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Oil shortages, climate change and collective action

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Concerns over future oil scarcity might not be so worrying but for the high carbon content of substitutes, and the limited capacity of the atmosphere to absorb additional CO_2 from burning fuel. The paper argues that the tools of economics are helpful in understanding some of the key issues in pricing fossil fuels, the extent to which pricing can be left to markets, the need for, and design of, international agreements on corrective carbon pricing, and the potential Prisoners' Dilemma in reaching such agreements, partly mitigated in the case of oil by current taxes and the probable incidence of carbon taxes on the oil price. The 'Green Paradox', in which carbon pricing exacerbates climate change, is theoretically possible, but empirically unlikely.

Keywords: exhaustible resources; climate change; carbon prices; Prisoners' Dilemma; international agreement; Green Paradox

1. Introduction

Growing affluence and population are putting increasing stress on the planet's resources, particularly fresh water, agricultural land, forests, biodiversity, key minerals including oil and the capacity of the oceans and atmosphere to absorb greenhouse gases (GHGs). Two such resources are in direct conflict—fossil fuel and the atmosphere. Burning all of the current estimates of fossil-fuel reserves without carbon capture releases CO_2 that would more than double pre-industrial atmospheric CO_2 concentrations. With high probability, that would result in global warming of considerably more than 2°C, with damaging climate changes, as well as ocean acidification. Conventional oil reserves alone do not appear to contain enough carbon to exceed the current target of limiting global warming to 2°C, but there are growing concerns that conventional oil will soon experience shortages that will not only be disruptive, but may also lead to the more rapid exploitation of even more carbon-intensive alternatives. This paper will ask what economics can say about oil shortages and their possible consequences, and about the larger question of agreeing collective action to mitigate climate change.

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In particular, it asks what are the key obstacles to such action, whether they would avoid or delay damaging climate change, or whether they might have perverse effects.

Any commodity or service that carries a positive price is by definition scarce—the lack of scarcity would cause the price to fall to zero—but a shortage suggests something more serious than mere scarcity. An economist would interpret shortage as excess demand, or a situation in which the demand, given the terms of access including the price, exceeds the amount supplied under those terms. Under ideal conditions (competition, full information, well-established property rights and no externalities), markets will price resources so that there is only scarcity, and no shortage. Shortages may be caused by either a temporary and unexpected disruption, or the suspension of market pricing, often for distributional reasons, as in wartime rationing. Oil markets are global, and can certainly respond to the possibility of increased scarcity, but national policies can also turn those market signals into situations of shortage. This paper considers well-designed policies that use market prices to minimize, rather than amplify, the costs of scarcity and climate change, and so ignores disruptions and shortages.

2. Oil: exhaustible resource theory and practice

Projections made in successive editions of the International Energy Agency's (IEA's) *World energy outlook* [1] (updated annually) reference scenario for 2030 oil demand were 119.9 million barrels per day ($\mathrm{mb\,d^{-1}}$, 5759 million tonnes of oil equivalent per year) in 2002, $116.1\,\mathrm{mb\,d^{-1}}$ in 2006, $106.4\,\mathrm{mb\,d^{-1}}$ in 2008 and $105\,\mathrm{mb\ d^{-1}}$ in 2009. Significantly, only $26\,\mathrm{mb\,d^{-1}}$ or 25 per cent of that is projected to come from existing fields, while 50 per cent is to come from fields yet to be developed or found, with the balance coming from natural gas liquids (double the 2000 level) and unconventional oil ($7\,\mathrm{mb\,d^{-1}}$). Differences in the reference scenarios reflect different price and economic-growth projections, as well as different policies in place at successive dates. The evidence for 'peak (conventional) oil' is estimated to lie between 2009 and 2031, after which conventional oil production will decline, although demand at unchanged prices would continue to rise [2]. Clearly, scarcity pricing should lead to rising oil prices, until prices are sufficiently high to elicit adequate supplies of unconventional oil,[1] including liquids from gas and coal. Estimated conventional oil reserves lie in the range 2000–4300 billion barrels (Gb) compared with cumulative production to 2007 of 1128 Gb [3].

The economic theory of pricing exhaustible resources like oil goes back to Hotelling [4], who considered a world of perfect certainty, with a known total stock of oil that could be extracted at known costs at unlimited rates at any moment, to be sold on competitive markets. His insight was to note that the value of oil in the ground at any date was the sales price *less* the extraction cost. This value, termed the rent, measures the scarcity value of that oil *in situ*. With perfect capital markets, the equilibrium rent now should be the same as the

[1] Unconventional oil is any resource that requires processing to produce the equivalent of conventional oil. Deep offshore oil is treated as conventional, if expensive to extract.

present discounted value (PDV) of its future rent whenever the well is producing. If the rent were less than the PDV of future rent, it would be better to keep it in the ground and wait until the price and rent rose enough, while if the rent were greater than any future PDV, it should be immediately extracted and sold in the market to give the highest (present-valued) profit.

