Does environmental regulation spur innovation?

A study of acid rain regulation and the power sector in the UK, 1960-1990

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This study seeks to establish whether stricter environmental legislation induces innovation. It focusses on the UK's regulatory response to the issue of acid rain in the late-twentieth century, and whether it spurred innovation in the 'green' technologies required to eliminate the pollution responsible. The usual approach of using quantitative regressions to establish a causal link is eschewed here on the grounds that it oversimplifies patent data as an indicator of innovation, does not rigorously explore the context behind innovation, and is not appropriate for the UK's unique regulatory approach. Instead a deeper, historical appraisal is needed. That appraisal finds that the UK approach did not induce significant innovation. A micro-level case study of one of the key technologies – fluidised-bed combustion – and the innovating firms responsible elaborates on this. Where innovation did occur it was driven by the OPEC crisis and the prospect of new environmental regulations overseas. The key point that emerges is that it is essential to go beyond the traditional cursory glance at the quantitative data if a deeper historical understanding of the determinants of innovation is to be reached.

Contents

Introduction.....5

Innovation and the environment.....5

Motivating theory.....6

Literature review.....10

Background.....13

Sources and Methodology.....22

Patents.....22

Regulation.....24

Fluidised-bed combustion.....24

Analysis.....26

Trends in patenting.....26

The EPO.....28

Patenting and regulation.....30

The Japanese anomaly.....32

Case Study: Fluidised-Bed Combustion.....35

Fluidised-bed combustion explained.....35

The UK pioneers.....37

OPEC.....38

Foreign demand.....40

A role for environmental regulations?.....41

The decline of fluidised-bed combustion innovation in the UK.....43

Conclusion.....47

Bibliography......49

Primary sources......49

Secondary sources......51

Appendices......61

Appendix A: Abbreviations......61

Appendix B: Patent classifications......62

Appendix C: Summary of developments in UK regulation......64

Introduction

Innovation and the environment

Two issues upon which economics is now heavily focussed are technological change and the environment. Numerous economic history studies have provided empirical evidence for the crucial role that technological advance has played in economic growth, from Landes' (1969) *Unbound Prometheus* to Allen's (2011) more recent appraisal the role of technology in the Industrial Revolution.[1] Attempts to explain the growth residual produced by Solow (1956) have resulted in a proliferation of endogenous growth theories with Romer (1986, 1990) and Lucas (1988) seeking to unpack an exogenous black box and bring technological change inside the growth theory tent.[2] Parallel to this, there has been prolonged debate amongst economists, ecologists and politicians since Carson's *Silent Spring* and the *Limits to Growth* report (Meadows et al., 1972) about economic growth and sustainability.[3] Our growing awareness of the detrimental impact that economic activity is having on the environment came to the fore in the last three decades of the 20th Century when acid rain, global warming and damage to the ozone layer were of global concern. As economics has increasingly encroached on environmental topics, discovering the drivers of innovation in environmental friendly technologies has become a topic of pressing concern. This study examines whether strict environmental regulation is one such driver.

1 Allen (2011), 'Why the industrial revolution was British: commerce, induced invention and the scientific revolution'

2 See Lucas (1986), 'On the mechanics of economic development'; Romer (1986), Increasing Returns and Long-Run Growth Increasing Returns and Long-Run Growth; Romer (1990) 'Endogenous Technological Change' and Grossman & Helpman (1994) 'Endogenous Innovation and the Theory of Growth'

3 The burgenoning sustainability literature has seen contributions from those operating within the neoclassical paradigm – Solow's (1993) 'An almost practical step towards sustainability' – and those firmly outside it – Daly (1974), 'The Economics of the steady-state'

Motivating Theory

Solving environmental problems is generally seen as a costly activity involving a binary choice between a cleaner environment and higher per capita incomes. The main 'cost' is reduced output because profit-maximising firms must now incur the full cost of their pollution. There are also monitoring and enforcing costs for new regulations. The benefit is that introducing legislation to limit the amount of pollution a firm can emit internalises a negative externality being imposed by the polluting firm on the rest of society. This leads to an improvement in environmental quality, increasing total social well-being. However, there is another potential benefit: innovation. The theory of induced innovation stipulates that forces exogenous to the innovation process alter relative prices and thus create a demand for technologies that will increase efficiency. For example, higher wages increase the cost of labour encouraging innovation in labour-saving technologies. In our case, by being forced to reduce pollution the price of pollution and the inputs that cause it increases. Firms are therefore given a clear incentive to invent new technologies that reduce emissions cheaply, or even entirely new production methods and products that eliminate the emissions altogether. This incentive is not merely provided to domestic polluting firms either. New regulations create a demand for new technologies that can be met by any firm that sees it as profitable. New firms entirely devoted to researching pollution abatement technologies may spring up. The demand from polluting firms in a country with strict environmental regulations can also be met by foreign suppliers and cross-border technology diffusion, although the effect is thought to be less direct and therefore less powerful. Whatever its origin, such innovation mitigates the overall cost of regulation and can be seen as a benefit worthy of encouragement.

One major contribution to this subject was made by Porter (1991). He went even further than simply saying there was 'some benefit' from new innovation. Instead he claimed the induced innovation benefits would be so large that they would outweigh the costs in terms of lost output and monitoring.[4] Countries adopting strict environmental standards, he argued, would gain a competitive edge in clean technology industries to the extent that stricter environmental regulation becomes beneficial irrespective of the *environmental* benefits to society that it is designed to produce. This “Porter hypothesis” as it has come to be known clearly holds sway in policy circles: only recently Christiana Figueres, the executive secretary of the UN Framework Convention on Climate Change, warned that a Republican in the White House in 2012 would see America cede the competitive edge in green technologies to China and Europe.[5] This idea of Porter's that regulations 'pay for themselves' is not seen as necessary here. Nevertheless, it is still possible to view regulation as inducing at least some degree of beneficial innovation and it is this that is under examination.[6]

However, clearly regulatory pressures are not the only means by which firms are induced into innovating. Changes in factor prices do not just come from regulators making dirty fuels more costly to burn – growing resource scarcity and the desire the project an environmentally-friendly image can be just as powerful in pushing firms to 'go green'.[7] In fact anything from wars to welfare system changes can lead to clear incentives for the development of new products and processes that exploit the altered market situation. In a comparison with the once dominant India, Broadberry (2008) attributes the rise of the

4 See Porter (1991), 'America's Green Strategy'
5 Report in *Guardian* March 9th 2012 http://www.guardian.co.uk/environment/2012/mar/09/republican-climate-change-us-president-china
6 Palmer, Oates & Portney (1995), 'Tightening Environmental Standards: The Benefit-Cost or the No-Cost Paradigm?' p.119
7 'Why firms go green' in *Economist*, November 12th 2011, http://www.economist.com/node/21538083

British textile industry to differences in wages.[8] Higher British wages meant higher capital intensity, inducing more technological change. Similarly, Ma (2004) sees overpopulation, resource scarcity and the influence of Imperialism as important stimuli for inducing technological and institutional change in Japan. These changes were responsible for the reversal of fortune in Japan's silk industry in the century following 1850.[9]

The induced innovation framework outlined thus far shall remain the dominant approach throughout this study in large part because the principal drivers of innovation identified here are to do with exogenous market forces altering prices and demand. However, there are still other theoretical frameworks for explaining technological change that deserve mention.[10] A path dependence approach highlights the notion that innovation will be biased by the technology that is already in use. Innovating so as to improve current products and processes incrementally is generally cheaper and easier than the wholesale replacement of 'obsolete' technologies with entirely new ones. This technological lock-in can be seen in the chemical industries of the US and Germany. The former adopted petroleum (rather than coal) feedstocks in the 1940s, whilst the latter did not make the switch till the 1960s due to engrained attitudes, skills and education.[11] In a study of technological change in the late nineteenth century UK gas industry, Matthews (1979) finds that the path dependence created by the cost of replacing old plant was key to explaining the diffusion of new technology. Innovation itself was more the result of cross-pollination with other seemingly unrelated research fields than exogenous changes in demand. In forwarding such an argument he is contesting the notion that it was rising

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8 Broadberry & Gupta (2009), 'Lancashire, India, and shifting competitive advantage in cotton textiles, 1700–1850: the neglected role of factor prices'

9 Ma (2004), 'Why Japan, Not China, Was the First to Develop in East Asia: Lessons from Sericulture, 1850–1937'

10 Ruttan (1997), 'Induced Innovation, Evolutionary Theory and Path Dependence: Sources of Technical Change'

11 Ibid. pp.1523

wage costs that were key to inducing labour saving innovation – an interpretation held by the unlikely alliance of Hobsbawm (1964) and Broadberry (2008).[12]

An evolutionary approach to technological change has resulted in studies seeking to understand the internal behaviour of innovators and the institutions necessary for fostering innovation. In fact, Mokyr (1996) sees an evolutionary metaphor as a vital tool for any economic historian seeking to explore the history of technology.[13] Attempts to take this approach beyond being merely a vague rhetorical device have led to the concept of National Innovation Systems (NIS). These are defined as 'a historically grown subsystem of the national economy in which various organizations and institutions interact with and influence one another in the carrying out of innovative activity.'[14] Various studies seeking to ascertain the 'character' of the environment in which innovation occurs in different countries have been conducted, with comparative analyses throwing light on the relative capacity of different country's institutions to produce innovation.[15] This emphasis on discovering the 'routines' and institutions that foster technological progress has also led to growing convergence with New Institutional Economics. Evolutionary economists have come to view institutions as “social technologies” and New Institutionalists regard technology as reducing 'transformation costs' compared to institutions which reduce 'transaction costs'.[16] Both the evolutionary and path dependence frameworks described above shall feature briefly when explaining the observed innovation trends, but it is an induced innovation approach that will provide the bulk of the explanation.

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12 Hobsbawm (1964), *Labouring Men,* pp.158-78

13 Mokyr (1996), 'Chapter 4: Evolution and Technological Change: A New Metaphor for Economic History?'

14 Balzat & Hanusch (2004), 'Recent Trends in the research on national innovation systems', pp.198

15 See Porter, Stern, & Furman (2001) 'The Determinants of National Innovative Capacity' and Furman & Hayes (2004), 'Catching up or standing still: National innovative productivity among 'follower' countries, 1978-1999'

16 Nelson & Nelson (2002), 'Technology, Institutions and Innovation Systems' and North & Wallis (1994) 'Integrating institutional change and technological change in economic history: a transaction cost approach'

Literature Review:

Establishing whether environmental legislation spurs innovation is no straightforward task. Previous research has almost exclusively attempted to do so by examining the correlation between an indicator of the stringency of environmental legislation and an indicator of innovative activity. A proxy for regulatory stringency can either be the actual emissions limit set by the regulator (some maximum amount of pollution that can be emitted by a power station for example) or a measure of the amount firms must spend to comply with environmental legislation (surveys of the amount firms spend on new equipment and production methods to adapt to new legislation are common here).[17] Innovation, on the other hand, is usually represented by either expenditures on R&D (inputs to innovation) or patenting activity (outputs from innovation) which, whilst far from perfect, are pretty much the only proxies available. Despite there being a general lack of comprehensive data for many of these indicators, there has still been much empirical work over the last two decades. Lanjouw & Mody (1995) and Jaffe & Palmer (1997) made two of the key early contributions to the literature and both of them find a significant positive link between the stringency of environmental legislation and innovation. However, both papers explore the issue by running large regressions for a range of aggregate datasets, and this has potential pitfalls as Jaffe & Palmer readily acknowledge:

> 'Perhaps the best way to overcome the aggregate nature of the data used in this study and to develop a better understanding of the nature of the relationship between regulation and innovation would be to conduct some focused industry studies.'[18]

[17] For example the US Pollution Abatement Costs and Expenditures (PACE) survey (1973-1994).

[18] Jaffe & Palmer (1997) 'Environmental Regulation and Innovation: a panel data survey', pp.618

Now since then there have been a number of more focussed studies. In a piece focussing on regulations for two specific pollutant gases (NO_X and SO_2) from coal-fired power plants in Germany, Japan and the US, Popp (2006) finds there is an inducing link between stricter domestic emissions limits and spikes in domestic patenting activity.[19] However, he finds no significant stimulus from changes to foreign regulations.[20] But even here there is still a neglected historical dimension – a lack of context. What almost all these studies have in common is that they use aggregated data to perform quantitative regressions that they then claim point to a causal link. The causality is implicitly assumed to be that regulations change and innovators then respond, although this is never rigorously explained. As such the literature is riddled with seemingly ad hoc adjustments with some authors lagging their data to allow innovators to respond, and others doing the reverse to suggest the innovation they observed was pre-emptive.[21] It is this failing that I will attempt to remedy by going beyond aggregate quantitative data and examining the records of the innovators themselves. This yields are far clearer understanding of what was driving innovation and when.

