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The economics of air pollution from fossil fuels

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David Newbery

Abstract
The paper sets out the economic theory for addressing externalities such as air pollution from burning fossil fuels and from road transport, and for public bads such as greenhouse gases, taking as examples the *Clean Air Act*, 1956, progress in reducing emissions from power stations, and recent concerns over the number of premature deaths from the rapid growth in diesel cars. That damage can be costed at 15p/litre of diesel on average. The last part discusses the efficacy of taxes, quotas or standards and the EU ETS for mitigating climate damage.

Keywords Air pollution, particulates, fossil generation, transport, emissions trading

JEL Classification H2, H23, H41, I18, Q51, Q54, Q58

Contact dmgn@cam.ac.uk
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The economics of air pollution from fossil fuels[1]

David Newbery
Energy Policy Research Group
University of Cambridge
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1. Introduction

Environmental quality, and notably the global climate, are said to suffer from the "tragedy of the commons" (Hardin, 1968) – what is owned by everyone is looked after by no-one and the free market will fail to deliver the right environmental outcomes - there is a *market failure*. Clean air and concentrations of greenhouse gases (GHGs, which cause global climate change) are *public goods*, in that if they are provided for one, they are available for all, and will be undersupplied by the free market. If we are to assess these claims and their implications for good energy and environmental policy, we need to probe more deeply in what economics has to say about markets, market failure and public goods, and the remedies that have been proposed.

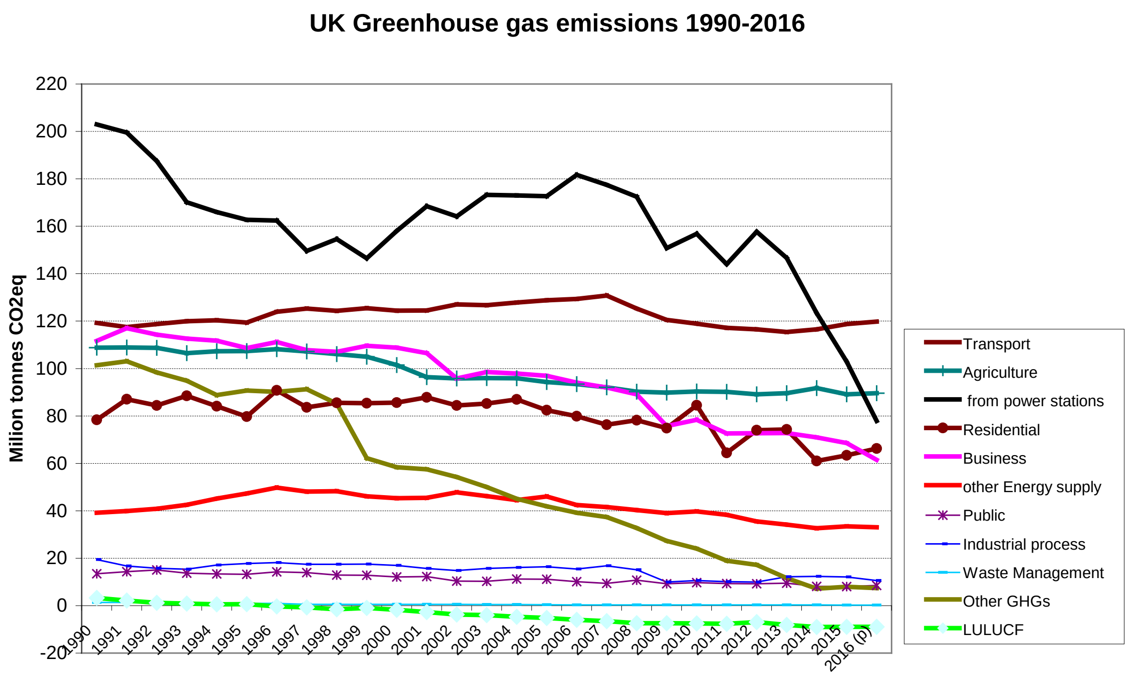

Figure 1 Sources of UK Greenhouse gas emissions 1970-2016

Source: https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2016

[1] This paper was stimulated by the project *In Search of 'Good' Energy Policy: A multi-disciplinary approach to energy and climate problems.* I am indebted to David Spiegelhalter for information about the health impacts of air pollution and Robert Ritz for comments.

Air pollution and greenhouse gases are primarily caused by burning fossil fuels, although agriculture is responsible for a significant share of the total GHG emissions, primarily from other GHGs than CO_2, as figure 1 shows.[2] Figure 2 charts the rapid fall in all these air pollutants from 1990, with the exception of ammonia (NH_3), about one-third of which comes from agriculture.

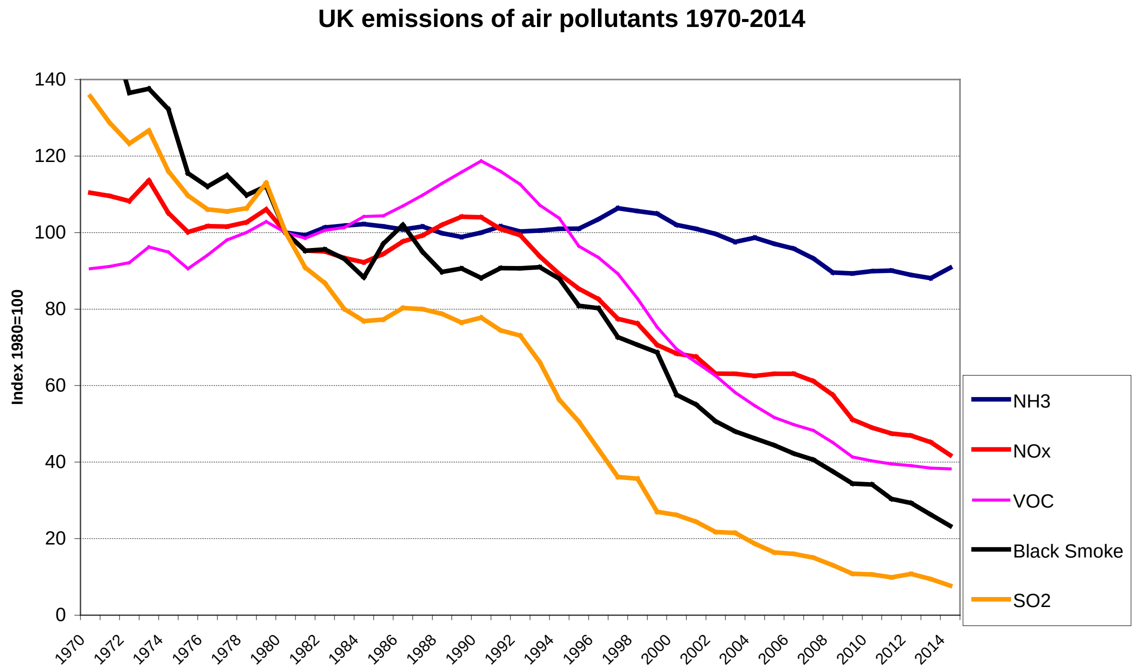

Figure 2 Index of emissions of UK air pollutants, 1970-2014
Source: http://naei.defra.gov.uk/data/data-selector?view=air-pollutants

