit of energy produced. Methane, in particular, is advantageous in this regard. For each carbon atom it has four hydrogen atoms, each of which produces about 30 percent of the energy of the carbon atom. Thus, with methane, the CO_2 output per unit of energy is less than half of that of coal which predominantly consists of carbon.

Whatever the fossil fuel is, the amount of CO_2 produced upon combustion is strictly proportional to the amount of carbon burned. In fact, combustion just means transporting the carbon from below ground to above ground where it enters the atmosphere. About 55 percent of the CO_2 entering the atmosphere is quickly absorbed by the oceans and the biomass, because it enters near the earth's surface. Unlike other greenhouse gases, carbon dioxide spreading into higher layers of the atmosphere disappears only very slowly with the passage of time. 45 percent of the emissions stay in the atmosphere after about 100 years, and another 20 percentage points disappear in the next 200 years. The remaining 25 percent build a very robust stock that will practically never disappear. The IPCC (2007) argues that it takes many thousands of years for the anthropogenic (caused by man) CO_2 to disappear from the air, so that emissions are extremely persistent. Archer (2005) as well as Archer and Brovkin (2006) find that the mean lifetime of CO_2 from fossil fuel combustion in the atmosphere is about 30–35 thousand years.

The Stern Review has provided a summary estimate of past, present and future CO_2 concentrations in parts per million (ppm) and the corresponding implications for the temperature of the atmosphere. The estimates considered most plausible by the authors of the report are listed in Table 5.2, together with information on the corresponding absolute

Table 5.2

The carbon supply potential and global warming

		Carbon content of the atmosphere (GtC)	CO_2 concentration of the atmosphere (ppm)	Average temperature (°C)
	Pre-industrial	600	280	14
	Today	800	380	15
Short term	2035 (Stern estimate)	1,200	560	17 (15.5–18.4)
Short term	All reserves burned: 850 GtC (estimated range 766-983)	1,183	555	17 (15.5–18.4)
Short term	2100 (Stern estimate)	1,900	900	19 (16.2–22.3)
Short term	All resources burned: 4773 GtC (estimated. range 3967-5579 GtC)	2,948	1,384	?
Long term (over 300 years)	All resources burned: 4773 GtC (estimated range: 3967-5579 GtC)	1,993	936	19.5 (16.8–22.3)

Note: Estimates about reserves and resources are taken from the World Resource Institute (2006), the World Energy Council (2000, p. 149) and EIA (2007). With regard to the estimates from BP (2007 pp. 6, 22, 32) as well as BGR (2005, p. 6 n.) we calculated the respective carbon contents. The short term is defined as the next 100 years, the time beyond 2300 we call the long term. According to the recent literature 45 percent of anthropogenic CO_2 emissions stays in the atmosphere after 100 years. After 300 years only 25 percent of emissions remain in the atmosphere forever. These estimates about the lifetime of anthropogenic CO_2 are taken from Archer (2005), Archer and Brovkin (2006) and Hoos et al. (2001). Temperature projections are according to the 5–95 percent climate sensitivity ranges from IPCC TAR 2001. See also Stern et al. (2006, p. 12).

stock of carbon (without the oxygen content of CO_2).[6]

The translation of the Stern results into absolute carbon quantities makes it possible to reconcile the forecasts with estimates of the world's reserves and resource. Reserves are those stocks that are known and worth exploiting at current prices. Resources also include stocks that are not well known and/or will become profitable only at substantially higher prices.

Estimates of reserves and resources are given by the World Resource Institute, the World Energy Council, the Energy Information Administration of the US Government, British Petroleum and the German Institute for Geosciences and Natural Resources (BGR). The carbon content of the respective published figures can easily be calculated (the carbon content itself, not the energy equivalent carbon contents). Accordingly, the values for carbon reserves range from 766 GtC (British Petroleum) to 983 GtC (World Energy Council). The values for resources range from 3967 Gt of carbon (BGR) to 5579 Gt of carbon (World Energy Council). In its second column, Table 5.2 lists these ranges as well as the average values of the sources screened.

Obviously, the average reserve estimate of 850 GtC yields a carbon content in the air that is about twice as much as in pre-industrial times and comes close to the Stern estimate for 2035, according to which the temperature will rise by 3°C, relative to pre-industrial times, from 14°C to 17°C. The scenario that the Stern report associates with the year 2100 and that would result in a temperature increase by 5°C to a level of 19°C, is associated with a carbon exhaustion of 1900 Gt. This is more than burning all reserves but much less than burning all resources.