Linked to these methodological problems are the shortcomings of the data itself. Problems with indicators such as 'numbers of patents' are routinely acknowledged, but they are generally believed to be no more than mere reasons for caution. In another study by Popp (2001) though, issues with patent data have made a significant difference to the conclusions reached. Here he was attempting to show that more patenting (and thus more

[19] Popp (2006), 'International innovation and diffusion of air pollution control technologies: the effects of NO_X and SO_2 regulation in the US, Japan, and Germany'
[20] Ibid.
[21] Lanoie, Patry & Lajeunesse (2001) only find a significant correlation when their patent data is lagged so as to account for the time it takes firms to respond following regulatory change. Similarly, spikes in patenting in Popp's (2006) study are seen to have been induced by regulation if they occur at or soon after the change.

innovation) occurred under a market-based pollution control regime than under the (theoretically inefficient) command-and-control system that preceded it. But rather than the number of patents going up after the new regulations came into force, they went down. As such Popp moved to differentiate between the purposes and values of various patents in order to show that the later patents were of greater significance for reducing pollution.[22]

This study will show in much the same way that not all approaches to environmental regulation have the same impact on innovation, and that generally not enough caution has been taken when using patent data. I will go further than simply looking for common trends between patent numbers and regulation changes, and analyse the firms and innovators behind the patents. However, instead of looking at the US, Germany and Japan, it is the UK – with its notably different regulatory approach – that shall take centre stage. It is predicted that, contrary to the preceding literature, changes in the UK's regulatory stringency will *not* be accompanied by sudden increases in innovative activity. This is largely due to the pace and style of British environmental regulation. Where apparent spikes in innovation do occur, other potential drivers – such as the OPEC oil crisis – are shown to be of much greater importance than domestic environmental regulation. This more historically conscious approach that pays heed to the context surrounding innovative activity is essential to formulating a reliable picture of the impact of environmental regulation.

22 Popp (2001), 'Pollution Control Innovations and the Clean Air Act 1990'

Background

This study focusses on air pollution, and whilst the atmospheric pollutant that features most prominently in the news today is CO_2, this was not always the case. In 1952 a thick fog descended on London between the 5th and 9th of December. Reduced outdoor visibility caused buses and ambulances to cease running. Indoor visibility was hardly better – performances of the opera *La Traviata* in Sadler's Wells had to be abandoned because the audience could not see the stage.[23] Such smogs were hardly new.[24] What became known as the 'Great Smog of 1952' was not initially thought to be particularly special.[25] But given anywhere between four and twelve thousand people were thought to have died as a result of it, a groundswell of public pressure led to the introduction of the 1956 Clean Air Act to reduce emissions of particulate matter and black smoke in the UK.[26]

Within two decades though it was not smoke, but acid rain that was top of the environmental agenda. Dramatic images from Eastern Europe and Scandinavia during the 1970s and 80s showed leafless forests and 'dead lakes' where fish stocks had vanished. The cover of a 1982 edition of *New Scientist* read 'Rain more acid than vinegar.'[27] Blame was laid at the door of two kinds of pollutants emitted from burning fossil fuels: nitrous oxides (NO_X) and sulphur dioxide (SO_2). These are the two pollutants on which this study focusses as they are the two most important causes of acid rain. As one of the largest economies in Europe, Britain was responsible for a sizeable portion of total emissions, and

23 Mayor of London (2002), 'Fifty years on: the struggle for air quality in London since the Great Smog of December 1952' pp.3

24 See Luckin (2003), '“The Heart and Home of Horror”: The Great London Fogs of the Late Nineteenth Century'

25 Brimblecombe (2006), 'The Clean Air Act after 50 years', pp.311

26 Following the smog the Committee on Air Pollution was set up and it's recommendations resulted in the 1956 Clean Air Act. The committee was nicknamed the Beaver Committee after its chair, LSE alumnus and founder of the Guinness Book of World Records Hugh Beaver. His personal records can be found in the LSE Archives. As for the death toll, early estimates by Wilkins (1954) put the toll at 4000, but recently it has been suggested by Bell, Davis & Fletcher (2002) that it might have been as high as 12,000

27 *New Scientist*, 12th August 1982, Vol 95 No.1318

the majority of the damage in Scandinavia was thought to be caused by pollution blown from Britain.[28] In light of the obvious negative externality imposed by these pollutants both locally and internationally, the scope for introducing legislation to control them was clear. Public concern over acid rain reached its zenith in the 1970s and 80s leading to regulation combat the problem being passed with the express aim of reducing emissions of SO_2 and NO_X. Any hypothesised effect that these regulations had on innovation would therefore be on technologies designed to reduce emissions of these two pollutants.

The analysis presented here is not only confined to two specific pollutants either. It is also confined to one particular source of these pollutants: coal-fired power stations. The focus on coal-fired power stations follows from the use of the same patent classifications as Popp (2006) to identify the technologies which would be expected to be stimulated by stricter SO_2 and NO_X regulations. There do not seem to be any problems with maintaining this restriction for the UK.[29] As can be seen from Figure 1 the vast majority of total coal consumption went to generating electricity. Also the UK over the past century that coal has been used to produce the majority of the UK's electricity. In 1964-5 some 84% of output was generated at coal-fired stations.[30] By 1990 it was still as much as 65% of electricity output (see Figure 2).

28 In 1965 UK power stations were responsible for 35% of all electricity in Europe produced from burning fossil fuels. UGD/309/1/24/13, 'Extracts from the Electricity Board Annual Report for 1964-5'

29 This would not be true if the UK produced a very small proportion of its electricity by burning fossil fuels such as coal, as in a country like Norway.

30 UGD/309/1/24/13, 'Extracts from the Electricity Board Annual Report for 1964-5'

Figure 1: British Coal Consumption by use, 1970-2005[31]

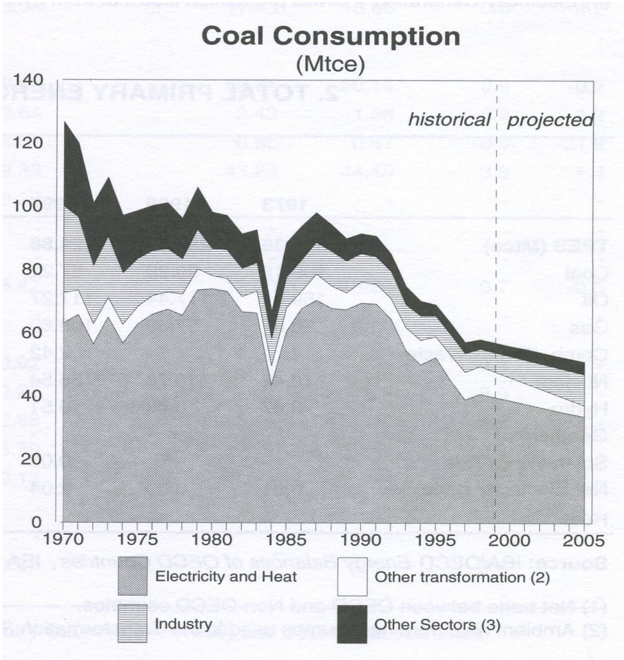
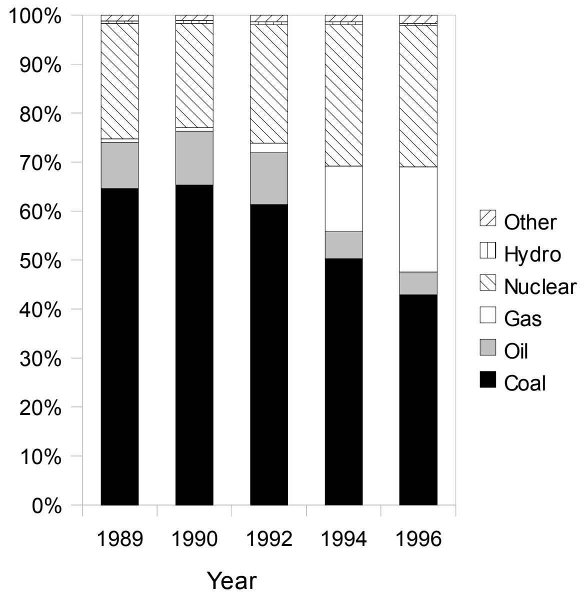


Figure 2: Thermal Input to Electricity Generation 1989-1996[32]



In light of the fact that burning coal was a major source of acid rain pollutants, that the majority of coal was used to generate electricity (Figure 1), and that the majority of electricity was generated using coal (Figure 2), regulating the coal-fired power sector was important for controlling Britain's emissions.

There are a number different ways that power stations can reduce their emissions in order to comply with new regulations. The most obvious one is to reduce output. However, given the rising demand for electricity throughout our period, this was hardly feasible. Figures 3 and 4 highlight the contributions of a range of different measures to reducing pollution:

31 Source: IEA (2000), *Coal Information 2000*

32 Source: Eames (2000), 'The Large Combustion Plant Directive (88/609/EEC): An Effective Instrument For Pollution Abatement?' pp.36

Figure 3: Causes of fall in NO_X emissions from electricity generation in the EU[33]

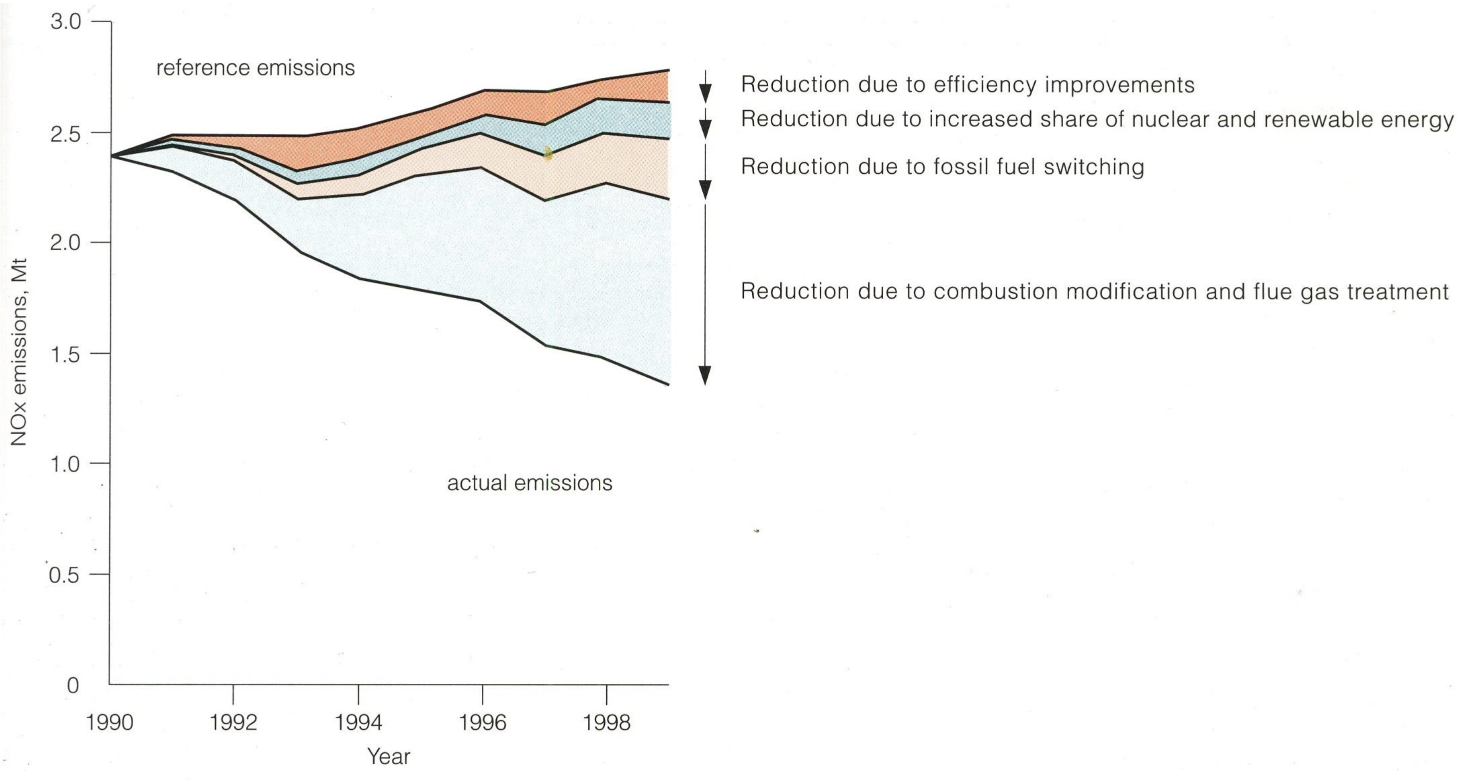
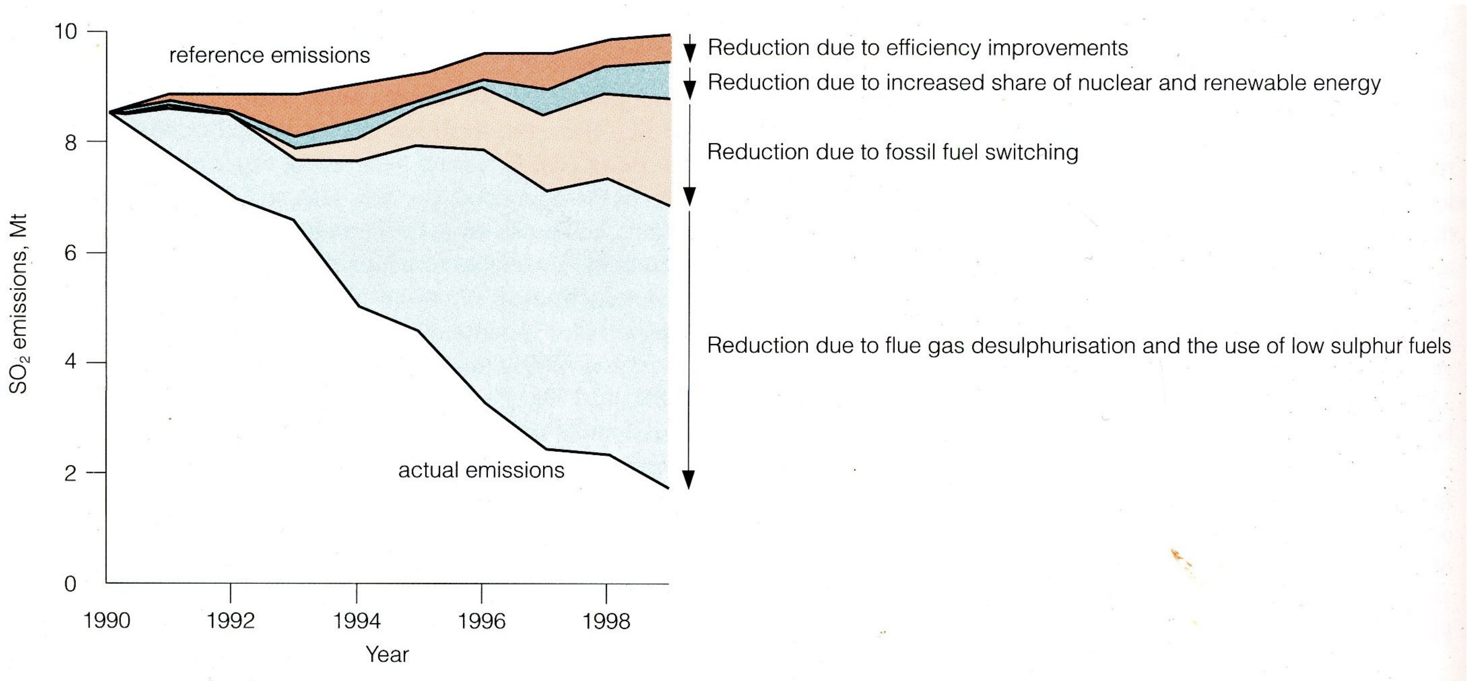