Economics is justly proud of its contributions to the understanding of markets and their properties. This paper sets out conditions under which markets work well at allocating resources efficiently, why markets can fail to deliver efficiency, and what remedies are available for their improvement. There is no guarantee that markets will deliver outcomes that are considered fair, just or equitable, and an important branch of economics is concerned with issues of distributional justice. In a well-ordered utopia, policy instruments would the targeted at specific problems. The budget would design tax and expenditure policies to deliver the best feasible social outcome. Specific policies would address specific market failures, concentrating on what well-functioning markets can deliver, which is efficiency. Issues of equity and fairness are best left to the budget and can be ignored when designing energy and environmental policy. While this may seem utopian, it remains a useful guide to policy design, departures from which need careful justification.

[2] LULUCF is Land Use, Land Use Change and Forestry and if absorbing carbon is negative

Much of the rest of the paper considers particular examples, starting with the problem of air pollution, the *Clean Air Act, 1956*, and subsequent attempts to quantify the impact and costs of road traffic pollution. The last part considers policies to mitigate damaging climate change, and the role and limitations of the EU Emissions Trading System in internalizing the external damage of greenhouse gas emissions.

2. The role and limitations of competitive markets

In their definitive text on *General Competitive Analysis,* Arrow and Hahn (1971) open with "There is by now a long and fairly imposing line of economists from Adam Smith to the present who have sought to show that a decentralized economy motivated by self-interest and guided by price signals could be compatible with a coherent disposition of economic resources that could be regarded, in a well-defined sense, as superior to a large class of alternative dispositions."

The sense in which this general competitive equilibrium is superior needs careful interpretation. A competitive equilibrium can be shown to be efficient (strictly, Pareto efficient) under restrictive assumptions: a complete set of markets, all agents have full information about all prices, and there are no transactions costs. Pareto efficiency means there is no other feasible allocation of goods in which no-one is worse off and at least one person is better off. With additional assumptions on production technologies, Arrow and Debreu (1954) proved the existence of a competitive equilibrium, ensuring that the claims of competitive equilibrium are not vacuous.

Several points need to be made. The particular competitive equilibrium depends on the allocation of endowments – the wealth, assets, skills, abilities and labour power of the agents – and there is no ethical reason to suppose that the resulting equilibrium is just. A reallocation of endowments would clearly make some agents worse off, but taxes on the rich to finance health-care for the many had been a step towards a more just society for most countries. The central theorem of welfare economics goes further, and argues that if these endowments could be costlessly reallocated, then different feasible equilibria could be generated, and, with some criterion for comparing them, the social optimum could then be supported as a competitive equilibrium. This would require the Benevolent Dictator to have perfect knowledge of all these endowments and then propose lump-sum taxes on, and transfers to, individuals. Lump-sum means that the amounts are independent of any actions taken by those individuals, whereas in practice taxes have to be based on observable attributes (e.g. property ownership) or actions (e.g. earning income, buying goods) of agents and as such likely distort choices. High taxes on goods reduce their demand; high income taxes reduce effort, encourage emigration or distort activities in the pursuit of ways of avoiding or reducing those taxes.

Public economics is concerned with the informational and incentive problems of choosing tax and expenditure policies to reach the best feasible outcome – feasible in the sense of respecting both the constraints on resources and endowments, and the limits set by the information available to the tax authorities when levying taxes. Considerations of equity and fairness are hugely important in almost all policy questions, and certainly in the design of good energy policy. The fact that the authorities are ultimately answerable to the electorate means that popular concepts of fairness may dominate those guiding more philosophically inclined welfare economists.

One the key theorems in public economics is that in the absence of market failures and externalities, indirect taxes (i.e. taxes levied on goods and services, in contrast to direct taxes levied on income) should fall on final consumers and not distort production (Diamond and Mirrlees, 1971).[3] A Value Added Tax on goods has this desirable property and is the recommended form of indirect taxation, to be supplemented by additional corrective taxes, discussed below. The force of these two theorems is that if market failures can be corrected, then the production side of the economy can be left to the free market. Market failures (potential market power) associated with natural monopolies may need regulation that mimics the operation of a competitive market to deliver efficiency, provided the costs of regulation are less than the costs of the market failure. (A natural monopoly arises where the least cost way of delivering a service is in a single firm, with the cost of supply the service from more than one competing firm materially greater.)

Issues of equity and distributional justice are properly the subject of the tax and expenditure system (most redistribution derives from benefits such as health, education and pensions that are closer to equal for all, while most tax systems are roughly proportional, see e.g. Newbery, 1997). Under reasonable conditions indirect taxes should be uniform (Deaton and Stern, 1986) and so taxes on individual goods or sectors would not normally be appropriate vehicles for redistribution. That leaves the pursuit of efficiency at the sectoral level important in the very obvious sense that if a situation is inefficient, then in principle we could find a better alternative in which at least one person is better off and no-one is worse off. Apart from envy, what is not to like with that?

This principle of Pareto optimality is more useful that might seem, for many regulatory changes are impeded because while they may lead to overall small gains, they often entail quite large individual gains and losses on participants. Environmental standards are frequently tightened, but they typically apply only to new purchases, notably for road vehicles, and if older vehicles are considered too polluting, they may be offered attractive terms for their replacement. When GHG emissions were subject to the EU Emissions Trading System (ETS) the firms covered by the scheme were allocated allowances based on their historic emissions, so that they would not be disadvantaged by the ETS (and many sector, notably the electricity generating sector, were able to pass on the price of the allowances and made a very substantial windfall profit, before they were required to buy allowances at auction). This principle of grandfathering existing rights

[3] Strictly, there should be no pure profits or rents, or they should be taxed at 100%, otherwise the production side of the economy impacts on incomes, and *may* provide an additional way of taxing final incomes not otherwise available through direct taxation. In a modern capitalist economy with an efficient direct tax system this is unlikely to be material.

can reduce otherwise effective lobbying that would resist attempts to correct market failures.

However, the conditions for market outcomes to be efficient are not only strong – no market manipulation or market power – but not immediately apparent from the list above.

2.1. Market completeness and missing markets

A complete set of markets means a market for every impact that affects well-being. A market for apples can provide my apple a day and keep the doctor away, but efficiency also needs a market for air quality, or a price on pollution, and, in the absence of government intervention, markets may fail to exist for such services. When my factory for making widgets emits smoke, or my car emits nitrogen oxides (NO_x), I may not pay the cost of the damage that these inflict on others unless I am taxed, or required to meet optimal emission standards. The design of such taxes or standards represents a major area of economic analysis and policy discourse, and is a key concern of this chapter.