The more interesting question is what happens when all resources are used up. The last two rows of the diagram refer to this case. If reserves were burned very quickly, say up to 2100, this would imply more than a quadrupling of the pre-industrial carbon content of the air. This would clearly be a catastrophic scenario where the temperature would rise way beyond 19°C where, in the words of the Stern Review, humans enter "unknown territory". We know of no forecasts that would dare make predictions about this case, and fortunately it seems very unlikely that resources could be burned over such a short period of time.

Over the very long run, say 300 years from now, where only 25 percent of the emissions stay in the air, the implications of burning all resources might be more manageable, as the temperature would then only increase to 19.5°C, as in the Stern scenario, up to 2100. Thus it would be essential for mankind to extract the carbon dioxide slowly enough to give nature a chance to absorb most of it and avoid catastrophic concentrations. Even then, however, the temperature would be high enough to cause permanent damage to the earth, as Stern et al. have convincingly demonstrated in their voluminous and carefully prepared report.

Nature has endowed mankind with a supply of reduced, oxidizable carbon in the ground. Economic decisions of resource owners transform the natural supply into a market supply, supply finds its demand via the price mechanism, and by the laws of chemistry the extracted carbon becomes CO_2 output. Obviously, therefore, the economics of global warming cannot be understood without understanding how the markets for fossil fuels work. The next section will go into this question.

5. The determinants of carbon supply: the ideal case

Supply reactions in the carbon markets are fundamentally different from supply reactions in normal markets for the simple reason that the stock of carbon in the ground is depletable and cannot be reproduced. The supply of nature is indeed as constant as was supposed in the thought experiment made above. However, there are two economic decisions by the resource owning firms that transform the supply of nature into a market supply. The firms have to decide (i) which parts of the given stock to extract in the long run and (ii) how to distribute this extraction over time. As a result of these decisions they implicitly also choose the current flow supply that determines the current CO_2 output and hence the current pace of global warming.

The first of these decisions depends on how the price of the extracted resource behaves relative to the unit extraction cost as the stock underground and with it

[6] The stock of CO_2 in the atmosphere is calculated by using 5.137×10^{18} kg as mass of the atmosphere, which means that 1 ppm of CO_2 corresponds to 2.13 Gt of carbon (Trenberth 1981). The Stern Review reported 380 ppm of CO_2 in the atmosphere, which corresponds to 800 Gt of carbon. The UN Environmental Program (1998) estimated about 750 Gt carbon in the atmosphere for the early 1990s; the CDIAC (2000) estimated 369 ppm of CO_2 and about 787 Gt of carbon in the atmosphere for the year 2000.

the current flow of extraction becomes smaller and smaller. If the resource is an essential, it is plausible to assume that the price will increase beyond all bounds as the extraction flow dwindles to zero. Thus a bit of extraction will always be profitable as long as some of the stock is left over, and no part of the stock of resources will be permanently exempt from extraction.

To be sure, the higher prices are, the larger are the endogenous incentives to avoid the combustion of fossil fuels by using other energy sources from solar to nuclear power and to avoid the waste of energy by a better insulation of homes or the use of hybrid engines and sophisticated common rail diesel engines. The spectrum of direct and indirect demand-reducing measures discussed above will be activated when prices increase, and this will in turn mitigate the price increase. This is what is behind the demand curves shown in Figure 5.2 and what is formally modelled in Sinn (2007a and b). However, it will be difficult to find perfect substitutes for carbon fuel that would limit the possible price increase sufficiently to make extraction unprofitable. For example, it is hard to imagine that air craft could ever be run on electricity from batteries or on non-carbon fuels such as hydrogen and still carry significant amounts of cargo, as the storage devices for such energy are huge and heavy. If a replacement fuel is used for aircraft, it will probably be bio fuel, which is based on carbon, too. However, the price of bio fuel will rise when more of it is demanded, as the land available for its production is very limited. According to the International Energy Agency, an area of 1.4 gig hectares, which is equivalent to all of the world's current arable land, would be necessary to completely satisfy the fuel requirements from world transport (IEA 2006, p. 289), which is less than one fifth of current fossil fuel consumption. The actual amount of land available for the production of bio fuel will be a tiny fraction of this area, as increasing food prices will create vigorous resistance against this type of energy production. The Tortilla Crisis of Mexico City in January 2007 illustrates the kinds of problems that will be encountered.[7] Thus, it is very unlikely that the possibility of substituting fossil fuel with replacement energy will ever be able to impose a price cap on fossil fuels. At higher prices, the demand for fossil fuels will be less, but it will never become zero. The last helicopter of the Chinese president will not stop operating until the stock of fossil fuels has been nearly exhausted.