Figure 4: Causes of fall in SO_2 emissions from electricity generation in the EU[34]



33 Source: Sloss (2003), *Trends in emission standards*, pp.51
34 Ibid. pp.50

The dark blue and light orange sections capture the role played by switching to alternative fuels that produce less, or even no, harmful NO_X and SO_2 emissions. This could be done by using less dirty coal with a lower sulphur content, or even switching to gas or nuclear. Another option, and the one with which this study is most concerned, is to use new technologies that help reduce or eliminate emissions. At the consumer level this would mean using electricity more efficiently through installing energy saving light bulbs, or reducing wastage. But the extent to which a change in environmental regulations would encourage this is debatable and difficult to measure. The reasons for using electricity more efficiently are far more numerous than wanting to prevent acid rain. Moreover, consumers are removed from the actual pollution and regulation process. UK regulations on the power sector stipulated the measures producers had to take, not consumers. This contrasts with regulations designed to reduce NO_X and SO_2 emissions that more directly affected consumers such as moves to fit catalytic converters to cars. As such this study will not be concerned with the impact of environmental regulation on innovations at the consumer end. This leaves us with technologies designed to reduce emissions in electricity production and it is this area that is the focus. These innovations can take two forms. The first are comparable to fitting a catalytic converter to your car as they remove pollutants from the exhaust (flue) gas *after* combustion. 'End-of-pipe' technologies such as this include flue gas desulphurisation (henceforth 'desulphurisation') for reducing SO_2 and selective catalytic reduction for reducing NO_X.[35] The second type of technologies are combustion modification technologies such as fluidised-bed combustion (FBC) or low NO_X burners. These are like having a more efficient car engine and cause less pollutants to be created *during* combustion. Figures 3 and 4 show the contributions of various pollution reduction methods to actual emission reductions in Europe. Clearly technology is

[35] Given the alphabet soup of acronyms and abbreviations used throughout this study a reference list can be found in Appendix A.

important (the light blue area is the largest on both graphs) but it is far from alone in reducing emissions. As such, in assessing any response to a pollution problem account needs to be taken of the range of options employed, rather than a blinkered focus on technology.

Another important foundation that needs to be laid before proceeding to the analysis is some background on the UK's unique approach to environmental regulation. Regulation of industrial pollutants at the start of our period was the responsibility of the Alkali Inspectorate. This was the first government pollution control agency in the world, established in 1863 to regulate emissions from Leblanc alkali works. Numerous revisions and expansions of the Inspectorate's remit culminated in the 1958 Alkali & Works Order which gave the Alkali Inspectorate responsibility for pollution from all large heavy industries. This resulted in a doubling of the number of plants under its jurisdiction, and most notably for our purpose, the responsibility for all power plant emissions.[36] To cope, the number of inspectors increased from a mere nine in 1957 to fifty by 1986.[37] The Alkali Inspectorate became the Industrial Air Pollution Inspectorate (IAPI) between 1983 and 1987, although this was due to a change of government department, not a shift in the way it operated. It then became Her Majesty's Inspectorate of Pollution (HMIP) in 1987 which, following the passage of the 1990 Environmental Protection Act, took control of regulating land and water pollution as well as just air.[38]

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36 Of course some power plants had been regulated prior to this, most noticeably Battersea, Swansea and Fulham which, due to their city locations, had been required to use desulphurisation equipment to reduce SO_2 emissions since the 1930s. Biondo, S.J. & Marten,J.C. (1977), 'A History of Flue Gas Desulphurization Systems Since 1850' p.950

37 Vogel (1986), *National Styles of Regulation: Environmental Policy in Great Britain and the United States,* pp.71-2

38 Jordan, A. (1993), 'Integrated Pollution Control and the evolving style and structure of environmental regulation in the UK' pp.7

The British regulator under its various guises had a fairly unique regulatory style:

> 'What sharply distinguished the British government's approach to pollution control not only from that of the United States but from that of any continental nation was its flexibility.'[39]

This flexibility arose because the British system was based on individual negotiations with polluters, rather than the US and German practice of setting a fixed emissions limit and leaving polluters to meet it or face prosecution. In short, one approach emphasised close negotiation whilst the other remained detached and litigious.[40] Unsurprisingly some have labelled such an institutional structure 'discretionary, collaborative and secretive.'[41] Either way, it is impossible to follow Popp (2006) in simply using a national statutory emissions limit as a measure of regulatory stringency – no such universal standards existed. Instead the general guiding principle of regulation was the phrase 'best practicable means' (BPM).[42] This was a vague concept that effectively gave full discretion to the regulator to decide on a case-by-case basis what measures a polluter should take through a balancing of whatever economic, environmental or political concerns it deemed relevant. Initially these concerns would be wanting to reduce environmental damage whilst not penalising industry and, in the case of power generation, raising electricity prices. However, growing foreign interference meant there was also an external pressure to comply with targets set

39 Vogel (1986), *National Styles of Regulation: Environmental Policy in Great Britain and the US,* pp.75

40 One of the few examples I could find of the IAPI taking legal action over a pollution infringement was against Battersea power station in 1973 and even then the case fell through due to a loophole in the law. TNA/BT/328/125, 'Reports of the Chief Inspector under the Alkali Act 1969-1974'

41 Jordan, A. (1993), 'Integrated Pollution Control and the evolving style and structure of environmental regulation in the UK' pp.5

42 'The expression "best practicable means," where used with, respect to the prevention of the escape of noxious and offensive gases, has reference not only to the provision and the efficient maintenance of appliances adequate for preventing such escape, but also to the manner in which such appliances are used and to the proper supervision, by the owner, of any operation in which such gases are evolved.' Alkali & Works Regulation Act, 1906, Ch.14 pp.14

by Europe.

In light of this flexible regulatory style with its preference for compromise over confrontation, an institution of equal if not greater importance to determining the regulatory response to acid rain was the Central Electricity Generating Board (henceforth the Electricity Board). Between 1957 and 1990 Britain's nationalised electrical utilities were under its control. As a public body it was able to lobby the government and the regulator much more effectively than would have been the case under a privatised system. In fact, on the issue of acid rain 'it was not so much a question of the Government wishing to impose further regulations, but rather of expecting the [nationalised] industry willingly to do what was necessary.'[43] This effectively amounted to self-regulation in which the Electricity Board held almost complete power over its own response, providing it sufficiently placated the regulator. Of course, pressure could be placed on it to change, but this arrangement had a significant impact on the capacity of British regulation to stimulate innovation.

It is predicted here that the British regulatory style induced very little innovation for two reasons. Firstly, because the BPM approach implicitly followed behind the technology as it only opted for tried and tested methods. Whenever any new abatement technology was agreed to be BPM and was adopted, it was because the regulator had required the polluter to implement that specific technology. As such, once that requirement was met, there was no further pressure on the polluter to innovate and adopt new, better technological solutions.[44] It is possible that some small degree of innovation could be observed in the run-up to new stricter regulations. For example, the Electricity Board was engaged in substantial research efforts into acid rain prior to announcing any new measures. However, the extent of this is questionable. Secondly, this approach generally

[43] Sheail (1991), *Power in Trust: The Environmental History of the Central Electricity Generating Board*, pp.249

[44] This fits with the theoretical literature on the dynamic inefficiency of command-and-control regulations.

produces only slow, gradual changes. Sudden, clear, blanket signals are avoided in favour of incremental moves so as to minimise the costs and uncertainty for industry. The Electricity Board unsurprisingly sought to avoid sudden changes in its demand for pollution abatement technologies. Also, by adopting regulations later, UK polluters could simply purchase technologies already developed abroad, rather than having to engage in innovation of their own. Given such a style of regulation as this, significant changes in innovation were unlikely. This contrasts with the traditional view of the impact of increases in the stringency of environmental regulation.

Sources and Methodology

Patents

As a measure of innovative activity, patent data for abatement technologies aimed at reducing electric utility emissions of NO_X and SO_2 is used. The patent data was compiled from the online database of the European Patent Office. The database contains records of over 45 million patents from 71 countries, each organised into various patent families according to a classification system. Each patent is given an ECLA classification based on the purpose to which it pertains and the classifications identified by Popp (2006) are used here.[45] Data on all the patents within a specified classification were collected for each year between 1960 and 2000 for the UK. For the purpose of making brief comparisons, the same data was collected for Germany and the US as well. The data from each classification was then merged to give all the abatement technologies pertaining to the control of the pollutants in question. Any duplicates were removed and then the data was sorted by application year and plotted on a graph.[46]

Before proceeding, the pros and cons of using patent data such as this should be noted.[47] For advantages, the UK coverage of the database dates back to 1909 so the construction of long time series is possible. Detailed technology specific data are available

45 ECLA means 'European Classification'; a system for classifying patents. Not to be confused with the Economic Commission for Latin America, the European College of Liberal Arts, or the Evangelical Lutheran Church of America. See Appendix B for details of the classifications used.

46 Duplicates arose when one patented innovation fell into more than one of classifications. Also, application year was used instead of granted year because the time between application and grant can vary (a Freedom of Information request to the IPO revealed that on average it is around 36 months http://www.ipo.gov.uk/foi-log188.pdf) and a firm's choice to apply for a patent relates more closely to the timing of innovative activity. Sorting by priority year proved difficult given the format of the data but this does not appear to be an issue.