Many such goods are *public goods* in that once produced for one person, they can be made available to others at no additional cost. If I make a radio or TV programme and then broadcast it to you, that broadcast could in principle be made available to everyone within range at no extra cost. If it is an excludable public good, I can restrict access to those who subscribe by encrypting it, and as a result charge for it, but many such goods, such as light houses, are not easily excludable and may need to rely on voluntary subscription, or public provision.

Air pollution is a public bad in that sense, as victims cannot avoid their individual consequences by paying the polluter to restrict the pollution just to them and not to others in the locality. In such cases markets will either work imperfectly (for excludable public goods) or not at all, and other social mechanisms are needed. Pigou (1920) argued that producers will pursue their private interests, which, if they cause external damage ("externalities"), will not be aligned with the public interest ("social welfare"). The factory emitting smoke causes damage that harms its neighbours but, unless charged for that damage, will not take the cost-justified measures to reduce the damage. Similarly, bee-keepers manage hives to produce honey and beeswax, but their bees provide valuable pollination services to orchards and farmers. Unless compensated, these beneficial externalities risk being under-supplied.

Pigou (1920) argued for a corrective "Pigovian" tax on damaging actions, or a corrective subsidy for beneficial externalities. These would correct the externality by aligning social and private costs and benefits and so internalize the externality. Producers would be incentivized to minimize all costs including, for example those from air pollutants and greenhouse gases, not just those paid for on markets. Producers of beneficial spill-overs, such as the learning-by-doing from deploying immature renewable energy, could be compensated and thereby encouraged to produce their efficient level.

A fuller analysis indicates that there is a "missing market" for the smoke, greenhouse gases or bee pollination services. Markets have two sides – a buyer who pays and a seller who charges for the good. Harmful externalities would require a negative price (i.e. a charge) on the emission of pollutants, and also a negative charge, i.e. a payment, to the "buyer" (recipient) of the pollutant, compensating for the damage suffered. Specifically, the payment would equal the marginal cost of the damage caused by the last unit of pollution received (which for greenhouse gases may be distant in time and space).

Coase (1960) argued that Pigou had overlooked an important aspect of externalities, for if transaction costs were sufficiently low, the agent experiencing the externality (beneficial or harmful) would have an incentive to bargain with the agent producing that externality and reach a mutually better outcome. Almond orchards in California thus pay bee-keepers to locate their hives in the orchard to ensure pollination,[4] and selling bee pollination services seems well-established in many countries. Greenhouse gases may be taxed or priced on markets that have been created to rectify the missing market.

In this bargaining approach, the allocation of well-defined property rights could be critical, ideally to the party that leads to the least transaction costs. The threat of a law suit, which requires unambiguous property rights, can then be effective in encouraging the offending party to negotiate. Thus the government may create clean air zones in which certain kinds of emission are prohibited, and restrict polluting activities to other locations. The local representative in a clean air zone then has a legal right to ban noxious emissions unless compensated, and may be able to negotiate a mutually satisfactory outcome, in a way that Coase (1960) envisaged. In criticizing Pigou, Coase was arguing for the decentralized solution of well-defined property rights and bargaining, against a centralized solution of government taxes, subsidies or regulation. Which option of tax or negotiation is better depends on relative transactions costs, which in turn depends (as with all tax solutions) on the cost of collecting, and the quality of, the information available to the agents making the decision (Farrell, 1987).

Bilateral negotiations when both parties are well-informed ought to lead to efficient outcomes, but a lack of information, threats, bluff and a sense of injustice can hamper that process. Economists have studied this in the *ultimatum game*, in which one player offers a division of a reward, which the other can either accept or reject, but if rejected neither gets anything. Experiments reveal that large deviations from a 50:50 split are deemed unfair and are often rejected, even though both parties would be better off agreeing (Henrich et al., 2004; Oosterbeek et al., 2004). If more than a few need to reach agreement and cannot agree a leader to negotiate on their behalf, inefficiencies may again persist.

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[4] See e.g. http://www.pressreader.com/usa/porterville-recorder/20170213/281925952764811

Society may agree to set up authorities or governments with powers to tax, charge, regulate, finance or provide the public good, as a solution to such coordination difficulties. A compromise between the Pigovian and Coasian approach that might improve on each was suggested by Farrell (1987), who noted that "bumbling bureaucrats" might find it hard to determine the right corrective tax, while Coasian bargaining might fail to overcome transaction costs. The compromise is for the state to prescribe a reference or default standard and then allow agents to bargain away from that if mutually advantageous.

This principle of opening central decisions to contestability by private agents (in this case allowing subsequent bargaining) can be a useful way of improving on the originally proposed solution. In Britain, connections to the electricity distribution system are subject to oversight by the regulatory agency, Ofgem, and covered by grid codes and standard connection agreements. The standard connection agreement is for firm access, in that once paid for, the holder has a right to deliver the contracted amount, and if the System Operator needs to curtail injections, the holder must be compensated for lost profit. The cost of providing that firm access, paid for by the generator, can be very high, and it may be much cheaper to use existing assets, but for a small fraction of the time to curtail injections. As a result of an interesting experiment (Anaya and Pollitt, 2015), the local distribution operator offered prospective windfarms the existing expensive connection option or a cheaper connection with guaranteed access for varying levels (94% or higher). These proved cost-effective and in the subsequent conference discussion of the trials, the regulator, Ofgem, and the generating companies were asked if there were any obstacles preventing this arrangement – to which the answer was no.

2.2. The *Clean Air Act, 1956* as an example

The Great London Smog of 1952, which may have led to the premature deaths of between 4,000 and 12,000 people (Bell et al., 2004) came after nearly seven centuries of attempts to address the harmful effects of smoke inhalation (starting in 1273 when the use of coal was prohibited in London as being "prejudicial to health",[5] and, more actively in the 19th century with the *Smoke Nuisance Abatement (Metropolis) Acts, 1853* and *1856*). Until the mid-20th century, such air pollution was considered an inevitable by-product of industrial success,[6] and the thrust of the *Smoke Nuisance Abatement (Metropolis) Acts* was to restrict emissions in (wealthier) populated areas while giving the right to pollute to industrial zones. Not surprisingly, given the westerly winds in the UK, West Ends became the smart addresses, and East Ends were occupied by the poor.