Admittedly there are other theoretical possibilities, but they hinge on very special limiting assumptions on the extraction cost and the price as time approaches infinity which cannot, in principle, be observed in this historical period of time. In what follows we will therefore assume gradual exhaustion as time goes to infinity, albeit at a speed that dwindles towards zero.

This does not mean that we presuppose the answer, for in our opinion the true problem of global warming is not whether some of the stock of fossil fuels underground will not be touched even after tens of thousands of years, but how resource owners allocate over time whatever they plan to extract over the next few hundred years.

In solving the intertemporal allocation problem, firms implicitly face a perpetual portfolio optimisation problem like an investment banker, choosing continuously between storing their wealth in the stock in situ and storing it in the form of financial assets. As fossil fuels become scarcer as depletion proceeds, their market price tends to increase over time, and sites of unexploited stocks become more valuable, generating capital gains for postponed extraction. On the other hand, present extraction generates financial income that can be invested in the capital markets where it also generates a return. Like the investment banker, clever resource-owning firms will allocate their wealth between financial assets and the resource in situ so as to maximise their total return. They will postpone extraction if the capital gain from doing so exceeds the interest that otherwise could have been earned in the capital markets. And they will extract at present and invest the proceeds in the capital markets if they expect a capital gain from the resource in situ that is lower than the interest on financial assets.

As all resource-extracting firms follow a similar decision rule, the emerging extraction pattern must be such that the resource in situ and financial assets generate roughly the same expected rate of return. If the capital markets are more attractive, because current resource prices are high and expected future prices are low, most firms will decide to increase current extraction at the expense of future extraction. This will reduce current prices and raise future prices, thereby increasing the potential capital gains from postponing

[7] The Tortilla Crisis, culminated in protests in Mexico City in January 2007. The price of maize, half of which was imported from the USA, more than doubled in the course of a year, primarily because of the increase in maize used for the production of bio ethanol. Mexico tried to solve the problem by imposing a state-administered price ceiling for tortillas made of maize, combined with duty-free imports of maize.

extraction. Conversely, if the expected capital gains exceed the return offered by the capital markets, firms will decide to postpone extraction such that current prices will rise and future ones will fall, reducing the capital gains. In equilibrium, when firms are indifferent between postponing extraction and investing in the capital market, the extraction path is chosen such that the capital gain just matches the return on financial assets.

In the simplest theoretical case where there are no extraction costs, this implies that the price of the resource in situ rises at a rate given by the market rate of interest. This implication is called *Hotelling's rule* according to Hotelling's (1931) seminal work on the behaviour of resource extractors.

Hotelling's rule is a piece of positive economics, describing how markets work. Interestingly enough, however, his market rule is equivalent to an intertemporal efficiency rule developed by Solow (1974) and Stiglitz (1974), disregarding the externalities from global warming, which was not seen as a problem at the time. Solow and Stiglitz saw the portfolio problem from the viewpoint of mankind rather than individual firms. Mankind has two alternatives for transferring wealth and hence consumption to future generations: it can bequeath the resources in situ or it can extract the resources now and use them for additional production of investment goods, such that a larger stock of man-made capital generating more GDP can be transferred to the future. Bequeathing an additional unit of man-made capital has the advantage of generating a real return equal to the marginal product of capital in production. Bequeathing an additional unit of the resource in situ may have the advantage that the extracted resource is able to make a greater contribution to the production of goods in the future than in the present, as a dwindling resource stock and hence a dwindling extraction flow makes the resource scarcer over time and increases the marginal product of the resource as an input to industrial production. In a social optimum, the growth rate of the marginal product of the extracted resource equals the marginal product of capital. If this condition, the so-called *Solow-Stiglitz efficiency condition,* is satisfied, an intertemporal Pareto optimum prevails, which means that it is impossible to find another extraction path that would provide future generations with a higher living standard without reducing the living standard of the current generation. The efficiency condition is the normative equivalent to the positive Hotelling's rule, as in a market equilibrium the marginal product of the extracted resource equals its price and the marginal product of man-made capital equals the market rate of interest.

Both Hotelling's rule and the Solow-Stiglitz efficiency condition can be generalised to the more realistic case of extraction costs. As the stocks of fossil fuels in situ are not all equally accessible, their extraction involves different unit extraction and exploration costs. Firms normally extract the stocks with lower unit costs first and then gradually proceed to those with higher unit costs as the resource becomes scarcer and buyers are willing to pay higher prices. Thus, unit extraction costs are stock-dependent, the unit cost being the higher, the smaller the remaining stock in situ.