47 Pavitt (1985), 'Patent Statistics as Indicators of Innovative Activity: Possibilities and Problems'

so it is possible to use patents to highlight key firms and innovations for further research. Patent data is also highly correlated with R&D data, but available for a wider range of technologies. Lastly, data on country of origin helps with analyses of the origins of innovation and cross-country flows of technological knowledge. There are several drawbacks though. Not all innovations are patented. Firms may opt for secrecy as a more effective policy. In fact, when looking through the archives of Peter Spence & Sons Ltd (one of the firms identified in the patent data) what documents I could find referred to secrecy and licensing agreements, not patent filings.[48] Another major criticism of patent data is that not all patents are of equal value. Some patents represent massive innovative change that will have a great impact whilst some will never make it off the drawing board to becoming marketed products. As such patents are a good measure of invention but not necessarily innovation. Moreover, patenting systems vary from country to country so the same innovation may receive multiple patents in one country and a single patent or even have their application rejected in another. The majority of the literature on the topic in question generally mentions these problems, but this study will show that simply paying lip service to them is not enough.

To do this it is noteworthy that patent data is not only useful for simply tallying up the number of patents in any particular year. Every original patent document includes a wealth of information: the name of the inventor, their nationality, their employer, and detailed descriptions of what exactly the technology in question is. As such a detailed investigation of one of the technologies in which UK firms were innovating is possible, and this study does just that.

48 PSA/1170, 'Signed copies of Peter Spence & Sons Ltd Secrecy Agreements for work between Degussa and themselves in 1958'

Regulation

Assessing the stringency of regulation is even less straightforward than measuring innovation. The UK approach to regulation cannot be boiled down to a single emissions standard as previously noted and there exists no data on the changing costs to firms of complying with regulation. As such a wide range of evidence is used in this study to establish the stringency of the regulatory response to acid rain. To understand the actions of the regulator, public records, internal letters, annual reports and speeches relating to the UK's various regulatory bodies are used.[49] These are located in the National Archives and have only been recently made publicly available. As for the Electricity Board, it is largely secondary accounts that are used to establish the chronology of changes in its approach.

Fluidised-bed combustion

After initial analysis of the aggregate patent data, the focus will shift to an in-depth case study of one of the innovations for which patenting is most prominent: fluidised-bed combustion (FBC).[50] One of the main domestic firms that crops up in the patent data, particularly for FBC technologies, is Coal Industry Patents Ltd. This was actually a subsidiary of the National Coal Board (henceforth the Coal Board) and so documents belonging to its research department – the Coal Research Establishment (CRE) – are available in the National Archives. Patents found in the back of CRE annual reports confirm this link as they match many of those lodged by Coal Industry Patents Ltd in the

49 As described earlier these were the Alkali Inspectorate, Industrial Air Pollution Inspectorate and Her Majesty's Inspectorate of Pollution.

50 An explanation of what exactly this technology does is found later in the section 'Fluidised-bed Combustion Explained'.

patent dataset. To market the research done at CRE globally, Combustion Systems Ltd (CSL) was created in partnership with British Petroleum (BP) in 1973. This, combined with information on the research arm of the Electricity Board – the Central Electricity Research Laboratories (CERL) – provides a fairly comprehensive picture of public research into acid rain and the various technological solutions.

Another firm that features prominently in the patent dataset is Babcock & Wilcox Ltd (henceforth Babcock). Babcock was an engineering company primarily concerned with manufacturing and servicing electric utility boilers for both nuclear and fossil fuel-fired power stations. It was created as a separate UK-based entity by the US Babcock & Wilcox Company.[51] The British company is of particular interest to us due to its location and its greater emphasis on FBC research. In 1975 it secured an agreement with CSL for information sharing and future joint research, making it part of an innovating cluster with some of the other research organisations already mentioned.[52] As such Babcock was a leading developers of FBC and in 1979 it formed Fluidised Combustion Contractors Limited (FCCL) to manage its work on FBC until 1985 when the operation was downsized from Crawley to London. After a written request the company granted access to their Glasgow archives. These have proved a rich source of information on the decisions underlying the development and marketing of FBC in the private sector. This is a key area in which this research differs from the rest of the literature. The factors stimulating innovation are not merely inferred from a correlation coefficient, but are directly discovered in the records of the innovators themselves.

[51] The US company famously supplied equipment for the Manhattan Project, the first nuclear submarine (the USS Nautilus) and one of its reactors was installed at Three Mile Island.

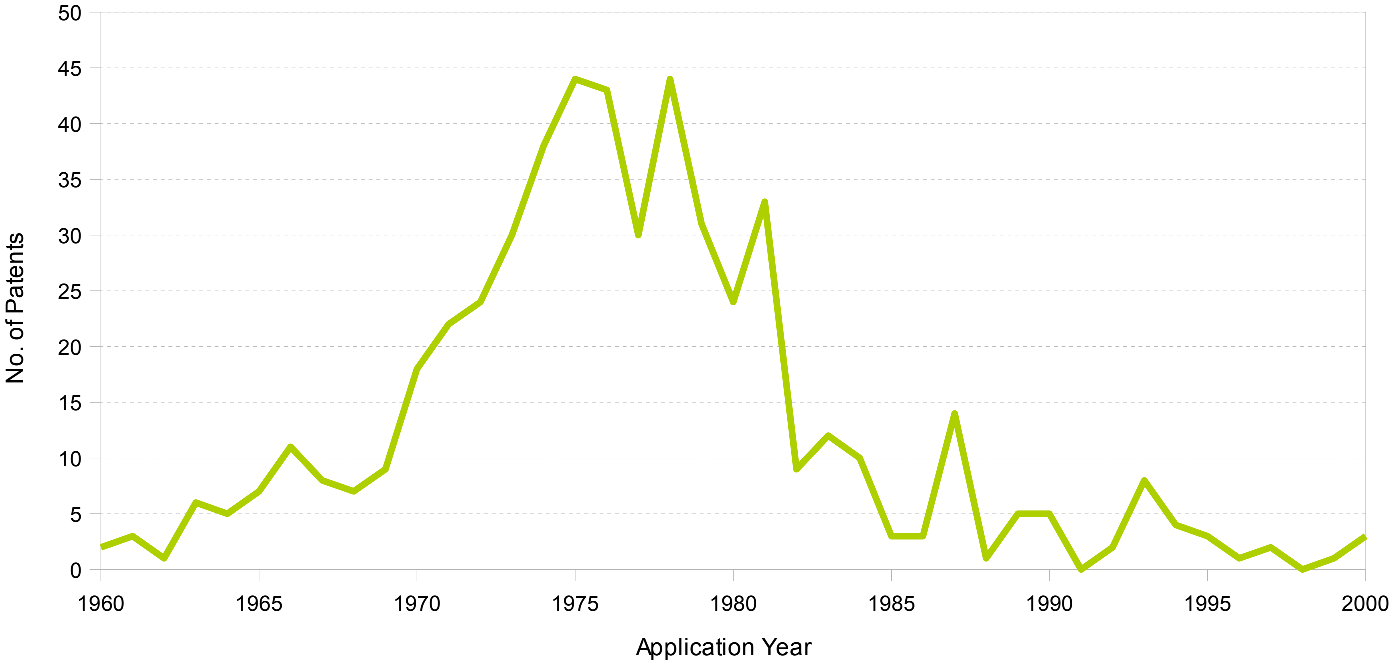
[52] UGD/309/1/24/12, 'Inter-company R&D committee, minutes of meeting in Lynchburg, 14th October 1975'

Analysis

Trends in Patenting

As can be seen from Figure 5, there is a clear rise in patenting in NO_X and SO_2 abatement technologies from the early-seventies to early-eighties.[53]

Figure 5: Total UK Patents in NOX and SO2 abatement technologies, 1960-2000



In Figures 6 and 7 the data is disaggregated by pollutant. NO_X patents peak earlier around 1974-76 compared to SO_2 patents which peak more sharply later in 1978.

[53] In the graphing of the data, it is noted that the numbers of patents in a year is a stock and thus ideally a bar chart would be used. However, the visual difficulties of graphing trends for different country data on the same graph in bar form (as in Figures 8 to 14) means that, for the sake of continuity a line is used.

Figure 6: UK Patents in SO2 abatement technologies 1960-2000

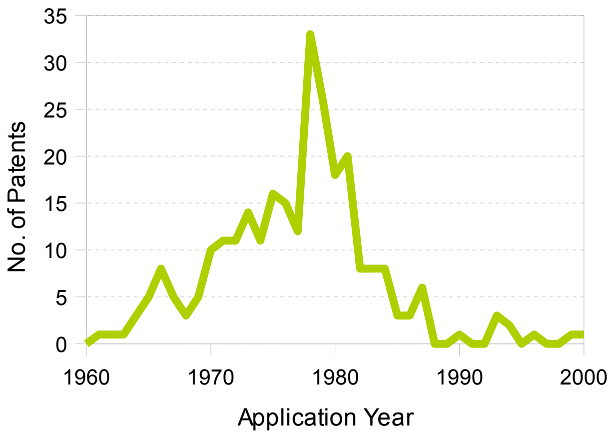
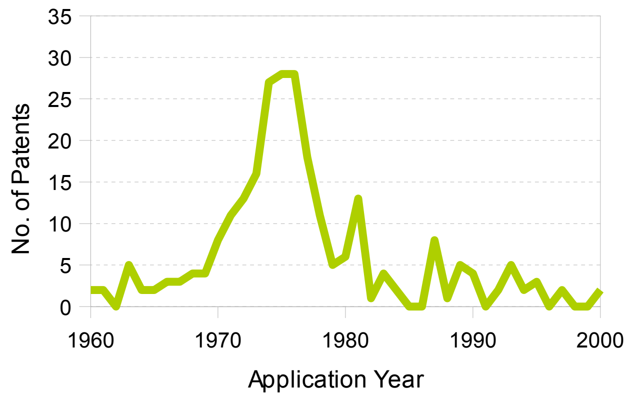


Figure 7: UK Patents in NOX abatement technologies, 1960-2000



Disaggregating the data yet further it is possible to analyse who is doing the patenting. Figure 8 shows that the spike in patenting for SO_2 abatement technologies is largely driven by domestic innovators (63% of total patents 1970-85) and as shall be seen later, the vast majority of these patents relate to fluidised-bed combustion. Figure 9 on the other hand, reveals the interesting result that it is Japanese firms, not British ones, that are responsible for the spike in patenting for NO_X abatement technologies (55% of total patents 1973-78).

Figure 8: UK Patents in SO2 abatement technologies by inventor's country of origin, 1960-2000

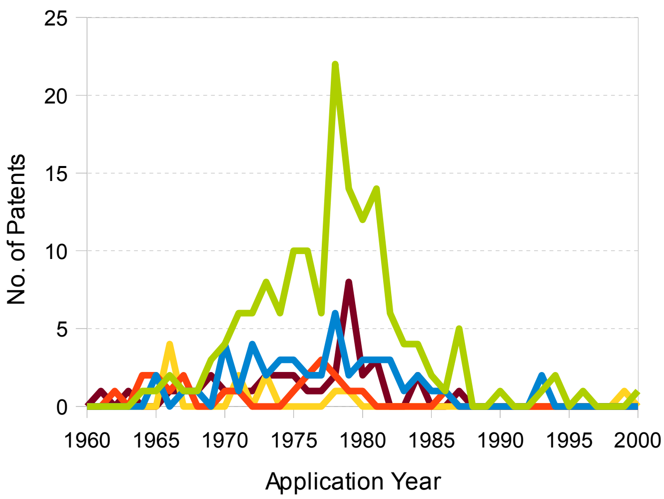
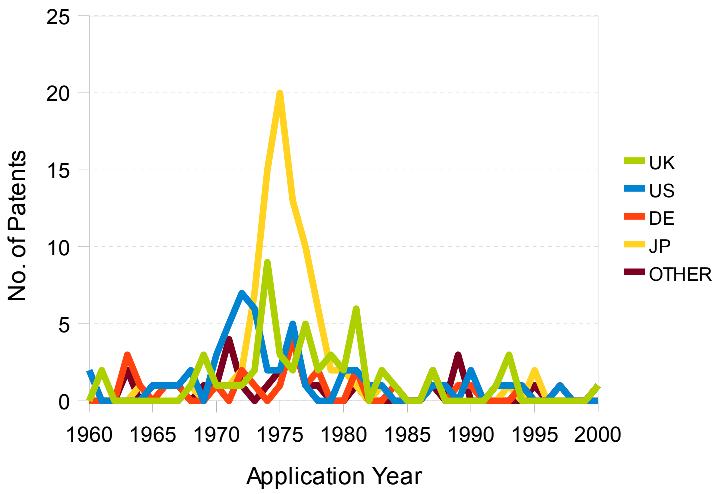