Fouquet (2011, fig. 3) tracks the pollution concentration in London from 1800 (when it started at 400 micrograms/m^3 Total Suspended Particulates, TSP) to a peak of 600 μg/m^3 in 1890 before falling to just over 100 μg/m^3 in 1950, just before the Great

[5] http://www.air-quality.org.uk/02.php
[6] http://bfa-ba.blogspot.co.uk/2007/06/attitudes-to-pollution-in-united.html

Smog and then steadily down to below 50 μg/m^3 by 1980.[7] Even after considerable medical evidence of the harm of smoke and the development of a smokeless form of coal, "coalite", invented by Thomas Parker in 1904,[8] which provided a technical fix that could have avoided smog, there was a clear reluctance to impose effective clean air policies. In the context of current concerns over climate change and the need for carbon pricing it is useful to consider the obstacles to solving the clear and present danger posed by smog,

First, coal burned in open grates gave immediate satisfaction to the users indoors, while the smoggy outdoors seemed an indirect consequence of each person's actions that no single person could remedy. The cheery homely glow was a benefit that families would not give up lightly for the dreary alternative of burning coalite in an enclosed stove, so there was little public pressure for action, except in dramatic cases like the Great Smog. Second, smokeless fuel was more costly to users (certainly in cost per unit of useful energy, but also extra costs of investment in closed stoves, while the perceived quality of the fire was lower and hence less valued). The logical policy would be a Pigovian tax on dirty coal to raise its perceived cost above that of coalite (adjusting for their different characteristics). However, a tax on coal high enough to cover the marginal damage in densely populated urban areas would be excessive for suitably zoned industrial use. Differentiating the tax on different uses of coal was impractical, while creating smokeless zones seemed more targeted.

Third, taxes are almost always politically unpopular, while standards that all have to obey can seem fairer, and have the merit that those experiencing them have an incentive to press for their wider extension. Thus after Germany enacted a Large Combustion Plant Ordinance (Grossfeuerungsanlagen-Verordnung or GFAVo) in June 1983, the German government pressed for similar standards being adopted for the whole of Europe. The European Commission proposed a Large Combustion Plant Directive based on the GFAVo in December 1983 (Newbery, 1990; Berkhout et al., 1989).

As a result, the *Clean Air Act, 1956* left it to local authorities to declare smoke control zones within which burning non-smokeless fuels was prohibited. Only when natural gas from the North Sea arrived in quantities in the late 1970s and with it the rapid penetration of gas-fired central heating, was this problem adequately addressed. Figure 3 (an amplification of figure 2) shows trends in emissions of various air pollutants since 1970 as well as the growth in domestic consumption of natural gas, which has displaced coal in domestic heating, where the two series move in almost exact opposition.

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[7] The current EU Limit values for TSP (gravimetric method) per year are 150μg/m^3 (EU Council Directive 80/779/EEC) – see http://www.eea.europa.eu/publications/2-9167-057-X/page021.html. TSP includes particulates above PM_{10} up to 30+ microns. Delhi, one of the most polluted cities in the world, experienced TSP of 370 μg/m^3, according to Fouquet (2011). WHO (2016) gives 2013 values for Delhi as 239 μg/m^3 for PM_{10} and 122 μg/m^3 for $PM_{2.5}$, reducing life expectancy by seven years (Spiegelhalter, 2017). London has 22 μg/m^3 (PM_{10}) and 15 μg/m^3 $PM_{2.5}$.

[8] by carbonizing coal at 640 degrees Celsius - see https://en.wikipedia.org/wiki/Coalite

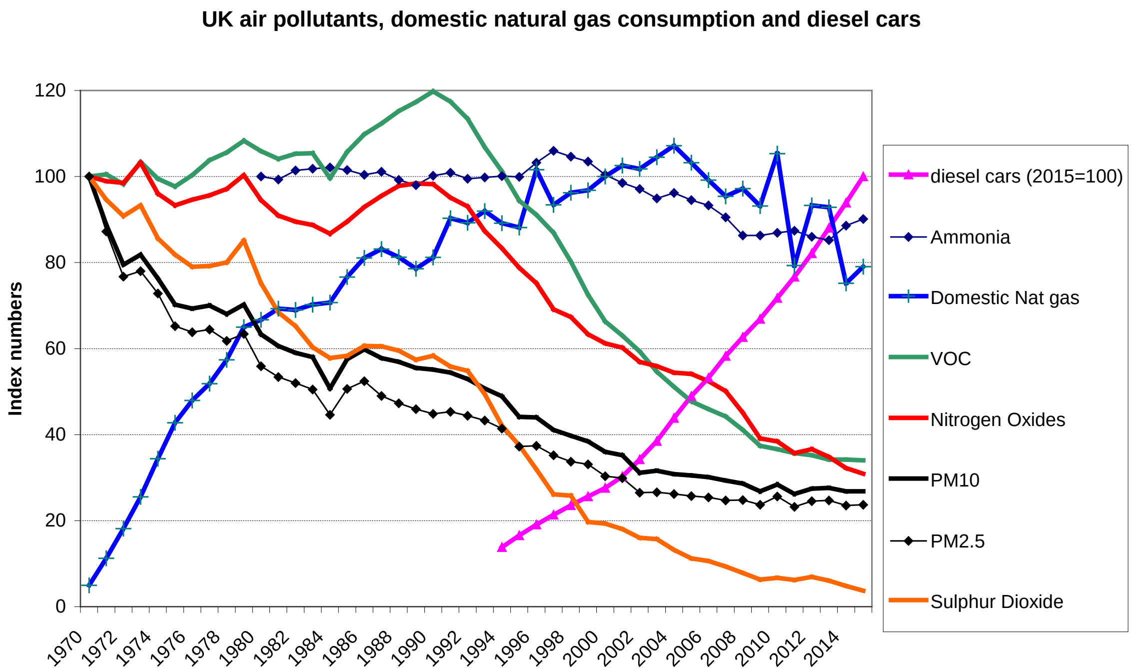

Figure 3 UK air pollutant emissions, domestic natural gas consumption and diesel cars

Source: Defra statistics at https://www.gov.uk/government/statistics/emissions-of-air-pollutants, Dept. of Transport *Great Britain Transport Statistics, 2015*

Particulate emissions are now measured by particulate matter of less than 10 microns (PM_{10}) and less than 2.5 microns ($PM_{2.5}$), although figure 2 shows the old measure of black smoke. Unfortunately the particulate data before 1970 are not readily available, but clearly the 40% drop in particulates (PM_{10} and $PM_{2.5}$) in Figure 3 within the first decade after 1970 mirrors the rapid penetration of natural gas from almost zero to 60% of its 2000 value (which is taken as 100). The implication for climate change mitigation is clear – if a suitably competitive zero-carbon alternative to fossil fuels can be developed, then decarbonizing will be much easier and more likely to succeed.

