Knowledge in pollution-saving technological change

A thesis submitted to the Department of Geography and Environment of the London School of Economics and Political Science for the degree of Doctor of Philosophy

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Declaration

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Thesis abstract

This thesis looks at the role that technical knowledge plays in the transition in industry away from pollution-intensive production methods. It uses econometric techniques and qualitative analysis to test three aspects of the relationship between knowledge and pollution-saving technological change-related outcomes, all in the context of US industry, and all with respect to conventional pollutants. The first paper observes that the level of industrial environmental R&D spending steadily declined from the late 1970s onward. Employing an estimation model with industry fixed effects, the hypothesis is tested that this decline was the result of the conditioning effect of greater flexibility in the design of the environmental policy on the environmental regulatory burden born by industry. The second paper investigates the sources of the change in SO2 intensity of electricity production undergone by electric power plants under the SO2 cap and trade program. Mixed methods including quantile regression are used to compare the effect of frontier technical knowledge on the extent of change undergone, relative to the effect of knowledge un-intensive techniques. The third paper investigates why a small number of inventions aimed at controlling pollution from automobiles turned out to be so much more technologically influential than the great majority of comparable inventions, which exerted very little technological influence at all. Negative binomial regression is used to test the effect of the composition of the stock of knowledge that the automobile companies brought to bear on the inventive process. These studies find that pollution-saving technological change is characterised more by the repurposing and adaptation of existing knowledge and by the churn among existing technologies, than by universal technological advance in dedicated environmental technologies. The implications for climate mitigation policy are discussed in the conclusions.

Table of contents

Tables and figures

Introduction

Paper 1

Paper 2

Paper 3

Introduction

One of the driving forces behind technological advance is the production and accumulation of technical knowledge. This research investigates the role that technical knowledge has played in technological change with respect to pollution emissions in the past, and the role that technical knowledge might play in technological change with respect to greenhouse gas (GHG) pollution in the future.

This research makes several original contributions. It uses new quantitative datasets to test three novel hypotheses about the role that knowledge plays in this specific kind of technological change: pollution-saving technological change. To test these hypotheses it uses method to 'suspend' the influence that the design of the policy instrument for controlling emissions tends to exert on the role of knowledge in this kind of change. The findings that flow from this research suggest that R&D and learning play a patterned and systematic role in pollution-saving technological change. On the basis of the body of evidence considered here, 'advanced' pollution-saving knowledge has historically played a smaller and more nuanced role in firms' technical responses to pollution control regulation than might be expected. When firms are left to decide their own technical change pathways, they go to length to adapt and repurpose the knowledge and technologies they already possess to the new problem of conforming to pollution control regulation. Only when firms have exhausted the technical possibilities of their pre-existing knowledge do they begin to search for new knowledge. In the subsequent process of learning and discovery firms tend to disfavour knowledge and technology that has no other purpose than controlling pollution. A pre-existing knowledge stock that is broad and diverse benefits the learning and discovery process more than a pre-existing knowledge stock that is narrow and specialised. This pattern sheds light on how knowledge-related factors shape pollution-saving technological change within the broader growth process.

1. Motivation

Economists have observed for centuries that advances in science and technology pass in lockstep with rising levels of human welfare. Economists have also wondered for centuries whether advances in science and technology will be able to sustain an indefinite rise in human welfare levels despite a finite and diminishing environmental resource base (Arrow et al 1995; Daly 1992; Ekins 2000; Malthus 1798; Meadows 1972; Neumayer

2003; Pearce and Warford 1993; Solow 1991). A key question is whether technological progress can be quick enough to compensate for the environmental costs of growth. This question sits today amidst worrying scientific evidence about the impact on human welfare that a destabilised climate could cause. At the heart of the question of how to sanitize the process of wealth creation is therefore technical knowledge: its production, its accumulation, its absorption, its variety and its embodiment in economic action.

In the last five years there has been a burst of interest in the role of knowledge and technology in mitigating the release of GHG emissions in the context of long run growth. Brock and Taylor (2010) for example set up a modified 'green' version of the Solow growth model that includes a constant rate of technological progress in pollution abatement. Brock and Taylor assume that this variety of technological progress advances at a constant rate, but they do not explore the role of learning, R&D and technical knowledge in that advance. Similarly, Acemoglu et al (2012) develop a model in which knowledge accumulation through R&D is both endogenous to the production activities of firms and 'directed' by policy toward a clean input sector. In their model, the redirection of R&D activity by policy from the dirty sector to the clean sector makes it possible for growth to be sustained indefinitely. Acemoglu et al's model is not based on empirical evidence about the relationship between R&D activity and clean production, however. Aghion and Howitt (1999) and Aghion, Hemous and Veugelers (2009) recognise that the 'technology of innovation' is relatively clean compared to the technology of producing tangible capital goods. They model a growth process in which sustained growth is not beyond the realm of possibility in an economy that continues to produce a steady flow of knowledge capital geared toward environmental protection. Their model would also benefit from empirical evidence about the relationship between knowledge and environmentally favourable growth outcomes. All of these recent contributions situate pollution-saving technological change at the heart of a cleaner growth process. They tend to pay less attention to the role that technical knowledge has played in cleaner growth empirically.

The aim of the present research is to investigate the role that scientific and engineering ('technical') knowledge plays in the process by which industry improves its productivity with respect to pollution emissions. A sustained increase in this kind of productivity would seem to be essential for a growth process that could be sustained over the very long term. Modern growth theory suggests that the accumulation and application of technical knowledge should be a defining feature in this kind of productivity improvement.

One reason that R&D and learning sit at the heart of these models of indefinitely sustained growth is that these growth models themselves are underpinned by the principles of endogenous growth theory. Endogenous growth theory has moved R&D and learning even closer to the core of the growth process (Aghion and Howitt 1999; Grossman and Helpman 1997). Some of the biggest advances in growth theory in the last 25 years have come from integrating the effects of learning, R&D and knowledge accumulation more fully into the account of how growth happens when it does, and why growth happens in some places but not others (Lucas 1988; Romer 1986). Technological advance also played a role in the neoclassical account of growth (Solow 1956; Nordhaus 1969). The difference in that account was that progress in the chemical, biological and engineering sciences ticked steadily along at a constant rate in the background. Firms benefitted from that constant progress by being able to combine capital and labour in increasingly productive ways. However, firms were unable to influence the rate of progress themselves. There was no feedback linking what firms did themselves in terms of learning or R&D to the economy-wide rate of technological progress.

Endogenous growth theory broke from the old assumption of a constant rate of technological progress (Romer 1994). The rate of progress could now be influenced not just by autonomous scientific advance, but by what firms actually did themselves. In the endogenous growth theory account, firms discover ways to combine inputs more productively by investing in R&D and engaging in learning-by-doing. R&D and learning-by-doing lead to the accumulation of a new kind of capital, knowledge capital. Knowledge capital raises productivity by augmenting how effectively firms use labour and capital. Knowledge capital is an unusual kind of capital because it is expensive to produce but comparably easy and inexpensive to reproduce. This means that the R&D and learning that one firm invests in benefits not just the productivity of the firm that has made the investment, but also the productivity of other firms in the economy that did not make the investment, both competitors and collaborators, through the spillover of knowledge to them (Antonelli 2002; Hall, Mairesse and Mohnen 2009; Jaffe, Trajtenberg and Fogarty 2000; Romer 1987).

This understanding of the endogenous role of learning and R&D in the growth process has strongly influenced current thinking about the role that knowledge plays in growth with respect to pollution. However, there is a case to be made that it may not be valid to extend the core endogenous growth theory logic to theories and policies concerned with cleaner, ‘greener’ growth.

Endogenous growth theory makes a convincing case that universally new technical knowledge plays an important role in helping firms derive more output from each unit of 'ordinary' inputs like labour and capital. But it may not follow that technical knowledge plays the same role in helping firms derive more output from each unit of an 'environmental' input. Productivity gains with respect to an environmental input may involve a different kind of knowledge, or involve using knowledge in a different way, or involve finding substitutes for acquiring new knowledge, or involve less learning and R&D with respect to controlling pollution altogether. Instead, environmental productivity gains may rely more on firms and industries shifting and switching between existing technologies. Productivity gains may arise more through the recycling and repurposing of existing knowledge than through the discovery and refinement of universally new knowledge. It may be incorrect to generalize endogenous growth theory's predictions about the effect of knowledge on ordinary productivity, to the effect of knowledge on environmental productivity.

A better understanding of the role of knowledge in pollution-saving technological change comes from appreciating the special characteristics of the environment as a production input. This research frames the environment as an 'input' that a firm or industry uses in its production process. This input is the capacity of the environment to assimilate pollution emissions (Cropper and Oats 1992; Lopez 1994). The environment as an input has features that set it apart from 'ordinary' inputs like labour and capital. It is a special kind of input. For example:

- It is possible for many firms to use the environment as a disposal sink all at once without impinging strongly on one another's use of that resource. The environment as an input tends to be non-rivalling, at least in the short term.
- It is generally costless for a firm to use the environment as a disposal sink in the absence of regulation.
- In the presence of regulation, the cost signal connected to using the environment is only as valid as the enforcement action of the regulator.
- Firms use labour and capital in innumerably different ways, however all firms use the environment in the same way, as a disposal sink.

These special characteristics of the environment as a production input motivate a closer look at the role of knowledge in the change process that reduces the use of that input. Due to the unique characteristics of the environment as an input there is reason to believe that learning and R&D play quite a different role in this specific change process than endogenous growth theory might predict.

2. Technology, industry and environment in broader perspective

Several research themes running through the science, technology and innovation studies (STIS), economic history and business and environment studies literatures shed light on the role that knowledge plays in pollution-saving technological change. This section discusses three themes from these literatures: (1) the differences between incremental and radical innovation events, (2) the distinction between 'hard' technology and 'soft' organisational changes that interact to shape the responses of firms and industries to pollution, and (3) the relationship between pollution reduction responses that involve end-of-pipe controls versus those that involve integrated, clean technology approaches. These three themes help to elaborate the ways that knowledge and technology have mediated the two-way relationship between industry and environment in the past, and they give some indication of the role that knowledge and technology are likely to play in facilitating deep GHG emission reductions in future.

To appreciate the differences between incremental and radical innovation events consider a thought experiment involving a factory in complete initial technological stasis. Imagine that the factory produces a single good and that the production method it uses to produce the good, the technology, never changes. Other things at the factory change, but not the production technology. Factory workers come and go but their skill sets never improve. Machinery eventually wears out and breaks down, and when it does, it gets replaced with the exact same type of machinery. The factory sells the good it produces to consumers who never get tired of the quality or price of the good. Also imagine that the factory pollutes but that the government does not require the factory to do anything about its pollution. The basic state of knowledge that underpins the factory's production technology stays exactly the same.

Incremental and radical innovation events mark different degrees of departure from some previous knowledge-state of production. Incremental innovation events mark small departures from an initial state of production and radical innovation events mark large ones. The different degrees of departure are easier to appreciate from a hypothetical initial state of technological stasis. An incremental innovation event might involve a factory worker learning how to operate a machine more skilfully. Historical experience shows that incremental innovation events tend to originate from on-the-job experience or from informal observation, rather than from deliberate, directed R&D (Arrow 1962; Dosi 1988).

Incremental innovation events tend to emerge in response to changes in the producer's external operating environment, for example a new requirement by government that a producer reduce its pollution emissions (Ashford 1993; Mowrey and Rosenberg 1979; Konnola and Unruh 2007). Incremental innovation events tend to fit comfortably within broader dominant technological forms and they tend not to be threatening to those forms. Rather than being threatening, incremental innovation events tend to refine dominant technological forms in ways that improve their functionality or usefulness (Abernathy 1978; Freeman and Perez 1988). Dozens of incremental innovation events can occur at a factory in the working life of a single worker.

Because incremental innovations are complementary and non-disruptive to prevailing dominant technologies they tend to be inexpensive to adopt. In the hypothetical factory example an incremental innovation introduced by a worker might pass from a suggestion by a worker into factory-wide production practice relatively quickly. If enough incremental innovation events were to occur at the factory then the consumers of the factory's good might begin to notice price or quality differences in the good.

When industrial facilities have faced the task of complying with pollution control regulation in the past, they have tended to prefer incremental solutions of one kind or another. These solutions might involve end-of-pipe approaches or process-integrated approaches, but they tend overall to be characterised by gradual, non-disruptive changes to the facility or production process. End-of-pipe solutions emphasise capturing regulated substances before they enter the environment (Lee and Rhee 2006). Filters or pollution-removal equipment is installed to remove pollution from the waste stream (Popp 2012). Catalytic converters on automobiles, flue gas desulphurisation units on power plants, and incinerating ozone depleting substances are examples of end-of-pipe solutions. End-of-pipe solutions tend to affect only the physical asset- and raw material flow-aspects of the facility. They tend not to alter the facility or firm's existing management or organisational structures or basic production strategy (Barney 1991). Once end-of-pipe hardware is installed, the way that the product or service is produced and delivered remains unchanged (Kemp 1993).

Process-integrated approaches by contrast place more emphasis on preventing pollution from being created in the first place (OECD 1987; Porter and van der Linde 1995; Russou and Foutes 1997). Integrated solutions may involve substituting clean materials or process agents for problematic or toxic ones. They may involve fine-tuning existing production equipment or re-working production process steps. The technical changes that flow from integrated solutions tend to penetrate the production process more so than end-of-pipe approaches (Theyel 2000). Process-integrated changes can be minor, incremental and non-disruptive, but a distinguishing feature is that they involve some consideration by the facility of the original source of pollution.

One reason that industrial facilities have favoured incremental solutions, either end-of-pipe or process-integrated, is that incremental solutions carry a smaller learning burden than non-incremental or radical ones. End-of-pipe solutions in particular 'contain' the learning burden to a separate piece of equipment or a separate process that does not perturb the core knowledge structures that the firm depends on for its revenue stream. These knowledge structures insofar as they define the firm's core production technology are often finely tuned and proprietary and therefore sensitive to alteration.

The amount of learning that a firm engages in when responding to a pollution reduction requirement specifically tends to be proportional to the depth of the reduction required by the regulator for compliance. For example, Murphy and Gouldson (2000) investigated the compliance response of chemicals and cement facilities in England and Wales to Integrated Pollution Control (IPC) regulation. Murphy and Gouldson found that facility managers consistently eschewed deeper, non-incremental changes in favour of simple, incremental, non-disruptive ones. They write:

> [This] research also indicates that because IPC is not associated with challenging targets for environmental improvement in the medium- to long-term it fails to establish the imperative for environmental improvement. As a result environmental issues have yet to be adopted as a strategic concern in regulated companies. One outcome of this is that the opportunities for more radical forms of environmental improvement are unlikely to be exploited. (2000: 34)

The industrial facilities considered in Murphy and Gouldson's study tended to resist more radical forms of technical change because more radical forms of change were not strictly necessary. Incremental changes were sufficient to meet the stringency of the targets set for them by IPC regulation. Production process 'tweaks' were commensurate with the shallow learning that was required to comply. More challenging pollution reduction targets on the other hand might have triggered deeper learning. Deeper learning might have led to fundamentally re-designed products and production processes that eliminate pollution and other environmentally harmful effects at the product, process or business model conception stage (Hawken et al 1999; McDonough and Braungart 2002).

Frequently, some of the most widely adopted, least disruptive, and cheapest changes for dealing with pollution do not involve 'hard' physical-material technical changes at all but soft' organisational changes. Organisational changes include appointing a dedicated environmental manager (Theyel 2000), moving environmental impact considerations higher up in the business decision making process or further back in the business planning process (Russo and Harrison 2005), adopting formal environmental management systems (Florida and Davison 2001), setting environmental standards for suppliers, and finding ways to incentivise employees to come forward with environmental improvement suggestions (Shrivastava 1996; Theyel 2000). One reason that organisational changes are attractive to firms is that they exploit well-honed 'soft' capabilities to manage people and processes that the firm already possesses. Re-jigging existing managerial hierarchies, existing performance management systems, existing planning frameworks, and existing accounting and inventory procedures to address the pollution problem can be more efficient and effective than inventing new ones. Soft approaches can be cheaper than new capital outlays. The ease of uptake of soft organisational technologies is consistent with the idea that these technologies allow firms to re-purpose and adapt their existing capabilities to new problems in ways that involve a minimum amount of new learning effort.

While organisational changes are often cheap and easy to implement, some argue that they run the risk of locking in 'inferior' pollution reduction solutions in the same way that positive network externalities feeding back from a large number of users can lock in 'inferior' physical-material technologies (Arthur 1989; David 1989). Organisational technologies like environmental management systems may improve firm environmental performance initially but also introduce structures that inhibit deeper learning and longer term improvements. Environmental management systems can institutionalise accounting standards, consulting relationships, and regulatory structures that perpetuate a focus on squeezing ever smaller environmental gains out of existing production systems rather than a focus on searching for altogether new, discontinuous, fundamentally clean production systems (Christensen 1997; Konnola and Unruh 2007). This sort of soft technology lock in problem underlines the point that whether or not a 'hard' technology makes economic sense to a firm partly depends on the organisational and management structures it already has in place (Nelson and Sampat 2001) as well as the short- or long-sightedness of the regulators' own demands (Kemp 1997).

Non-incremental or radical innovation events mark a very significant departure in the state of the technological art – something more like a jump than a step. Radical innovation can unfold over decades or lifetimes and they tend to be much more disruptive of prevailing technological forms. Radical innovation events are often characterised by the formation of universally new conceptual connections, configurations, principles or designs

(Freeman 1974; Garcia and Calantrone 2002; Dahlin and Behrens 2005) and they often transform the way that some primary human need is satisfied (Geels 2002). They tend to affect a wide variety of industries that might not otherwise have a great deal in common (Helpman 1998; Lipsey et al. 1999). The extent of departure from the technological state of the art is much greater than that brought about by an incremental innovation event.

The distinction between 'incremental' and 'radical' innovation events as they occur in the real world is not as clear cut as these simple labels might imply. This is because the degree of departure or technological novelty that an innovation event marks depends on the technological frame of reference in which that event occurs (Geels 2002; Unruh 2002). An innovation event can be 'radical' within a narrow frame of reference but 'incremental' in a broader one. Hall and Andriani (2003) give an example of an innovation event that took place in a British firm involved in the production of motorised lawn care equipment. This example helps illustrate how the meaning of the terms 'incremental' and 'radical' innovation events can be context dependent:

> The project was concerned with the relaunch of a grass-cutting machine designed to edge lawns with a vertical cut and to trim borders with a horizontal cut. The old machine, which was to be replaced, was able to carry out both functions by turning the head containing the rotating cutter through 90°. The visionary brief for the new machine was: "Develop an innovative product in half the normal time." The vision was quickly translated into the following goals: no increased cost, higher margin, and the elimination of the moveable head, which market research had established consumers did not like. The radical innovation involved a breakthrough, which followed the recruitment of an industrial designer who suggested in a brainstorming session that the cutting functions could be changed by turning the whole instrument over, not just the cutting head. (Hall and Andriani 2003: 147)

Described here is an innovation event that gave way to an altogether superior design for a piece of lawn care equipment. Within the technological frame of reference of the lawn care equipment company, flipping the whole instrument over to perform a second cutting function was a very significant departure from the way the company had designed its grass cutting machines in past. The authors later describe how instead of adjusting the device to merely 'do things better' the firm had figured out a way for the device to 'do better things' (emphasis added), which constituted a non-incremental innovation event for the firm (2003: 146). However, at the level of technological reference of the lawn care equipment industry as a whole this 'breakthrough' would probably be considered something closer to an incremental event.