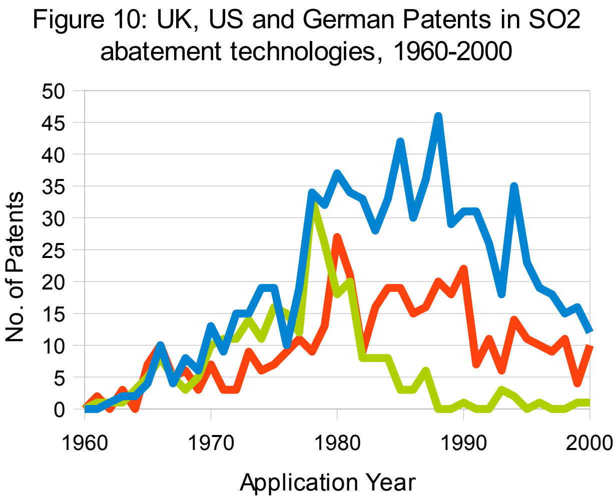
Figure 9: UK Patents in NOx abatement technologies by inventor's country of origin, 1960-2000

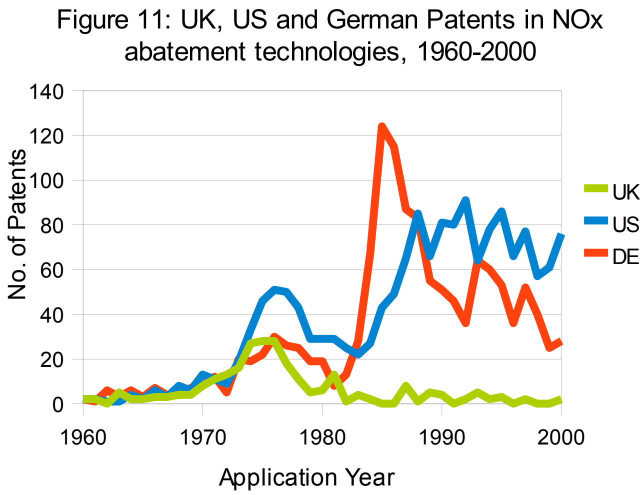


How does this patenting activity compare with data collected for Germany and the US?[54] In

[54] The US, German and UK patent systems are broadly similar with the time between application and grant generally falling between the 2-3 year mark. Still, short of surrendering the possibility of saying anything at all, any cross-country comparisons engaged in here remain cautiously approximate. As such the absolute patent numbers are treated only as a very rough guide to innovative activity.

Figure 10 we can see that the rise in UK patenting for SO_2 abatement technologies occurs at a similar time to jumps in the US and Germany, although innovation appears to be more persistent in the US and Germany with significant degrees of patenting continuing throughout the eighties and nineties. As for NO_X abatement technologies, patenting in all three countries rises to a peak in the mid- to late-seventies, although unlike the UK, both Germany and the US see a second larger surge in patenting in the mid-eighties that then persists (particularly for the US) throughout the following decade. Innovation in the UK is fairly transient then compared to the more persistent activity observed for the US and Germany. A final point to note is that UK NO_X patenting is on a significantly smaller scale than is observed for the US and Germany (note the change in scale on the y-axis in Figure 11).





The EPO

One possible explanation for the precipitous decline in UK (and German) patenting after its initial peak may be the introduction of the European Patent Office (EPO) in June 1978. Since its inception the number of patents granted by the office (in effect bundles of national patents granted in one unified procedure) has increased rapidly with many firms regarding it as preferable to seeking patenting through individual national patent offices.[55] Figures 10 and 11 both show an increase in EPO patenting for both SO_2 and NO_X technologies which may suggest that rather than innovative activity declining as indicated by the earlier national data, firms were simply choosing to patent with the EPO instead. However, the fact that EPO patenting for either pollutant from UK firms is almost non-existent (Figures 12 and 13) suggests that this almost certainly isn't the case for Britain.

Figure 12: European Patents in NOx abatement technologies by inventor's country of origin, 1960-2000

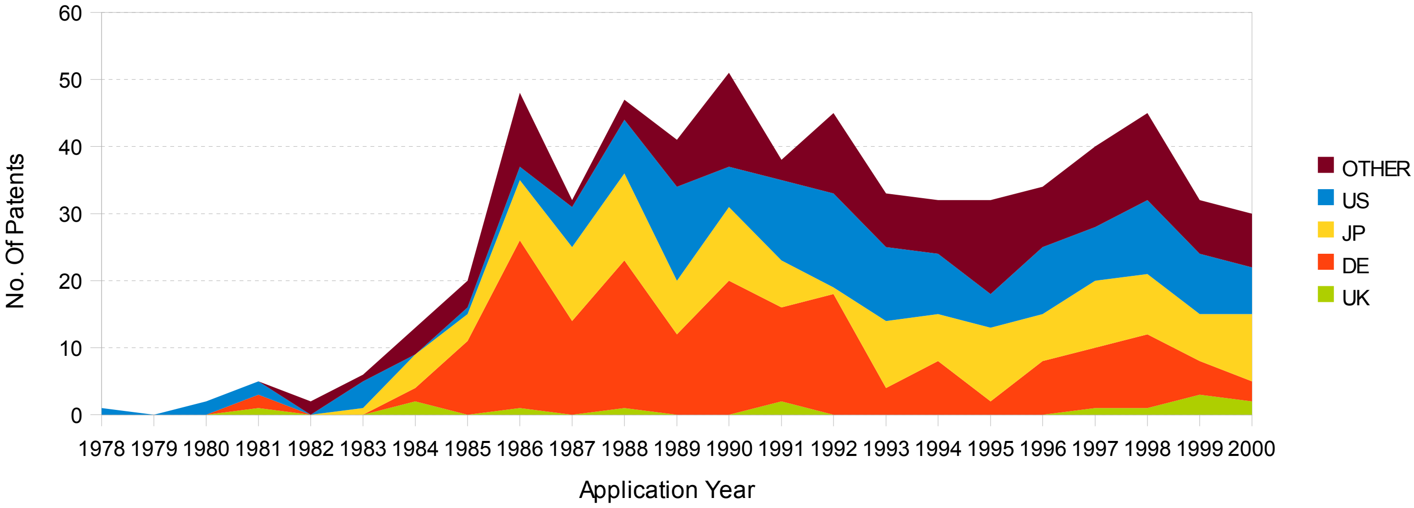
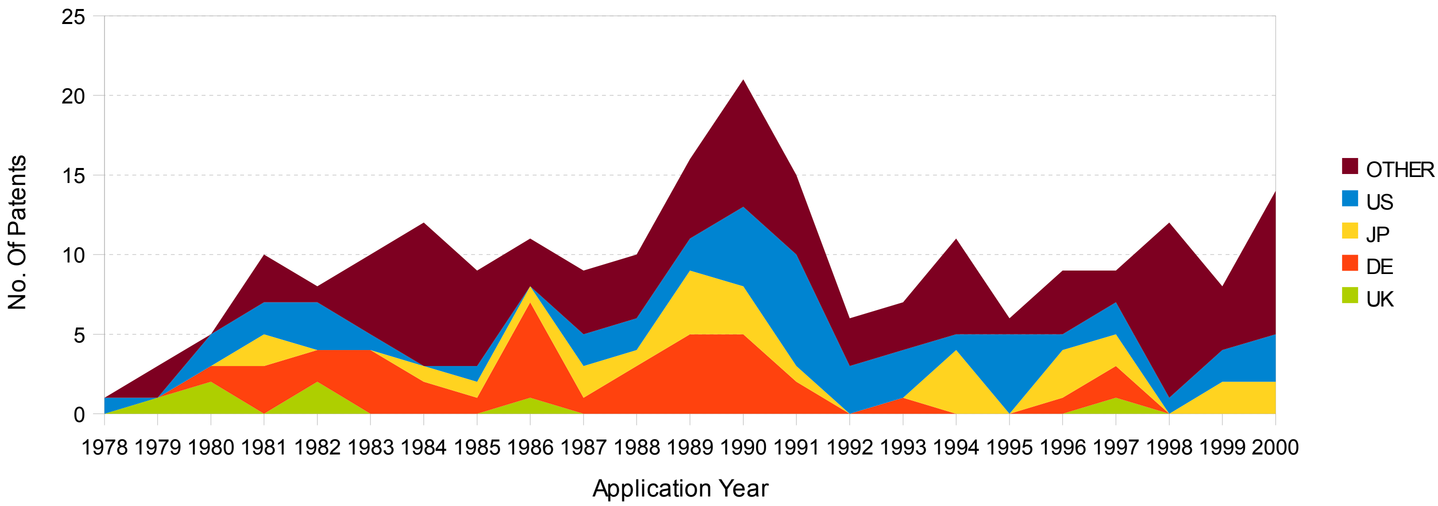


Figure 13: European Patents in SO2 abatement technologies by inventor's country of origin, 1960-2000



55 P.O.S.T. (1996), *Patents, research and technology: compatibilities and conflicts*, pp.1

Patenting and regulation

Do the trends in the patenting data identified fit with information on regulatory stringency? The simple answer is no. As can be seen from Table 1 in Appendix C, there was no significant change in the stringency of the regulatory environment being faced by NO_X and SO_2 polluters in Britain during the 1970s when innovation apparently peaked. The 1974 Control of Pollution Act only required the provision of information on emissions, not any reduction of them.[56] In the same year the Electricity Board readily admitted in a letter to the regulator that 'the public may have to experience a slight deterioration in the environment … until our economic position improves or the right quality of coal is again available.'[57] Clearly environmental concerns were still secondary to economic ones. The 1979 Long Range Transboundary Air Pollution Convention was mainly focussed on international cooperation on research and policy. Neither it, nor a 1980 European Directive set any binding targets for emissions reductions. In fact, in 1981 the Electricity Board and the Royal Society both claimed the costs alleviating acid rain damage to Norwegian fisheries vastly outweighed the benefits.[58] Actual binding changes that required polluters to reduce emissions only came in 1984 when UK adopted the European Air Frameworks Directive, and even this was not fully implemented until 1990. It was not until 1986 that the Electricity Board announced any plan to fit new abatement technology. The announcement said it would use desulphurisation and low NO_X burners at any new power plants, as well as embarking on a (fairly modest) retrofitting programme which was not intended to be

[56] 'A local authority may ... require the occupier of any premises in its area to furnish ... information as may be specified ... concerning the emission of pollutants and other substances into the air from the premises.' Control of Pollution Act (1974) pp.100

[57] TNA/BT/328/125, 'Reports of the Chief Inspector under the Alkali Act 1969-1974'

[58] Sheail (1991), *Power in Trust: The Environmental History of the Central Electricity Generating Board*, pp.237

completed for another decade.[59] The UK's response to acid rain is thus best summarised as being one of avoiding binding commitments and focussing on research and information gathering until 1984. After this it agreed to reductions of gradually increasing strictness.

Now, the traditional approach in the literature would simply look at when actual binding changes were made to regulation (the mid-1980s) and then see if these correlated with spikes in patenting. Clearly this would lead to the conclusion that environmental regulation did not induce innovation because the patenting spike occurs much earlier (the late-1970s). This is in complete contrast to patenting in Germany (see Figure 11) where firms seemed to respond dramatically to the tough new standards implemented there in 1983.[60] However, if one takes into account the unique nature of the British regulatory approach as described earlier, then the fact that there was not a spike in patenting in the mid-1980s is unsurprising. Once desulphurisation was classed as being BPM and the Electricity Board's retrofitting plan announced in 1986, there was little further incentive for innovation. As such that patenting had flat-lined when regulatory stringency increased is not unusual, but rather entirely to be expected. What is puzzling though is the fact that innovation appeared to occur substantially at all. This begs the question: what motivated the peak in patenting during the 1970s? It is unlikely that such a large response was pre-emptive when the UK was one of the developed nations least likely to enact new regulations.[61] To better understand what exactly was behind the rise in patenting a case

[59] In 1986 the Electricity Board announced desulphurisation retrofitting on 6GW of old plant, but in the United States desulphurisation was already in use at over 50GW of plant. Rubin, Yeh & Hounshell (2004), 'Experience Curves for power plant emission control technologies', pp.56

[60] Popp (2006), 'International innovation and diffusion of air pollution control technologies: the effects of NO_X and SO_2 regulation in the US, Japan, and Germany', pp.56

[61] Whilst actual changes to the UK's regulations for reducing NO_X and SO_2 emissions did not come until the mid-eighties, that some changes were expected is undeniable. For example, the 1979 Long Range Transboundary Air Pollution Convention may not have contained any binding commitments, but the Electricity Board still regarded it as a 'discernible weakening' of the UK's position as it did mean the UK had pledged in principle 'to limit and as far as possible gradually reduce and prevent air pollution'. As such whilst actual demand for abatement technologies did not come till 1986, a demand for new solutions and improvements to current ones almost certainly preceded then. But this was hardly unique to the UK. In fact the UK seemed one of the least likely amongst developed nations to adopt new standards in the

study of one of the key innovations in the patent data will be conducted. Before embarking on this though, a brief explanation of the unusual influx of Japanese patenting for NO_X abatement technologies is in order.