In that context the switch from coal, first to natural gas and then increasingly to renewables has dramatically lowered the carbon intensity of electric generation in Britain from 1990 on, to the point where in 2016 coal was completely displaced in some periods for the first time in over a century. Figure 4 shows the recent squeezing of the share of coal in generation and by April 2017, there have been days with zero coal generation for the first time since power was first generated in the 1880s..

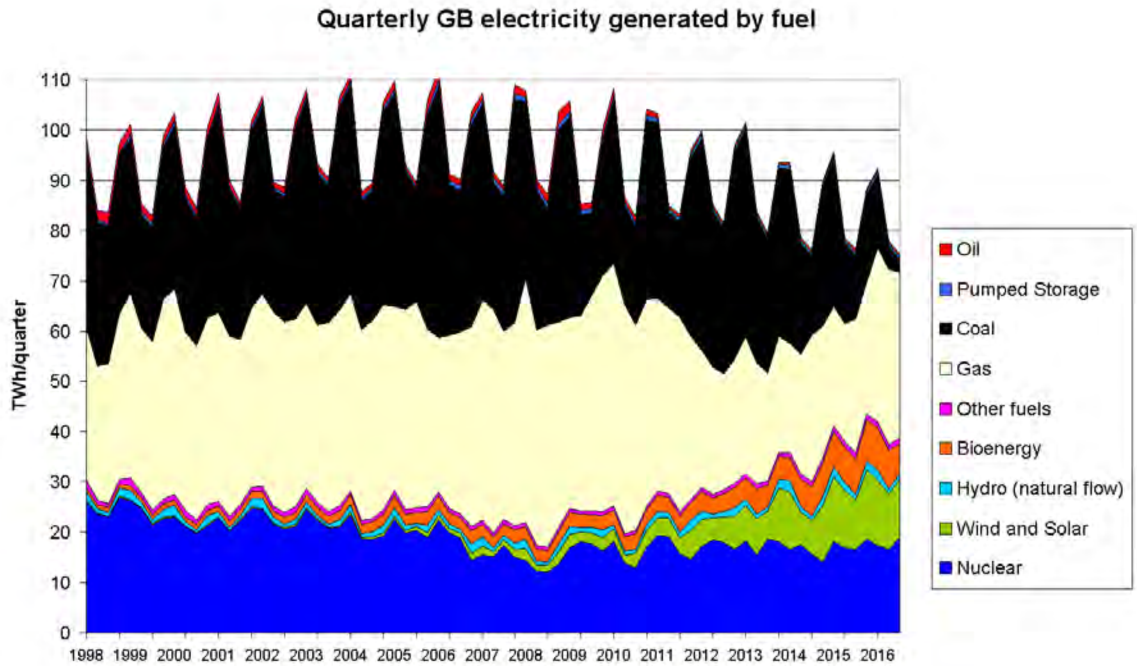

Figure 4 The fall of coal and the growth of renewable electricity, 1998-2016
Source: UK Digest of Energy Statistics, 2017

2.3. Traffic-related air pollution

Now that smog from domestic coal fires has largely ceased to be a problem with the rise in gas-fired central heating, attention has turned to the health impacts of road traffic. The *Daily Mail* (23/2/16) claimed[9] "Lethal legacy of dash for diesel: Air pollution is 'killing 40,000 a year in the UK'", taking the number of 40,000 from the Royal College of Physicians (2016). Figure 3 shows the rapid rise in diesel cars since 1990. It had been widely appreciated for some time that compression ignition (diesel) engines emitted higher levels of particulates and NO_x, and that these had serious health impacts,[10] but steadily tightening standards, improvements in design lowering costs, and their greater fuel economy held out the promise that they could reduce transport CO_2 emissions.
The scandals which erupted in September 2015 when the United States Environmental Protection Agency (EPA) accused Volkswagen of manipulating emissions data (so-called "dieselgate") cast doubt on the efficacy of laboratory measurements of vehicle emissions. Apparently heavy goods vehicles' emissions are measured more accurately and as a result actually produce less damaging pollution than cars (ICCT, 2016). One obvious solution is to improve the accuracy of measurements, and possibly to adjust the annual road licence charge to reflect differences in emissions. The UK Government is now considering

[9] At http://www.dailymail.co.uk/news/article-3459430/Lethal-legacy-dash-diesel-Air-pollution-killing-40-000-year-UK.html
[10] The Royal Commission on Environmental Pollution's 18th report (RCEP, 1994) pointed to growing medical evidence from COMEAP, and COMEAP (1998).

allowing cities to create low emission zones or charge diesel vehicles for entering city centres – a policy already supported by the EU.[11]

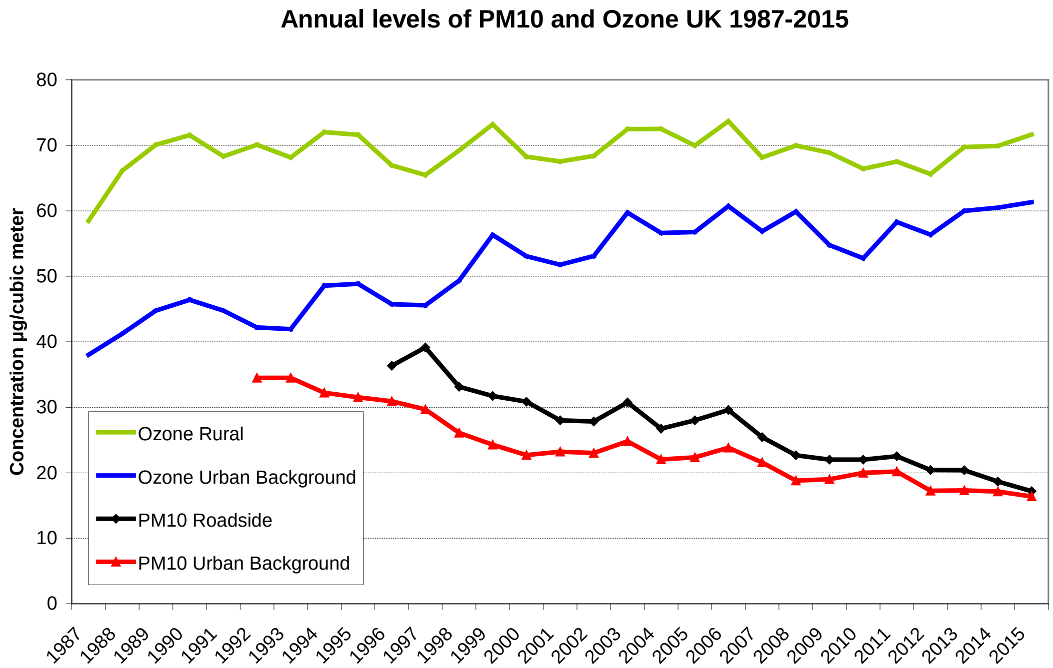

Figure 5 Air quality measures for UK 1987-2015
Source: Defra statistics at
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/517681/Air_Quality_National_Statistic_2015_final.pdf
Note: WHO (2016) computes $PM_{2.5}$ for London as 15 µg/m^3, 68% of the 22 µg/m^3 PM_{10}.