In the simplest case, if the extraction cost is very low compared with the oil price and is taken as zero (a good approximation for the supergiant mid-east oil fields), then the competitive price of oil will rise at the rate of interest. If the price now is p_0, then its price at date t will be $p_t = p_0 \mathrm{e}^{rt}$, where r is the rate of interest at which future rent is discounted. If we know the demand as a function of price and time (acting as a proxy for future income), $D_t = D(p_t, t)$, then cumulative consumption can be determined, and the current stock of oil, S_0, will be depleted at date T when cumulative demand $\int_0^T D(p_t, t)\mathrm{d}t = S_0$. If at that date, oil is to be replaced by some substitute that is available at price p^*, then the price now will be $p^* e^{-rT}$, where T has been determined by the depletion condition. The price at any subsequent date t will be $p^* \mathrm{e}^{r(t-T)}$.

This model can be readily modified to accommodate positive production costs, and if they are constant at m per barrel, the price at date t will be just $p_t = m + (p^* - m)\mathrm{e}^{r(t-T)}$. Models that take account of a range of more complex cost and market conditions can be found in Dasgupta & Heal [5], Newbery [6] and Karp & Newbery [7]. Figure 1*a* shows the equilibrium price and demand when there is a sequence of oil fields of increasing cost.

How well does this model predict oil prices? Figure 1*b* shows that real oil prices dramatically jumped in 1974 and again in 1979, in the period in which the USA was moving from near self-sufficiency to a quadrupling of oil imports, tightening the world oil market, encouraging resource nationalism and consequential political tensions. Prices then collapsed, first as Organization of the Petroleum Exporting Countries (OPEC) cartel members were tempted to cheat and increase supplies, to which Saudi Arabia responded and reasserted its swing position in OPEC by flooding the market to support its preferred price and output share.

Nevertheless, at each date after the initial price rise, analysts were tempted to use the Hotelling theory to predict that future prices would rise at something like the rate of interest from then on. Graphs of forecast prices against the subsequent actual prices look like a spiny porcupine with forecasts rising at 3 per cent (real) from current levels, while prices drifted down until 2000. Clearly, the model fails to capture important aspects of reality—such as market power and the difficulty of sustaining a cartel by national quota allocations, supply constraints, ambiguities over ownership, the changing balance within OPEC between hawks and doves, surges in exploration and rapid technical improvements in off-shore drilling, the oil-induced recession and inflation of the 1980s, to mention but some. To return to the original model, we should not be surprised at the volatility of the spot oil price as it should depend on estimates of future reserves, their cost, the cost of substitutes and the discount rate, all of which are uncertain and subject to periodic major revision. Nevertheless, the economic argument is clear—oil prices today depend on future developments and particularly the transition from conventional to unconventional oil or other alternatives, as well as being heavily influenced by market structure and tax policy (which affects demand).