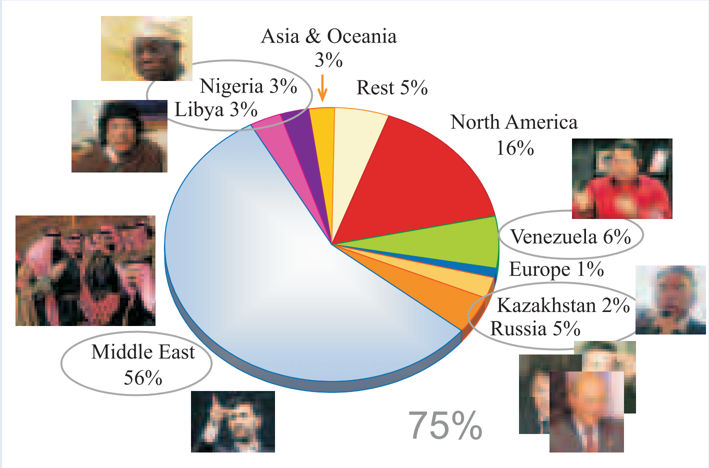
With stock-dependent extraction costs, the intertemporal market equilibrium, as discussed above, is modified insofar as the rule that the capital gain from postponing extraction be equal to the interest on a financial investment now translates into an equality between the rate of interest and the price increase of the resource relative to the price net of the unit extraction cost. Similarly, without considering the damage from global warming, the condition for intertemporal Pareto optimality has to be modified. It now requires that the marginal product of capital be equal to the increase of the marginal product of the extracted resource relative to the marginal product net of unit extraction costs. However, the modified Hotelling's rule still coincides with the modified Solow-Stiglitz condition, implying that, in principle, markets ensure an efficient intertemporal extraction path.

6. Sources of market failure

In reality, resource markets do not work as efficiently as the above discussion suggests, because there are various sources of market failure, the most important ones arguably being insecure property rights and global warming.

Insecure property rights constitute a severe problem for resource owners given that substantial fractions of fossil fuels are located in countries with unstable political conditions. This is only a limited problem for coal, huge sites of which are located in China and the US. Methane and, in particular, crude oil, however, are heavily affected by this problem. Figure 5.3 illustrates the problem for the case of crude oil reserves as quoted in 2007.

Figure 5.3



Source: Energy Information Administration, 2007.

75 percent of the world oil reserves are located in Venezuela, Kazakhstan, Russia, the Middle East, Libya and Nigeria, regions with unstable political conditions and unstable property rights. It is not José Manuel Barroso or Angela Merkel but people like Hugo Chavez, Vladimir Putin and his oligarchs, Mahmud Ahmadinejad or Muammar al-Gaddafi who determine how quickly the oil is extracted and how quickly the world is warming up. And unfortunately, there is every reason to fear that it will be warming up too quickly.

Insecure property rights in oil fields imply that resource owners have little interest in leaving the oil underground, because they feel uncertain about whether their descendants or their clans will be able to enjoy them in the future. Perhaps a revolution will take place that brings a rivalling faction to power. Perhaps democracy will be introduced, sweeping away the previous ruling class of the country. Given these uncertainties, it is better to extract the oil as quickly as possible and invest the proceeds in Swiss bank accounts.

From a more formal perspective, insecure property rights imply that a capital gain that matches the market rate of interest is not enough to make resource owners indifferent between extraction and conservation. Instead, the extraction path must begin with a higher current rate of extraction which over time shrinks faster so that the capital gain on the resource in situ will rise sufficiently to compensate for the expropriation risk. This diminishes the hope that market forces will be able to generate the Pareto optimal extraction path.

This is even more true as the Pareto optimal extraction path itself may require more resource conservation than is implied by the modified Solow-Stiglitz efficiency condition. The reason is that the extracted carbon (or rather 25–45 percent of it, as argued above) is accumulated in the atmosphere in the form of CO_2, creating ongoing damages whose repair absorbs a certain fraction of GDP. The possibility of avoiding some of these damages by postponing extraction makes postponing more attractive from a social perspective. Postponing not only means that the resource is able to make a higher marginal contribution to GDP in the future because it will be scarcer then. It also means that a higher consumption level will be possible because a lower fraction of GDP is needed to repair and accommodate the damages global warming will cause. Thus future generations' consumption of produced goods can be increased without reducing the present generations' consumption of such goods when more of the resource stays underground and less man-made capital is produced.[8]

The two externalities both tend to widen the gap between efficient and actual extraction of fossil fuels. Insecure property rights mean that markets extract the fossil fuels faster than they would in the case of secure property rights, and Pareto efficiency in the case of global warming implies that extraction should proceed more slowly than even a perfect market with secure property rights would achieve. In other words, insecure property rights speed up global warming, while extraction should in fact be slowed down relative to what would have been optimal without global warming.