At the broadest, society-wide frame of technological reference, some of the most recognisable non-incremental innovation events of the last 100 years have involved significant roles for government actors. ‘Mission-oriented’ R&D projects commissioned by government and carried out by industry-government partnerships have been behind some of the most important advances in biological, nuclear, and information & communication sciences (Greenberg 1966; Hall 2012; Sherwin and Isenson 1966; Soete and Arundel 1997). For example, the invention of the modern jet engine which dramatically lowered transportation times in the civilian sphere is often attributed to aerospace innovation in the military sphere directed by military technology planners (Jewkes, Sawers and Stillerman 1961). Direct government action seems to have been less important in the non-incremental innovation events that defined the 18th and 19th centuries, however (Brimblecombe 1987; Schmookler 1962; Schmookler 1965). The emergence of the coal combustion /steam engine/mechanical power complex during the industrial revolution in England between 1750 and 1820 was heavily dependent on private finance, private innovation effort and private organisational structures (Meisenzahl and Mokyr 2012; Pearson and Foxon 2012). In the United States, the emergence of the automobile and the railroads as well as in the electrification of homes and factories was closely connected to innovating, risk-taking individuals and firms (Jewkes, Sawers and Stillerman 1961). Government played a more indirect role in these earlier events by funding and performing some basic R&D, by maintaining a system of intellectual property rights and by keeping monopoly forces in check through the enforcement of anti-trust laws.

In the long history of technological transitions in industry the influence of government actors through pollution reduction regulation on those transitions is a relatively recent phenomenon. This does not mean that industry did not engage in pollution-saving innovation prior to the mid-20th century. The industrial revolution in England created unprecedented air pollution problems (the focus of the present research), especially in cities. Brimblecombe (1987: 90 – 106) describes some of the ways that industry adapted to deal with the pollution problem. Factories raised the height of the chimneys they already had in place or they built new chimneys altogether to better disperse air pollution. Fuel suppliers experimented with charring coal and wood into something like briquettes. This made the fuel less bulky, more transportable and cleaner burning, but it does not appear to have seen very widespread uptake. Benjamin Franklin is said to have pushed for a smoke abatement technique to be incorporated into the design of the early steam engine. The technique involved re-burning the smoke from fresh coal by conducting its smoke through the coal that was already fully ignited, thus incinerating the smoke.

Highly polluting, primitive atmospheric engines were eventually replaced by high pressure steam engines designed by James Watt. These new engines introduced a similar firing procedure to Franklin's that considerably reduced smoke emissions. The Royal Navy is said to have chosen anthracite coals for its steamships so that the passage of its vessels would be less detectable to potential enemies. In the 1840s a brewery called Meux's Brewery on Tottenham Court Road in London is said to have been forced by local residents to switch to cleaner burning fuels (cleaner coal) because the smoke from the establishment was damaging the residents' interior furnishings (Brimblecombe 1987: 90 – 106). A good deal of this anti-pollution innovation activity seems to have occurred in response to direct social pressure applied by the sufferers of pollution emissions on the industrial emitters.

Other accounts describe how long-wave technological transitions in energy and transport have reduced the impact of industry on the environment in absence of anti-pollution regulation and in absence of direct social pressure. Ausubel (1989) describes how wood was the dominant construction material for the rapidly expanding railroad system in the United States in the mid and late 19th century. Railroad trestles, railroad bridges, some rails, most rail car bodies and especially railroad cross-ties were all fashioned out of wood. Wood also fuelled the locomotives. Voracious consumption of wood placed pressure on forest resources, wood prices began to rise, and innovations emerged to reduce dependence on the resource. Cross-ties came to be impregnated with creosote which tripled their useful life by preventing rotting, and concrete cross ties emerged in regions in Europe where wood was particularly scarce. More directly relevant to pollution emissions specifically is the transition in personal transportation from horses to automobiles at the end of the 19th century. Ausubel (1989: 76) observes that horses as a personal transportation mode emitted about 940 grams of emissions per mile while the automobiles that replaced them emitted about 5 grams per mile. It has also been widely observed that the carbon content of newly developed energy resources has been steadily declining during the last 200 years. Wood came to be replaced by coal in many applications, then coal by oil, then oil by natural gas (National Research Council 1986).

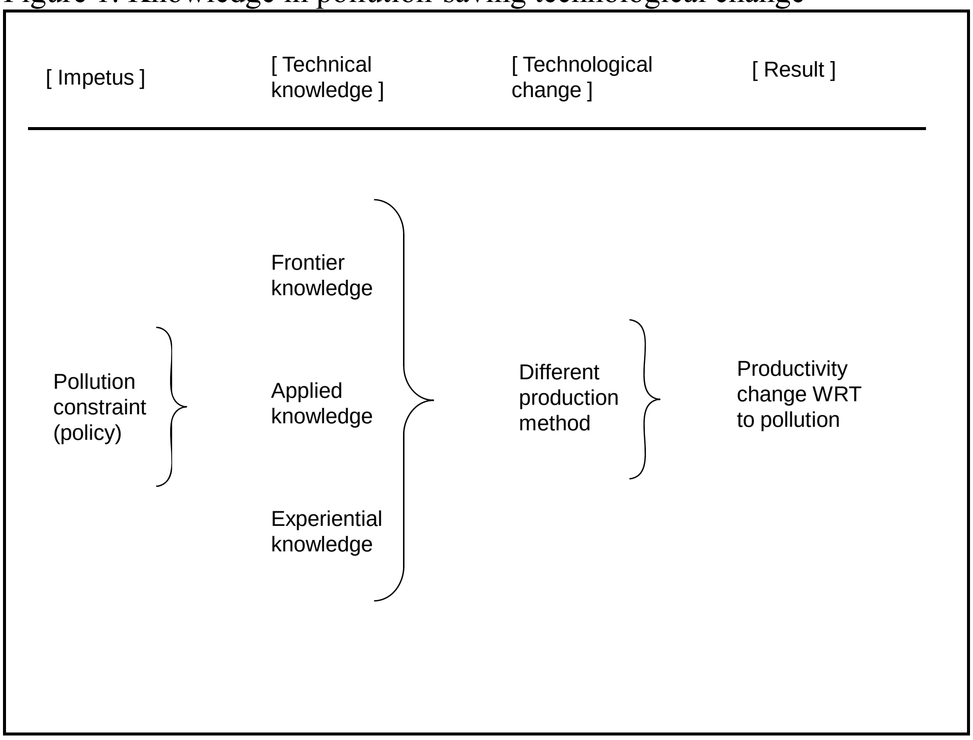
It is important to point out that these long wave transitions were pushed along by a huge variety of social and economic forces and that concern about reducing pollution is likely to have been a relatively weak force especially in absence of direct pollution control regulation. The firms, individuals and other actors that perpetuated these transitions were likely to have been responding in much greater measure to changing consumer preferences, widening demand for transportation and energy services, changing resource availability and changing input prices, and the advancement of scientific understanding that made new production methods possible. To the extent that these long-wave transitions did reduce pollution and natural resource use, this effect seems in many instances to have been more incidental or accidental than the result of deliberate innovation activity by industry directed at reducing pollution emissions.

These questions about the role of knowledge creation, innovation and technological change with respect to industrial pollution are taken up empirically in a relatively modern context in the three studies to follow. The next section now turns to setting out a structured way to investigate the role that technical knowledge has played in modern industrial transitions away from 'consuming' various regulated conventional pollutants.

3. The meaning of knowledge, technological change and technological progress

This section sets out what is meant by technology and knowledge in this research. It explains how the different attributes of knowledge are conceptualised and measured, including the quantity, the degree of newness, the degree of advancedness, and the type of knowledge. It distinguishes between technological change and technological progress. It elaborates how policy gives rise to a technological change process that is marked by a change in the productivity of output with respect to pollution, as illustrated here.

Figure 1: Knowledge in pollution-saving technological change



This research is concerned with the role that learning and R&D play in the space between the enactment of the policy constraint (impetus) and the final productivity change with respect to pollution emissions (result). The fourth column in Figure 1 is the link between this technological change process and the cleanness of the broader growth process. Productivity change with respect to pollution emissions that is insufficiently quick or extensive will eventually retard or truncate growth.

In this research a 'technology' is a production possibility. This follows Joseph Schumpeter (1939) and others who considered that a technology is the human possibility to produce something (Romer 1994). A technology is the ability to systematically and repeatedly carry out a productive transformation of materials and energy from lower value form to higher value form (Metcalf 1995: 34), yielding some product or state that is useful to human beings.

A heart transplant procedure, petroleum cracking, and fire are all technologies in this sense. Each of these technologies embodies the possibility to manipulate and recombine lower value materials and energy into higher value goods and services. Each reflects a capability to render in the material world some outcome desirable to human beings. A technology like fire can become embodied in a physical artefact, like a cigarette lighter. Artefacts embody technology in the same way that manufactured goods embody labour. But an artefact is not itself a technology, and to possess an artefact is not necessarily to possess the technology. This is because it is possible to derive the benefit of a technology embedded in an artefact without actually understanding how the technology renders that benefit possible (Layton 1974). The possibility to produce fire exists in its purest and most enduring form separately from the cigarette lighter.

The core feature of a technology is the technical knowledge that makes the productive transformation of materials and energy possible. Knowledge only exists in people. People can transpose the technical knowledge they possess into written instruction manuals, procedures, formulas, software, diagrams, sketches, designs and blueprints. They do this to codify their ideas and make them easier to transfer between people through learning (Amin 1999; Arrow 1969; Arrow 1974). The immediate result of codification is information, not knowledge. When knowledge is disembodied from a human host it becomes information. Information is not as useful as knowledge. Information cannot on its own yield a product or state that is useful to human beings because it lacks the implementing human agent. Information needs to be reabsorbed by a person through learning to become knowledge again. Only then can it enable a productive transformation of materials and energy.

This research considers that knowledge has attributes. Some of the attributes of knowledge are its quantity, advancedness, newness and type.

The unit of denomination of a quantity of knowledge is the 'idea' following Peri (2005). An idea is equally 'sized' to every other idea in the same way that a dollar is equally sized to every other dollar. A person possesses many ideas at once. Ideas are equal in size but unequal in other attributes. Differences in other attributes make some ideas more 'useful' than others. A stock of knowledge (Nadiri and Prucha 1997) is the number of ideas a person or group of persons possesses at a given point in time.

Another attribute of knowledge is its degree of advancedness. The advancedness of an idea refers to its productive potential relative to all other ideas at a given point in space and time. The production possibility frontier (PPF) (also the technology possibility frontier (TPF) and the innovation possibility frontier (IPF) (Binswanger and Ruttan 1978; Nordhaus 1969; Ruttan 1959)) begins to get at the idea of distinguishing among ideas by their degrees of advancedness. In these accounts the most advanced ideas sit on the frontier itself because they hold the possibility for the most productive method of making something that exists at a point in time. At the frontier sits the method of instantly producing a steady flame from the smallest possible quantities of fuel, air, ignition device and labour. Less advanced methods sit before the production possibility frontier because they use more resources to achieve the same result.

As a device for positioning ideas relative to one another in terms of their degree of advancedness, the PPF does not capture the dimension of time. It is a-temporal. A technology may sit on the frontier relative to all other technologies that exist at a single point in time. But the same technology may sit away from the frontier relative to all other technologies that exist at all points in time. To overcome this problem one can think about a continuous envelope of PPFs stretching from the present moment over all previous moments indefinitely backwards in time. This makes it possible to consider an idea's degree of advancedness relative not just to its idea-contemporaries but to all related ideas that have ever existed in time. This time dimension is important for distinguishing, below, between technological change and technological progress with respect to environmental inputs.

An idea can also be characterised by its degree of newness. Ideas come into existence by taking root in the human mind through research, discovery and learning. Not all new ideas are of an equal degree of newness. An idea can be new to a single person, new to a firm, new to an industry, new to a region or nation, new to the world at a particular point in time, or new to the world for all points in time to date. If an idea is new in the everywhere-in-the-world-for-all-points-in-time-to-date sense, then it is universally new (Furman, Porter and Stern 2001). An idea that is universally new tends to also be characterised by the greatest degree of advancedness. An idea coming into existence that falls short of the technological frontier is likely to be a replica of an idea that already existed elsewhere. Sub-frontier ideas are only 'locally' new to the individual person, to the firm, to the industry or nation, or to the point in time (Antonelli et al 2006).

Ideas that come into existence can be characterised as frontier, applied or experiential knowledge, as in Figure 1. Frontier knowledge has also been described as 'basic', 'pure' or 'scientific' knowledge (Gibbons and Johnston 1974; Gibbons and Gummett 1977). Frontier knowledge tends to emerge from structured scientific investigations that formally test established scientific laws and principles through the application of established procedures (Vinceti 1990). Applied knowledge tends to emerge from the less-structured investigation of questions of immediate interest to the researcher. These investigations tend to produce knowledge that is useful to the individual researcher but which may not necessarily be useful to a wider community. With applied knowledge, the ideas that are created that are new to the investigator probably already existed elsewhere. Experiential knowledge is relatively easy to replicate and tends not to be particularly advanced. Experiential knowledge is continually being produced and reproduced in very large quantities through learning of common practice and established routine (Arrow 1974; Nelson and Winter 1985).

Firms acquire technical knowledge in ways other than by performing R&D. Firms acquire knowledge through learning by doing, imitating one another, hiring-in knowledge in the form of labour, buying-in knowledge embedded in new equipment, tinkering informally, purchasing technical blueprints, experiencing production accidents, and reverse-engineering products and processes (Archibugi, Howells and Michie 2003; Arrow 1962; Boerner et al 2001). Knowledge acquired in these ways extends the technology frontier for the acquiring firm locally but not the technology frontier for all firms universally in the way that formal R&D tends to. These knowledge acquisition activities often replicate and transfer existing knowledge from one entity to another.

'An' innovation is a commercially viable product or process that arises from a production possibility. 'Innovation' is the process of searching for knowledge of any degree of newness and developing that knowledge into a commercially viable product, process or service (Basberg 1987). An 'invention' is a production possibility that advances the technology possibility frontier universally. An invention comprises of new ideas plus a way of rendering those ideas into a physical form or method. An invention makes some outcome desirable to human beings technically feasible for the first time (Nordhaus 1969; Rosenberg 1985). An invention is not an invention in the truest sense if it has already come into existence elsewhere. Holding the definition of an invention to a standard of universal newness means that no two inventions can be identical. Inventions are heterogeneous by definition (Podolney and Stuart 1995).

Ideas can also be characterised by type. An idea's type is something like its 'task relevance'. Knowledge of the principles of fuel combustion is more relevant to discovering a method of producing a steady flame than is an equal amount of knowledge of cell division in biology. Ideas occupy different locations in knowledge space or technology space (Breschi, Lissoni and Malerba 1998; Jaffe 1987; Schankerman 1998). If two ideas are primarily relevant to performing the same task then they occupy the same general location in technology space. If a third idea is primarily relevant to performing a different task then it occupies a different location in technology space.

Locations (or fields) in technology space are separated by distance. Two knowledge fields can be proximate or distant. Distance can be between two ideas within a single technology field or between groups of ideas across technology fields. The distance between two fields is small if a scientist who is a specialist in field A would find it easy to absorb knowledge from field B which is not his or her own, or to apply knowledge from field B in practice, or to produce knowledge in field B him or herself (Breschi, Lissoni and Malerba 1998). The distance between fields is large if the scientist in field A would have difficult doing any of this in field B. The distance between knowledge fields is asymmetrical. The scientist who normally produces new ideas in field A can have an easier time producing new ideas in field B than a scientist working in field B has producing new ideas in field A (Cincera 2005).

This research is interested in the type of knowledge that is created primarily for the purpose of reducing pollution. To this end, all knowledge across the terrain of technology space is divided into two types according to the end use the scientist or engineer had in mind when they produced the knowledge (OECD 1999). If the knowledge was created primarily for reducing pollution then it is 'environmental' knowledge. If the idea was created primarily for any other purpose then it is 'ordinary' knowledge.

Important to this research is the distinction between technological change and technological progress. Most technological change is merely 'churn' among pre-existing production methods. Technological 'change' is the constant switching and shifting between existing technologies, both technologies at the technology frontier and also technologies away from it. A firm tends to undergo technological change in response to external stimuli in its production environment (Abernathy 1978; Utterback 1979). External stimuli include shifting consumer tastes, rising or falling fuel prices, social phenomena like industrial action, resource scarcity and policy events (Hicks 1932; Blackman and Bannister 1998). In a technological 'change' framework, if a technology does a good job of exploiting the features of its production environment then it is a 'good' technology. If a technology is ill-suited to its environment then it is a 'bad' technology. Within a technological 'change' framework it is only possible to compare technologies in terms of their relative suitedness to the production environment.

The idea of technological 'progress' by contrast makes it possible to compare technologies in terms of their intrinsic merits by measuring the direction and extent of change that each technology makes possible (Newell, Jaffe and Stavins 1999; Sue Wing 2006). The direction of technological progress is denoted by whatever input the new production method has made it possible to use less of, relative to the previous production method. The direction of technological progress can be universal or it can be local. The input saved can be labour, capital, energy or the environment. The input of interest here is the use of the assimilative capacity of the environment to absorb pollution emissions (Cropper and Oats 1992; Lopez 1994). The extent of technological progress is denoted by the change in the relationship between output and the input of interest. When output increases but the quantity of the input used remains the same, greater productivity with respect to that input has been achieved. The same is true when, symmetrically, output remains fixed but the quantity of the input decreases (Gillingham, Newell and Pizer 2008; Loschel 2002). This relationship is reflected in the final column of Figure 1 above.

4. Research approach

The biggest empirical problem in trying to understand the role of knowledge in pollution-saving technological change is the wide variation in the kinds of policies governments use to discourage pollution emissions. Variation in the design of the environmental policy shapes how firms deal with the pollution problem (Kemp 1997; Kemp and Pontoglio 2011; Vollebergh 2007). Environmental policies vary widely in terms of timing, stringency, flexibility, type, objective, credibility and enforcement. These policy design aspects all affect how firms involve knowledge, and the acquisition of knowledge through learning, in their compliance response. These design aspects determine whether a firm responds to the policy by undertaking pollution control R&D of its own, by buying-in abatement technology from elsewhere, by imitating what its competitors do, by finding ways to comply that involve the minimum amount of new knowledge creation possible, or by doing nothing at all. In each such potential response technical knowledge plays a distinctive role.

This means that there are as many potential 'roles' for knowledge to play in response to policy as there are policy design permutations. This creates the central methodological problem in this research, namely that the role of knowledge in pollution-saving technological change is fundamentally shaped by the policy context in which that change occurs.

One way to deal with this problem would be to catalogue the many varied roles for knowledge across the range of possible policy designs. Such a catalogue of roles might make it possible to say that under the grams-per-mile standards commonly used to regulate automobile emissions, basic science R&D plays a large role in firms' compliance strategies. Such a catalogue of roles might also make it possible to say that under a cap and trade regime used to control SO2 from electric power plants, basic scientific knowledge plays a small role in firms' responses. The problem with cataloguing is the limited predictive power of this approach. A catalogue of roles for knowledge will only ever be as useful in prediction as the catalogue is reflective of future policy designs and future policy contexts. No two pollutants have the same properties, no two policies are designed exactly alike, and the economic context across nations and time is in constant flux. What would be more useful than a descriptive catalogue of the roles for knowledge would be a generalizable statement about knowledge's singular 'role' across these varied policy design contexts and circumstances.

A better research approach than cataloguing is to treat the policy influence effect as a nuisance variable. The policy influence effect can be seen to be distorting and obscuring the underlying role that knowledge truly plays in pollution-saving technological change. The nuisance variable approach recognises that it is inherently difficult to observe the true and basic nature of this singular role for knowledge in empirical reality. This is because, in empirical reality, the distortive influence of policy is every-present in the technological change process of interest. Yet at the same time it is only ever possible to observe any role for knowledge at all in this variety of technological change in the presence of an environmental policy stimulus. This means that the central methodological challenge of this research is *to identify the role that knowledge plays in a change process that generally only occurs in the presence of a policy stimulus, net of the effect of the nature of that* *stimulus*. To glimpse the role of knowledge 'independent of' and 'undistorted by' the policy influence effect requires that two things be present in the research strategy.