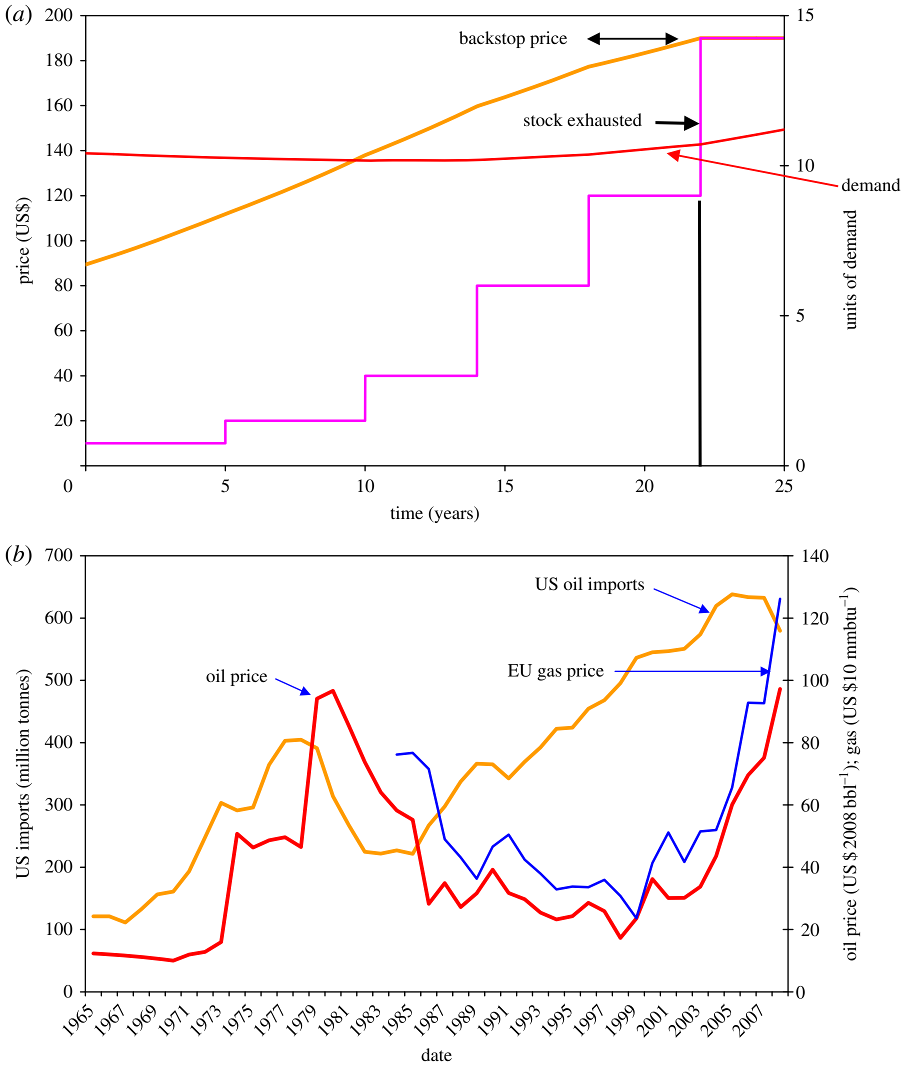

Figure 1. Exhaustible resource prices in theory and practice. (*a*) Schematic of demand for an exhaustible resource (as indicated), its competitive price (rising to the backstop) and unit extraction cost (stepped line) for a discount rate of 5%, demand growth of 1.5% per annum and elasticity of demand of −0.5. (*b*) World oil and European Union (EU) gas prices (US $2009) and US oil imports, 1965–2008 [8]. (*a*) Orange line, price; pink line, cost; red line, demand. (*b*) Orange line, US oil imports; red line, oil prices; blue line, EU gas prices. (Online version in colour.)

3. Climate change

GHG emissions are a global stock public bad—emissions anywhere impact climate for everyone everywhere, and GHGs are persistent, so that there is little difference in the damage done from emissions today and the next year. To quote the Stern Review ‘Climate change presents a unique challenge for economics: it is the greatest and widest-ranging market failure ever seen’ [9, p. i]. Given that it is the stock of GHGs that sets climate change in motion, the question to ask is how the absorptive capacity of the atmosphere relates to the stock of unextracted carbon in the form of fossil fuels (while recognizing the importance of other sources and sinks of GHGs, notably land-use and forest-cover change and livestock). Current modelling suggests that to have a 50 per cent change of preventing global warming of 2°C from pre-industrial levels, we can only release another 500 Gt of carbon, compared with past emissions of 500 Gt of carbon—we are half way to exhausting our trillion tonne global carbon budget, as figure 2*a* illustrates.

Figure 2*a* also shows the amount of carbon locked up in fuel reserves, showing that the low estimate of conventional oil, gas and coal reserves are larger than the 2°C absorptive capacity of the atmosphere, while exploiting that and unconventional oil and gas would probably take us to 4°C. If we add the very uncertain estimates of the potential resources, the bar goes outside the range considered [8,12,13]. Clearly, if we are to avoid damaging climate change, we need to ensure that either we do not exploit all current fossil reserves, or that we capture the CO_2 and store it securely in geological reservoirs. That explains the urgency in demonstrating carbon capture and storage (CCS) technology, as well as discouraging excessive fossil-fuel use. The economics of mitigating climate change are thus relatively straightforward in theory—we need to limit the cumulative emissions of GHGs.

The approach to date, starting with the Kyoto Protocol, is to agree country-specific emission targets, initially for annex I countries, and typically specified as average emission rates relative to 1990. Figure 2*b* shows that although annex I countries accounted for only a quarter of the population, they account for 70 per cent of emissions.

The European Union (EU) has addressed its emissions targets through the EU emissions trading system (ETS), under which member states are allocated an annual quota of emission allowances (EUAs) based on (unsurprisingly inflated) estimates of what they considered they needed. These EUAs are freely tradable and can be banked from year to year. Phase I ran from 1 January 2005 to 31 December 2007 and EUAs could not be banked beyond that date. Phase II runs until 31 December 2012 and second-period EUAs can be carried over to phase III.

There are two reasons for creating a tradable emissions permit. The fundamental reason is that it puts a price on CO_2 with the intention that all installations covered by the ETS (roughly half of total EU CO_2 emissions) face the same charge for emissions. Installations that can reduce emissions cheaply will do so and sell (or not buy) EUAs, while those for whom reduction is more costly will prefer to buy EUAs, until the marginal cost of abatement is the same everywhere, and the total cost of abating the required amount (the cap) is minimized. In contrast, regulations specifying limits for each installation are likely to deliver any given amount of abatement at higher, and perhaps much higher, total cost, as there is no guarantee that it will be equally costly to abate the final tonne in each installation.