7. The green policy paradox

Let us now return to the question of how demand policies affect global warming. Stern et al. (2006) emphasised the effect of price signals on the consumers of fossil fuels. They implicitly seem to assume that the time path of producer prices is fixed, such

[8] See Sinn (2007a) for a formal proof of the condition for intertemporal Pareto optimality in the presence of global warming.

that supply at each point in time is perfectly elastic and demand alone determines the transactions volume. However, the truth is far from this assumption. As nature's supply of carbon fuels is given, the market supply that resource owners generate from nature's supply may also be rather rigid and may therefore ultimately determine the transactions volume in the fossil fuel markets and hence the pace of global warming. Thus, how the demand-reducing measures and the price signals they cause for the producers affect the supply path of fossil fuels becomes the crucial question.

The reactions of the supply of fossil fuels have little in common with the supply reactions of reproducible commodities, as the intertemporal allocation problem implies that a supply reduction in the present will lead to a supply increase in the future and vice versa. To be sure, an exogenous demand reduction in the present that depresses the price today will give producers the incentive to produce less; but producing less today simply means postponing extraction. In the future, when prices are back to their normal path, supply will even be higher than otherwise would have been the case. Conversely, exogenous demand reductions in the future that depress future prices will imply less extraction in the future but more in the present. Whether global warming slows down after the introduction of demand-reducing policy measures therefore depends on the whole time path of such measures from now into the future expected by the suppliers. If the expected exogenous demand reductions are balanced over time, the extraction path may not react at all, so that no environmental benefits are achieved.

Long and Sinn (1985) gave these thoughts a more precise meaning. They showed for a very general class of extraction cost functions that the supply reactions depend on how the fall in demand induced by policy measures would change the time path of the present value of producer prices, given the old supply path as would have prevailed without government intervention. Call the difference between the old and the new price at a particular point in time the "absolute price wedge" and call the ratio of the absolute price wedge and the old price the "relative price wedge". If the present value of the absolute price wedge induced by policy measures declines over time, the supply path will become flatter because firms will prefer to postpone extraction. If the present value of the absolute price wedge rises, the reverse is true; and if the present value of the absolute price wedge is the same for all points in time, supply will be time invariant.

To translate that into a specific policy measure, assume all governments of the consuming countries levy a time-invariant ad-valorem tax on the consumption of fossil fuels. With the given old supply path this tax would depress the producer price at all points in time by a given percentage of the respective old price, which means that the relative price wedge is constant. Now assume for a moment that extraction costs are negligible implying that, according to Hotelling's rule, the consumer price rises at a rate given by the rate of discount. The absolute price wedge will then also rise at this rate and hence be constant in present value terms, as required for the neutrality result cited. Thus, a constant ad valorem tax on fossil fuel consumption will indeed leave the time path of extraction unchanged if there are no extraction costs.

However, governments cannot easily commit to levying a tax at a constant rate. What if resource owners expect the rate to be increased over time, say due to an increasing awareness of the CO_2 problem by the public? As shown in Sinn (1982) and Long and Sinn (1985), in this case they will advance their sales to avoid the increasing future tax burden. Global warming will accordingly accelerate, a phenomenon that Sinn (2007b) has called the *green paradox*. The green policy paradox gives a deeper meaning to the initial remark that the supply reactions of firms that sell exhaustible natural resources follow another logic than those of normal firms, showing that the price signals that taxes yield do not depend on the level of taxes but on their change over time.

This contrasts sharply with the views expressed by Stern et al. (2006) as well as Newberry (2005), who argue that the carbon consuming countries should introduce carbon taxes to create a common worldwide price signal for the consumers of fossil fuels inducing them to curtail their demands. It is true, of course, that a carbon tax that, at each point in time, reflects the present value of the stream of marginal social damages from a unit of carbon extracted at that point in time would, in principle, be able to induce an efficient extraction path. However, such a tax would not in general be constant over time but would have to follow a particular time path that cannot easily be calculated and would involve the risk of major policy mistakes, as the above discussion has shown. When extraction costs are negligible and the tax is constructed on an ad-valorem base, the tax would be neutral if its rate stayed constant over time, and it would even exacerbate the problem of global warming if the tax rate increased over time.