First, there needs to be an appreciation of the possibility that a singular role for knowledge exists 'net' of the policy influence effect and somewhat apart from, but rooted in, the varied and unsystematic roles that are empirically observable. Second, there needs to be an appropriate and purposive set of methodological devices in place for testing different aspects of this pattern. Method that is effective in this regard will create the conditions to test for the hypothesised role of knowledge in a way that does not succumb to the nuisance influence of the policy design.

Both of these elements exist in the research strategy in the three papers in this volume. The papers use econometric modelling and original datasets to formally test for the presence of hypothesised relationships. However, statistical modelling is not relied on as the sole arbiter of what is believed to be true. This is because, in a sense, a statistical model is only ever as 'good' as the understanding of the modeller of the relationship being modelled. It is fully possible to accurately model relationships that are not in fact true.

In this research strategy, every effort has been made to ensure that the statistical modelling work is rooted firmly in theory. The conceptual framework discussed earlier in this section gave precise meanings to terms commonly used in the literature to discuss technological change. This makes it possible to be clear in the hypotheses about what is being tested, and to be clear in the test results about what constitutes evidence that supports or refutes the hypotheses. Each paper critically and lengthily reviews relevant prior theoretical and empirical work. Each paper examines the findings from the model in the context of the findings of that prior work. Each paper uses empirical analogy to consider the role of knowledge in pollution-saving technological change. It does this by drawing a comparison with the role of knowledge in energy-saving technological change, for example.

More tactical and practical devices are used to ensure that the relationships tested in the models are not being driven by extraneous factors. Qualitative evidence and statistical description are used to draw out background relationships and conditions that guide the researcher's understanding of the process being modelled, and in turn guide the specification decisions that underpin the model. All three papers look at air pollutants. This minimises variation in policy design across pollution types. All three papers look at the relationship of interest in the context of industrial transitions in a single country, the United States. This eliminates cross-country variation that might arise in the design of the same instrument type. Testing for relationships within-country also holds constant the effect of non-environmental policies working in the background at the national level, like R&D tax incentives. All three papers go to length to measure the kind of technological change and knowledge that is specifically pollution-saving. This research avoids wherever possible second-best proxies like technological change and knowledge that is energy-saving. There are strong reasons to believe that the forces that drive pollution-saving technological change are very different to the sources that drive energy- and other ordinary input-saving technological change.

The research approach that runs throughout these studies deals with the empirical distortion caused by the policy influence effect by choosing policy contexts selectively and strategically. Case selection is used to study the policy influence effect directly, or to neutralise the effect, or to hold it constant as a background factor. This makes it possible to observe an underlying role for knowledge in pollution-saving technological change that arises across the evidence in the three papers.

The first paper handles the policy influence effect by embracing it. The dependent variable is industrial environmental R&D spending data from the National Science Foundation covering the years 1972 – 1994, across 30 industry groups. These data show that the level of environmental R&D spending began to decline from about 1979 onwards before dropping off sharply around 1990. The paper operationalises one aspect of environmental policy design: the degree of 'flexibility' given to firms to decide how they will go about complying with pollution control regulations. The paper then tests the hypothesis that the degree of flexibility in the prevailing policy regime conditioned the effect of the environmental regulatory burden on the level of environmental R&D spending. That is, the model tests the effect of the abatement burden on environmental R&D spending conditional on policy regime flexibility. The paper deals with the policy influence effect by testing how one aspect of environmental policy design, flexibility, impacts on the creation of pollution-saving technical knowledge.

The first paper finds that the degree of flexibility conditionally diminishes the effect of the regulatory burden on industrial environmental R&D spending. It also finds that flexibility may open the door for less formal, 'lower-order' types of knowledge to play a role in compliance. The important methodological point is that this paper handles the policy influence effect by embracing it, rather than by minimising it or effectively holding it constant as do the other two papers.

The second paper deals with the policy influence effect by choosing a policy context that is as neutral with respect to firms' technology and knowledge production choices as can be. SO2 cap and trade resulted in considerable reductions in SO2 emissions from electric power plants. It resulted in considerable overall productivity gains in electricity generation with respect to SO2 emissions. This is exactly the kind of productivity outcome that is of interest from the point of view of 'green' growth theory. The important methodological point is that while government action induced considerable change in firm production methods in an SO2-saving direction, the form of government action (cap and trade) exerted very little influence over how firms went about achieving this productivity change. Cap and trade was largely technologically neutral.

The dependent variable in the second paper is the extent of productivity change with respect to SO2 emissions undergone by about 600 electric power plants affected by cap and trade. The paper tests the effect of different types of knowledge and techniques on that outcome. It uses a combination of qualitative case material and quantile regression analysis to compare the effect of knowledge intensive and knowledge unintensive techniques in the change process. It finds that some of the most important changes enabling SO2 reductions at the level of the plant occurred far upstream of the plant itself. Very important changes occurred in the coal mining, railroad and industrial boiler manufacturing industries. At plant level, the magnitude of the effect of frontier knowledge tended to be overshadowed by the magnitude of the effect of pre-existing, knowledge un-intensive techniques. The methodological approach of the second paper to dealing with the policy influence effect is to neutralise it. A policy context is chosen that exerts as little influence as possible over the knowledge and technology choices firms made in undergoing the technological change required of them. This reveals a role for knowledge that is relatively undistorted by the policy influence effect.

The policy context in the third paper, automobile emission control, was by contrast anything but neutral with respect to how firms went about complying with regulators' demands. In the automobile emission control context, the approach of regulators was to set emissions standards just beyond the comfortable technological reach of the automobile companies. This pushed the automobile companies to undertake a considerable amount of original R&D to conform with the standards. The third paper uses this bias in policy design toward frontier knowledge production as a methodological device.

This 'technology forcing' policy context is used to understand the factors that led a small handful of pollution-saving inventions to become so much more technologically influential than others. Patent citation data show that the great majority of pollution-saving inventions were 'dead ends' in the words of Podolney and Stuart (1995). The third paper estimates a negative binomial model of the determinants of the level of a pollution-saving invention's technological influence. It finds that an important determinant of invention influence is not just the size of the knowledge stock that the automobile company brought to bear on the inventive process, but the composition of the knowledge stock. More diverse knowledge stocks led to more influential inventions. More specialised knowledge stocks led to less influential inventions. In the third paper, a single policy impetus pushes a body of new pollution-saving inventions into existence. This single policy impetus reduces the range of possible causes for why some of those inventions might be more technologically influential than others. The policy influence effect is held constant in this way.

Other specific methods considerations are discussed in the context of each paper. These more specific considerations relate to the econometric and data handling choices taken to test the specific hypotheses. The reader should refer to the econometric evidence sections of the individual studies for the detail of these considerations.

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Paper 1: Do flexible instruments really induce more environmental R&D?

Abstract

A number of recent policy proposals have called on governments to increase annual spending on climate mitigation R&D by billions of dollars per year, at a time when many nations face severe fiscal austerity. This paper investigates whether it is realistic to expect flexible environmental policy instruments, of the type in widespread use today, to stimulate a lot of environmental R&D spending on their own. The hypothesis developed is that increasingly flexible forms of environmental regulation tend to bring a conditional reduction in the level of environmental R&D spending, all else being equal; and that flexible approaches to climate mitigation policy are not likely to induce the large amounts of environmental R&D that some corners of the induced innovation literature predicts. Panel data from the National Science Foundation on pollution abatement R&D spending are used to test this hypothesis for 30 industry groups over 22 years. The results show that the policy regimes that gave more control to market forces for the way compliance was achieved tended to diminish the effect of the environmental regulatory burden in motivating environmental R&D. One implication of this finding is that the quest to raise environmental R&D spending may be a good thing in its own right. Further, the efforts to increase the flexibility of environmental policy regimes may also be a good thing in its own right. However, greater flexibility can undermine the incentives regulated firms have to invest in environmental R&D.

1. Introduction

A large increase in research and development (R&D) spending for greenhouse gas (GHG) control is one element being proposed for a post-Kyoto climate stabilisation framework (Atkinson et al. 2011; Hoffert et al. 2002; Mowrey, Nelson and Martin 2009; US National Academy of Sciences 2009; Prins and Rayner 2007; Prins et al. 2010; Rees 2006). One such proposal for the United States involves scaling-up climate-related R&D spending to the levels that were in place during the Manhattan Project in the 1940s (Mowrey, Nelson and Martin 2009). Another proposal involves increasing US federal spending on clean energy R&D from four billion to 25 billion dollars annually for a decade or more (Hayward et al. 2010). A further proposal involves raising R&D spending for GHG abatement technologies to eight billion dollars annually for the next nine years (Newell 2008). Also, in Europe, the low and volatile price of emission permits under the Emission Trading Scheme (ETS) does not appear to be inducing as much clean energy technology development and deployment as policymakers might like. This has led to calls in Europe for greater public support for climate mitigation R&D and accelerated technology development through R&D tax credits or direct public spending on basic R&D (Delbosc and de Perthuis 2009; Nordhaus 2011; Hepburn and Stern 2008).

The justification behind these proposals tends to come from the idea that even under an environmental policy instrument that puts a price on the environmental externality, like the EU ETS, firms will still underinvest in the activities that create the technical knowledge needed for low-cost GHG abatement. Underinvestment happens because a big share of the returns from R&D of any type, climate or otherwise, tends to accrue to society rather than to the individual firms making that investment. This means that the returns to R&D are almost never fully privately appropriable (Antonelli 2002; Hall and Van Reenen 2000). Since markets alone do not reward firms sufficiently for investing in R&D due to these positive externalities, the argument goes, governments should intervene with policies like R&D tax credits to correct the externality.

This paper looks at the effect that policy instruments like the ETS in Europe and the proposed carbon tax in the US (Nordhaus 2011) should realistically be expected to have, in their own right and on environmental R&D spending levels. It looks at the effect that increasingly flexible forms of regulation, such as those being used and proposed for GHG control, are likely to have on the type of technical knowledge firms make use of in the environmental compliance process; and the extent to which policymakers can expect formal R&D of the type proposed above to play a role in that compliance process. To investigate these questions, this paper tests the conditioning effect policy flexibility has on the effect of the environmental regulatory burden on environmental R&D spending activity historically. It uses panel data from the US National Science Foundation covering 22 continuous years. The length and placement of these 22 years gives enough variation in the degree of policy regime flexibility to test the conditioning effect of flexibility on the level of formal technical knowledge creation involved in firms' responses to the environmental regulatory burden.

The paper finds that, in the context of the United States for these 22 years, the more heavily policymakers relied on using economic incentives to motivate environmental compliance, the less environmental protection R&D the regulated firms chose to conduct per dollar of environmental regulatory burden. The National Science Foundation data show that US industry steadily decreased its environmental R&D spending levels from about 1979 onward as increasingly flexible forms of regulation legitimised wider and less original forms of compliance, and made it permissible for firms to use wider and less original forms of knowledge in compliance. The interpretation of the results also suggests that in place of formal R&D, firms came to make greater use of informal technical knowledge that could be obtained more cheaply from sources other than through their own R&D, and which became increasingly permissible under less rigid compliance rules. The paper does not directly test whether informal knowledge substituted for the formal knowledge obtained through R&D, but it both controls for this possibility and finds persuasive theoretical evidence that firms came increasingly to acquire the knowledge they needed for compliance in ways that did not involve very much formal R&D at all. These ways may have included learning by doing and using, gleaning knowledge from the patent record, acquiring knowledge in the form of labour, stealing knowledge from competitors, buying knowledge embedded in new equipment, creating informal knowledge through tinkering, imitating market leaders, purchasing technical blueprints, and reverse-engineering products and processes (Arrow 1962; Boerner et al. 2001; Archibugi, Howells and Michie 2003).

Through a critical reading of the theoretical literature, Section 2 develops the hypothesis that greater regulatory flexibility weakens the incentives regulated firms have to respond with formal environmental R&D to the cost of compliance they bear under environmental regulation. Section 2 also develops the explanation for the historic decline in environmental R&D spending: that greater flexibility strengthens firms' incentives to acquire cheaper, 'lower-order' knowledge forms in place of the kind of knowledge they would acquire through formal R&D. This explanation is developed theoretically and controlled for, but not tested directly. Section 3 describes the method and data used to test the hypothesised conditioning effect of policy flexibility on environmental R&D spending. Section 4 gives the results of the test along with a discussion of the quality of the model specification and estimations. Section 5 discusses the implications of the research for theory, for policy, and for future research in this area.

2. Theory and hypothesis

This section looks critically at the idea that environmental R&D activity plays a large role in the technological change that takes place under policy instruments that use economic incentives to motivate compliance. It looks at the evidence for expecting policy flexibility to condition the effect of the regulatory burden on environmental R&D spending. It also looks at the evidence for expecting policy flexibility to unconditionally influence R&D and related outcomes. These ideas are examined through the lens of the innovation inducement effects of different instrument designs; through the analogous example of the effect that electric power sector liberalisation had on R&D spending in that sector in the 1990s; and by tracking the rising influence of market forces on the functioning and design of environmental policy instruments in the US over time.

a. Flexible environmental policy and R&D

There is broad agreement in the literature looking at the innovation inducement effect of different policy instrument types that instruments that give firms economic incentives to improve their environmental performance are more economically efficient than instruments that do not (Magat 1979; Downing and White 1986; Milliman and Prince 1989; Jung, Krutilla and Boyd 1996; Popp 2010; Kemp and Pontoglio 2011). However, this agreement tends to break down around the question of why, exactly, economic instruments are more efficient. The cap and trade system for GHGs that has been set up in Europe (the ETS) and the proposed carbon tax for the US are examples of economic instruments (Nordhaus 2011).

It matters why, exactly, economic instruments are more efficient. If these instruments are efficient because they stimulate firms to deal with the environmental regulatory burden by creating a lot of new formal technical knowledge through R&D, then it might make sense to subsidise the cost of that critical ingredient, formal knowledge creation, through an R&D subsidy. But if these instruments are efficient because they stimulate firms to deal with the regulatory burden by imitating, adopting and otherwise acquiring lower-order forms of technical knowledge instead, then an intervention like an R&D subsidy would risk being ineffective and wasteful. This is because it could create conflicting incentives to encourage firms to comply in a way that involves a lot of new R&D, when the signals that the policy framework is sending point clearly toward pragmatic, low-cost, low-R&D ways of complying.

The idea that formal knowledge creation through R&D plays a driving role in pollution-saving technological change is a recent phenomenon. Orr (1976) was one of the first to argue that the uniform emission standards popular with governments in the early 1970s should be abandoned in favour of instruments like effluent taxes and permits. His reasoning was that these instruments would allow for what he called continuous 'adaptation'. Orr argued that economic instruments give producers incentives for 'continuous and detailed technological adaptation to the impacts on the environment of growth' (442). Orr further stated that one criterion for evaluating the desirability of different policy instruments should be the extent to which the instrument gives firms the liberty to adapt their production methods to the constantly changing price of inputs, including the changing price of environmental inputs brought about by growth-induced resource scarcity. This gives reason to think about the policy instrument choice exerting a conditioning effect on how firms go about dealing with changing environmental input prices. In earlier contributions like these, authors like Orr were not arguing that economic instruments would necessarily stimulate a great deal of R&D in response to scarcity, but rather that these instruments would give firms the fullest possible leeway to adapt to unrelenting change. Adaptation could include R&D if the firm saw fit, but it could also include many other non-R&D forms of adaptation.

The body of work that followed Orr consistently finds that the most efficient instruments are the ones that involve economic incentives, like emission taxes and permits. But these studies are inconsistent in the amount of credit they give to R&D for the technological change that it brings about. The conditioning effect of the instrument on the way technological change proceeds is frequently not made explicit. Downing and White (1986) for example looked at the effect of different instrument types on 'innovation'. They found that economic instruments give firms the most consistently adequate incentives to innovate. They defined innovation as:

> a discovery that will reduce the cost of controlling emissions… [which] normally involves an initial cost or investment (e.g., research and development expenses) and then a subsequent cost reduction or saving if the innovation is employed. (1986: 19)

For Downing and White, 'innovation' meant much the same thing as R&D. There are numerous ways for firms to innovate by acquiring and applying knowledge in ways that do not involve R&D. This passage shows that Downing and White are attributing a significant part of the technological change that economic instruments bring about to R&D. This is at the very least inconsistent with what Orr was saying. Orr stated that economic instruments are efficient simply because they give firms the leeway they need to adapt in whatever way necessary, by whatever method. Downing and White said that economic instruments are efficient because they give firms the strongest incentive to positively 'innovate' through 'e.g., research and development'.

Technology adoption plays an important role in environmental technological change. Technology adoption usually involves less R&D than front-line inventive activity (Stoneman 2002; Popp 2006). Milliman and Prince (1989) extended Downing and White's work by modelling the effect of the different instrument types on total social gains from a broader environmental technological change process involving invention, diffusion and a ratcheting-down response by the regulator. Milliman and Prince found that this three-stage process also yielded the largest social gains from economic instruments generally, but with a caveat. The caveat was suppliers. Suppliers are special because they do not discharge emissions themselves. Milliman and Prince found that suppliers have very weak incentives to do R&D under economic instruments because there is no control authority present to require polluting firms to adopt whatever new control technology the suppliers invent. Supplier incentives to perform environmental R&D essentially collapse under economic instruments (1989: 256). Milliman and Prince's finding is one of the first acknowledgements that economic instruments might actually be bad for promoting new innovation activity by certain firms insofar as innovation involves formal R&D. These findings present the possibility that some economic instruments may condition the compliance response of at least some actors to reduce the amount of R&D they perform relative to the amount of R&D they would have performed under rigid, inflexible instruments.

Other studies find that environmental compliance under economic instruments may involve a lot less formal knowledge discovery through R&D than some of the prior literature predicts. Jung, Krutilla and Boyd (1996) again found that economic instruments were the most economically efficient; but again one needs to look critically at what exactly they attribute this efficiency to. Jung, Krutilla and Boyd attribute the efficiency to the 'development and adoption of advanced pollution abatement technology' (95). The issue with this is that technology 'development' and technology 'adoption' involve very different amounts of R&D. Their combined treatment makes it impossible to separate out the 'efficiency' effect of each. They model the composite effect as a decline in the marginal cost of abatement faced by individual firms (see their footnote 5). Jung, Krutilla and Boyd do not give explicit theoretical evidence that the efficiency benefit of economic instruments rests primarily on the new technical knowledge that comes about through the formal R&D they stimulate. Nor do they show that these instruments necessarily induce the creation of a lot of universally new technical knowledge that would be useful for environmental compliance. This theoretical finding would benefit from an empirical test of the conditioning effect of economic instruments on the response of affected firms to the regulatory burden in terms of the level of formal R&D spending they undertake.

Adopting another firm's technology might be an adequate substitute for a firm performing R&D of its own and explain how technological change proceeds. However, other studies suggest that economic instruments do not trigger very much new technology adoption. Malueg (1987) for example directly challenged the idea that the efficiency of permit trading rests on the incentives it creates for firms to adopt new pollution control technology. Malueg's key insight was that when a firm faces an external permit price set by competitive market forces, this price can be so low that it makes it uneconomical for the firm to adopt new technology at all, since the most economical way to comply is by buying cheap permits. Writing in 1987, three full years before lawmakers in the US created the SO2 permit trading program under the 1990 Clean Air Act Amendments, Malueg predicted that:

> ... since the demand for the more effective pollution abatement technology may fall with the introduction of trading, it is possible that investment in research and development of new pollution abatement technologies may also fall after trading is introduced. (1987: 56)

Malueg's prediction that environmental R&D spending might actually fall under a permit trading program was almost exactly in line with what actually happened (Popp 2002; Taylor, Rubin and Hounshell 2005), as will be shown in the next section. The permit trading program seems to have altered the compliance responses of SO2-producing power plant operators in such a way that caused them to eliminate a good deal of their environmental R&D spending. Malueg's prediction was also consistent with what happened to R&D spending in the electric power sector when policymakers embarked on a program of electricity sector liberalisation in Europe and the United States beginning in the 1990s. Here the policy flexibility effect on R&D was direct and unconditional. When policymakers left it to market forces to decide the technical means of complying with a broad set of rules, there was a steep drop-off in R&D spending both for general purposes and for environmental purposes specifically (Sanyal 2007).