The second reason is political—it is much easier to agree a target future level of emissions and to allocate quotas to each country on the basis of past levels of emissions than it is to agree a price for CO_2. In addition, existing installations can be allocated EUAs, which they are free to use or sell, and hence they are typically better off as a result. Imposing a carbon tax would make all emitters worse off, unless the government were to hand back the revenue in proportion to

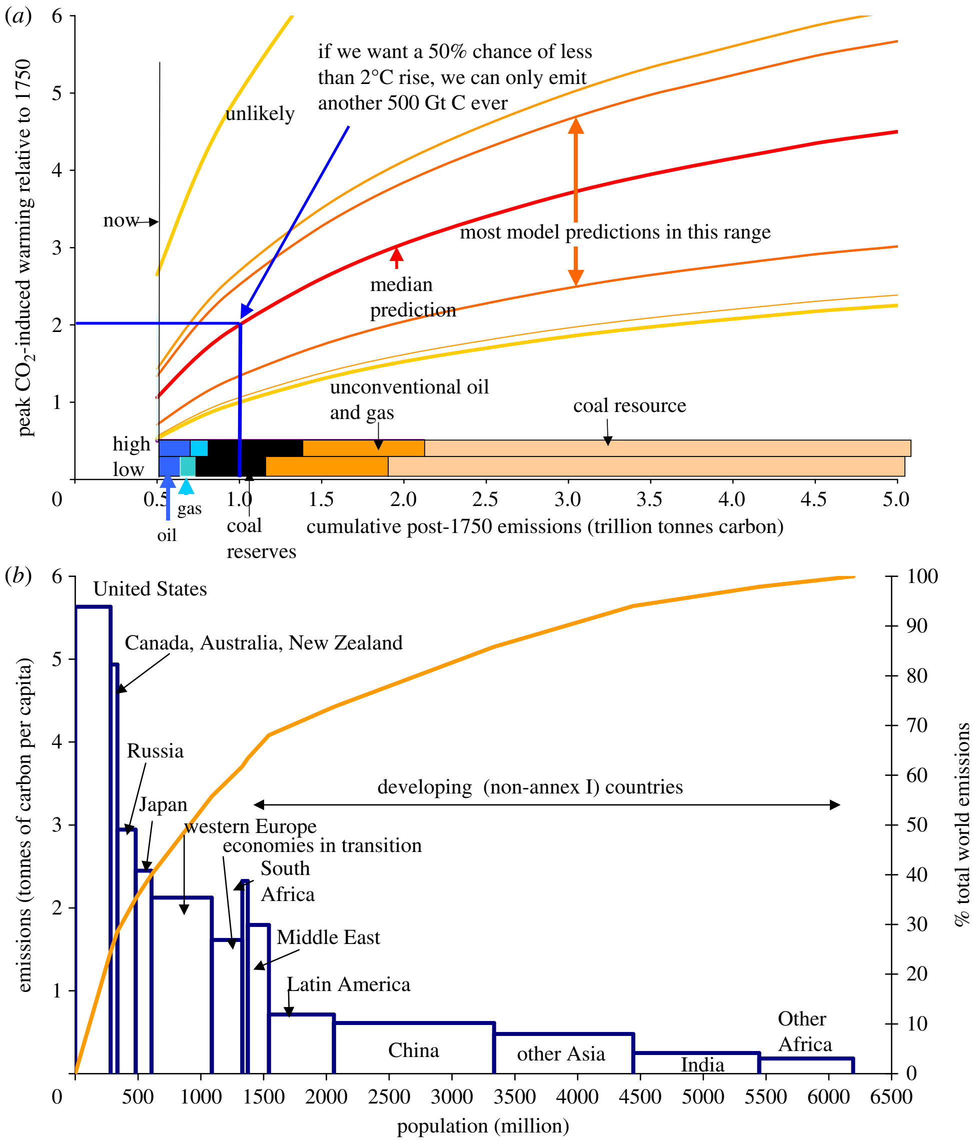

Figure 2. Global warming threats and sources: (*a*) illustrative peak global warming versus cumulative emissions 1750–2500 and stocks of fossil fuel carbon; adapted from [10]. (*b*) CO_2 emissions per head against population in 2000 (areas represent total emissions) [11]. (Online version in colour.)

base-year emissions. Of course, consumers are worse off under the free allocation scheme, but they almost certainly do not realize this until it is too late. The electricity industry provides an excellent example of this political economy, as the European Commission (CEC) required all member states to freely allocate at least 95 per cent of base-year entitlements to generating companies, who were then free to sell them, at a price that in 2005 reached over 30 € EUA^{-1}, or

25 € MW h^{-1} for coal-fired generation. Politicians might naively have thought that as they were compensated for the cost of CO_2, they would not need to raise electricity prices, but in liberalized markets the price of electricity immediately reflects the carbon cost of generating the most expensive electricity (where cost includes fuel and CO_2). Had the electricity companies been required to bid for EUAs in an auction or buy them in the ETS market, the most expensive plant would have broken even, if, as was likely, it had the highest emission rate, and more carbon-efficient plant (e.g. gas fired) would have made more profit (equal to the difference in carbon intensity times the EUA price—or 0.4 EUAs/MW h for a combined-cycle gas turbine). As they had all been given free allocations, the leading five countries experienced a windfall estimated at between 23 and 71 billion euros [14]. Fortunately, this is now recognized, and generators will have to buy all their required EUAs in phase III.