The green policy paradox can be generalised to the more realistic case with extraction costs as well as to other demand-reducing policy measures such as subsidising bio fuel, wind mills and photovoltaic devices and investing in research and development to find a technical break-through in nuclear fusion. Let $\tau(t)$ be the expected relative price wedge produced by a demand reducing policy or, to be more precise, the expected relative decline of the producer price of carbon at time t that would be induced by that policy if the entire supply path from now to the distant future remained unchanged. As shown in Sinn (2007b), the neutrality condition for the supply path that ensures that this path will indeed remain unchanged is

$$\hat{\tau} = r\,\frac{g(S)}{P(R)}\text{, (borderline case for neutral demand reducing policies)}$$

where $\hat{\tau}$ is the growth rate of the relative wedge τ; r is the rate of discount; $g(S)$ is the unit extraction and exploration cost, which depends on the stock of resource in situ, S; and P is the price of the resource at a particular point in time before the policy-induced demand reduction. If τ rises faster than given by this equation, firms have an incentive to advance sales. The extraction path becomes steeper with more extraction in the present and near future and less extraction in the more distant future. Conversely, if τ rises more slowly, which could mean that it stays constant or declines, the supply path becomes flatter and global warming will slow down, as is intended.

The equation shows that in the absence of extraction costs ($g = 0$), the demand reducing policy is neutral if $\hat{\tau}$ is zero, that is if the relative price wedge τ is a constant. If the demand- reducing policy is brought about by an ad valorem tax on resource consumption, τ can be interpreted as the tax rate, and as such the equation confirms the result cited above. However, as explained, τ has a more general meaning applying to all demand-reducing measures that would dampen the producer prices of fossil carbon fuels with a given supply path.

When extraction costs are taken into account, the criterion for neutrality is a moderate rise in the relative price wedge in line with the terms on the right-hand side of the equation. The neutral rate of increase in the relative price wedge caused by demand-reducing policies is a fraction of the discount rate given by the share of the price needed to cover the extraction cost. It follows that a demand-reducing policy that would dampen the price path proportionately at all points in time, if the extraction path remained unchanged, will result in a flatter extraction path and will therefore slow down global warming. This is indeed the reaction expected by the green policy-makers.

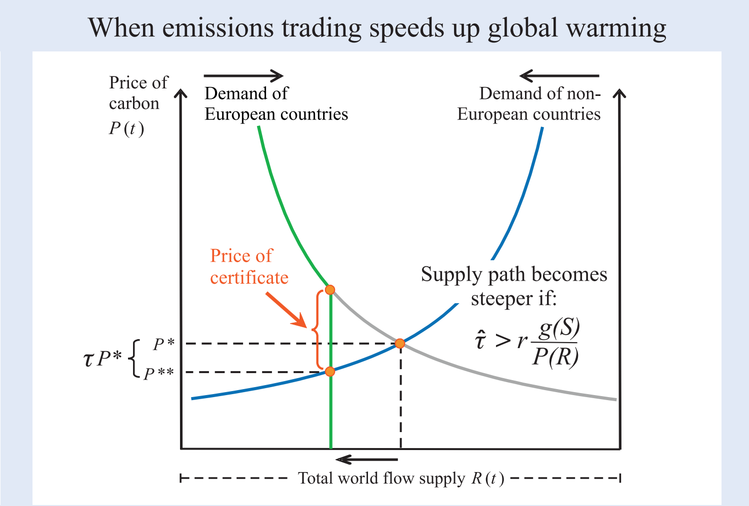
However, the problem is that the green policy makers must be able to credibly commit themselves to no tightening of the demand-reducing policies in the future. This condition is not typically met in reality. To the contrary, green policy programs are often defined such that the respective measures are gradually phased in, gaining strength over time. This may then give rise to the green policy paradox even if extraction costs are not negligible.

There are many examples. As explained above, the Kyoto Protocol of 1997 defined the target to reduce CO_2 output by 8 percent over the period from 1990 to 2010. In 2007, the EU Council decided to reduce EU emissions of greenhouse gases by as much as 20 percent relative to the 1990 level. The Council promised to stick to that decision irrespective of what other countries would do and it offered an even larger decrease of 30 percent provided that other developed countries committed themselves to similar emission reductions. The tools to reach these goals include an increase in energy efficiency, an increase in the share of renewable energy sources and an increased use of bio fuels (the additional emissions from deforestation not being counted). Moreover, the EU is planning to limit CO_2 emissions of newly licensed cars to 120g per km by 2012 (a policy criticised as hidden protectionism for the small cars produced in France and Italy) and the inclusion of air traffic in the emissions trading system by 2011 for flights within the EU and by 2012 for all international flights to and from EU countries. All of this means that the demand-reducing policies will become stronger over time.