If the creation of universally new knowledge through R&D accounts for a smaller part of the efficiency benefit of economic instruments than one might expect, then this raises the question of what does in fact account for the efficiency benefits of these instruments. One possibility is that economic instruments are efficient because they legitimise simple, quick, low-risk, inexpensive, and generally R&D un-intensive compliance methods that tend to involve replicating, recycling and repurposing technical knowledge that already exists. That is, they may be economically efficient precisely because they let firms avoid doing environmental R&D at all, not because they push firms to perform more R&D.

Much like Malueg (1987) above, Dreisen (2003) argued that permit trading leads the firms with the very cheapest abatement opportunities to exploit these opportunities with 'routine', 'off-the-shelf', and 'adequate' technology that itself does little if anything to push out technological frontiers (2003: 10098-10101). The firm then sells the permits on the permit market at prices that undermine the weak incentives other firms had in the first place to develop or adopt new technology. In a different study, Parry, Pizer and Fischer (2000) looked at which policy option for dealing with a hypothetical pollutant would bring about the bigger welfare gains for society: (a) large-scale investment in R&D to bring down the cost of abatement; or (b) implementing a policy that simply corrected the externality. Parry, Pizer and Fischer found that the welfare gains from R&D are typically smaller (in the authors words 'perhaps much smaller' (2000:15)) than the gains from simply correcting the externality. This is because it takes a long time and a lot of R&D spending to accumulate enough knowledge to substantially lower the abatement cost.

In Nordhaus' original DICE model (1994), Nordhaus looked at where GHG savings were likely to come from over the next 100 years. He found that some of the largest GHG reductions were likely to come from global energy demand reduction and fuel switching from coal to natural gas, rather than from radically new forms of energy generation or pollution control. Similarly, Grubb and Ulph (2002) reviewed the role that environmental policies play in stimulating 'innovation' for environmental protection and energy efficiency, where 'innovation' for them explicitly includes formal R&D. Grubb and Ulph found that while it is possible that environmental policies alone induce this kind of innovation:

> The principal conclusion of this paper is that while environmental policies *may* induce innovation that will lead to cleaner technologies, the theoretical and empirical evidence we have does not give us a great deal of confidence that environmental policies alone will be sufficient to bring about major environmental innovation. (2002: 104)

Again it is important to point out that 'innovation' in Grubb and Ulph's conceptualisation includes R&D and that here they find that environmental policy alone may not be 'sufficient to bring about major environmental innovation'. The problem is the assumption that 'major environmental innovation' necessarily includes large amounts of new environmental R&D and that this is a prerequisite for environmental technological change. This assumption is exactly what could lead policymakers to channel large amounts of money into environmental R&D subsidies like the ones discussed in the introduction. In fact, there is little solid evidence that flexible environmental policy instruments condition the response of firms to increase the R&D intensity of their compliance responses. Indeed the balance of the theoretical evidence suggests that flexible instruments condition the responses of firms in the opposite way. Grubb and Ulph's assumption glosses over the possibility that 'major environmental innovation' already takes place under economic instruments, but that it looks more like technological 'adaptation', 'tinkering' and 'learning' than universally new knowledge creation through R&D leading to 'progress'.

This subsection took a critical view of the idea that the creation of new-to-the-world knowledge plays the driving role in environmental technological change under flexible instruments like the ones in broad use today, for example in the EU ETS. It was argued that compliance methods involving lower-order forms of knowledge like adopting technology developed by other firms, switching to less polluting fuels, and repurposing commercial knowledge to participate in permit trading, also play an important role. This suggests that lower-order knowledge came to substitute for universally new knowledge obtained through environmental R&D when the environmental policy design made this permissible. The next subsection develops this line of argument from a different angle by looking at the unconditional effect of the wave of policies aimed at liberalising the electric power sector in Europe and the United States in the 1990s on R&D spending by electric power utilities.

b. Electric power sector liberalisation and R&D

Beginning in the early 1990s the governments of the US, Japan and several European nations began taking steps to liberalise their electric power markets. Their two main goals were to bring down the delivered cost of electricity and to improve the reliability of the electricity supply (Sioshansi and Pfaffenberger 2006; Newbery 2002; Joskow 2008). The reforms aimed to meet these goals by introducing greater competition among electric power suppliers, by reducing or eliminating price controls, by privatising previously state-owned electric power generation facilities, and by lowering the level of regulatory oversight. This set of changes is referred to as 'liberalisation' in this context.

In the immediate wake of these changes, R&D spending by the affected utilities dropped considerably, in some cases dramatically, across most of the countries that implemented the reforms (Jamasb and Pollitt 2008; Sanyal 2007). The relationship between liberalisation and the R&D spending drop-off is used here to continue to build, by analogy, the hypothesis that increasingly market-based forms of environmental regulation had the effect of undercutting the already weak incentives firms had to create universally new forms of knowledge through environmental R&D.

In the electric power sector the unconditional relationship between liberalisation and R&D spending is well substantiated in the literature. Jamasb and Pollitt (2008) reviewed the industrial organisation literature to see what it would have predicted about the effect of liberalisation on R&D spending in formerly state-run industries. Jamasb and Pollitt found that such reforms would have been predicted to lead to the elimination of a considerable amount of R&D focused on projects with long-term returns in the drive for efficiency through cost-cutting. They show that this prediction was born out empirically in a number of Italian, French, German and Japanese electric utilities, which all decreased their R&D spending in the 1990s immediately after liberalising reforms in those countries. Other studies view electricity from a product point of view. Aghion et al. (2005) tested the relationship between intensity of product market competition and the amount of inventive activity conducted by firms participating in those markets. Aghion et al. found an inverted U-shaped relationship between competition intensity and inventive activity. The relationship they found was unconditional and did not depend on any intermediary variable. Their finding implies that inventive activity increases in a positive relationship with competition intensity to a certain point in an initial stage, but then decreases in a negative relationship with competition intensity in a later stage once a threshold has been passed.

The drop-off in R&D spending in the electric power industry that occurred after liberalisation was probably not coincidental. Sterlacchini (2006) found that the largest European energy and telecommunications utilities reduced their total R&D spending by 33 per cent during the period 2000-2005 following liberalisation. During that same period the same utilities reduced their R&D spending as a proportion of sales from 1.1 to .7 per cent. Gugler (2003) investigated whether more intense market competition in the Australian energy sector brought about by liberalisation led the affected firms to replace long-term spending priorities like R&D with short-term spending priorities like paying dividends to shareholders. Gugler's evidence of the spending patterns of 214 Australian firms for the period 1991-1999 showed that liberalisation heightened the tensions within firms over how to allocate cash among R&D, new investments and shareholder dividends. Company R&D spending correlated negatively with new investment expenditure and with dividend payments, meaning non-R&D spending priorities effectively crowded out R&D spending.

While the evidence suggests that exposure to stronger market forces through liberalisation decreases the level of R&D activity performed by affected firms, liberalisation also appears to increase the quality or productivity of the R&D that does not get cut. Sharper competition tends to re-focus the remaining R&D on the most worthwhile projects. Munari (2003) looked at the unconditional effect of liberalisation on R&D productivity in two French electric utilities. Munari found that scientific researchers based in the utilities applied for a larger number of patents on their inventions after privatisation than before. In a different study, Calderini and Garrone (2003) studied the effect of liberalisation on the productivity of two types of R&D, basic and applied, in 17 European telecommunications and electric power utilities. They measured R&D productivity using indicators of output per researcher. Calderini and Garrone found that after liberalisation, the productivity of basic R&D as measured by scientific article publications per researcher decreased, but the productivity of applied R&D as measured by patents per researcher increased. The unconditional effect of liberalisation in the electric power sector seems also to have made applied R&D activity more productive.

These studies imply that transitioning to an environmental policy regime that makes greater use of economic incentives affects not just the level of R&D spending, but also the productivity of that spending. Market forces probably exert countervailing effects on R&D spending. They cut out the R&D that cannot be sustained commercially or whose effect can be achieved with more accessible lower-order knowledge forms. The evidence suggests that exposure to more intensive competition leads firms to strike a different, lower equilibrium in terms of R&D spending relative to the previous, lower intensity level.

However, the evidence also shows that market forces improve the productivity of the remaining R&D by forcing firms to focus just on the projects with the most immediate returns.

If both the level of R&D and the productivity of R&D changed under electricity sector liberalisation, then it is also reasonable to expect that the aim of R&D projects changed as well. Defeuilley and Furtado (2000) looked at the effect of electricity sector reforms in the UK and the US on the nature of the R&D conducted in the affected utilities. They found that the affected utilities re-oriented their R&D effort toward projects with shorter-term 'concrete' applications that managers felt would strengthen the company's technical position relative to competitors. Elsewhere, Jacquier-Roux and Bourgeois (2002) studied the unconditional effect of liberalisation on patenting activity by 15 global energy-related companies. These companies were divided into utility operators and electricity equipment suppliers. Jacquier-Roux and Bourgeois found that after liberalisation of the energy industry as a whole, patenting activity decreased for the utility-operator companies but increased considerably for the equipment suppliers. This suggests that the locus in the economy of where R&D is actually performed can also shift under liberalisation, as from utility operators to energy equipment suppliers in the findings of Jacquier-Roux and Bourgeois. Thus it is probably the new productivity imperative unleashed by greater competition intensity that drives both the shorter-term focus of R&D projects as well as the disbandment and re-concentration of R&D in wholly new sectors to the ones where R&D was being performed previously.

An important study linking the R&D response under electricity sector reforms and the R&D response under market-based environmental policies is Markard, Truffer and Imboden (2004). Markard, Truffer and Imboden investigated how renewable energy innovation activities in electric power utilities changed under electric power sector liberalisation, looking at the unconditional effect of liberalisation on these activities. They interviewed 30 utility managers at utilities in Switzerland, Germany and Holland who had direct experience with these changes. Markard, Truffer and Imboden report that under monopoly, major environmental technology initiatives like the desulphurisation of coal-fired power plants and the introduction of nuclear and wind power capacity tended to be driven by political and regulatory forces. R&D was primarily focused on maintaining and upgrading the technical quality and security of electricity supply. Under monopoly, utilities' total systems evolved toward higher technical quality continuously over time.

Markard, Truffer and Imboden report that after liberalisation, a major new focus for R&D became cost reduction. Utilities formed more cooperative research ventures with other electricity service providers and equipment manufacturers. Instead of acquiring new technical knowledge by performing their own R&D, the utilities developed new strategies of monitoring and evaluating the technology development activities of their competitors. Utilities started innovating to meet customer wants. In terms of renewable energy, the utilities used their innovation resources to develop marketing strategies for selling hydroelectricity that already existed in their generation portfolios before liberalisation, to customers as 'green'. Under liberalisation the utilities used green power marketing to improve their corporate image and thereby prevent customer switching. Utilities developed capacity in renewable certificate trading and learned to navigate the influence of green power regulatory frameworks. In Markard, Truffer and Imboden's account, almost all of the innovation and R&D activity conducted by utilities in the post-liberalisation era was aimed at adjusting utilities' commercial strategy to respond to external market changes. Almost none of it was aimed at new technical knowledge creation in, for example, cleaner forms of electricity generation through formal R&D on technical projects.

This subsection brought together an evidence base examining the idea that regulatory frameworks designed to exploit the efficiency of competition and incentives in the electric power sector also lead to changes in R&D activity by the affected utilities. Liberalisation has tended to exert an unconditional negative effect on R&D spending levels. In addition to exerting a negative effect on spending levels, liberalisation also seems to lead to more productive R&D spending in the R&D that does not get cut. Liberalisation also seems to lead to R&D projects that are more applied in nature and which have shorter-term returns. Liberalisation has also led to the uprooting and relocation of the R&D function across sectors into a new, more efficient distribution.

The next subsection develops further the hypothesis that these changes in formal knowledge creation activity also occurred in response to the transition to increasingly market-based forms of environmental regulation, in the US specifically. It does this by recounting the changes to the form of regulation in the area of pollution control from automobiles and in the area of sulphur dioxide control from electric power generation. This gives an empirical basis for structuring the formal test of the causes of environmental R&D spending primarily as a function of the environmental regulatory burden, conditional on the degree of flexibility in the prevailing environmental policy regime.

c. The liberalisation of environmental policy

The same changes that policymakers introduced rather abruptly into the US electric power sector in the 1990s have been introduced incrementally in pollution control policy over the last 40 years. This subsection recounts those changes in the approach to regulating conventional pollutants from automobiles and sulphur dioxide from electric power plants. These sources accounted for 84 per cent by weight of all regulated air pollutant emissions in the US between 1970 and 2000 (US EPA 2008). As will be shown, regulators have transferred to market forces increasing amounts of control over how regulated firms comply with emission limits set by the state. What were once uniform emission standards, prescriptive abatement methods and rigid compliance timelines have given way to 'flexible' standards, negotiable timelines, and compliance methods decided increasingly by the regulated entity as opposed to by the regulator (Dietz and Stern 2002; Kochtcheeva 2009). This subsection builds further the hypothesis that these changes diminished the incentive firms had to search for new formal technical knowledge through R&D. The changes are tracked through four dimensions of environmental regulation: the temporal dimension, the spatial dimension, the between-firm and between-facility dimension, and the abatement method dimension.

In 1970, policymakers approached automobile emission regulation by directing the automobile manufacturers to reduce carbon monoxide (CO), hydrocarbon (HC) and oxides of nitrogen (NOx) emissions from all the new vehicles they sold in the US by 90 per cent by model year 1976 (US CAAA 1970; Reitze 2001). Under this approach the state decided the temporal dimension of compliance absolutely by giving the automobile manufacturers a fixed period of five years to meet the reductions. In the spatial dimension the state required the automobile manufacturers to sell 90 per cent cleaner vehicles both in major cities with intense ambient air quality problems and high damage costs, and also in rural areas with no significant air quality problems and low damage costs. That is, policymakers allowed zero latitude for emission limits to vary across space. In the between-firm dimension, virtually every vehicle from every automobile manufacturer had to meet the standard. Neither within-company 'fleet averaging' nor between-company emission credit trading was allowed in the early days (White 1976). In terms of abatement methods, there was almost no way for an automobile manufacturer to satisfy the demands of the state besides making physical technical changes to their vehicles, such as by pushing out the technological frontier through formal R&D.

Most of this had changed by the time of the 1990 Clean Air Act Amendments. Policymakers proceeded with their regulatory approach with less rigidity and more flexibility in all four dimensions (US CAAA 1990). In the temporal dimension, regulators required that new exhaust pipe emission standards be met through two smaller step changes, with deadlines in 1994 and 2004, rather than through one big step change by a single date. In the spatial dimension policymakers wrote into the 1990 Amendments a provision that allowed the automobile manufacturers to differentiate the vehicles they produced for California and for the other 49 states. This introduced spatial differentiation by only requiring that the vehicles meeting the most stringent standards (so-called ultra-low emission vehicles (ULEVs) and zero emission vehicles (ZEVs)) to be sold in California where the damage costs were generally highest. This means that to the extent that the automobile manufacturers needed to perform new R&D to bring ULEVs and ZEVs into existence, they only had to do it for vehicles sold in California, and not for all the vehicles they sold throughout the entire nation. In terms of abatement methods, a 'fuel neutrality' provision in the 1990 Amendments let the automobile manufacturers design ULEVs and ZEVs around virtually any clean alternative fuel or fuel combination they chose. This left the decision process over what would eventually be the dominant clean vehicle fuel to market forces. The automobile manufacturers could perform R&D to develop new-to-the-world fuels if they wanted, but this was not a requirement of the regulation, and they could equally choose to fall back on clean fuels already in existence. In the inter-firm dimension, the Amendments set out new requirements on the content (benzene) and characteristics (volatility) of fuels for the most heavily polluted regions in the country. The legislation created a program allowing oil companies, fuel importers, fuel refiners and fuel blenders to earn tradable credits for exceeding the mandatory fuel specifications. The first subsection above already discussed the effect of economic instruments like permit trading systems on R&D spending levels. On the whole these changes in the regulatory approach illustrate how much more flexible the regulatory regime relating to automobile emission control became over time.

The same pattern of increasingly flexible regulatory form is observable along the same four dimensions in the approach to sulphur dioxide emissions from electric power plants. The 1970 CAA Amendments stated that any new fossil fuel fired boiler proposed to be built in a heavily polluted area could emit no more than 1.2 pounds of SO2 per million British thermal units (MMbtu) of heat input (US CAAA 1970; Reitze 2001). This standard was fixed and largely inflexible. Any firm proposing a new boiler or expanding a plant in a heavily polluted area that did not meet this standard would be denied planning permission by the planning authority. In terms of abatement methods, policymakers also set out rules that more or less required new and expanding plants as well as some existing plants to meet the standard by installing flue gas desulphurisation (FGD) units to cleanse gasses of SO2 before being released into the atmosphere. Policymakers put these requirements in place even though many utilities would have preferred the cheaper and simpler abatement method of burning lower-sulphur fuels like lignite coal and natural gas (Joskow 1998).

By the late 1970s policymakers had begun to allow new and expanding power plants to comply with the emission standards in an increasingly wide and flexible range of ways (US EPA 2001; US CAAA 1977). In the between-firm dimension, the ‘offset mechanism’ introduced in the 1977 CAA Amendments allowed new and expanding plants to be granted planning permission if they were able to purchase sufficient emission reduction credits (ERCs) from existing sources to offset the new emissions caused. In the within-firm dimension, ‘netting’ rules introduced in 1980 allowed new and expanding plants to avoid triggering the 1.2 MMbtu standard as long as they could keep net facility emissions below the trigger threshold. They could do this, for example, by decreasing emissions from elsewhere in the same facility at the same time. ‘Bubbling’ came into practice in 1980. The term ‘bubbling’ means that a facility with several emission points, like a petroleum refinery, could apply to the EPA to treat all these emission points together as if they were subject to a single aggregate limit. In the temporal dimension, regulators began allowing plant operators to ‘bank’ emission reductions from the late 1970s. Banking let plant operators save as credits the surplus emission reductions they earned in low abatement cost time periods, and apply these later in high abatement cost time periods. The Environmental Protection Agency (EPA) formalised the rules for offsets, netting, bubbles and banking in its 1986 Final Emission Trading Policy Statement (US EPA 1996; 2001). In the abatement method dimension, the SO2 permit trading program set up in 1990 more or less eliminated the regulator’s preference for scrubbers that was built into the prior, more rigid framework. Trading led to many plant operators abandoning flue gas desulphurisation for a range of other lower-tech and lower cost abatement methods including fuel switching and load optimisation.

These examples show that the same kinds of policy events that led to the drop-off in R&D spending in the electric power sector also occurred in the sphere of pollution control between 1970 and 2000. In the sphere of pollution control, regulators turned over to market forces substantial areas of decision making that were once controlled by the state. These specific examples from the automobile and SO2 pollution control cases illustrate how these changes were observable in the spatial dimension, the temporal dimension, the between-firm dimension and the abatement method dimension of environmental regulation.

The evidence in this and the previous three subsections leads to the hypothesis that the level of environmental R&D expenditure responds to the level of the environmental regulatory burden, conditional on the degree of flexibility in the prevailing environmental policy regime. This implies that if two separate firms face the same environmental compliance task, but one firm faces the task under a highly flexible regime and the other under a rigid regime, than the firm complying under the flexible regime will spend less on environmental R&D in dealing with the task, all else being equal. This hypothesis is stated formally as follows:

Hypothesis: The degree of flexibility built into the prevailing environmental policy regime conditions the effect that the regulatory burden has on the level of environmental R&D spending. The more flexibility the policy regime gives firms to decide themselves how to go about dealing with the regulatory burden, the lower the level of environmental R&D they will choose to spend.