The experience of the ETS is well known and points to its key failure. Prices rose steeply in March 2006, when the actual emissions data were released, showing, unsurprisingly, that countries and firms had exaggerated their future emissions in order to secure more free allocations. The EUA price dropped sharply and eventually fell to zero in late 2007, as these EUAs could not be carried over to phase II. The second-period price started promisingly and rose to 30 € EUA^{-1} in mid 2008 before steadily falling to less than half that value as a result of the increased target for EU renewable energy by 2020 and then the global recession [15]. The ETS thus failed to give clear and stable carbon-price signals for investors choosing generating plant with an expected life of 25–60 years.

That brings us to another economic insight—whether it is better to stabilize the quantity of emissions or the price. If there is complete information and no uncertainty, the efficient level could be achieved either by issuing the correct number of quotas or setting the pollution tax at the marginal damage cost at the efficient level. This equality of outcome breaks down under uncertainty or with asymmetric information (e.g. if the policy maker does not know the true cost of abatement but producers do). Weitzman started a lengthy debate by observing that under uncertainty, taxes or charges are superior to quotas if the marginal benefit from abatement schedule (i.e. the marginal damage of emissions) is less steep than the marginal cost of abatement schedule [16]. But as observed earlier, emissions today contribute to the total stock of CO_2 as do emissions next year, and one more tonne today can be offset by one less tonne next year. At any moment, the marginal damage of emissions is almost independent of the amount, making the marginal benefit of abatement effectively flat, and giving a clear preference for stabilizing the price, not the cap on total emissions.

Figure 3 shows that the correct emissions level is Q^* and price t^*. If the marginal cost schedule is incorrectly located and the quota set at Q, the cost of the error resulting will be the large lighter shaded area, whereas setting the charge (incorrectly) at t would lead to the small cost of error (shaded dark).

What investors need if they are to make rational low-carbon investment decisions is a credible time path for future CO_2 prices. Theory shows that the price of CO_2 should rise at close to the rate of interest in equilibrium.[2] As new information arrives and reduces uncertainties about the absorptive capacity of the

[2]See the electronic supplementary material.

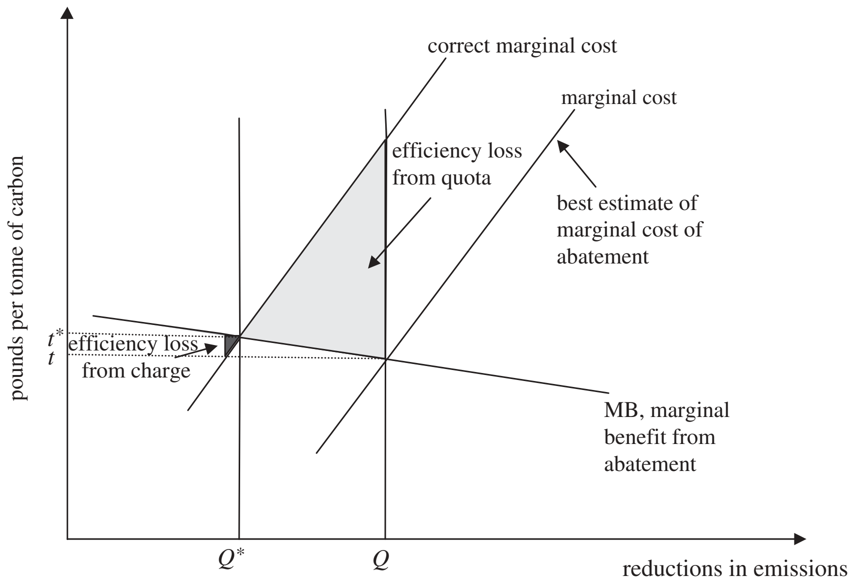

Figure 3. Costs of errors in setting prices or quantities.

atmosphere, the technologies and their costs for abatement, so we shall be better placed to adjust the time path of CO_2 prices required to guide us to long-run equilibrium. One might expect that new information is as likely to raise as lower the required carbon price, so that at any moment, the current price should be the best estimate of the required price. If governments (or the CEC) are to credibly reassure investors making risky durable investments, it would be desirable to issue contracts for differences (CfDs) on the projected future carbon price, thus reassuring investors that subsequent changes caused by new information or other circumstances would not needlessly increase their investment risk.[3]

The ETS could make the transition to a price rather than quantity system in various ways, of which the most simple would be to move first to 100 per cent auctioning of all EUAs (as proposed for electricity after 2012), and for the CEC to retain sufficient allowances to sell more if the price rises above the desired level, and to sell fewer if the price threatens to fall, acting rather like a central bank in stabilizing its currency. An attractive alternative would be to replace the ETS by a requirement that member states impose carbon taxes on the carbon content of fuels burned, thus extending the ETS to the entire economy and greatly simplifying the management and monitoring of emissions.