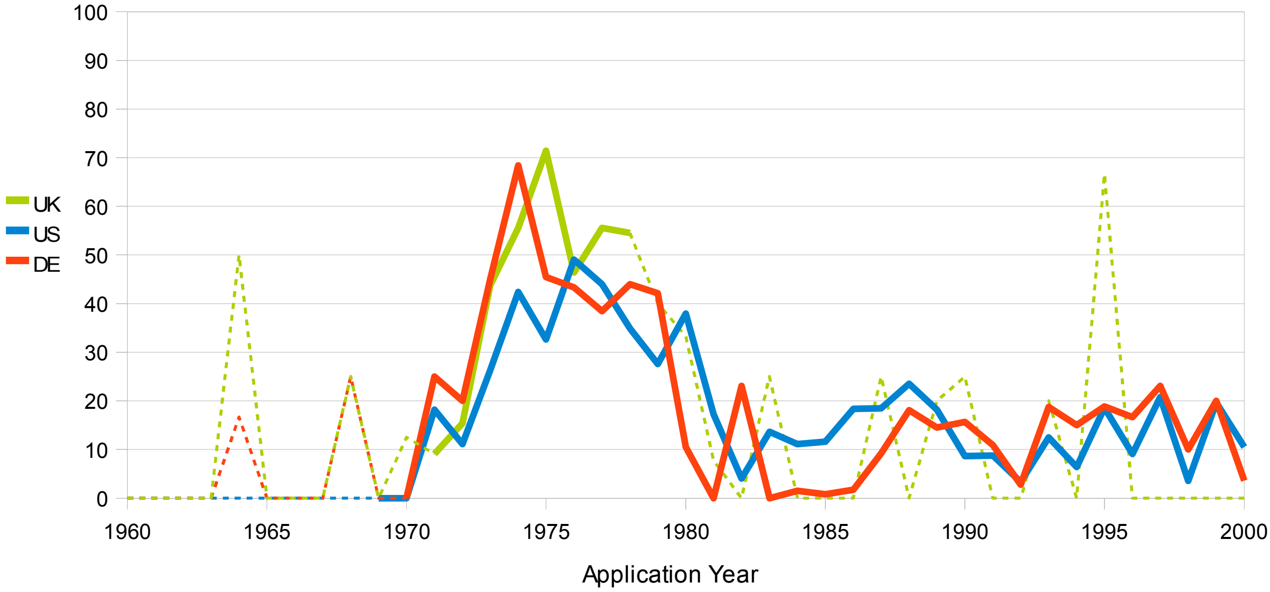
The Japanese anomaly

As noted earlier, Figure 9 suggests the spike in patenting activity for NO_X abatement technologies was driven by Japanese firms, not British ones. That innovations for reducing NO_X emissions should come from Japan is not necessarily surprising. In 1968 Japan became one of the first countries to introduce strict statutory controls on NO_X emissions for both new *and existing* coal-fired power plants. In light of this it seems reasonable to presume, as Popp (2006) does, that this meant the pressure to innovate on Japanese firms was stronger and occurred earlier than was the case elsewhere. However, just why Japanese patenting in Britain peaks during that 1970s is not clear. One question to ask is whether this was a purely British phenomenon. Did Japanese firms suddenly move to patent their NO_X abatement technologies only in Britain in the mid-seventies, or was this a global trend? Figure 14 shows the percentage of total patents for NO_X abatement technologies that were granted to Japanese firms in the UK, US and Germany.[62]

1970s.

[62] The dashed lines are spurious results because the total number of patents in that year was low (taken as below ten) making any percentage highly erratic. The sudden spike in the percentage for the UK in 1995 is indicative of this. Notably, the majority of the UK percentages are thus classed as spurious, indicating the generally low level of patenting compared with the US and Germany.

Figure 14: Percentage of Patents for NOX abatement technologies granted to Japanese firms



Normally for developed nations such as these one would expect domestic firms to be doing the majority of the patenting. Importantly though, in all three countries there is a significant rise in the percentage of patents granted to Japanese firms during the 1970s. The percentage then falls back to a stable level of around 10-20%. The fact that this trend is not limited to the UK suggests it is being driven by global or specifically Japanese factors. A plausible hypothesis may be the following. Japan was a pioneer in developing selective catalytic reduction technologies to reduce NO_X emissions due to its early adoption of strict NO_X standards from 1968 onwards.[63] This explains the rise in patenting globally as Japanese firms were ahead of technological developments elsewhere. It is possible they then sought to patent abroad in anticipation of other countries adopting similar NO_X regulations in the future. This also fits nicely with growing global concern over acid rain in the 1970s. Such a hypothesis is certainly plausible, but clearly needs a more detailed appraisal of the relevant innovating sector in Japan. The relationship should not, as is the norm in much of the literature, simply be assumed based on a correlation.

[63] Rubin, Yeh & Hounshell (2004), 'Experience Curves for power plant emission control technologies', pp.58

Unfortunately there is not scope for such a micro-level appraisal of Japanese firms here, but it is to a micro-level appraisal of British innovation in another abatement technology – fluidised-bed combustion – to which we now turn.

Case Study: Fluidised-bed Combustion

A possible explanation for the peak in patenting for NO_X abatement technologies has just been offered. However, in order to better understand what was causing the peak in UK patenting for SO_2 technologies, a more in-depth exploration of what caused British firms to innovate when they did is in order. Over half of all the patents identified as dealing with SO_2 abatement refer explicitly to fluidised-bed combustion (henceforth FBC) and as was noted from Figure 8, the spike in patenting for these technologies was driven by domestic firms. This was because during the 1970s the UK was considered a world leader in FBC research. As such understanding what was motivating progress in that particular technology is key to explaining the patenting trend and attempting to square it with the hypothesised relationship with environmental regulation.

Fluidised-bed combustion explained

Fluidised-beds are a special kind of furnace invented in the 1920s. Initially they were used for small industrial and chemical applications. It was not until the 1950s that coal was used as an input and only in the 1960s that the possibility of using them for large-scale electricity power generation was taken seriously. The basic concept is as follows:

> 'You take a boxful of sand. … You blow air up through the layer of sand from below. The rising air lifts the sand particles, until the sand churns and bubbles like a boiling fluid: a "fluidised bed." You then heat the churning particles up to incandescence ...[until] it looks like boiling lava. Any fuel – indeed anything even slightly combustible – that you drop into the incandescent bed will at once be ignited and burn. The heat released by the burning fuel will then keep the bed hot, and the start-up heating can cease.'[64]

Burning fuel in this manner has a number of advantages:

- Almost any fuel can be burnt in the bed, including cheap low grade coal, ash or even peat.
- Heat is transferred much more efficiently than by conventional burning meaning reduced input costs for a given energy output.
- Greater efficiency means smaller boilers can produce the same energy output, lowering the capital costs of converting from oil- or gas-fired boilers to coal ones.
- Greater efficiency also means combustion can take place at lower temperatures, reducing NO_X emissions.[65]
- If limestone is added to the bed it reacts with sulphur in the coal drastically reducing SO_2 emissions.

In light of these characteristics, FBC is clearly a technology that can significantly reduce NO_X and SO_2 emissions. However, it should be noted that there are numerous non-environmental benefits to FBC: reduced input costs, reduced capital conversion costs,

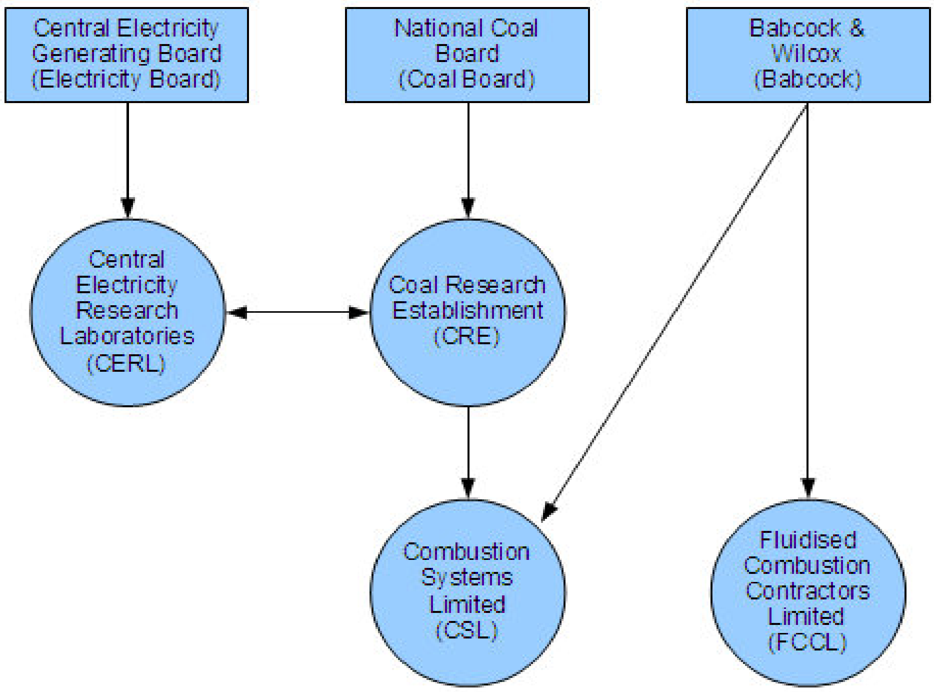
[64] Patterson, W. (1981), 'Hotbed of controversy', from *The Guardian,* 19th March 1981 pp.1 (online version)
[65] It seems odd that FBC technologies are neglected by the patents collected for NO_X abatement technologies. This may suggest a flaw in the patent classifications used.

reduced maintenance costs, greater versatility for inputs and possible applications. This provides the bulk of the answer as to why UK innovation occurred when it did.

The UK pioneers

Figure 15 shows how the innovating cluster identified for FBC research was organised.[66]

Figure 15: Relationships in British FBC research



At the start of our period the UK was the world leader in FBC research with the Coal Board and BP forming the focal point of activity in the 1960s. A small minority of researchers at the Electricity Board's Central Electricity Research Laboratories (henceforth CERL) and the Coal Board's Coal Research Establishment (henceforth CRE) continued work on the

[66] The rectangles at the top are the 'parent' firms or organisations. The circles represent their various subsidiaries that dealt exclusively with FBC research and development. Arrows point to important collaborative relationships.

technology throughout the 1960s despite a lack of interest in coal due to an influx of cheap oil and gas. In fact one contemporary refers to Raymond Hoy (one of the leading UK researchers in FBC) and his colleagues as 'pariahs', citing government cuts in funding as explaining the fall in their staff numbers from eighty to six by 1972.[67] Nevertheless, a memo from a meeting in 1976 between Babcock and the Coal Board describes the UK being 'ahead of the world' and a 'world leader' in FBC development.[68] It was this that led Babcock to set up Fluidised Combustion Contractors Limited (henceforth FCCL) in 1979. The UK's status as a pioneer of FBC research is therefore central to understanding why patenting occurred there at all. But that pioneer status was not induced by exogenous market forces. Rather it was largely the internal product of the actions of a few individuals continuing to research in spite of the UK government being enthralled with North Sea oil and gas and the expansion of nuclear power. The big question then, is why the sudden interest in FBC in the 1970s? The principle reason was the OPEC oil crisis.

OPEC

In 1973 the price of oil rocketed. Prior to this coal had been declining in popularity but almost overnight it became veritable black gold. Figure 16 shows the change in the price of coal relative to oil using 1969 as a base year.