The European Union's agreed limit values for PM_{10} is for an annual average of less than 40 µg/m^3, which figure 3 shows has been a struggle to meet in many urban areas. The UK has set new targets for $PM_{2.5}$ of 25µg/m^3 'cap' for hotspots and a 15% reduction in PM $_{2.5}$ levels in all urban locations by 2020.[12] Figure 3 shows that although the average roadside particulates (PM_{10}) are falling, ozone, caused by nitrogen oxides, increasingly from diesel engines, is rising. So too are volatile organic compounds (VOCs), much of which is transported to the UK from the Continent.

Spiegelhalter (2017) traces the sources of the claimed 40,000 deaths back to a series of studies of the health impact of air pollution. COMEAP (2010) summarizes evidence that a 10µg/m^3 increase in $PM_{2.5}$ increases the average risk of dying each year by 6%, while DEFRA (2015) estimated that a 10µg/m^3 increase in NO_2 would raise the risk of dying by 2.5% (but the two effects are not simply additive). As the average

[11] http://urbanaccessregulations.eu/low-emission-zones-main
[12] http://www.environmental-protection.org.uk/policy-areas/air-quality/about-air-pollution/particles/ Note the WHO target for PM2.5 is 10 µg/m^3 – see http://www.who.int/mediacentre/factsheets/fs313/en/

exposure to $PM_{2.5}$ in the whole of the UK (not just urban) is 9µg/m^3 and as there are 600,000 deaths per year, 9/10 x 6% x 600,000 = 32,400 deaths from particulates (the rest come from NO_2, mostly from diesel vehicles, see DEFRA, 2015). Spiegelhalter (2017), endeavouring to increase public understanding, puts this in another light, citing the relative risk of air pollution as "very roughly, pro-rata, like an extra hour watching TV, being another 3 kg overweight, or having an extra drink …(or smoking) around 1.04 per cigarette per day".

One way of quantifying the damage of diesel emissions is to estimate the number of Quality Adjusted Life Years (QALYs) lost as a result of their emissions (Newbery, 2005). Spiegelhalter (2017), using COMEAP (2015) estimates, gives the impact as 340,000 Life-years lost as a result of the 7 month shortening of life expectancy from air pollution (not quality adjusted, which might reduce it as the impact will largely be on those who are already suffering from a decreased quality of life through poor cardiovascular health). NICE,[13] the UK's National Institute for Health and Care Excellence, considers expenditures of £20-30,000/QALY to be justified in a cash-strapped National Health Service, a figure that has not increased for many years. Deloitte (2009) updated the Department for Transport's value of a prevented fatality (VPF) to just over £1.6 million, which, if the expected life years lost is 40, gives a higher QALY of £40,000.

At £40,000/life year, the cost of UK $PM_{2.5}$ pollution would be £13.6 billion/yr, but not all of this is attributable to transport pollution. Newbery (2005) estimated that in 1999 perhaps 4.4 µg/m^3 PM_{10} (perhaps 3 µg/m^3 $PM_{2.5}$) were attributable to road transport, since when figure 3 shows that particulates have fallen, ozone has risen, and diesel vehicles have increased by a factor of five (fig. 1). This is one third the total used to estimate 340,000 life years, so on that basis transport might be responsible for 115,000 life years lost or £4.5 billion/yr. If 75% is attributable to the 30 bn litres/yr diesel used, the cost would be 15p/litre, whereas the excise tax on diesel in 2017 was 60p/litre, but part of that is for other pollutants, and a considerable part should be considered as a road user charge (Newbery, 2005; Newbery and Santos, 1999). Petrol, far less polluting, is equally taxed and so one cannot interpret some part as a corrective Pigovian tax.

However, recent measurements outside the laboratory have shown wide variations between different vehicles with the same fuel consumption, and so a uniform increase in diesel would not differentiate between low and higher polluting vehicles. A combination of a higher excise on diesel, higher annual road fund license charges based on the model's measured emissions (similar to differential license fees based on CO_2 emissions), and entry charges to clean air zones again based on vehicle, could deliver a more targeted approach, as well as generating revenue to cover the cost of any scrappage scheme.

[13] At https://www.nice.org.uk/advice/lgb10/chapter/judging-the-cost-effectiveness-of-public-health-activities

3. Taxes, prices or standards?

Most air pollutants impact a large number of individuals who are unlikely to negotiate directly with the polluter, and at best may lobby for public action. There are exceptions, and Börkey et al., (1998) report a private agreement between a Volvo plant and a British Petroleum refinery near Göteborg in Sweden in which the refinery paid Volvo to cover its car park and prevent corrosion from sulphur dioxide. Notably, other neighbours were not compensated. In the absence of problems of subsequent Coasian bargaining, there are three options for addressing pollution externalities. The first is a tax on the pollutant. This could be (most simply) on an observable precursor to the resulting emissions (e.g. sulphur in oil products that when burnt gives sulphur dioxide, SO_2) but this does not encourage scrubbing to remove the SO_2 from the emission stream. Taxing the emissions solves that problem and can work for point sources, but not for numerous mobile sources like vehicles where taxes on the sulphur content of road fuel have been effective (DEFRA, 2004). Setting the right tax on emissions for local air pollutants that have impacts downwind is difficult, as the marginal damage will depend on who and what is downstream (and will vary with weather and wind direction).

The second alternative is to limit the total amount of emissions (nationally, as with SO_2 and carbon dioxide, CO_2) or regionally by airshed as for NO_x in some countries (e.g. in California). Emission permits or allowances in total equal to the target can then be allocated or auctioned, and trading will establish a price that has the merit of encouraging the permits to be allocated efficiently to deliver the least-cost clean up via this "cap-and-trade" mechanism. The US *Clean Air Act, 1990* allocated permits to reach average annual emissions of 8.95 million tons per year over a period, with those allocated permits free to either bank them for future use or sell them now and purchase them later if needed. This delivered a price for emissions that encouraged the installation of desulphurization equipment (flue gas scrubbers), a rapid fall in their cost as a competitive market developed, and a shift to low-sulphur coal and oil, reflected in price differences in sulphur content, (Ellerman et al., 2003). The resulting auction price was less than 10% of some forecasts (Harrington et al., 1999).

The last solution is to set a performance standard with penalties for non-compliance. When there are millions of individual vehicles, it is impractical to charge each for their emissions, which vary with design and vintage, and, more worrying for any policy, may be hard to verify by simple testing, as "dieselgate" demonstrated. The standard economic objection to setting standards is that they will not deliver any given level of reduction at least cost, as some emitters will face a very high cost of reducing emissions which other emitters could have done at a fraction of the cost. This argument carried sufficient force for the US Environmental Protection Agency to switch from emissions standards to cap-and trade for SO_2 and NO_x, where there were a limited number of large combustion plants that could be closely monitored, but is unlikely to work for dispersed mobile sources like vehicles.