In the past, carbon taxes have been notably unsuccessful in the EU (except for the Nordic countries, and even these exempted trade-exposed sectors). The gradual evolution from grandfathered emission rights to full auctioning, then stabilizing prices, and finally replacing them with carbon taxes, might be more

[3]A carbon CfD would have a strike price, c_t, at date t for one EUA in each year for some specified number of years (e.g. 25). If the actual carbon price in year t were C_t, the holder would be entitled to receive $(c_t - C_t)$ per CfD, if $c_t > C_t$, and would be required to pay $(C_t - c_t)$ per CfD, if $c_t < C_t$. One-sided CfDs would entitle the holder to receive compensation if the actual price were below the strike price, but would allow the holder to benefit from any upside risk.

Table 1. The climate-change game.

		country 2	
		A	N
country 1	A	(10, 10)	(−50, 110)
	N	(110, −50)	(5, 5)

politically palatable. Indeed, in the UK, the Committee on Climate Change [15] has recommended that the government put a floor on the CO_2 price, either by persuading the CEC to reform the ETS, or failing which, by some other means—advice accepted in the Conservative–Liberal coalition agreement. One fiscally attractive UK solution would be to transform the current climate-change levy into a carbon-correction levy imposed on the carbon content of all fuel, with rebates equal to the EUA price for the covered sector.

4. Reaching global agreement

It is one of the more impressive achievements of the EU that it has managed to reach agreement on more stringent emissions limits than were accepted under the Kyoto Protocol, and is willing to tighten them (from a 20% reduction relative to 1990 to a 30% reduction) if non-annex I countries agree to satisfactory limits. It has accepted the need for an 80 per cent reduction by 2050 and the UK has written this into a legally binding limit in the Climate Act. But the EU only accounts for about 15 per cent of global emissions and without tighter limits for the annex I countries than under Kyoto, extended to include non-annex I countries, the likelihood of remaining within the one trillion tonne carbon limit looks small to vanishing.

Again economic theory can explain why this is so and what might be needed to avoid the tragedy of the global commons. In its simplest form, there are two countries, 1 and 2, who must decide whether to abate (A) or not abate (N). The pay-offs are as described in table 1—(pay-off to country 1, pay-off to country 2). There is no external means of enforcement, so that any agreement must be individually rational, that is, each player (country) will make a choice based on her own interests, given the predicted choice of the other player.

If this game is played once, then we have the classic Prisoners' Dilemma:[4] each would prefer that they both play A, in which case they each receive 10, but as they cannot sign enforceable binding agreements, each will play N, which is a dominant strategy, meaning that it is the best for each to play regardless of what choice the other makes. The outcome is the inferior Nash Equilibrium (N, N), and each receives only 5. However, if the game is played repeatedly, there is the potential for agreement on the superior outcome (A, A), provided that it is in each player's interest to continue to cooperate. Suppose each discounts future

[4]In the original form, the prisoners are separated and told that if they implicate their colleague, they will go free and the other will be severely punished, and if both testify, each will receive a reduced sentence, but if neither testify, they will both be charged with a lesser offence (which would be their best joint outcome).

returns at rate r, then we can ask what is the highest value for r, r^*, that allows continued cooperation. This will require the greatest cost to not cooperating, which in the game specified here is to refuse to cooperate ever again (the so-called grim strategy). This strategy is clearly a (sub-game perfect) Nash equilibrium, since if either player stops cooperating and plays N, it is in the best interest of the other to play N.

The value of r^* will make deviating in the first period for a net gain of 100 no more attractive than the consequence of accepting five less in each subsequent period for ever, so $r^* = 5\%$. Any higher discount rate will make deviation more attractive, while a lower rate will allow less severe punishments for deviation to support cooperation. Another insight that recurs repeatedly is that low discount rates are an essential element in addressing climate change, as high rates of discount make the future benefits of mitigation smaller, and raise the cost of the very capital-intensive low-carbon technologies (wind, nuclear power, CCS, etc). The discount rate turns out to be a critical determinant of the incentives to cooperate, the estimated future damage of global warming, and the cost of capital-intensive low-carbon mitigation strategies.