The next section develops an empirical test of this hypothesis.

3. Research approach

This section describes the econometric model used to test the hypothesis. It discusses some of the decisions taken in the specification of the model including the decision to use industry fixed effects and the decision to specify the model in log-linear functional form. All variables used in the model are described in terms of data sources, measurement units and key trends that inform the hypothesis and the broader research question. Special emphasis is given to explaining the meaning of the ‘environmental R&D’ dependent variable.

a. Model specification

The model tests the effect that the environmental regulatory burden exerts on the level of environmental R&D spending, conditional on the presence of environmental policy regime types embodying different degrees of flexibility. The dependent variable is the level of environmental R&D spending. It is regressed on a vector of independent variables, $\mathbf{Z}$, plus a classical error term:

$$y = \mu + \beta\mathbf{Z} + \varepsilon$$

The first variable of interest in the vector **Z** measures the level of regulatory burden as annual pollution abatement and control (PAC) expenditure. Also of interest in vector **Z** is a set of dummy variables denoting the degree of flexibility in the policy regime that was prevailing at the time that the PAC expenditure was made. A set of three dummy variables is used to capture the degree of policy regime flexibility, and PAC is interacted separately with two of these, leaving the third as the omitted category. The PAC variable and the policy regime dummies are discussed in detail below.

Within the vector **Z** the conditioning effect of the policy regime is tested by interacting the PAC expenditure variable with the policy regime variable. This is appropriate because the PAC expenditure variable only measures the level of the regulatory burden. It contains no information about the legal restrictions that the prevailing policy regime type places on how firms are allowed to deal with the burden. The policy regime variable does, however, contain information about the legal restrictions incumbent upon firms in the compliance process. The interaction implements the test of the effect of PAC expenditure on the dependent variable *conditional on the modifying effect of the policy regime*. PAC expenditure is expected to exert a positive effect on the dependent variable on its own in an unconditional relationship. But when PAC expenditure is interacted with the variable denoting the presence of the most flexible policy regime type, PAC is still expected to exert a positive effect on the dependent variable, but this effect should be smaller on account of the conditioning effect of flexibility.

The model is fitted to panel data with repeat observations on annual environmental R&D spending over 22 continuous years, 1972-1994, for each of 30 two and three-digit industry groups (SIC 20-39). Industry fixed effects exploit the panel structure of the data. Fixed effects deal with unobserved, time-constant variation in environmental R&D spending that is specific to the industry group. There may be more opportunity for technological progress in drugs and medicine than in textiles and apparel, for example. Industry fixed effects deal with the possibility that environmental R&D is less forthcoming in industries which are mature or impervious to technological progress or where technological gains are more difficult or expensive (Jaffe and Palmer 1997; Fung 2004).

With fixed effects, the model takes the form:

$$y_{i,t} = \mu_i + \beta \mathbf{Z}_{i,t} + \alpha_i + \varepsilon_{i,t}$$

Subscript i denotes industry group and t denotes year. The term μ is an intercept, β represents the coefficients on the independent variables, α is the industry group-specific fixed effect, and ε is an error term capturing residual heterogeneity. The model is estimated by the time demeaning method (Wooldridge 2003; Allison 2009).

The model is fitted to environmental R&D spending data that come from the National Science Foundation's (NSF) Industrial Research and Development Information System (IRIS) database. PAC data come from the US EPA. All spending data are deflated to real 1992 dollars using the BEA's fiscal year GDP price index. The data were gathered by NSF and EPA under a common conceptual and statistical framework for measuring the economic impact of environmental programs in the US (see Cremeans 1977 for a discussion of this framework). The NSF and EPA stopped gathering environmental R&D and PAC data after the mid-1990s (NSF 1999a). This makes it impossible to test the effect of the policy regime on environmental R&D activity post-1994, which is why the time series stops after that year.

The model is estimated in log-linear functional form. Comparison tests were performed of the fit of a log-log specification where all continuous independent variables were logged; a log-log specification where only the independent variables of interest were logged; a linear-linear specification where no variables were logged; and a linear-log specification where all independent variables were logged. The log-linear form gave the highest within-R-square value of all five candidate functional forms (.234). By contrast the within-R-square for the log-log specification (all independents logged) was .202; for the log-log specification (only independents of interest logged) it was .189; for the linear-linear specification it was .055; and for the linear-log specification it was .104. The log-linear specification also gave the fit with the most homoscedastic distribution of error terms when the error terms were plotted against the dependent variable. This distribution is shown in Section 4 in the discussion of checks on the quality of the model. The data are therefore fitted to the full model:

$$\text{(ln)Environmental R\&D spending}_{i,t} = \mu_i + \beta_1 \text{PAC spending}_{i,t} + \beta_2 \text{Market-based regime dummy}_t + \beta_3 \text{Flexible regime dummy}_t + \beta_4 \text{PAC} * \text{market-based regime dummy}_{i,t} + \beta_5 \text{PAC} * \text{flexible regime dummy}_{i,t} + \beta_6 \text{Year}_t + \beta_7 \text{Employment}_{i,t} + \beta_8 \text{Ordinary R\&D spending}_{i,t} + \varepsilon_{i,t}$$

The next two subsections describe what each variable measures and any important trends in them, beginning with the dependent variable.

b. Dependent variable

The dependent variable is *total spending on pollution abatement R&D by private industry and the federal government combined*. In the NSF survey questionnaire used to gather the data, 'pollution abatement' has a precise meaning. The meaning of 'pollution abatement' rests in turn on the meaning of the term 'pollutants'. Pollutants in this context refers to:

> …all the classes of measurable agents (forms of matter or energy) that are discharged to common-property media from a government or market-related activity so as to cause loss of welfare to a human receptor. (Cremeans 1977: 102)

This means that 'pollution' in the dependent variable includes emissions to any environmental medium (air, water, land, other) from automobiles, electric power plants and manufacturing facilities. It includes emissions that take the form of solid waste, or heat, noise and radiation. It was not intended to include emissions of what are recognised today as GHGs.

'Pollution abatement R&D' therefore means R&D for the purpose of eliminating the emission of pollutants to 'outside the firm's property or activities' as through R&D aimed at prevention, treatment or recycling (NSF 1999c: 10). Pollution abatement R&D explicitly excludes R&D for improving environmental aesthetics or equipment durability. It excludes R&D for conserving energy or natural resources, and for increasing employee comfort, health or safety (NSF 1999c: 10-11).

This means that the idea of 'environmental R&D' is defined more narrowly but also more precisely in this paper than it has been defined in other studies. For example Brunnermeier and Cohen's (2003) dependent variable, environmental protection patents, included patents on inventions related to renewable forms of energy production as well as patents on inventions related to direct forms of pollution control and waste management (Brunnermeier and Cohen 2003). In the NSF data, R&D activity for renewable forms of energy would have been excluded if the purpose of the R&D behind the renewable energy patent was to create a new energy supply source and not abate pollution. The purpose of R&D is known only by the respondent. For Horbach (2008) 'environmental innovation' was defined as any firm's effort to develop a new product as long as that firm belonged to the 'environmental sector'. Horbach determined membership in this sector by the firm's answer to the question: 'Does your firm offer goods or services related to the reduction of environmental impacts?' (2008: 167). It is difficult to think of a firm that would not want to find a way to respond to this question in the affirmative. New products or services for almost any purpose could therefore be included in this 'environmental innovation' definition. Arimura, Hibiki and Johnstone (2007) defined environmental innovation to included R&D for 'environmental conservation' and 'environment-related' purposes, but they do not give a more precise meaning.

A precise definition matters for identifying the conditioning effect of economic instruments on environmental R&D activity through the PAC burden. The three studies just mentioned generally define and measure environmental R&D to include effort other than that to abate pollutant emissions 'to outside a firm's property or activities'. In doing so they open up the possibility for environmental R&D to respond to a range of factors besides the pollution control burden and the form of the pollution control regulatory instrument. Factors that could influence a more loosely defined 'environmental' R&D variable include government incentives for clean energy development and changing energy prices. These factors are connected to R&D for pollution control, but they obfuscate the effect that the pollution control burden and the form of pollution control policy have on R&D to deal with those burdens specifically. Recall that the policy problem that motivated this investigation was the role that R&D for GHG abatement is likely to play in GHG control, not the role of R&D in the provision of energy goods, which ordinary market forces should respond to more readily.

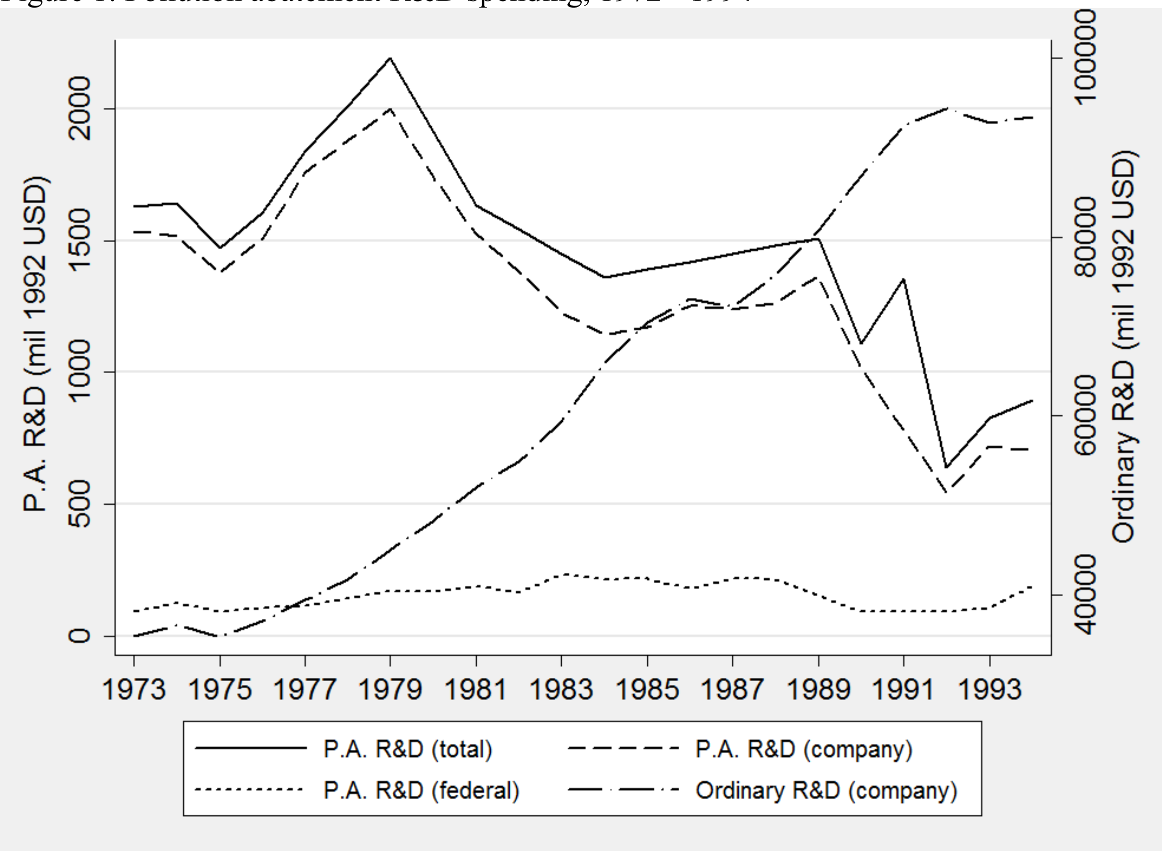
The big advantage of environmental R&D as it is defined here, as R&D for the purpose of pollution abatement only, is that it deals with the 'dual purpose' problem (Tucker 1994; OECD 1999) that hampers so much environmental innovation research. Again the survey questionnaire takes care of this problem when it instructs respondents on how to treat R&D spending that may be aimed at several purposes at once:

> If the only purpose of the R&D spending is pollution abatement, include the total expenditures on the project. If pollution abatement is only one of several purposes, report only the R&D costs associated with. When the separation of joint costs is not feasible, include the total R&D costs for a project if the purpose is primarily (more than 50 per cent) for pollution abatement. (NSF 1999c: 11)

This means that the NSF pollution abatement R&D spending data get around the dual use problem by asking respondents to report their R&D spending based on their guiding aim or intention in undertaking the R&D. If the respondent had pollution abatement as well as non-pollution abatement aims, then they should have omitted the part with non-pollution abatement aims. With patents, the purpose of knowledge creation activity cannot be known with this level of precision.

Interesting spending trends emerge when 'environmental' R&D is measured this way. Figure 1 shows that private industry rapidly increased its pollution abatement R&D spending in the early 1970s to a peak of about two billion (real 1992) dollars per year in 1979 during the rigid environmental policy regime described in the last section. However, throughout the 1980s the rate of spending gradually decreased. From about 1990 onwards the rate of spending decreased dramatically. As for federal government spending, this closely tracked private industry spending up until about 1990 when it began to increase sharply around the same time that private industry spending was dropping off. In Figure 1, pollution abatement R&D spending is read against the left axis.

Figure 1: Pollution abatement R&D spending, 1972 - 1994



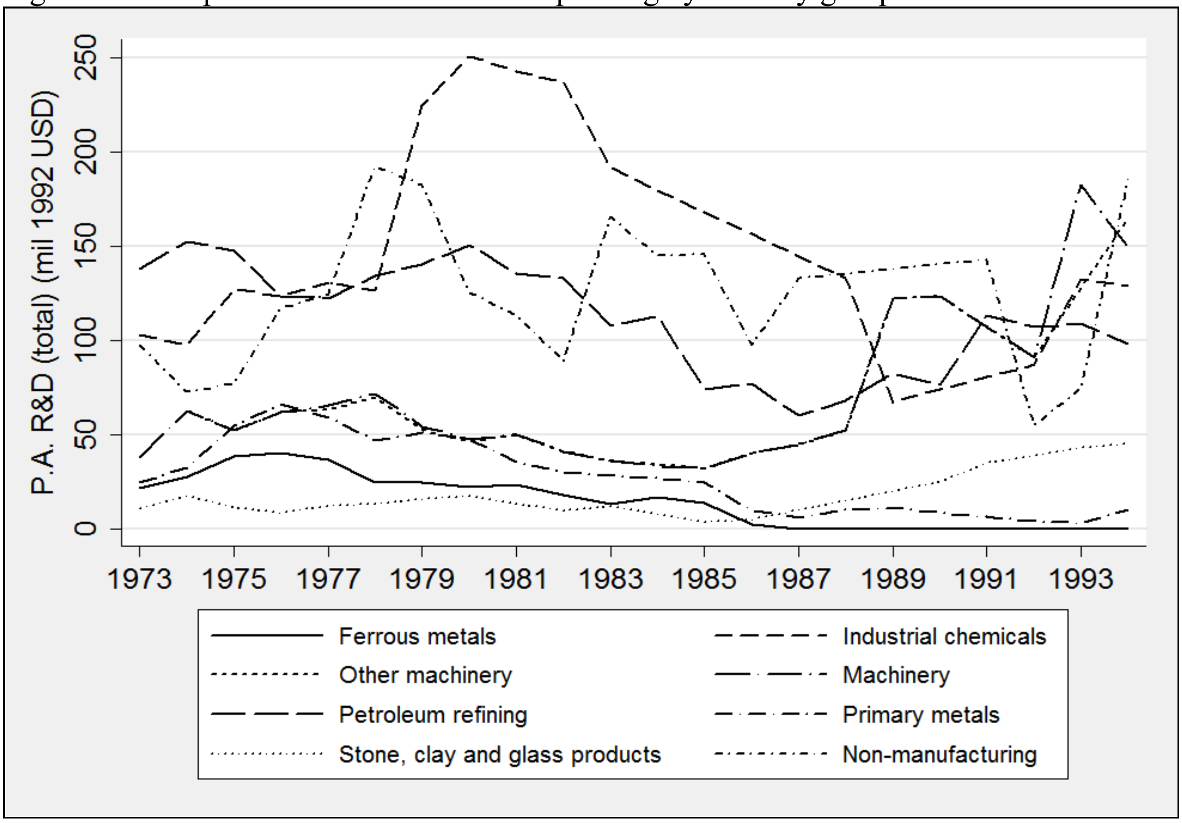
Note: Millions of 1992 dollars. PARD (private) and PARD (federal) are read against the left axis. Non-PARD (private) is read against the right axis. The PARD data come from Vogan (1996); the non-PARD data come from the NSF's IRIS database. All spending is deflated using BEA's fiscal year GDP price index.

The right-hand axis of Figure 1 shows that private industry was increasing its level of spending on R&D for all other 'ordinary' purposes at the same time it was decreasing its level of spending on pollution abatement R&D specifically.

To get a sense of the scale and composition of this activity, private industry and the federal government combined spent about 50.5 billion real 1992 dollars on pollution abatement R&D over the total 22 year period. Private industry spending accounted for about 30.5 billion of this, while federal government spending amounted to around 19 billion. State and local government spending accounted for the rest. Looking at the 50.5 billion dollars of R&D a different way, about 55 per cent was for air pollution, 14 per cent for water pollution, five per cent for solid waste and 23 per cent for noise and radiation.

The data are broken down by industry group in Figure 2. This shows that some of the industry groups that were spending the most on pollution abatement R&D started decreasing their spending around 1980 consistent with the national trend. The major exception, however, is the machinery industry group. Machinery began increasing its rate of spending around the time that the heaviest spending industry groups, chemicals and petroleum refining, began decreasing their spending.

Figure 2: Total pollution abatement R&D spending by industry group



Note: Millions of 1992 dollars

The spike in spending by the machinery industry group supports the idea that the transition to more flexible instruments triggered an uprooting of R&D from some sectors and the relocation of that R&D to other sectors, resulting in a new distributional R&D pattern compared to the less flexible regime (as in Jacquier-Roux and Bourgeois 2002).

The constraints of the earlier policy regime might have straight-jacketed each industry group into performing its own R&D, however efficient or inefficient the return for that effort might have been. The transition to an increasingly flexible regime involving economic incentives seems to have triggered a more efficient R&D distribution. This distribution let the dirtiest industry groups abandon R&D projects with a relatively low return. The machinery industry group seems to have been a winner from this process, or at least one destination for the displaced R&D function. The restructuring may have created new opportunities to develop and sell cleaner machinery goods to downstream buyers.