Taxes and charges or prices work by inducing polluters to demand less polluting equipment and creates a demand-pull in the market for innovation. Standards on e.g. the equipment suppliers (car manufacturers, power stations) create a supply-push for innovation that can be remarkably effective in driving down the costs of meeting the standards. DEFRA (2004) gives convincing evidence that the *ex ante* estimate of costs produced in consultations over setting standards appear to often considerably exceed the *ex post* actual costs. In the transport sector DEFRA evaluated nine policies whose *ex ante* estimate of costs ranged from £16.1 billion to £22.8 bn but whose *ex post* costs were estimated to be from £2-4 bn. In the electricity sector the *ex ante* total estimate ranged from £6-30 bn and *ex post* to about £2bn (DEFRA, 2004, p145). Similarly, Harrington et al., (1999) find a bias to over-estimating regulatory compliance costs, primarily as the induced technical progress was ignored and often substantial (inevitably, given that the rules for estimating compliance costs assume no technical innovation).

Moreover the reductions achieved were substantial compared to business as usual. Policies in the UK reduced SO_2 in road transport by 96% by 2001, and by 77% in electricity generation (largely through the switch to gas induced by favourable relative gas to coal prices). Policies reduced NO_x by 36% in road transport and 58% in electricity generation, which also experienced a policy-driven reduction of 78% in PM_{10} (DEFRA, 2004, p131).

With improving measures of the damage and abatement costs, the Government passes tighter abatement laws, increasingly on the basis of impact assessments (e.g. DEFRA, 2013). The response is likely to be to develop cheaper solutions (filters, scrubbers, smokeless fuel). The benefits need to be measured in terms of money, which presents challenges. Health benefits are normally measured by QALYs on the basis of which medical procedures and drugs are assessed by NICE. Similarly, accidents are often similarly measured or by the value of a fatality prevented (VFP). Both require a measure of a QALY or VFP, and there is a rich literature on both. Clearly, considerable ethical issues are needed in their measurement. In addition, the value of environmental impacts needs to be costed, either by the cost of restoration or the value to users and potential users, itself a whole sub-discipline of environmental economics (see e.g. GOS, 2010).

3.1. Climate change mitigation

Climate change “is the greatest and widest-ranging market failure ever seen” (Stern, 2007), not only because its solution requires agreement among a large fraction of the world’s nations, but they need to act now to prevent damage to future generations. While these future costs are uncertain, there is a very high probability that they greatly exceed the costs of efficient and coordinated mitigation. In one sense the market failure is simple – greenhouse gases (GHGs) are global stock pollutants, meaning that the damage done is the same wherever they are released, and GHGs persist for centuries. Indeed, the timescale for some impacts such as ocean warming is millennia; although at the other extreme arctic sea ice may disappear within decades. That suggests that a single price regardless of the source of the release is sufficient to address the problem. Furthermore, a large fraction of GHGs come from burning carbon, and so taxing the carbon content of the fuel would be the simplest solution. Carbon capture and storage could then be credited with the carbon sequestered. Other GHGs and agriculture admittedly pose more difficult monitoring issues. However, only a few Nordic countries (with no coal) have imposed carbon taxes on fuels. The solution is therefore clear – to properly price GHGs – but the problem is that GHGs are either not priced at all or are subject to very low prices per tonne of CO_{2e} (Dolphin et al., 2016 - low relative to any plausible estimate of the marginal damage done, e.g. as computed by EPA, 2016 or Stern, 2007).

The fact that GHGs are persistent stock pollutants has a number of implications – the social cost of carbon (GHGs are measured by their carbon or CO_2 equivalent, CO_{2e}) depends not on the rate of release but on the total stock, which only changes slowly with emissions. That means that the social cost of carbon (measuring its damage) should not vary much with emissions, but only with the stock (and new information about future damage). In addition, actions to mitigate climate damage have to persist over long periods of time, and policies therefore may be slow to deliver the perceptible changes that an impatient public demands. The difficulty of action is exacerbated as the source of most of the problem, burning fossil fuels, takes place in highly durable equipment whose stock takes a long time to replace. Coal-fired power stations built now will likely last 50-60 years, while inefficient housing stock may only be replaced 1% or less per year in advanced countries. Another implication of a stock pollutant with a low rate of absorption is that the cost of the damage done (the social cost of carbon) will increase over time at the social discount rate as the cost of future harm approaches. One of the better aspects of a 'cap-and-trade' system of auctioning allowances to emit that can be banked is that their expected future prices rise at the rate of interest, as a result of arbitrage – if their price is expected to rise faster than the cost of borrowing money, agents will borrow and but now, driving up their present price, while if not, agents will sell, bank the cash and wait until allowances are cheaper than their accumulated savings. Of course, information changes and with it the expected future and hence present price of allowances, so figure 6 below does not suggest that market prices follow this rule.

In terms of global agreement, 142 Parties of the 197 Parties to the Convention on Climate Change (COP 21) had ratified by 5 October 2016, and hence the threshold for entry into force of the Paris Agreement was achieved.[14] However, the agreement is voluntary, and currently falls far short of delivering sufficient, credible and binding agreements to take adequate action. Quite apart from the difficulty of reaching such a commitment, there is the difficult of determining a suitable price for carbon. Stern (2007) and US EPA (2016) both point out that the social cost of carbon today depends critically

[14] http://unfccc.int/paris_agreement/items/9444.php although the future status of the US under President Trump remains a major concern.

on three hard-to-measure parameters. The first is the social discount rate, where figures between about 1% and 5% have been proposed (e.g. Nordhaus, 2007). If damage can occur a century from now, the present value of £1 million 100 years hence discounting at 5% is only £7,600, but discounting at 1% is £37,000, justifying substantially more current investment in mitigation. Second, the economic and social magnitude of the potential future damage is even harder to assess. More severe floods and crop failures are almost inevitable, but their implications for death, diseases, war, and mass migration are far less certain, but certainly possible and definitely very costly. Finally, there is the problematic ethics of weighing future impacts against the yardstick of current money (needed to assess the value of mitigation), even if we could predict how many future people would suffer how much equivalent loss in consumption.

One simple and rather naïve approach is to assume that lives are equally valuable in a utilitarian sense, which has the implication that £1 reduction to a person enjoying a level c of consumption is worth n times as much as £1 reduction to a person enjoying nc consumption. This in turn has the implication that the social discount rate is just the rate of growth of consumption per head plus a small addition for the possibility of extinction, which is the way Stern (2007) came up with an estimate of 1.7%. Others, notably Weitzman (1998) and Gollier & Weitzman (2010) have correctly argued that this simple rule only applies if all consumption grows at the same rate, and if, plausibly, some experience far worse futures, or if there are small risks of catastrophic outcomes, then the social discount rate should be considerably reduced.