To return to the case of climate-change agreements between sovereign states, the benefits of individual abatement are a small contribution to reducing cumulative emissions and hence a small reduction in the equilibrium temperature rises. The costs are the higher costs of abatement rather than not, but in addition, there are further opportunity costs. If all other countries agree to abate by agreeing measures that raise the effective price of CO_2 (either by a cap and trade system, regulations or a carbon tax), then the demand for fossil fuels will decrease, and so will the price at each date (although the tax-inclusive fuel price will be higher). Countries that drop out of the international agreement will benefit from cheaper fossil fuel, and, if there is a free trade, will be able to produce carbon-intensive manufactures and products (steel and cement) for export to other countries (like China today), where the cost of producing these goods will be higher.[5] So the cost of joining the international agreement includes the foregone opportunity of access to cheap fuel and high export demand.

The impact of carbon taxes on fossil-fuel prices can be examined in the Hotelling model of exhaustible resources, with some surprising results. Much depends on the carbon intensity of the backstop technology and the cost structure of conventional fuels. The electronic supplementary material shows that if the backstop is zero carbon (e.g. nuclear or solar power with biofuels and hydrogen), if fuel-extraction costs are zero and in instantaneous elastic supply, then a global carbon tax that rises at the rate of interest (as it should) will merely depress the pre-tax price of fuel by the amount of the tax, leaving the post-tax price and the date of exhaustion unchanged. The price will not increase, demand will not fall, and emissions (from oil) would not be reduced. Countries opting out of the climate agreement will enjoy cheaper oil than they do at present, and will thus increase their consumption, so the total level of emissions would increase, and the oil would be depleted faster than with no intervention, worsening global warming. This is Sinn's 'Green Paradox' in which a poorly designed carbon tax can accelerate global warming rather than having its intended effect [18].[6]

[5]The problem of carbon leakage has been extensively studied (e.g. [17]).
[6]There is extensive literature provoked by this paradox [19].

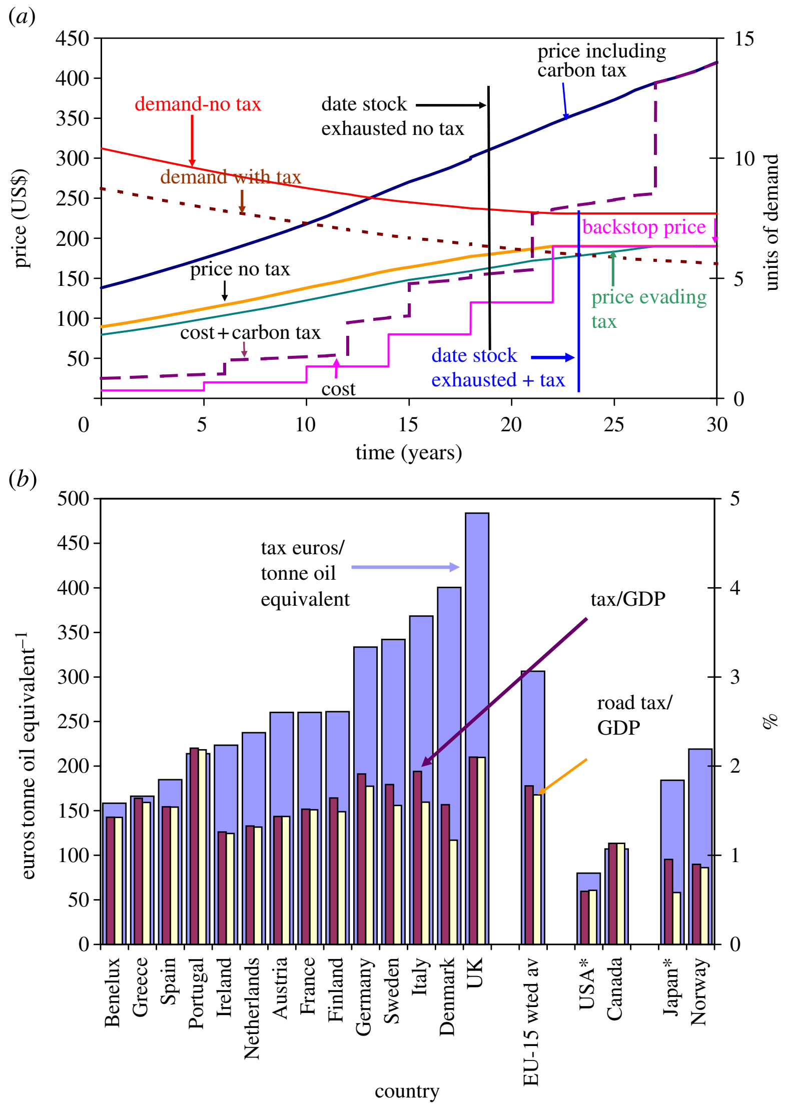

Figure 4. Carbon and fuel taxes in theory and practice. (*a*) Theoretical impact of a carbon tax on the price and demand for an exhaustible resource like oil and (*b*) level of oil taxes in various countries in 2002, from CEC and IEA [20,21]. (*a*) Highest line, price including carbon tax (as indicated); dashed stepped magenta line, cost plus carbon tax; orange line, price; pink line, cost; green line, price not paying carbon tax (as indicated); red line, demand (as indicated); brown dashed line, demand taxed. (*b*) Purple wide bar, tax euros/tonne oil equivalent; left thin bar, tax/gross domestic product as % (right-hand axis); right thin bar, road tax/gross domestic product as % (right-hand axis). (Online version in colour.)