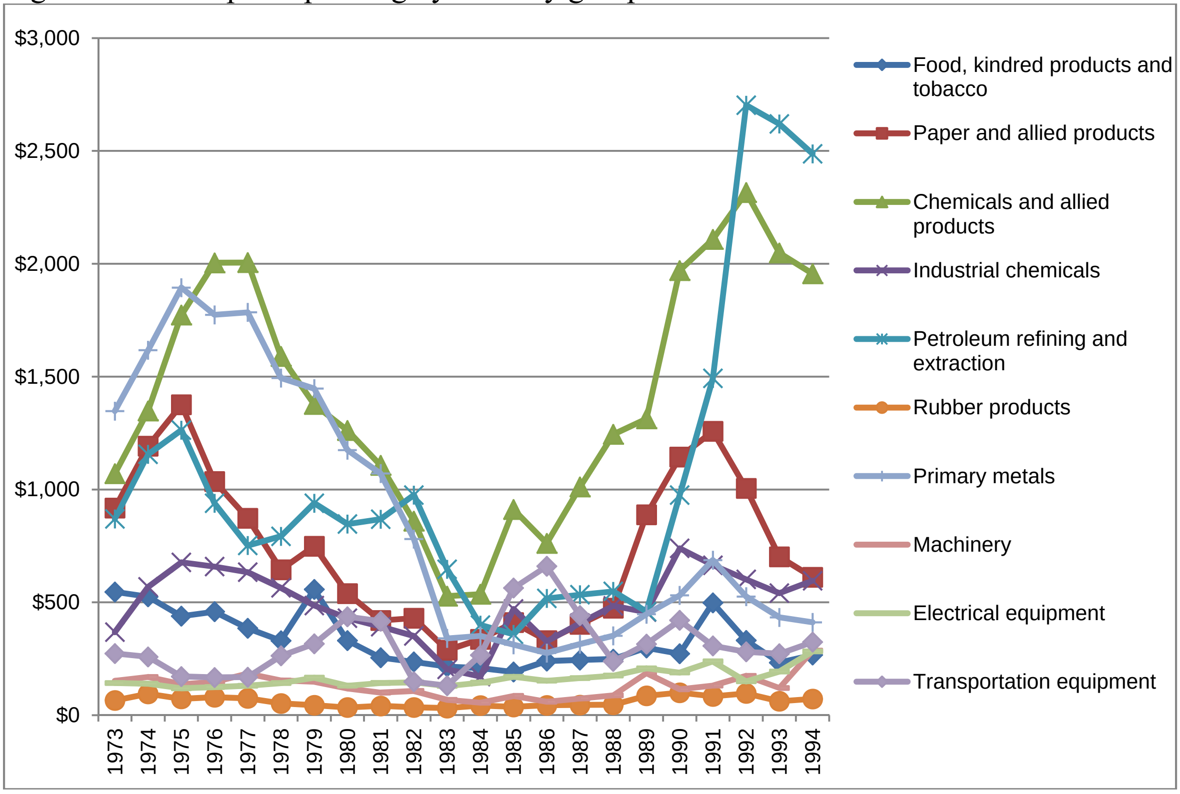
c. Main explanatory variables

Total PAC expenditure is one of the constituent terms in the interaction variables used to test the hypothesis. PAC spending measures the level of environmental regulatory burden. It measures only the level of that burden and does not contain any information about the nature of the restriction the prevailing regulatory regime type placed on how firms were allowed to deal with that burden. PAC measures expenditure by each industry group to abate emissions to all four environmental media: air, water, solid waste and other. It includes treatment, collection/disposal, waste minimisation, source reduction and recycling. PAC expenditure explicitly excludes R&D spending (US Department of Commerce 1993).

The variable used in the regressions is total PAC expenditure. Total PAC expenditure is the sum of PAC capital expenditure and PAC operating expenditure. It would be a major omission to leave out one type of spending, not least because they show different level trends over time. In the estimations, total PAC expenditure is lagged by three years. The lag length is based on Popp's (2002: 9) finding that energy technology patenting activity responded to energy price changes with a lag of about 3.7 years (2009: 9) and Jaffe and Palmer's finding that ordinary R&D spending in the US responded positively to a moving five year average of PAC operating expenditure (1997: 614).

Disaggregating total PAC expenditure into capital and operating expenditure shows some informative descriptive trends. Figure 3 shows that PAC capital spending peaked for many industry groups around 1977 and again around 1990, which were both years when Congress passed major amendments to the Clean Air Act.

Figure 3: PAC capital spending by industry group



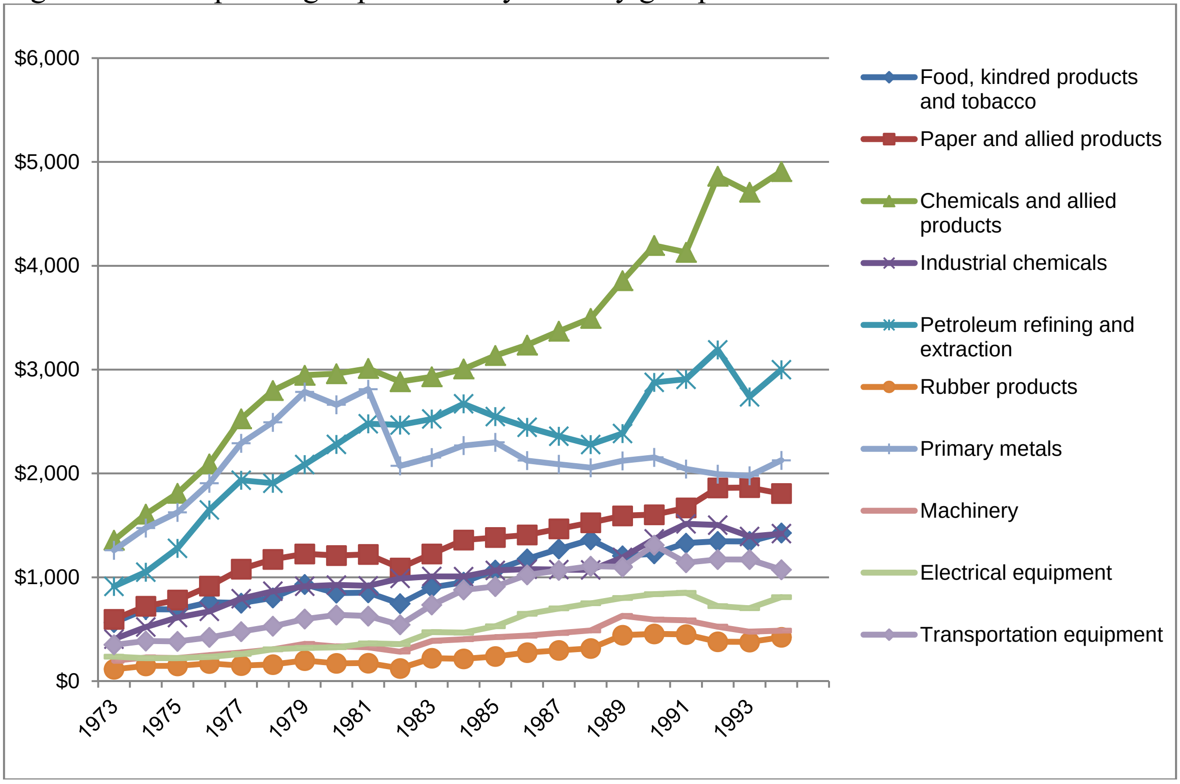
Note: Millions of 1992 dollars

PAC capital expenditure includes new durable capital goods that add to the stock of fixed pollution control assets.[1] PAC operating expenditure by contrast measures annual spending for day-to-day costs related to the management of an establishment's pollution abatement obligations.[2] PAC operating expenditure does not spike and fall around the time of major legislative events as shown in Figure 4. Rather PAC operating expenditure steadily increases for most industry groups during most of the 22 year period.

[1] This includes end-of-line structures, production process enhancements and pollution monitoring equipment. Capital expenditure excludes capital equipment with a primary purpose other than environmental protection. It excludes equipment for improving health, safety, environmental aesthetics or employee comfort as well as the cost of manufacturing pollution abatement equipment where this is the primary business activity of the respondent.

[2] Including spending on contracted waste disposal services; payments to government for waste collection; handling, treatment or disposal of wastes created by the production process; testing and monitoring of emissions; operation and maintenance of pollution abatement equipment; fuel and power costs for operating pollution abatement equipment; compliance and environmental auditing; salaries and wages for time spent on environmental reporting requirements; the cost of developing pollution abatement operating procedures; and permits (US Department of Commerce 1993).

Figure 4: PAC operating expenditure by industry group



Note: Millions of 1992 dollars

To put these PAC figures into perspective, total PAC spending over the full 22 years for all industry groups together was about 125.5 billion for capital equipment and around 305.1 billion for operating expenditure, in real 1992 dollars. Combined PAC expenditure was about 430.6 billion. In 2010 dollars it would cost about 693 billion dollars to buy this much pollution control. This means that total PAC expenditure during these 22 years amounted to about 88 per cent of the cost of the 787 billion economic stimulus package the US Congress approved under the American Recovery and Reinvestment Act in 2009.

Environmental policy regime type is a set of dummy variables representing the three broad environmental policy regime types that US environmental regulators transitioned through during the period 1973 – 1994. These variables make up the second part of the interaction terms. Some of the markers of the policy regime transition were discussed in Section 2 with respect to automobiles and electric power plants. That section showed how market forces came to play an increasingly prominent role in the design and implementation of pollution control regulation in these policy areas over time, and that this transition was observable in the spatial dimension, the temporal dimension, the between-firm dimension, and the abatement method dimension.

The degree of flexibility of a policy design can be thought of in terms of the number of options allowed to the polluter by the regulator for achieving compliance

(Stavins 1998). A policy design at the rigid, non-flexible end of the flexibility spectrum typically permits a narrow range of abatement options. These options might include installing a specific piece of abatement equipment or adopting a specific production process. A rigid policy design tends to foster an adversarial, low-trust relationship between the state as authoritative enforcer and the firm as passive complier (Fiorino 2006). In doing so it tends to constrain the universe of technically feasible compliance possibilities the firm could potentially choose from to the much narrower range of possibilities the regulator understands, believes will work, and is able to identify and anticipate. A rigid design also tends to set uniform emission standards across polluters that disregard variable abatement costs across pollution points, time and space. Standards tend to be enforced with disproportionate penalties for non-compliance.

A flexible policy design reduces some of the 'hard edges' and attendant inefficiencies of the rigid design. As discussed in Section 2 (a) – (c) a flexible policy design acknowledges that marginal abatement costs vary across firms, time, pollution points, and space. It acknowledges that the overall cost of achieving the overall emission reduction under the policy can be reduced by allowing for a wider range of abatement methods (Stavins 1998). A flexible design provides ways for firms to exploit the cheapest potential reductions through policy provisions like 'offsetting', 'netting', 'bubbling' and 'banking' described previously in Section 2 (c). Provisions like these let firms choose from a broader set of compliance options than is usually permitted under a rigid design. These provisions do not however give firms complete access to the full universe of technically feasible compliance options. A flexible policy design is something of a halfway house between a rigid design and a market-based design.

A fully market-based policy design cedes almost complete control over how emission reductions are achieved to market forces. This design also cedes considerable control over when, where in spatial terms, and in which sectors emission reductions can occur. A market-based policy design embodies the greatest possible degree of flexibility in terms of available compliance options. It emphasises performance and emission reductions over conformance and compliance (Fiorino 2006). It re-casts the role of the regulator from actively picking and monitoring the uptake of the 'best' technologies, to designing and enforcing the rules by which producers and consumers of emission reductions relate to one another within an overarching emission reduction policy framework (Stavins 1998; Bennear and Coglianese 2012). The regulator exerts very little influence over how emissions reductions are actually technically achieved in this framework. This leaves market participants to choose from as close as possible the full universe of technically feasible emission reduction possibilities.

In the model, this variation across the spectrum of the degree of flexibility in policy design is modelled as three separate policy regimes: the 'rigid' regime that prevailed during the years 1973 – 1979; the 'flexible' regime in the years 1980 - 1988; and the 'market-based' regime from the years 1989 – 1994. The policymaking events that roughly demarcate these periods were discussed in Section 2. Each regime is represented by a dummy variable. The base category is the rigid regime.

This is not the first investigation to use an interaction strategy in which one of the constituent terms of the interaction is essentially a time period dummy. The policy regime dummies in the interactions are comparable to the variables used in the interactions in other studies using fixed effects. Vella and Verbeek (1998) for example interacted the formal education level of male wage earners with year dummies to see if the effect of education on wages remained the same over time. Also using individual fixed effects, Allison (2009) tested whether children's antisocial behaviour levels changed over time by interacting the age of the individual children with year dummies. In this investigation, the policy regime type variable varies over time just as the year dummies do in these studies, the only difference being that the policy regime type dummies involve longer periods of time: of seven, nine and six years respectively.

d. Control variables

Employment is domestic employment of R&D performing companies measured in thousands of employees. It is used as an industry scaling variable following Jaffe and Palmer (1997) to preclude spurious correlation between PAC spending and pollution abatement R&D spending based on industry size. On its own, this variable correlates with the dependent variable with a Pearson's of .51.

Ordinary R&D spending is total industrial R&D spending net of the portion devoted to pollution abatement R&D, in millions of 1992 dollars. NSF defines R&D as a planned activity carried out by scientists and engineers for the purpose of discovering new technical knowledge (basic research), applying existing knowledge to the creation of a new product or process (applied research), or applying existing knowledge to the improvement of a present product or process (development) (NSF 1999b). This variable includes all three. It should associate positively with pollution abatement R&D.

Year is a linear time trend capturing all extraneous influences on R&D spending that are linked to time, including the acquisition of knowledge of lower-order form, but also any and all other time-linked influences. It is a control variable, not a test variable. The variable is measured as a simple linear time trend. This is consistent with the way that the sources of 'autonomous' technological advance were modelled prior to the beginning of the effort to endogenise technological advance in growth-and-environment models that emerged in the late 1990s (Nordhaus 1994; Popp 2004; Gillingham, Newell and Pizer 2008).

One effect that the time trend is likely to capture is the increasing importance of non-R&D forms of knowledge in regulated firms' compliance methods. Lower-order forms of knowledge tend to be less expensive to acquire, and this type of knowledge would be expected to substitute for formal knowledge creation (R&D) over time. There are three reasons for expecting this lower-order knowledge component of the time trend to substitute for formal R&D and exert a negative effect on R&D spending over time.

The first reason to expect a negative effect is that firms were probably able to draw on an increasingly large stock of pre-existing pollution abatement knowledge over time instead of, and as a replacement for, performing their own R&D (Popp 2002; Griliches 1990; Evenson 1991). Greater accumulated stockpiles of knowledge made new R&D less necessary. The optimal empirical approach here would have been to construct moving stocks of knowledge from the dependent variable itself and to include these stocks as an independent variable in the model. This was not possible because there are gaps in the data that prevent calculating a smooth accumulation of knowledge over time. The time trend is a proxy for steady accumulation.

The second reason to expect a negative effect is that pollution abatement R&D effort probably consolidated in research institutes and research joint ventures over time. Consolidation of R&D activity would have taken place through the formation of joint research ventures between firms and through increasing firm membership in research institutes established to carry out research of common interest to industry, on industry's behalf. A concrete example of this is the Electric Power Research Institute, a non-profit company set up in 1973 to carry out R&D on issues of interest to electric power utilities. EPRI's membership today accounts for over 90 per cent of the electricity generated and delivered in the US, but this was not the case in 1973. The expectation is that firms came to acquire more of the knowledge they needed for compliance second-hand from external research organisations and research partnerships, and that this second-hand knowledge lessened the need to conduct R&D themselves.

The third reason to expect a negative effect from the time trend is that it probably captures pre-existing knowledge of abatement methods or related processes that firms possessed already but which they were precluded from using under the restrictions of the early, rigid policy regime. More of the knowledge firms held in other areas probably became relevant in dealing with the pollution control burden as the more flexible regime made using that prior related knowledge legally permissible. For example, under the most rigid regime an understanding of fuel substitution would not have been useful knowledge for a firm in dealing with a pollution abatement burden because fuel substitution was essentially prohibited by the regulator as a compliance method. However, as the policy regime became more flexible it became increasingly permissible for firms to use or repurpose knowledge they already possessed in related areas and to apply it for the first time to pollution abatement problems. It is expected that the 'activation' of latent, fallow knowledge brought forth by the policy regime change essentially broadened the available stock of lower-order knowledge available for pollution abatement. This in turn substituted for the need to perform formal R&D.

Table 1 summarises the variable definitions and descriptive statistics.

Table 1: Variable definitions and descriptive statistics

Variable	Definition	Obs	Mean	SD	Min	Max
Pollution abatement R&D expenditure	Millions of 1992 dollars (*i, t*)	591	87.312	199.651	0	1,210
Total PAC expenditure	Millions of 1992 dollars (*i, t*)	682	887.602	1,128.093	0	6,237
Rigid regime	Dummy (1973 - 1979 = 1; all others 0)	726	0.318	0.466	0	1
Flexible regime	Dummy (1980 - 1988 = 1; all others 0)	726	0.409	0.492	0	1
Market-based regime	Dummy (1989 - 1994 = 1; all others 0)	726	0.273	0.446	0	1
Time trend	Linear time trend	726	1,983.500	6.349	1973	1994
Employment	Thousands of employees (*i, t)*	609	522.025	580.842	12	6,152
Ordinary R&D spending	Millions of 1992 dollars (*i, t*)	591	5,095.854	8,857.036	2	89,594

4. Regression results

This section tests the hypothesis set out in Section 2 using the model developed in Section 3. It discusses the interaction approach used to implement the test and interprets the substantive meaning of the coefficients of interest. Various issues and checks on the robustness of the model are discussed.

a. Implementation of the hypothesis test

Recall the hypothesis developed in Section 2:

The degree of flexibility built into the prevailing environmental policy regime conditions the effect that the regulatory burden has on the level of environmental R&D spending. The more flexibility the policy regime gives firms to decide themselves how to go about dealing with the regulatory burden, the lower the level of environmental R&D they will choose to spend.

The test of this hypothesis is implemented by interacting PAC expenditure with the dummy variable for the flexible policy regime (1980 – 1989) and by interacting PAC expenditure with the dummy variable for the market-based regime (1990 – 1994). The rigid policy regime (1973 - 1979) is the omitted base category. Again, the reason for the interaction approach is that the PAC expenditure variable only contains information about the level of the regulatory burden. It does not contain information about how firms were allowed to deal with that burden. This is the reason for testing the effect of PAC expenditure on pollution abatement R&D expenditure conditional on the modifying effect of policy regime type. The test result is interpreted through the coefficient on the interaction once all control variables are in place. The expectation is that PAC expenditure will exert a positive effect on the dependent variable on its own. When PAC is interacted with the dummy variable for the market-based regime, it should still exert a positive effect on the dependent variable, but this effect should be smaller on account of the conditioning effect of the market-based regime. The interaction of PAC with the flexible regime dummy should also lessen the effect of PAC, though not by as much as the market-based regime.

b. Estimates and interpretation

Table 2 gives the main regression results. Specification (1) includes only the independent variables PAC expenditure, the market-based regime dummy and the flexible regime dummy. In this specification, the constituent variables are included separately from one another. They are not interacted. This makes it possible to observe that the within-R-squared increases from .040 to .106 when their interaction is included in the next column, specification (2). In specification (2) the interactions themselves are statistically significant at the one per cent level for [PAC * market-based regime] and at the five per cent level for [PAC * flexible regime]. The signs on both interactions are negative as expected.

Table 2: Regression evidence

VARIABLES	(1) lnPARD	(2) lnPARD	(3) lnPARD	(4) lnPARD
PAC expenditure (millions 1992 dollars)	0.000388***	0.000796***	0.000504***	0.000504***
	(3.903)	(6.275)	(4.316)	(2.773)
Market-based regime dummy	-0.280***	0.107	0.506**	0.506**
	(-3.153)	(0.977)	(2.562)	(2.475)
Flexible regime dummy	-0.180**	-0.00673	-0.0273	-0.0273
	(-2.280)	(-0.0679)	(-0.208)	(-0.212)
PAC * market-based regime		-0.000456***	-0.000230***	-0.000230**
		(-5.622)	(-3.050)	(-2.090)
PAC * flexible regime		-0.000225***	-5.48e-05	-5.48e-05
		(-2.972)	(-0.795)	(-0.719)
Employment (thousands)			0.000463**	0.000463
			(2.252)	(1.244)
Ordinary R&D (millions 1992 USD)			4.48e-05**	4.48e-05
			(2.473)	(1.108)
Time trend			-0.0590***	-0.0590***
			(-4.302)	(-3.536)
Constant	2.561***	2.224***	119.0***	119.0***
	(25.14)	(18.53)	(4.389)	(3.606)
Observations	504	504	411	411
Within-R-squared	0.040	0.106	0.234	0.234
Number of industry groups	31	31	29	29

T-statistics in parentheses. *** p<0.01, ** p<0.05, * p<0.1. For the full specification (column 4) an F-test value of 4.85 with probability greater than 0.01 rejects the null that the independent variables are jointly insignificant.