Economists have made other important contributions to the understanding of policy choices for climate change mitigation, apart from the extensive, welfare-economics based analysis of the social cost of carbon. A carbon price can be either delivered by fixing the quantity (the cap) and then trading, as in the EU Emissions Trading System (ETS) (2003/87/EC), or fixing the price through some form of carbon tax or charge, such as the Carbon Price Support introduced in the 2011 UK Budget (HMT, 2011). The classic argument for setting a carbon price is based on Weitzman (1974), who noted that in the face of uncertainty, a price instrument (tax or charge) dominates a quantity instrument (a cap or quota) if the marginal benefit of reducing emissions is flatter than the marginal abatement cost schedule. The marginal damage of a tonne of CO_2 now is essentially the same as a tonne emitted in 10 years' time, as CO_2 is resident in the atmosphere and oceans for a century or more. Thus the marginal benefit of abatement is essentially flat in the rate of emissions, even if the marginal damage is steeply increasing in the stock of emissions (Grubb & Newbery, 2008).

Weitzman's original result was derived from a static model with uncertainty resolved immediately after abatement choices, and so only suitable for flow, not stock pollutants. It may be suitable for short-run operating decisions of existing capacity (whether to run coal or gas-fired plant more intensively), but is not well-suited to investment decisions in highly durable capacity. Nuclear and coal power stations have a life of 60+ years, even if gas-fired plant and wind turbines have shorter (20+) year lives, periods that commit to significant lock-in of cumulative emissions and hence a lock-in to a higher and more damaging stock of greenhouse gases (GHGs).

To deal with these lock-in and stock effects, one needs an intertemporal model in which damage depends on the stock of pollutant, not the flow. Newbery (2016b) summarizes the research done to demonstrate that Weitzman's original argument in favour of taxes rather than quotas for this case remains robust. The evidence of the EU ETS supports this, for after its launch in 2005, the EU Allowance price shown in Fig. 6 rose rapidly to nearly €30/tonne CO_2, before collapsing to zero by December, 2007, the end of the first period. Second period prices similarly rose to €30/tonne CO_2, before collapsing as a result of increased targets for renewable energy and the global financial crisis. The ETS thus failed to give an appropriate long-term price signal.

EUA price October 2004-June 2016

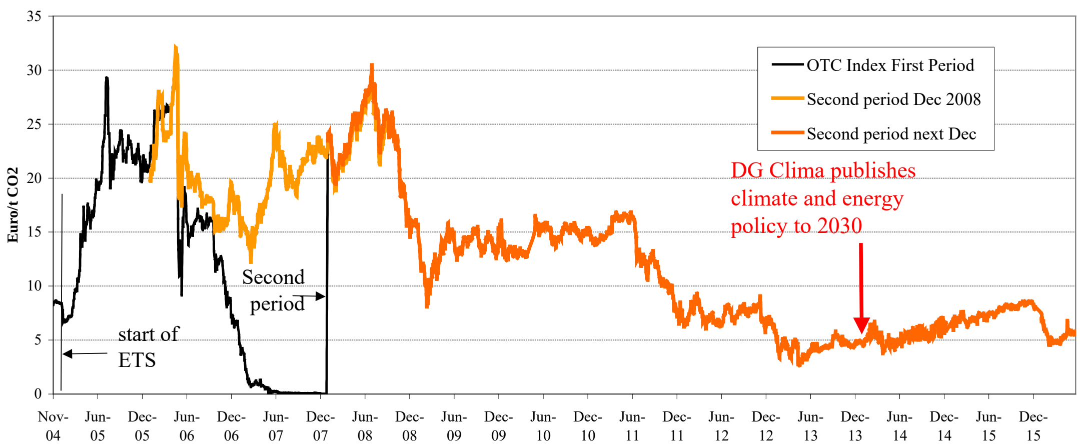

Figure 6 The EU Allowance price for CO_2 in the EU Emissions Trading System
Source: EEX

Clearly, the ETS carbon price is neither adequate, credible nor durable, and a poor guide for durable investment decisions in generation. So why, given persuasive arguments, do most jurisdictions choose quotas like the ETS rather than taxes? The simple and persuasive explanation is that quotas can be handed out to the emitting companies, who would otherwise effectively block any attempt to tax their emissions, while the voting public, observing such free allocations, believes that they will therefore not increase the prices of the products of the emitting industries. In the case of electricity, the Emissions Allowance Price was immediately added to the cost of generating from fossil fuels, as the allowances had an opportunity cost – they could be sold if not used. Keppler and Cruciani (2010) estimated that generating companies made excess profits of €19 billion per year in Phase 1 of the ETS (2005-7). Fortunately, the EU moved to auctioning permits for the power sector in 2012, so that at least the revenues were available and could be used to subsidize e.g. renewable energy, where subsidies are an efficient (Pigovian) compensation for learning spillovers (Newbery, 2017a, 2017b).

4. Conclusions

Economists are sometimes accused of being market fundamentalists, of wishing to get the government out of the market place, and not caring for the social and distributional impacts that markets may deliver. This paper attempts to set that misperception right. First, public finance and policy in general needs to choose instruments that are well-targeted to deliver objectives. Intervening in markets is almost always less effective at delivering distributional justice than more direct methods (targeted public expenditures, such as health care, unemployment insurance, pensions, direct taxes). That leaves markets to be corrected for market failures, not as mechanisms for addressing poverty.

There are exceptions to this rule, in that in an imperfect world of Manifesto pledges and the difficulties facing any tax reform, intervening in particular markets may be "third-best" ways of addressing public concerns – hence governments may ask regulators to address fuel poverty rather than leaving it to the government to address poverty. Indeed, natural monopolies, such as transmission and distribution (wires and pipes), by definition are cheaper to provide through one (regional) company than many competitive companies, and a direct implication of that is that their efficient price will not cover their full cost. The balance is collected by regulated tariffs, and is akin to a tax, and it is quite appropriate to consider the distributional impacts of such charges, while, as with all public finance decisions, balancing equity gains against efficiency losses.

Economists do indeed have a well-developed theory of what a competitive market can and cannot achieve – under restrictive conditions (market completeness) it can deliver efficiency, but even then it cannot unaided deliver distributional justice or equity. The concept of market completeness is extremely helpful in designing policies that attempt to remedy market failures, which are pervasive for environmental goods and in energy markets. Policies can also fail, as policy makers often lack the information necessary to make improving interventions, and it may be better to define property rights (e.g. in carbon emissions) and use auctions or markets to properly price these rights.

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