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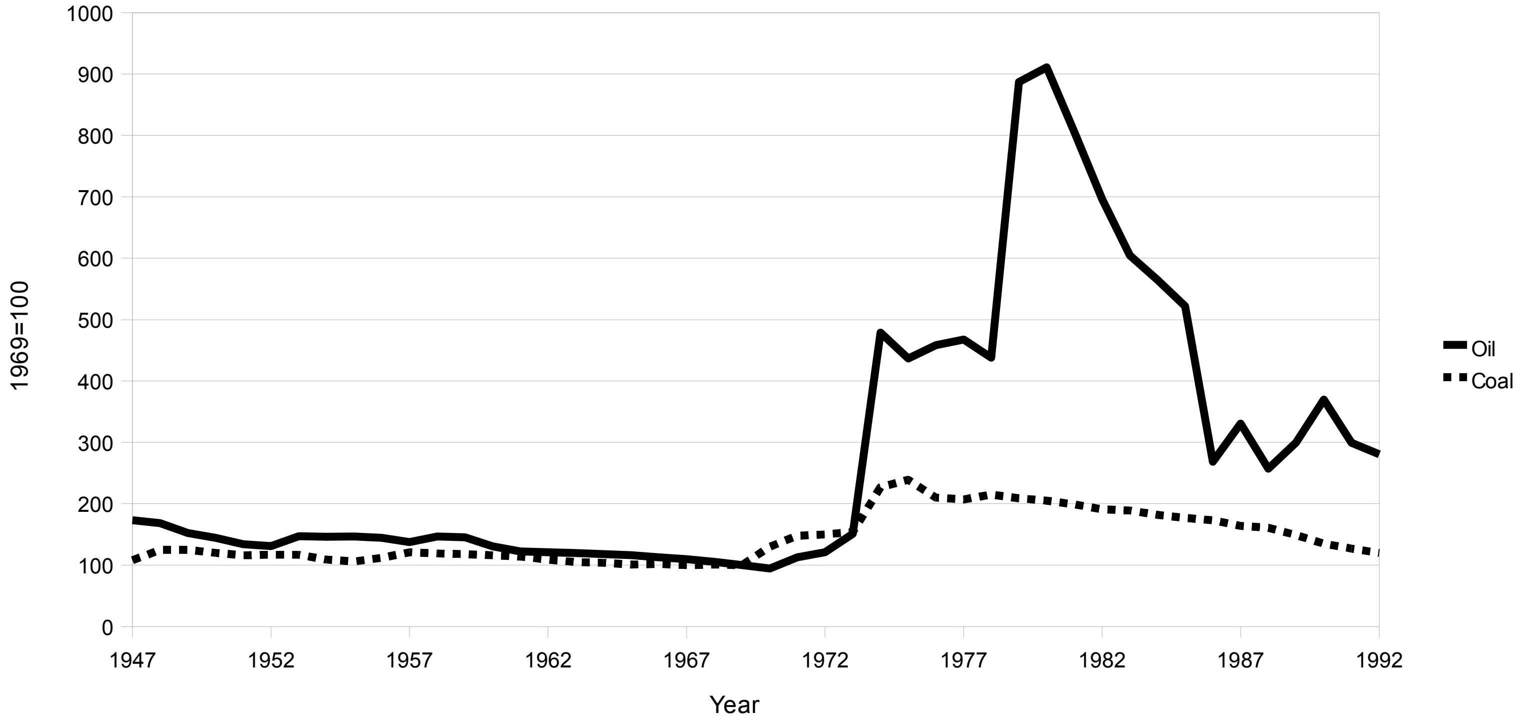
[67] Patterson, W. (1983), 'A new way to burn', *Science* 83 (April 1983), pp.2 (online version)

[68] UGD/309/20/22/2, 'Memorandum for Coal Board meeting, February 9th, 1976'

Figure 16: Oil and Coal Prices, 1947-1992[69]



Due to this dramatic change there was now a huge demand for a combustion technology that would allow current oil-fired boilers and furnaces to be converted cheaply to use coal. A meeting of the Babcock R&D committee in October 1973 referred to 'the fuel situation and the possible need to burn more solid fuel, some perhaps of poor quality', citing FBC as a potential remedy.[70] A further meeting two years later noted 'the current situation on fossil fuels was such as to promote a move back to coal' and as such an agreement had been reached to collaborate on FBC projects with CSL.[71] Normally switching a boiler from oil or gas to coal was expensive but FBC provided a solution, as the 1973 CRE Annual Report notes:

'With the improving position of coal there is substantial interest in the

69 Source: BP Statistical Review of World Energy (2011) and Ellerman (1994), 'The World Price of Coal'.
70 UGD/309/1/24/12, 'Inter-company R&D committee, minutes of meeting at Renfrew, 11th October 1973'
71 UGD/309/1/24/12, 'Inter-company R&D committee, minutes of meeting in Lynchburg, 14th October 1975'

> conversion of oil-fired boilers and furnaces to coal-firing. Direct substitution of the oil burner ... by a conventional coal stoker would reduce output by about 50%. A fluidised-bed burner is being developed ... with the objective of allowing conversion without loss of output'.[72]

Here the lock-in created by previously adopted oil and gas boilers made FBC, rather than conventional coal furnaces, a desirable technological solution. The distinctly non-environmental incentive for the development of FBC created by the OPEC crisis is a major reason for interest in the technology that matches the patenting spike during the 1970s.

Foreign demand

However, it was not just the UK that was moving back to coal. The impact of the OPEC crisis was a global one, and in fact it was foreign demand that was central to spurring UK innovation in FBC. The dominance of foreign demand is perhaps best highlighted by the extent of foreign contracted research done by the CRE and FCCL. The 1975 CRE Annual Report notes that they were researching FBC 'under contract to the [USA] Electric Power Research Institute'.[73] A report two years later reveals a similar story:

> 'A number of investigations have been sponsored by different organisations, including the US Dept. Energy, Curtiss-Wright (US), General Electric Co. (US), ... the American Electric Power Company, Babcock & Wilcox and Stal Laval (Sweden).'[74]

72 TNA/COAL/100/17, 'Coal Research Establishment 1973 Annual Report', pp.20
73 TNA/COAL/100/19, 'Coal Research Establishment 1975 Annual Report', pp.18
74 TNA/COAL/100/20, 'Coal Research Establishment 1977 Annual Report', pp.25

The situation is little different for the research done at CERL. Scientist there were 'engaged exclusively on contract research, most of which [was] carried out for organisations in the USA.'[75] At Babcock too, a reference list of the testwork and designs that FCCL was under contract for as of 1983 is dominated by customers from countries such as Canada, South Africa, Holland, and the USA.[76] This overseas demand varied depending on regional factors.[77] In fact, the extent of the diffusion of FBC technology appears to have been highly path dependent. Developing nations in Asia generally constructing new output capacity accounted for 52% of FBC capacity by 2000, compared to 26% and 22% for North America and Europe respectively, where the retrofitting of desulphurisation to existing plant was the dominant trend.[78] However, another very important regional factor driving foreign demand for research into FBC was the existence or prospect of new environmental regulations on SO_2 and NO_X emissions.

A role for environmental regulations?

As has already been discussed earlier, the UK approach to regulation over our period cannot really be viewed as a significant stimulus to FBC research. There was some interest in FBC from the UK government, but as has been shown by the extent of foreign contracting UK researchers needed to survive, it was on the whole lacking. But in light of this important role for foreign demand in pushing forward UK research into FBC, it is still

[75] TNA/COAL/100/21, 'Coal Research Establishment 1978 Annual Report', pp.29

[76] UGD/309/89/6/1, 'FCCL Fluidised Bed Combustion Reference List, 1983'

[77] The USA, Germany and China sought to exploit their plentiful stocks of poor quality coal using FBC in large part because it was the only technology capable of burning such low grade fuels efficiently. Scandinavian countries were especially attracted to FBC due to its ability to burn peat and because of their large paper and pulping industries. Koornneef, Junginger & Faaij (2007), 'Development of fluidized bed combustion: An overview of trends, performance and cost', pp.28

[78] Ibid. pp.29

possible to reintroduce environmental regulation as an inducing factor in our explanation. The introduction to a CSL catalogue puts the situation rather succinctly:

> '[FBC's] characteristics enable fuel – irrespective of its ash or sulphur contents – to be burned efficiently at high combustion intensities, while keeping the emission of SO_2 and NO_X well below any of the rigid standards which are either in force or proposed.'[79]

This convergence of a renewed demand to burn coal and a need to meet new emissions standards is the key to the sudden interest in FBC during the 1970s. For example, the 1970 Clean Air Act and its subsequent revisions set new limits on SO_2 emissions in the USA. This created a need for a combustion process which could allow the USA's abundant supplies of low quality, high sulphur coal to be burnt without breaching new standards on emissions. That the US regulator determined that FBC was one of the 'best available technologies' to meet those standards was a clear stimulus to innovation in the US.[80] Implicitly though, the extent of US contracting described earlier means environmental regulations there did have an impact on UK innovation in FBC. The 1978 CRE Annual Report points to a 'worldwide interest in ... FBC ... as a means of controlling emissions of sulphur oxides' as leading them to establishing two new laboratories to explore the idea.[81] Contrary to Popp (2006) then, the evidence presented here suggests foreign regulations, both enacted and anticipated, did weigh on the minds of innovators in the UK, particularly given the extent of foreign contracting mentioned earlier. As such there is still a place for environmental regulation in explaining the patenting spike, albeit a diminished one relative

[79] UGD/309/89/6/1, 'FCCL Fluidised Bed Combustion Reference List, 1983' and 'Selective list of Testwork/Designs already undertaken by FCCL'

[80] Banales-Lopez & Noberg-Bohm, (2002) 'Public Policy for energy technology innovation: A historical analysis of fluidised-bed combustion development in the USA' pp.1178

[81] TNA/COAL/100/21, 'Coal Research Establishment 1978 Annual Report', pp.19

to the impact of the OPEC crisis.

The decline of fluidised-bed combustion innovation in the UK

There are a number of possible explanations for the decline in UK patenting for FBC during the 1980s. The recovery of oil is the most obvious reason for a fall in demand for coal technologies such as FBC, especially given it provided the central explanation for its rise in the first place. In fact this is explicitly acknowledged by the CRE in their 1987 Annual Report.[82] However, there were arguably other factors at work as well: foreign demand and investment for FBC far exceeding that of the UK's or the UK's poor climate for innovation generally are both possible reasons that require exploration.

Broad indictments of UK industrial innovation are not new; the economic history of Britain's decline from being the 'workshop of the world' is littered with them.[83] In keeping with this Pavitt paints a rather dreary picture of the UK's attitude to innovation and industrial policy in 1980.[84] As well as highlighting the flagging performance of UK heavy electrical equipment producers, he identifies 'a heavy concentration of innovative activities … in aerospace and other defence-related activities, [but] … small innovative expenditures and poor export performance in many other sectors of the economy.'[85] Freeman & Soete (1997) point to the same overemphasis on military, nuclear and space programmes and its drain on environmental and energy orientated research, with roughly 60% of the UK's

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82 The CRE attempted to remain optimistic, stating that 'despite these setbacks [caused by the fall in oil prices] the short/medium term prospects look reasonably encouraging.' TNA/COAL/100/28, 'Coal Research Establishment 1986 Annual Report', pp.2

83 See for example, Aldcroft (1964) 'The Entrepreneur and the British Economy, 1870-1914'; Crafts (1998) 'Forging Ahead and Falling Behind: The Rise and Relative Decline of the First Industrial Nation' and Broadberry & Crafts (1990) 'Explaining Anglo-American Productivity Differences in the Mid-Twentieth Century'.