In specification (3), the three control variables are added: Employment, Ordinary R&D spending, and the Time trend. These account for competing explanations for the apparent relationship between the interactions and (ln) pollution abatement R&D. When the control variables are included in specification (3), the signs on the interactions remain negative, the t-scores on the interactions decrease and the coefficients on the interactions become smaller. In specification (4) the model is estimated with robust standard errors to further guard against heteroskedasticity. Including robust standard errors reduces the significance level of [PAC * market-based regime] from the one per cent level to the five per cent level. The variable [PAC * flexible regime] is no longer significant. The significance levels of the independent variables Employment and Ordinary R&D also change under specification (4). The implications of these changes are discussed below.

The test of the hypothesis rests on the coefficients of the interactions [PAC * market-based regime] and [PAC * flexible regime]. In order to interpret the substantive meaning of the interaction coefficients it is necessary to first interpret the substantive meaning of the PAC expenditure variable, which is a constituent of the interaction, and which is included separately in the full model.

In specification (3) the positive coefficient on PAC expenditure of .000504 implies that a one unit (one million dollar) increase in PAC expenditure (lagged by three years) associates with about a .05 per cent (five one hundredths of one per cent) increase in pollution abatement R&D spending on average, all else being equal. To get this semi-elasticity interpretation the coefficient is multiplied by 100 since the dependent variable is logged. Mean pollution abatement R&D expenditure over all industry group-years in the data set is 87.3 million dollars (Table 1), for example. This implies that in substantive terms, an increase of .05 per cent equates to an increase of 4.3 million dollars. This is a small and statistically significant positive relationship. This small, positive, unconditional relationship between the regulatory burden and environmental innovation activity is consistent with similar findings in the induced innovation literature (Hicks 1932; Brunnermeier and Cohen 2003; Jaffe and Palmer 1997; Popp 2002).

Against this interpretation of the coefficient on PAC expenditure it becomes possible to interpret the meaning of the coefficients on the interaction terms. The interactions give the change in the slope of the relationship between PAC expenditure and pollution abatement R&D that is attributable to the policy regime effect (Brambor, Clark and Golder 2006; Jaccard and Turrisi 2003). The coefficient on [PAC * market-based regime] in specification (3) for example is -.000230. This implies that the slope of the relationship between PAC expenditure and pollution abatement R&D decreases by this amount under the market-based regime relative to the baseline rigid regime, all else being equal. Specifically, the market-based regime weakens the effect of PAC on pollution abatement R&D expenditure by about 45.6 per cent, holding all else constant. To calculate the 45.6 per cent decrease in the effect of PAC on R&D attributable to the market-based policy regime, the adjusted coefficient is first calculated as: [coefficient on PAC expenditure – coefficient on (PAC expenditure * market-based regime)] or [.000504 - .000230] = .000274. This value .000274 reflects the effect of PAC expenditure on pollution abatement R&D conditional on the effect of the market-based policy regime. This value is 46.5 per cent smaller than the coefficient on PAC expenditure by itself, which is .000504.

This implies that a million dollars of PAC expenditure motivates less R&D under the market-based regime than it motivates under the baseline rigid regime. In substantive terms, if a one million dollar increase in PAC expenditure under the baseline rigid regime stimulates a .05 per cent (4.3 million dollar) increase in pollution abatement R&D, then the same one million dollar increase in PAC expenditure under the market-based regime stimulates a .027 per cent (2.3 million) increase in pollution abatement R&D expenditure. These estimates imply that the amount of R&D stimulated by a unit of PAC expenditure is smaller under the market-based regime than under the rigid regime, which is consistent with the hypothesis.

The coefficient on the other interaction term [PAC * flexible regime] is interpreted in the same way. The coefficient on [PAC * flexible regime] also gives the expected negative sign. The conditioning effect of the flexible regime also weakens the effect of PAC on pollution abatement R&D, but by a smaller amount than the market-based regime. The coefficient on [PAC * flexible regime] is -.0000548 in specification (3). This is interpreted the same way as above. First, the adjusted coefficient is calculated as: [coefficient on PAC expenditure – coefficient on (PAC expenditure * flexible regime)] or [.000504 -.0000548] = .000449. The value .000449 is the effect of PAC expenditure on pollution abatement R&D conditional on the effect of the flexible regime. If a one million dollar increase in PAC expenditure under the baseline rigid regime stimulates a .05 per cent (4.3 million dollar) increase in pollution abatement R&D, then a one million dollar increase in PAC expenditure under the flexible regime stimulates a .045 per cent increase (3.9 million dollar) in pollution abatement R&D. The conditioning effect of the flexible regime is 10.8 per cent smaller than the effect of PAC expenditure by itself under the baseline rigid regime.

The coefficient on [PAC expenditure * flexible regime] is not significant at conventional levels in specification (3) once the controls are added but it is significant at the ten per cent level in specification (5). The sign is correct in all specifications and the size of the coefficient is correct in all specifications relative to the size of the coefficient on [PAC * market-based regime]. This means that the evidence for the conditioning effect of the policy regime characterised by the greatest degree of flexibility (1989 – 1994), the market-based regime, is statistically significant, but that the evidence for the conditioning effect of the policy regime characterised by an intermediate degree of flexibility (1980 – 1988), the flexible regime, is not as strong.

Before proceeding to the interpretation of the other independent variables, it is important to point out that the interpretation of all the independent variable coefficients in the model is slightly different under fixed effects estimation as here than under OLS. The independent variable coefficients correspond to the expected per cent change in the dependent variable holding all other variables in the model constant, *and controlling for all unobserved time-constant heterogeneity achieved by the industry fixed effect.* As discussed above, one such source of influence in this study would be the varying levels of technological opportunity across industry groups.

All of the control variables give the expected sign. The coefficient on the Employment variable is positive and significant as expected in specification (3) and positive in specification (4). This implies that the larger the industry group by number of employees, the more the industry group spends on pollution abatement R&D, all else being equal. This variable controls for the possibility that the R&D spending level changed because the size of the industry measured by Employment grew or contracted.

The coefficient on Ordinary R&D spending is positive and significant in specification (3) and positive in specification (4). As expected, the more an industry group spends on R&D for all other non-pollution abatement purposes, the more it spends on R&D for pollution abatement, with all else remaining equal. The magnitude of the effect is small. A one million dollar increase in Ordinary R&D leads to about a .004 per cent increase in pollution abatement R&D. This is not the effect on pollution abatement R&D attributable to industry group scale (which is captured by the Employment variable). Neither is it the effect on pollution abatement R&D attributable to intrinsic technological opportunity (which is captured by the industry fixed effect). Ordinary R&D gives the effect of the industry group's general tendency and capacity to perform R&D on its tendency to respond to environmental regulation through R&D.

The Time trend control variable capturing all time-linked influences on the level of pollution abatement R&D spending also gives the expected negative sign. One influence that the Time trend is expected to capture is the increasing importance of lower-order knowledge in firms' compliance processes over time. The negative sign is consistent with the idea that lower-order, less expensive forms of knowledge substituted for the higher order forms of knowledge that would otherwise have been acquired through formal R&D.

c. Model quality checks

Various checks were performed on the quality of the model. Plümper and Neumayer (2011) argue that a model's robustness should be evaluated in terms of the stability of the direction of the coefficients, the stability of the size of the coefficients and the stability in the statistical significance of the coefficients. However, a model can be robust by these criteria without being 'good' in a broader sense. That is, there are many robust models that are also bad. A model that holds up to critical scrutiny and which can be relied on to legitimately inform policymaking should satisfy some additional criteria. It should show that the model estimates are not being fundamentally biased by poor specification decisions; that special techniques like interactions are correctly constructed and interpreted; that the underlying data are appropriate; and most importantly and above all else, that the model is soundly theoretically specified.

Stability in sign direction is not a significant issue in the model. Table 2 shows that the signs of all substantively interesting variables remain stable across all four specifications. This includes [PAC * market-based regime], [PAC * flexible regime] and all the control variables. Only the sign on the market-based regime dummy switches from the 'parsimonious' specification (1) to the more complete specifications (2) – (4), and this variable is not substantively interesting in these later specifications.

Nor is stability in the size of the coefficients a significant issue. For PAC expenditure and the two interactions, the coefficient size decreases when the control variables are added. This is to be expected. The order of magnitude remains the same. The discussion in the last subsection showed at length that the substantive meaning of these coefficients is not unrealistic. The small, positive, unconditional effect of PAC expenditure on its own is consistent with Brunnermeier and Cohen's findings, for example. Brunnermeier and Cohen found that a one million dollar increase in PAC expenditure led to an increase in environmental patenting activity of about .04 per cent.

Coefficient size could possibly be affected by collinearity between PAC expenditure and the control variable Employment, through an industry group scale. Dropping Employment does not change the magnitude, sign or significance level of the interactions in any significant way, but it does reduce both the within and between R-squared. When Employment is dropped and a different measure of industry group growth/contraction is added in its place (annual industry group sales, a measure of output), there is no significant change in the size or significance level of the coefficients on the interaction terms, either with or without robust standard errors. Finally, recall from the descriptive trend in Figure 2 of Section 3 that the machinery sector showed a countervailing trend of increasing R&D spending which began around the late 1980s. Dropping this sector from the estimations changes the coefficient on [PAC * market-based regime] from -.000230 to -.0001907, which is not a big difference. See Table 3 in the appendix for these test results.

If there is an unsatisfying aspect to the model with respect to Plümper and Neumayer's (2011) robustness criteria, it is in the statistical significance of some of the independent variables under specification (4) with robust standard errors. A model estimated from panel data with cross-sectional observations on industry groups should ideally give significant coefficients even when the errors are clustered on those observations. The interaction [PAC * market-based regime] both remain significant at conventional levels under specification (4). The time trend remains significant. The control variables Employment and Ordinary R&D become non-significant at conventional levels, however. Both remain positive. Alternately dropping the Employment and Ordinary R&D variables does not change this result. See Table 3 in the appendix for these test results. Both variables were left in the final specification because there were valid theoretical reasons to do so as discussed in Section 3 (d) and because both variables are controls after all.

A model that holds up to critical scrutiny and which reliably informs policy should also give estimates that are not obviously biased. A common source of bias is a heteroskedastic distribution of the error terms when the error terms are plotted against the predicted values. This basic check on model estimate quality is very rarely reported, but should be if the estimates are to be taken seriously.

Figure 5: Error term distribution

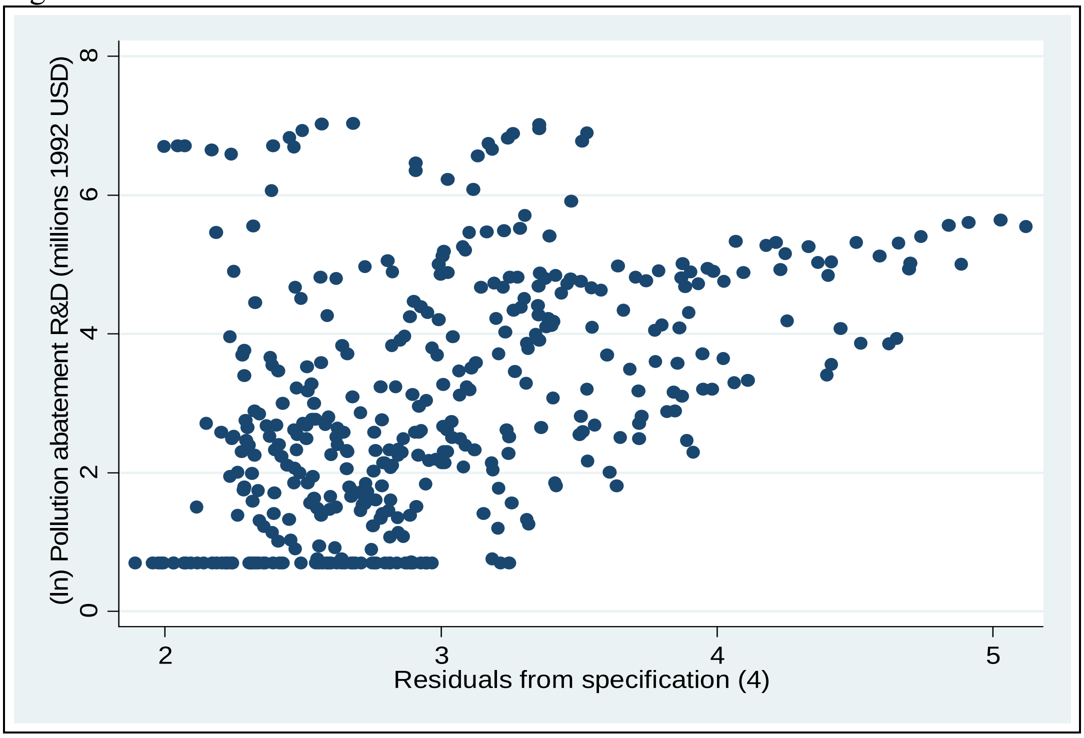


Figure 5 plots the predicted values of the dependent variable from specification (4) in Table 2 against the residuals. The distribution should spread evenly in a band around the y-axis mean and broadly, it does. The observations that bunch in a horizontal line in the bottom left are an artefact of the log transformation. Pollution abatement R&D spending observations with a value of zero were given an arbitrary value of two to validate the transformation, lest these observations be dropped. Much more uneven distributions appear when the dependent variable is estimated in linear form, for example.

A model which is valid and simply 'good' should make sure that special techniques like interactions are correctly specified and interpreted. An interaction will only give unbiased estimates when all of the constituent terms of the interaction are also included in the model. When the model contains more than one interaction, some authors suggest that the interaction of the interactions should also be included (Brambor, Clark and Golder 2006), while others suggest that this is not necessary (Jaccard and Turrisi 2003; Allison 2009). The full specifications in Table 2 and the interpretations to follow account for all constituent terms.

Believable models with reliable estimates should also acknowledge the strengths and limitations of the underlying data. The precise measurement of the dependent variable was discussed at length in Section 3 (b). The R&D spending data were compiled by the National Science Foundation from a random sample of 16,000 US manufacturing firms (US Department of Commerce 1993), which gives confidence in the representativeness of the sample to the population. On the other hand, Table 2 shows that the number of observations in the model drops by about 20 per cent between specifications (2) and (3) when the control variables are added. This is because the NSF withheld data points for certain industry group-years either to avoid disclosing the identity of individual companies or because the NSF's estimates were not sufficiently reliable to publish (NSF 1999b). Probing into these suppressed observations shows that they tend to come from three-digit industry groups (SIC 283 Drugs and medicine), from industry groups with lower PAC burdens (SIC 366 Communications equipment) and from industry groups with low levels of pollution abatement R&D spending (SIC 384-387 Optical, surgical, photographic and other instruments). Re-estimating the model without these industry groups shows that the signs, sizes and significance levels of the coefficients on all variables of interest remain stable both with and without robust standard errors. See Appendix 1, Table 4 for these test results.

The number one consideration in evaluating the quality of a model must be the extent to which the model is rooted rigorously in theory. Every sign, coefficient and significance level; every special estimation technique; every error term inspection; every dataset regardless of its likeness to the relationship being tested, can be invalidated by a model that in truth represents a process that widely diverges from the one that the researcher intends the model to represent. Fundamentally, a model that is 'good' must be a model that is theoretically well-specified. Section 2 went to length to develop a strong but grounded hypothesis about the conditioning effect of different policy regime types on the relationship between regulatory burden and environmental R&D spending.

The model was rooted in theory in several other ways. It set out a framework for discussing controversial and ambiguously termed ideas related to environmental technological change in the literature. It critically reviewed the relevant theory itself. It looked at the relationship of interest in the analogous case of electricity sector deregulation. It also empirically tracked the increasingly flexible approach to environmental regulation in the United States along the temporal dimension, the spatial dimension, the between-firm and between-facility dimension, and the abatement method dimension. During the course of this research many modifications and improvements were made to the specification of the model in arriving at the preferred model in Table 2. But many more modifications were made to the author's own expectations about how the relationships that the model itself aimed to represent should and do behave in reality. In this sense it could be said that the model in Table 2 is 'good' because it is both robust to tests of the internal statistical quality of the model, and also because it closely represents a process that appears from the weight of the theoretical evidence to be real and true.

The next section discusses the implications of the results presented in this section.

5. Analysis and contributions

This investigation was broadly motivated by a burst of recent proposals arguing that governments should increase public spending on R&D for GHG abatement technologies, and in most cases that governments should increase this spending dramatically. Such proposals sit in the context of extremely worrying physical scientific evidence about the scale of disruption to human activities that unmitigated climate destabilisation would cause. They also sit in a context of severe fiscal austerity in those western democracies that have been leading the charge against climate destabilisation. The tax-paying public are making even more acute demands on the efficiency and efficacy with which public funds are used to conduct climate policy. This paper questioned whether it is realistic to expect firms to spend large amounts of money on environmental R&D under the policy instruments favoured by governments today that leave many aspects of the compliance process to market forces. More broadly it shed light on the effect that environmental policy regime types embodying different degrees of flexibility are likely to have on the level of new knowledge created through formal R&D aimed at dealing with environmental problems.

This study challenged the idea that flexible policy instruments that use economic incentives to motivate environmental compliance naturally induce more environmental R&D spending than policy instruments that do not use economic incentives, all else being equal. Section 2 found that the theoretical evidence for the link between flexibility and environmental R&D is weak. Much stronger evidence was found for the idea that flexible instruments give firms the latitude to undertake what Orr (1976: 442) called 'continuous and detailed technological adaptation' to changes in the availability of environmental inputs. R&D for environmental protection clearly falls within the realm of activities a firm might undertake in adapting, but there are also dozens of ways for a firm to adapt that do not involve undertaking very much environmental R&D at all. The degree of flexibility in the prevailing policy regime is what decides the extent to which a firm is allowed to exploit the full range of technically feasible adaptation possibilities.

This paper finds econometric evidence to support the idea that a greater degree of policy flexibility leads to less environmental R&D spending, using data for about 30 industry groups over 22 years. It finds evidence that the market-based policy regime diminished the effect of environmental regulatory burden in motivating environmental R&D spending relative to the base line rigid policy regime, even after controlling for a range of potentially competing explanations, and employing industry fixed effects. That is, under the influence of the market-based regime, the same million dollars of PAC expenditure motivated about 46 per cent less environmental R&D spending than it did under the rigid regime, all else remaining equal. In these comparative terms the negative effect of the market-based regime on environmental R&D spending is considerable. In substantive level terms this effect is small, but then again the effect of PAC expenditure on environmental R&D under *any regime type* seems to be quite small in level terms following the findings of similar studies (Brunnermeier and Cohen 2003).

While these findings are suggestive of a particular relationship between regulatory flexibility and environmental R&D spending in one country, during one time period, under a very specific definition of environmental R&D, it would not of course be prudent to infer causality from them. There are other reasons aside from the trend toward greater regulatory flexibility in the United States that could have driven the downward trend in environmental R&D spending. For example, in the early 1980s under the Reagan administration, Congress passed the National Cooperative Research and Production Act in response to the concern that US anti-trust law was being applied too strictly to corporate research joint ventures. By setting out certain research joint ventures that would not be treated as triggering anti-trust action, the Act could have enabled firms to pool their individual environmental spending on joint R&D projects, which would have reduced the total amount of environmental R&D expenditure overall. The Act would have effectively changed the market structure within polluting industries insofar as R&D was concerned by allowing for greater consolidation and concentration. If this were true then one would expect to also find evidence of declining ordinary R&D spending alongside environmental R&D spending since the Act should have had the same effect on both. This study does not find evidence that ordinary R&D spending also declined from 1980 onwards.

Another plausible counter explanation is that environmental R&D spending declined because government and firms had together built up enough technical knowledge in pollution abatement by the early 1980s to effectively ease back on new formal knowledge production. Their stock of formal knowledge might have been sufficient by that point to still meeting prevailing pollution standards without doing very much new R&D. Firms may have been able to 'coast' on the fruits of their 1970s R&D expenditure through the 1980s and early 1990s. While can be difficult to observe why firms conduct environmental R&D in the first place, it is even more difficult to observe why firms *do not* conduct environmental R&D or choose to conduct less of it compared to previous levels. This counter explanation was dealt with within the regressions, albeit imperfectly, through the time trend control variable, which was used to capture this and other possibilities related to the effect of pre-existing formal and informal knowledge stocks on the environmental R&D spending level.