Of course, this is an extreme assumption, and figure 4*a* illustrates the effect of positive extraction costs and a backstop for oil that is more carbon intensive than conventional oil (as would be the case with oil sands, liquids from coal, etc). The case with no climate agreement shows the oil price rising to the backstop price, while demand initially declines as price rises, but then increases as income grows.

With a global carbon tax that has the effect (as far as consumers are concerned) of raising the cost of extraction by the amount of the embedded carbon (extraction, processing and transport) and which, in this case, raises the cost of the backstop, the price now rises to reach the tax-inclusive backstop cost (the highest line at the right), demand is depressed, and the date of exhaustion is delayed. The price for a single small country that refuses to join the agreement is shown at the line indicated 'price not paying carbon tax' and is not far below the price with no agreement at all. In this case, the carbon tax mainly falls on consumers, not producers, and the fuel price rise is almost as great as the tax. The Green Paradox is avoided.

Mejean & Hope [22] have explored the impact of carbon taxes on conventional and unconventional oil, paying attention to the uncertainties surrounding estimates of future costs, learning rates that drive down costs, demand elasticities, the carbon price and discount rate, and find that between 81 and 99 per cent of the carbon tax will feed through into the final (tax-inclusive) price of oil, with a consequential impact on cumulative emissions. Nevertheless, the incentive to avoid paying the carbon tax remains equal to the size of the tax, and if, as seems most likely, the consuming countries impose this, the world price of oil will indeed be lower than the domestic price in compliant countries.

The incentives to impose carbon taxes are thus apparently weak, and the Prisoners' Dilemma real. Indeed, the simple repeated model above is over-optimistic in several ways. First, there are not just two countries, but many. Although the same punishment strategy can still support cooperation, the incentives to deviate or cooperate will depend on the size of the costs and benefits, which probably change with more countries. Second, the game is not unchanging and infinitely repeated, but changes over time. The damages are (initially) distant, very uncertain and unequally distributed across the planet, with some countries possibly gaining from global warming. All these make the problem more intractable, but there are some positive aspects.

First, there may be local incentives to shift taxes from distorting productive decisions and discouraging work and enterprise (as current income and profits taxes do) to correcting environmental harms, as would a carbon tax. Countries would keep their carbon-tax revenues, as well as enjoying better future standards of living if climate change is mitigated. Second, many countries already find it attractive to tax oil products, partly as it is easy, and partly to pay for road infrastructure. Figure 4*b* shows that most EU countries collect about 2 per cent of gross domestic product in oil-tax revenue, and that this comes mainly from taxes on road fuels (although this could change with a shift to road pricing and electric vehicles).

If fiscal self-interest is not sufficient to encourage countries to voluntarily accept carbon taxes as a coordinated policy for climate change, then the Prisoners' Dilemma suggests that more powerful sanctions might be needed against non-compliance. The least aggressive of these would be border taxes on the deemed carbon content of any imports from non-compliant countries, justified under the World Trade Organization (WTO) as correcting a subsidy on the fuel used, and rebated to the extent that the country could demonstrate that the fuel was properly charged on its carbon content. That may not be sufficient, but the logic of the Prisoners' Dilemma shows why it might be necessary.

5. Conclusions

This paper provides only a very brief survey of some of the economic principles that are relevant to the analysis of oil shortages and climate change, illustrated for the case where they interact in interesting ways through peak oil and the carbon content of fossil fuels. Exhaustible resource theory, the theory of correcting market failures caused by externalities, public good/bad problems and the difficulty of collective action illustrated by the Prisoners' Dilemma, and its possible resolution in cases of repeated interaction through punishment strategies, all provide tools to guide policy analysis. Stern [9] took over 600 pages to both quantify and analyse the economics of climate change, specifically asking how to estimate the social cost of carbon and the benefits of mitigating climate change, neither of which have been addressed here in this necessarily abbreviated account.

The aim instead has been to identify the incentives facing key actors (consumers, voters and their governments) and the extent to which decentralized market solutions might be used, with corrective carbon taxes, to reach a more satisfactory solution to climate change and oil and gas scarcity. Even if all conventional oil and gas will eventually be burned, a carbon tax can raise the price of other fossil fuels to the level at which they are either not used (being replaced by zero-carbon alternatives), or their emissions are sequestered to satisfy the 2°C atmospheric carbon budget.

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