Even if the strengthening of demand-reducing policies is not formally announced, a growing intensity of green arguments in the media makes it very likely that additional policies to reduce fossil fuel demand will be put in place in the future. An important goal of all environmentalists is to bring the US, China and India on board. If that goal is achieved, major price cuts in world carbon and oil markets, relative to what the price otherwise would be, will result. All of this is likely to make resource owners expect a sharply increasing price wedge. If this wedge increases faster than the cost share times the discount rate, they will tilt their extraction path towards the present and global warming will accelerate.

The green paradox is possible with all the demand-reducing measures cited in Section 2 to the extent they do not follow endogenously from the foreseeable price increases but from exogenous policy measures that change the resource owners' expectations of future market conditions. Subsidies to alternative fuels, demand-reducing constraints on car manufacturers and public programmes for the development of new energy sources are all bad news for the resource owners, inducing them to speed up their extraction. Unfortunately, even the EU emissions trading system may have this implication, as its standards are to be tightened over time. While 1734 million tonnes of CO_2 allowances were allocated to the first trading period from 2005 to 2007, aggregate allowances were reduced to 1623 million tonnes in the second period running from 2008 to 2012,[9] and it can be expected that further cuts will be enacted upon the prolongation of this system.

Figure 5.4



Source: Sinn (2007c).

Figure 5.4 helps to determine the effect of emissions trading on the pace of global warming. As in Figure 5.2, there are (green) European countries and others, each endowed with their specific carbon demand curves. The graph refers to any given year and demonstrates the implication of the trading system relative to a situation where such a trading system is absent. For other years, there will be similar graphs with other positions of the curves and other widths between the vertical axes, as the extraction volumes change over time. Suppose for a moment, to be able to apply the theorem cited above, that the time path of the flow of worldwide carbon supply remained unchanged by the policy measures such that the diagram has the same width in each year as it would without the policy change. Suppose further the European countries impose a quantity constraint on their CO_2 emissions which they implement by way of the certificate trading system. The reduced European demand for fossil fuels will then depress the world market price as shown in the figure with the move from P^* to P^{**}. The European price, which fossil fuel consumers have to pay, will be P^{**} plus the price of certificates, indicated by the curly bracket. The absolute price wedge is τP^*, and the relative price wedge is τ.

For each year, a graph like Figure 5.4 defines a specific relative price wedge. Due to the tightening of emissions standards in a growing world economy, the relative price wedge is likely to be higher in the future than in the present. It follows from the result cited above that when the rate of growth of this price wedge is greater than the cost share times the rate of discount, the extraction path will, in fact, not remain given but will become steeper, giving rise to the green policy paradox. There will be more extraction in the present and the near future, and less extraction in the more distant future relative to what would have prevailed without the emissions trading system. Thus, the graph shown in Figure 5.4 would become wider in the present and near future and narrower in the more distant future. Global warming accelerates. Good intentions do not always breed good deeds.

8. Useful policy measures

What are the policy measures that avoid the risk of adverse supply reactions discussed in the previous sections and do work? How can global warming really be mitigated? We distinguish here

- fiscal measures that flatten the supply path
- measures to protect property rights
- binding quantity constraints with an improved Kyoto Protocol
- storing CO_2.

[9] See EU press release IP/07/459.

A fiscal measure to flatten the supply path would be the introduction of an ad valorem tax on the consumption of fossil fuels that shrinks over time. While this would be a straightforward and safe policy from an economic perspective, it is hard to imagine it in practice, as no government could convincingly commit to it. As the world becomes warmer, the voices calling for action will become stronger and stronger. It strikes us as impossible from a public choice perspective that a gradually declining tax on fossil fuels could ever be introduced.

Alternatively, one could try to internalise the positive externality resulting from not extracting the fossil fuel resources by subsidising the stock underground, so that resource owners would find it more rewarding to postpone extraction. Again this is only a theoretical possibility without a chance to be implemented. Given that, in the opinion of the consuming countries, the resource-owning countries are already charging excessive prices, the public will never agree to subsidise the resource owners in addition.