84 Pavitt (1980), *Technical Innovation and British Economic Performance*

85 Ibid. pp.9

public R&D budget going to defence and aerospace across the period in question.[86] In a study of the capacity of the institutions in different nations to foster innovation, the UK was classed as a 'middle tier' country whose innovative capacity remained fairly unchanged between 1978 and 1995.[87] This contrasts with 'leading innovator' countries such as the USA who maintained its high level, and Germany, Japan and Sweden who all joined it following marked growth in their capacity.[88]

The extent to which these broad generalisations about national institutions and funding are relevant for FBC innovation is difficult to discern. Britain's disproportionately large investment in nuclear technologies is certainly one element of public policy that could be viewed as dousing funding and demand for FBC.[89] The 1985 CRE Annual Report notes the competitive threat to coal technologies that the increasing use of nuclear posed.[90] It is also telling that in 1984 the Electricity Board proposed new nuclear power stations, rather than more technologically sophisticated coal ones.[91] This emphasis on alternative fuels instead of coal technologies saw UK expenditures on pollution abatement control as a percentage of GDP actually fall from 1985 to 1990 from 0.7 to 0.4%. This contrasts with Germany and the US where the level remained steady at around 1.5%.[92] In fact, the decline of coal power generation relative to gas and nuclear sources following the privatisation of the power industry in 1990 (see Figure 2) was the main reason the UK was able to meet its SO_2 and NO_X targets.[93] The detrimental impact of poor UK funding for FBC innovation is highlighted in a memorandum for a Coal Board meeting in 1976 to discuss

86 Freeman & Soete (1997), *The Economics of Industrial Innovation,* pp.394
87 Furman & Hayes (2004), 'Catching up or standing still? National innovative productivity among 'follower' countries,1978–1999', pp.1345
88 Ibid.
89 In Figures 3 and 4 the graphs are for the EU as a whole. For the UK specifically the light orange and dark blue shaded sections (representing reductions due to increased nuclear and changing to alternative fossil fuels such as gas) would be relatively larger.
90 TNA/COAL/100/28, 'Coal Research Establishment 1985 Annual Report', pp.2
91 Sheail (1991), *Power in Trust: The Environmental History of the Central Electricity Generating Board*, pp.256
92 OECD (1993), *OECD Environment Data 1993*, Table 14.2A
93 Eames (2000), 'The Large Combustion Plant Directive (88/609/EEC): An Effective Instrument For Pollution Abatement?' pp.36

funding for future FBC projects:

> 'We have also had direct discussions with the Electricity Board and Utility Companies in Sweden, America and Canada. The Dept. of Industry rejected our application because of shortage of funds and lack of interest from the Electricity Board.'[94]

The same memorandum then goes on to note that 'other large-scale experimental plants are being built in America and Germany, but we are currently ahead of the World'.[95] That lead continues to look ever more precarious in a joint paper by Babcock and General Electric Company in 1976 which points out that 'the timing for commercialisation of FBC is likely to have a significant effect on the market share secured by the developers of the British technology. At the present time large sums are being spent in the development of FBC, particularly in Germany and North America.'[96] These 'large sums' point to a very different approach abroad. The classification of FBC as a 'best available technology' in the USA has already been mentioned, but government sponsored demonstrations and utilities regulation reform were also key to encouraging the development and diffusion of FBC in America.[97]

Now, to say that there was no state support in the UK for FBC would be wrong – probably one of the largest single expenditures by the Electricity Board on research into reducing acid rain emissions was the 50% share they contributed to a £28 million experimental FBC programme at Grimethorpe.[98] But such support was patchy and seems

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94 UGD/309/20/22/2, 'Memorandum for Coal Board meeting, February 9th, 1976'
95 Ibid.
96 UGD/309/20/22/2, 'Memorandum for Coal Board meeting, February 9th, 1976'
97 Banales-Lopez & Noberg-Bohm (2002), 'Public Policy for energy technology innovation: A historical analysis of fluidised-bed combustion development in the USA'
98 Sheail (1991), *Power in Trust: The Environmental History of the Central Electricity Generating Board*, pp.252

less significant in light of the Electricity Board's total annual research budget of over £200 million by 1987.[99] Instead the Electricity Board and Coal Board concentrated consistent sizeable portions of their research efforts on discovering the effects of acid rain, rather than on the technologies required to combat it.[100] As late as 1990, FBC was viewed as a 'relatively untried technology, particularly on large power plants'.[101] desulphurisation, on the other hand, had been deployed in the USA throughout the 1970s on almost 50 power stations with a combined generating capacity of approximately 28GW.[102] Following additional joint Electricity Board/Coal Board assessments of the technology in 1983 and in the face of falling oil prices, there was growing acceptance that desulphurisation and low NO_X boilers would provide the *technological* aspect of the UK's acid rain response.[103] Waning support for FBC in the 1980s is therefore unsurprising and it has resulted in the bulk of today's FBC market going to American, German and Scandinavian firms.[104]

99 Ibid. pp.255

100 Such efforts included a jointly funded £5 million project for collaboration between the Royal Society and Swedish and Norwegian Academies; a study on lake acidification at Loch Fleet in Scotland; a number of controlled experiments at CERL into the effects of acid rain exposure on trees and crops; and ongoing basic coal science research at CRE. This is not to say that this was a bad policy. In fact it has been argued by Sheal (1991) and Eames (2002) that the UK's measured effects-based response turned out to be more efficient than Germany's sudden over-zealous move to unilaterally install desulphurisation as of 1983. Nevertheless, this does not alter the fact that the UK response was not conducive to FBC development.

101 Roberts ,Liss & Saunders (1990), *Power Generation and the Environment*, pp.72

102 Rubin, Yeh & Hounshell (2004), 'Experience Curves for power plant emission control technologies', pp.56

103 TNA/COAL/100/25, 'Coal Research Establishment 1985 Annual Report'

104 Koornneef, Junginger & Faaij (2007), 'Development of fluidized bed combustion: An overview of trends, performance and cost', pp.33

Conclusion

This study has sought to understand whether environmental legislation in the UK to combat acid rain succeeded in inducing innovation. It was predicted that due to the slow adoption of stricter regulations on SO_2 and NO_X, and the manner in which those regulations were constructed and imposed, innovation in the UK should have been fairly minimal. It was certainly not predicted that there would be any sudden rises in innovative activity, particularly following actual changes to regulatory stringency. To assess whether this was the case, patent data was used as an indicator for innovation. Interestingly, the patent data collected did appear to show large increases in innovation during the 1970s, with patenting for both NO_X and SO_2 abatement technologies rising to a peak, before declining into the 1980s. This clearly does not fit with the traditional view of induced innovation following regulation. An understanding of the unique nature of British regulation helps explain the generally low level of patenting and the lack of a spike in the 1980s, but there must have been other factors at work in the 1970s. For NO_X abatement technologies, a hypothesis was offered that because the majority of patenting was by Japanese firms, the spike represented Japanese firms seeking to take advantage of the early lead they had in that field. That early lead is almost certainly attributable to the passage of strict NO_X regulations in Japan from 1968 onwards, although this requires greater exploration. Also, because similar patenting trends were observed for both the US and Germany, it is plausible to suggest that the influx of Japanese patenting in the 1970s was a global, rather than purely British, phenomenon. However, this still left the peak in patenting for SO_2 abatement technologies which was largely driven by domestic innovators. To explain this apparent anomaly it was necessary to embark on an in-depth historical exploration of the innovators responsible for one of the most prominent abatement technologies identified in the patent data: fluidised-bed combustion. Evidence from a number of public and private centres for innovation in FBC revealed that there were two key factors that had been driving interest in the technology during the 1970s: the OPEC oil crisis and, to a lesser extent, new or proposed environmental regulations, particularly overseas. Both combined to create a huge demand for FBC as it could burn coal and other cheap, dirty fuels in an efficient and clean manner, reducing input and conversion costs. However, whilst Britain's early lead in FBC research helped make the spike in activity during the 1970s possible, falling oil prices, the concentration of demand overseas, a poor domestic environment for innovation, and a solution to acid rain based on other technologies and nuclear power, all caused UK innovation in FBC to stagnate by the end of the 1980s. In fact, the dearth of UK patenting for abatement technologies other than FBC – technologies in which it did not have a head start and which did not have powerful non-environmental benefits – is consistent with the depiction of British regulation presented here. Still, the importance of environmental regulations abroad to explaining the actions of Japanese firms and foreign demand for FBC, does mean they still have a place as an inducer of innovation. The key point to note is that simply viewing patents as little more than a tallied number can easily lead to an erroneous interpretation of the role of environmental regulations. Only through a historically informed micro-level analysis that seeks to understand the context underpinning innovative decisions can a clearer understanding of the links between environmental regulation and technological change be reached.

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[Abbreviated to TNA/COAL/100/15 etc.]

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[Abbreviated to TNA/AT/99/19 etc.]

The National Archives (TNA); Records of the Board of Trade and of successor and related

bodies (BT); Board of Trade and successors: Alkali Inspectorate and successors: Unregistered Records (328); Various documents (88, 125)

[Abbreviated to TNA/BT/328.88 etc.]

University of Glasgow Archives (UGD309); Records of Babcock Energy Ltd, boilermakers and engineers, London, England and Glasgow, Scotland (1); Document type: minutes of meetings (24); Various documents (12,13)

[Abbreviated to UGD309/1/24/12 etc.]

University of Glasgow Archives (UGD309); Records of Combustion Systems Ltd (20); Various document types and numbers (6/1, 22/2 and 29/1)

[Abbreviated to UGD309/20/22/2 etc.]

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[Abbreviated to UGD309/20/22/2 etc.]

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[Abbreviated to PSA/1170 etc.]

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Appendices

Appendix A: Abbreviations

Public agencies:

IAPI = Industrial Air Pollution Inspectorate

HMIP = Her Majesty's Inspectorate of Pollution

Electricity Board = Central Electricity Generating Board

Coal Board = National Coal Board

International bodies:

EEC = European Economic Community

UN = United Nations

UNECE = United Nations Economic Commission for Europe

Patenting:

EPO = European Patent Office

ECLA = European Patent Classification system

FBC related firms and organisations:

CERL = Electricity Board's Central Electricity Research Laboratories

CRE = Coal Board's Coal Research Establishment

BP = British Petroleum

Babcock = Babcock & Wilcox Ltd

FCCL = Babcock's Fluidised Combustion Contractors Ltd

CSL = Combustion Systems Ltd

Abatement technologies:

Desulphurisation = Flue Gas Desulphurisation

FBC = Fluidised-Bed Combustion

Pollutant gases:

NO_X = nitrous oxides (refers collectively to NO and NO_2)

SO_2 = sulphur dioxide

CO_2 = carbon dioxide

Miscellaneous Jargon:

BPM = best practicable means

Appendix B: Patent data classifications

The following ECLA patent data classifications were used to search for the relevant pollution abatement technologies in the EPO's esp@cenet database.

The ECLA classification system is particularly useful as it is more detailed than the standard IPC system as it means technologies relating specifically to SO_2 or NO_X can be identified. The classifications used are taken from the 'Appendix B' of Popp (2006) and further information on the procedure used in that paper to identify said classifications can be found in 'Appendix A'. Both can be found here: http://www.nber.org/papers/w10643

Unfortunately it was not clear how the patent classifications under the heading 'General Pollution Control' had been selected and how exactly they were intended to be included in the analysis. A quick search of patents in these categories revealed inventions seemingly unrelated to the specific pollutants in question. As such these classifications have been omitted.

NO_X pollution control:

F23C 6/04B

F23C 6/04B1

F23C 9

B01D 53/56

B01D 53/56D

B01D 53/60

B01D 53/86F2

B01D 53/86F2C

B01D 53/86F2D

B01D 53/86G

B01J 29/06D2E

SO_2 pollution control:

B01D 53/14H8

B01D 53/50

B01D 53/86B4

F23C 10

Appendix C: Summary of developments in UK regulation

Table 1: Selected notable UK developments in pollution control for SO_2 and NO_X emissions[105]	
Year:	Notes:
1958	Remit of regulator expanded to include all power station emissions. Electricity Board established.
1972	Sweden raises 'acid rain' issue at United Nations Conference. 1972 Station Environment Steering Committee ambivalent: 'Left to itself, there seemed little risk, despite increasing public concern over the environment, of the United Kingdom implementing further restrictions on SO_2 emissions.'
1974	UK Control of Pollution Act requires all polluters to readily provide information on their emissions.
1979	UK signs United Nations Long Range Transboundary Air Pollution Convention committing to cooperation on research and policy as well as abatement *in principle*.
1980	European Directive on air quality standards (80/779/EEC) sets *guide* limit values for pollutants.
1983	Regulator regards desulphurisation as now being 'best practicable means' (BPM) given it is already in widespread use in Japan and the US. Electricity Board reluctant to acquiesce and adopts strategy of 'visible movement with minimum penalty' so as to avoid direct government regulation.
1984	UK adopts European Air Framework Directive 'on combating of air pollution from industrial plants' (84/360/EEC). For the first time UK has an obligation to provide emissions data to Europe and meet its NO_X and SO_2 reduction targets. Electricity Board discuss with government how reductions could be achieved by increasing nuclear power capacity instead of fitting desulphurisation.
1985	1st UNECE Sulphur (Helsinki) Protocol commits signatories to a 30% SO_2 reduction on 1980 levels by 1993; the so-called '30 percent club'. UK does not sign.
1986	Electricity Board announce that desulphurisation to reduce SO_2 emissions will be fitted to all new power stations and 6GW of old power stations to be retrofitted 1987-1996. Fitting of low NO_X burners to all new and 23GW of old power stations. FBC shows promise but no chance of being used to meet deadlines in 1990s. No plans to use selective catalytic reduction technologies.
1988	European Large Combustion Plants Directive adopted (88/609/EEC) which sets tougher limits for new plant and overall national emissions ceilings.
1990	UK Environmental Protection Act. Privatisation of UK electrical utilities. 1984 Air Frameworks Directive implemented.
1994	UK signs UNECE Oslo Protocol which sets new tougher national targets for SO_2 emissions.

[105] Sources: Sheail (1991), *Power in Trust: The Environmental History of the Central Electricity Generating Board*; Eames (2001), 'The Large Combustion Plant Directive (88/609/EEC): An Effective Instrument For Pollution Abatement?'; Vernon (1988), *Emissions standards for coal-fired plants*; and Sloss (2003), *Trends in emission standards*.