A somewhat more promising solution is the introduction of a unit tax on fossil fuel consumption. If the tax remains constant over time, its present value declines, and hence, as shown in Sinn (1982), markets will postpone extraction. In fact, such a tax could even be efficient under special theoretical circumstances. Suppose that a marginal unit of carbon extracted creates a constant marginal damage, b, in all future years from the time of extraction to infinity, and suppose further that the rate of interest, i, is time invariant. In that case, the present value of the stream of marginal damages would be equal to b/i at all points in time regardless of when the extraction takes place. A constant absolute tax wedge of b/i would therefore be able to correctly compensate for the distortion resulting from global warming. However, under realistic conditions, b will be far from being a time-invariant constant such that no simple tax rule will be available. Moreover, even a unit tax could produce the green paradox if its rate were to increase sufficiently fast due to the increasing awareness of the public about the problem of global warming.

Another option is to make alternative investment less attractive for the resource owners, who extract fast in order to invest their proceeds in financial assets. If, say, the Western world made an active attempt to close the tax heavens of this world and imposed source taxes on the capital income earned by resource owners, the resource owners would face a permanent incentive to postpone extraction and keep larger stocks of the resource in the ground. The measure would reduce the discount rate of resource owners and would be a powerful policy instrument to flatten the supply path and mitigate global warming.

A similar implication could be expected if the Western world threatened the resource owners with the expropriation of their financial savings. This threat would also reduce the discount rate of resource owners and counteract the threat of expropriating their resources in situ which in itself tends to accelerate extraction and global warming. However, it would be very difficult and dangerous to implement such a policy if only because it would also undermine the credibility of the financial system as such and scare off normal savers. But increased legal efforts to sequester the financial assets of current or past dictators (and their entourage) in oil-producing countries charged with various criminal offences could serve the same purpose.

An alternative possibility to make resource conservation more attractive for the resource owners would be a strengthening of their property rights in the resources themselves. If the dictators of the oil exporting countries were less afraid of being replaced by their rivals or, for that matter, by a Western style democracy, there would be less reason for them to rush to convert their resources into financial assets. However, again, both from a practical point of view and from the perspective of humanitarian values, these conclusions are disquieting, to say the least. It is beyond our expertise to come up with policy conclusions regarding war and peace.

Despite the disappointing results of our analysis concerning demand policies, the policy of imposing quantity constraints via an emissions trading system could be given another try. It would be essential though to make the system tight without any exceptions to avoid the countervailing demand increases resulting from the relative decline in world energy prices. A truly strict monopsony of the consuming countries would be able to dictate its quantity constraints on supply and force the resource owners to adjust their extraction quantities to whatever demand the monopsony chose.

Mind, however, that this would basically be a central planning solution with all the errors and inefficiencies history has shown. Its success would depend on politicians having the proper knowledge to implement the right extraction paths and being benevolent agents who act on behalf of mankind's future. We are sceptical whether such a solution would feasible, but we are afraid that mankind may ultimately be forced to choose it. We agree with the Stern Review that convincingly argued that the problem of global warming is the world's largest externality ever. The choice will undoubtedly be one between various evils.

What remains as policy options goes beyond the attempt to modify supply and demand for fossil fuels but seeks the solution in storing the CO_2 generated by combustion processes away from the atmosphere. There are two promising alternatives. The first is sequestration. In addition to the pipeline and transportation network linking the fuel sites with the places of combustion, there could be a second one to transport the CO_2 back to the "mines" from where the carbon came and store it there in liquid form under extremely high pressure. The space emptied underground could be refilled with the remainders of the combustion process. Unfortunately, this would not only be very expensive but one could doubt whether it is technically feasible, because much more storage space would be needed than that emptied by extraction. For example, upon combustion one cubic meter of anthracite generates 5.4 cubic meters of liquid CO_2, and one cubic meter of crude oil generates 3.6 cubic meters of liquid CO_2 (55 bar at 20°C). Hence, additional space would have to be sought. But even if the search were successful, the safety problems involved would be large. After all, CO_2 is heavier than oxygen so that any leakage from below ground could have fatal risks for the population living above. A similar remark is appropriate with regard to attempts to pump the CO_2 into the sea. The risks for maritime life and the nutrition cycle could be larger than the advantages from slowing down global warming.

A much safer storage device is trees. Not too long ago, a much larger area of the world's surface than today was covered by trees. Trees store the reduced carbon that photosynthesis filters out of the atmosphere. It is estimated that each year deforestation contributes 18 percent to the increase in the CO_2 content of the atmosphere, more than all the traffic of the world.[10] If deforestation could be stopped and true afforestation in net terms, which leads to an expansion of the world's forests, could be brought about, a substantial contribution to solving the problem of global warming would be made.

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

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