Still another possibility is that the nature of ordinary R&D changed in such a way over time that it effectively subsumed the purpose of, and need for, environmental R&D. There is considerable evidence in the innovation studies literature looking at firm responses to environmental regulation that suggest that innovation for pollution reduction becomes increasingly integrated the more deeply firms understand the pollution problem. Through cumulative learning and thus over time firms' pollution reduction strategies can evolve from focusing narrowly on removing pollutants from the waste stream to altering or re-designing the sub-systems and junctures in their production processes that create pollution in the first place. One possibility is that firms kept doing R&D for environmental protection at high levels throughout the 1980s and early 1990s, but because pollution reduction had shifted from an end-of-pipe concern to a strategic concern, what was in fact R&D for environmental protection was reported not as 'environmental R&D' but as 'ordinary R&D'. Under this explanation environmental protection became so embedded in the innovation process that clean ordinary R&D became the 'new normal'.

The important point about the regulatory flexibility hypothesis tested in this study is not the magnitude of the effect: it is the direction of the effect. A good deal of the induced innovation literature would have predicted the market-based regime to induce more, not less environmental R&D spending (Downing and White 1986; Jaffe, Newell and Stavins 2003; Martin, Muuls and Wagner 2011). This finding cuts against those prior expectations. The reason for this is partly explained by the vagueness of the prediction of the theory itself, for example: should flexibility induce more formal R&D relative to a rigid regime? Should it induce more technology adoption? Should it induce more 'innovation'? Or should it merely induce low-tech 'adaptation', in Orr's words. This study reduces some of these inconsistencies by testing the effect of flexibility on at least one response type. The response tested, formal R&D, happens to be of direct contemporary policy interest.

The test findings help to sharpen the predictions of this literature by shedding new light on why exactly flexible instruments are consistently found to be so much more economically efficient than rigid ones (Tietenberg 1998; Tietenberg and Lewis 2009; Hahn and Hester 1989). It is true that under certain circumstances greater flexibility can lead to firms inventing new, cost-reducing abatement methods as through undertaking formal R&D. These findings suggest that important R&D for this purpose occurred in the machinery industry group beginning in the late 1980s under the market-based regime that might not have occurred under a less flexible regime. These findings show that letting markets choose the method, location and timing of abatement can also have the flip side effect of squeezing out activities like R&D whose rewards are longer-term and whose rewards predominately accrue to society. This means that in some situations flexible instruments may be efficient precisely because they lower the cost of compliance by *letting firms avoid doing as much R&D as they were doing before* and particularly R&D that was redundant, expensive and uneconomical. At least in the short-term an instrument can also be efficient because it leads to less R&D, not just because it leads to more R&D.

The answer to the question that this paper set out to answer, namely whether flexible instruments really induce more environmental R&D than rigid instruments, is therefore the following. Given these data, greater policy regime flexibility seems to diminish the extent to which the environmental regulatory burden motivates environmental R&D spending relative to the baseline rigid regime. Flexibility diminishes the inducement effect of the regulatory burden gently when the policy regime is characterised by mere flexibility, but it diminishes the inducement effect of the regulatory burden more strongly when the policy regime turns over extensive control of the abatement method choice to market forces. The descriptive evidence also suggests that the degree of flexibility may not condition the effect of the environmental regulatory burden this way equally across industry groups. The machinery sector example from Figure 2 suggests that some sectors responded positively to greater policy regime flexibility. This may have been because the incentives created by the market-based regime had the effect of relocating R&D activity away from the sectors where it would have achieved small returns under the new regime, to the sectors where it would achieve large returns.

This finding is constructive on its own from the point of view of policy. But if formal environmental R&D does in fact play a less important role in pollution-saving technological change under highly flexible regimes, then it is important to ask what forms of knowledge and knowledge acquisition do play a role. This paper also developed the idea that, at the same time that flexible regimes weaken the incentives firms have to perform environmental R&D, they also strengthen the incentives firms have to acquire and apply lower-order forms of knowledge. Firms still needed to acquire knowledge which was new to them to deal with their regulatory burdens under flexible regimes. This analysis suggested that they just go about using or acquiring knowledge of a different degree of novelty, and/or acquiring it in different ways. The lower-order knowledge effect was not directly tested with a bespoke variable in this paper. However, the time trend that captured this as well as all other time-linked influences on environmental R&D spending does not give evidence to suggest that the negative effect of lower-order knowledge acquisition is unrealistic or unsubstantiated.

This idea of grading knowledge by its quality or novelty leads to the possibility that knowledge types substitute for one another. If this is true then the implication for policy would be the following. If the kind of technical knowledge that makes pollution-saving technological change occur under market-based instruments is not the kind of knowledge that comes out of formal R&D, then this weakens the argument for using public funds for formal R&D. Rather it suggests that governments could make a bigger impact on the rate of technological change and the cost of transitioning from one state to another, by finding ways to incentivise firms to replicate, imitate, circulate, repurpose, diffuse and adopt technical knowledge related to abatement that already exists. Policy mechanisms to induce technological change this way are hardly being discussed.

This paper also makes an empirical and methodological contribution. It analysed, for the first time to the knowledge of the author, a dataset that is directly relevant to the current discussion about the role of R&D in climate change mitigation. It is unusual to find a dataset measuring environmental R&D spending that covers 22 continuous years in this literature. The author is not aware of another study using environmental R&D spending data that covers this long a time period. Kemp and Pontoglio (2011) recently pointed out that a barrier to understanding the causes and effects of environmental technological change is the lack of studies that employ fixed effects on panel data covering extended time periods. This study addresses that need directly. Other studies have covered ten, 12, 12 and 20 year periods (Popp 2002; Brunnermeier and Cohen 2003; Jaffe and Palmer 1997; Popp 2002), almost all have used patent data and not all have employed fixed effects. This study exploited the variation in environmental policy regime that was observable over 22 years in the US to test the conditioning effect of regime type on environmental R&D, while employing fixed effects.

This study also brings more precision to the way malleable but important ideas like 'environmental R&D' can and should be conceptualised and measured. It points out how patent data studies can never fully know what a patented invention was invented 'for', whether to lower the cost of the environmental regulatory burden or to respond to another economic pressure, like rising energy prices. This uncertainty in the patent data can lead to identification problems (Griliches 1990). The seemingly tedious analysis of the NSF survey questionnaire in Section 3 (b) showed that a big advantage of the pollution abatement R&D data is that it gets around this 'dual use' problem that prevents researchers from ever fully knowing what patent data is really measuring. These pollution abatement R&D data measure something very specific. They measure R&D activity that was aimed at preventing, treating and recycling pollutants to outside the firm's property. This critical appreciation of what 'environmental innovation' can and should mean helps to reduce the extent to which future investigations work at cross purposes in identifying the causes and effects of pollution-saving technological change.

When 'environmental R&D' is defined this way, it emerges that the rate of real annual pollution abatement R&D spending in the US was steadily declining during the period 1980 – 1994, even though some patent studies suggest the opposite was happening (Nameroff, Garant and Albert 2004; OECD 2008: 36; Hascic, Johnstone and Michel 2008). This is not the first study to point out this general decline (Lanjouw and Mody 1995; Nemet and Kammen 2007; Sanyal 2007) but it is the first study to the knowledge of the author to look at the trend comparatively across industry groups; to hypothesise that market-based forms of environmental regulation are partly responsible for the decline; to formally test that hypothesis with industry fixed effects; to distinguish conceptually between higher and lower-order knowledge forms; and to suggest that the rise of lower-order forms of knowledge also played a role.

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7. Appendix

Table 3: Model quality checks

VARIABLES	(1) ln(PARD)	(2) ln(PARD)	(3) ln(PARD)	(4) ln(PARD)	(5) ln(PARD)
PAC expenditure (millions 1992 dollars)	0.000504***	0.000653***	0.000559***	0.000473***	0.000694***
	(4.316)	(5.847)	(4.798)	(4.055)	(5.100)
Market-based regime dummy	0.506**	0.567***	0.581***	0.445**	0.684***
	(2.562)	(2.986)	(2.919)	(2.215)	(3.019)
Flexible regime dummy	-0.0273	0.0462	0.0419	-0.0221	0.236
	(-0.208)	(0.372)	(0.321)	(-0.165)	(1.637)
PAC * market-based regime	-0.000230***	-0.000324***	-0.000270***	-0.000191**	-0.000389***
	(-3.050)	(-4.515)	(-3.568)	(-2.520)	(-4.529)
PAC * flexible regime	-5.48e-05	-0.000105	-8.95e-05	-5.08e-05	-0.000206***
	(-0.795)	(-1.552)	(-1.302)	(-0.735)	(-2.636)
Ordinary R&D (millions 1992 USD)	4.48e-05**	3.27e-05*	4.13e-05**	1.59e-05	
	(2.473)	(1.911)	(2.200)	(0.816)	
Employment (thousands)	0.000463**			0.000795***	0.000485**
	(2.252)			(3.629)	(2.057)
Time trend	-0.0590***	-0.0606***	-0.0642***	-0.0526***	-0.0378**
	(-4.302)	(-5.001)	(-4.811)	(-3.806)	(-2.481)
Sales of R&D performing companies			1.93e-06*		
			(1.654)		
Constant	119.0***	122.3***	129.6***	106.4***	76.92**
	(4.389)	(5.106)	(4.906)	(3.890)	(2.551)
Observations	411	468	409	392	446
Within R-squared	0.234	0.207	0.229	0.253	0.130
Number of industry groups	29	29	29	28	31

t-statistics in parentheses: *** p<0.01, ** p<0.05, * p<0.1

(1) Baseline specification, same as column (3) in Table 2, the preferred specification
(2) Employment dropped
(3) Sales substituted for employment
(4) Machinery sector dropped
(5) Ordinary R&D dropped

Table 4: Estimates without industry groups with missing values

VARIABLES	(1) ln(PARD)	(2) ln(PARD)
PAC expenditure (millions 1992 dollars)	0.000687***	0.000687***
	(4.870)	(3.276)
Market-based regime dummy	0.688***	0.688***
	(2.767)	(3.412)
Flexible regime dummy	0.275*	0.275
	(1.735)	(1.105)
PAC * market-based regime	-0.000377***	-0.000377***
	(-4.170)	(-2.884)
PAC * flexible regime	-0.000216***	-0.000216
	(-2.617)	(-1.671)
Employment (thousands)	0.000504**	0.000504
	(2.008)	(1.319)
Time trend	-0.0402**	-0.0402**
	(-2.413)	(-2.730)
Constant	81.66**	81.66***
	(2.478)	(2.801)
Observations	394	394
Within R-squared	0.134	0.134
Number of industry groups	25	25

(1) Estimates without the following industry groups which had a large number of missing observations: Textiles and apparel; Drugs and medicine; Communications equipment; Transportation equipment; Optical, surgical, photographic and other equipment; Scientific and mechanical measuring instruments.
(2) Same, with robust standard errors

Paper 2: How ‘technological’ is pollution-saving technological change?

Abstract

This paper questions the *a priori* assumption in some areas of the environmental technological change literature that new-to-the-world frontier knowledge and technologies play the driving role in improving productivity with respect to pollution emissions under market-based instruments. Whether or not frontier knowledge plays a major role in this kind of transition matters for how, and indeed if, policymakers should get involved in technology policy for climate change mitigation. This paper looks at the knowledge intensity of the responses by electric power plants to the requirements of the US SO2 cap and trade programme. A mixed methods approach is used. Quantile regression is used to test the effect of frontier knowledge across the full distribution of SO2 intensity change undergone by the plants. Qualitative analysis looks at how upstream changes in supplier industries framed the technological possibilities for realising these changes. The paper finds (a) that frontier knowledge-intensive techniques did not play the driving role in SO2-saving technological change that might have been expected, (b) that pre-existing and relatively knowledge unintensive techniques did play the dominant role and (c) that some of the techniques that played the biggest role originated in stereotypically 'dirty' industries. This would have made them hard to identify as priority 'environmental' technologies beforehand. The findings suggest that more confidence can be placed in markets, within robust regulatory frameworks, to decide which innovations play the dominant role in greenhouse gas (GHG) reductions. This is so even if the innovations that markets produce are unglamorous and/or inconsistent with preconceived ideas about how GHG-saving technological change 'should' look.

1. Introduction

There is a sense in some corners of the environmental technological change literature that environmental technologies which are 'new' in the sense of being 'new-to-the-world' have been decided *a priori* as the centrepiece of policies to deal with the creation and accumulation of greenhouse gasses (GHGs) (Barrett 2006; Hoffert et al. 2002; Bosetti and Tavoni 2008; Castelnuovo et al. 2005; Riahi, Rubin and Schrattenholzer 2004). The assumption in favour of advanced technology approaches to GHG control leads those who make that assumption to the conclusion that the research task before us is to discover: why new environmental technologies are slow to emerge; to what extent is market failure preventing the emergence and uptake of environmental technologies; and what is the best form of intervention to correct the failure and support these technologies into widespread use (Jaffe, Newell and Stavins 2005; Fischer and Newell 2008; Foxon et al. 2005; Popp 2010). One under-discussed point of view in this literature is the idea that giving this amount of attention to the best mode of intervention may be premature and unnecessary, and may even be counter-productive. Intervening in favour of the development and deployment of the new technologies we perceive to be 'environmental' frequently does not question the assumption that technologies which are 'new' and 'environmental' will necessarily be the technologies that deliver the cheapest, swiftest pathways to emission cuts. Nor does this kind of intervention acknowledge the extent to which technologies with these characteristics have accounted for emission cuts in comparable processes of environmental technological change in the past.

An example of a policy that reflects the relatively unchallenged nature of this assumption is the US Patent and Trademark Office's (USPTO) recent decision to accelerate the approval process for patent applications on inventions qualifying as 'green technologies'. In December 2009, the USPTO began giving review priority to these inventions. It is now administrative policy at the USPTO for patent examiners to automatically advance for accelerated consideration any patent application 'pertaining to environmental quality, energy conservation, development of renewable energy resources or greenhouse gas emission reduction' (USPTO 2009: 6466). One risk of this programme is that by selectively advancing the patent applications that the USPTO perceives to be green, the Green Technology Pilot Program effectively downgrades all other applications the patent office designates by default to be non-green, to secondary importance in the approval process. It is well known that the USPTO has historically struggled to keep up with the sharp rise in patent application activity since 1983 (Hall and Ziedonis 2001), although the bottleneck is being addressed. The risk is that the cost of delaying the approval of non-green applications will outweigh the benefit of accelerating the approval of 'green' patent applications. To the extent that growth in a knowledge-based economy depends on an impartial system of intellectual property protection, delaying the award of protection to patentable ideas perceived to be non-green could hamper growth rates, slow the rate of increase in national prosperity levels, and diminish a nation's willingness to pay for emission reductions relative to a situation in which the economy was growing more quickly (Stern 2006).

Policies of this type are guided by sound intentions, but they assume that the technical knowledge required for cheap and rapid GHG emission control is, or will be, 'new-to-the-world' in the sense of it being patentable, as compared to technical knowledge that has been, or will be, accumulated through a pragmatic, on-the-job learning process, through trial-by-error, or by means better characterised by the creation and application of 'applied' technical knowledge of the type that tends not to get patented. Strategies like the one implicit in the USPTO approach[3] also assume that the most important new technical knowledge for reducing emission levels is likely to emerge in industry sectors and technology classes we think of today as 'green' because they are ostensibly dedicated to environmental protection, rather than in the sectors and classes we think of as 'non-green' or just 'ordinary'. Strategies like the USPTO's assume that policymakers are better than markets at selecting the cheapest, most viable methods for doing abatement, high-tech or otherwise. In some ways these policies emerge from an outdated regulatory mindset in which the state played a much greater role in deciding how firms should go about reducing emissions than prevails today.

This paper takes a sceptical view of idea that new-to-the-world environmental technical knowledge and advanced 'frontier' environmental technologies are indispensable to the technological change process industries pass through en route to reaching states of production that emit less pollution. This scepticism is healthy because, if we are to continue to make policy for dealing with GHG emissions that is genuinely based on evidence and not unduly on speculation or hope, then it is instructive to look at what role this kind of advanced technical knowledge and capability has played in comparable industrial technological change processes in the past.

To inform this matter, this paper looks at the role that environmental technical knowledge and technologies played in the industrial technological change process that

[3] And also in other strategies to boost environmental technologies – see European Commission 2004 and Defra 2007.

unfolded in response to the sulphur dioxide (SO2) cap and trade programme established in the United States under the 1990 Clean Air Act Amendments (CAAA). SO2 and GHGs are different pollutants in many respects[4] and SO2-saving technological change will only ever be an imperfect proxy for GHG-saving technological change. However, there are also parallels that make SO2-saving technological change one of the least-bad proxies for GHG-saving technological change. The policy instrument inevitably shapes the nature of the technological response that industry mounts to an emission constraint. Climate policy in Europe and the United States is generally following the policy instrument path forged by SO2 cap and trade and other policies designed to incorporate incentives and price signals for emission control. In many cases the actual physical electric power plants in the US that came into conformance with the SO2 controls under the 1990 CAAA *are the exact same electric power plants* that will eventually need to come into conformance with GHG regulations for the US electric power sector. These plants are likely to face that new round of policy possessing similar geographic features and constraints, similar relative knowledge and skills sets, similar ownership structures, similar electricity supply obligations and similar relationships with regulators.

Tested here is the hypothesis that under the SO2 cap and trade programme, technical knowledge and technologies dedicated to environmental protection exerted a small and relatively insignificant effect on the extent of technological change undergone to reduce affected electric power plants' SO2 intensity of electricity production. Technical knowledge and technologies better classed as 'ordinary' are expected to have exerted a larger and more considerable effect on the extent of technological change undergone, if technical knowledge exerted a detectable effect at all on the extent of emission-saving technological change. Technological change is expected to be better explained by low-tech production method changes that were relatively unintensive in new-to-the-world technical knowledge and which emerged from areas of industry that would not have been expected to be concerned with environmental protection.

Evidence is found to support this hypothesis. The technical knowledge, methods and techniques that accounted for the largest part of observable change in the SO2 intensity of electric power production involved factors other than frontier technical knowledge. The

[4] Perkins and Neumayer (2008) summarise these handily: the great majority of SO2 emissions originate from stationary, point-source, coal-burning facilities mainly in the electric power sector while CO2 emissions come from a much wider range of point and non-point sources spanning many industrial sectors. Scientific understanding of the acidifying effect of sulphur deposition on ecosystems is relatively certain and mature yet scientific understanding of the extent of anthropogenic involvement in the warming process and the secondary effects of warming on ecosystems is comparatively less mature and more uncertain. The time lag to damage from SO2 emissions is a few months or years while the time lag to damage from CO2 can be decades or longer.

main factors driving the extent of technological change undergone at plant level were: adaptation and investment by the coal mining and railroad industries supplying the electric power plants, switching to cleaner fuels at the electric power plants themselves, the use of abatement technologies known well before 1990, and the initial characteristics of the electric power plants themselves. A considerable amount of evidence shows that the plants and industries affected directly or indirectly by cap and trade consistently shied away from compliance methods that would have involved acquiring and applying large amounts of new technical knowledge of the type being prioritised by the USPTO and other government environmental technology policies (European Commission 2004; Defra 2007). Affected plants and industries consistently chose compliance methods that were simple, well-known, quick, pragmatic, uncomplicated, low in technical knowledge of the type that might be acquired through formal R&D, and cheap.

Section 2 argues that a significant body of the environmental technological change literature does not refute the hypothesis that low-new-knowledge and low-tech compliance methods have played a major role in this kind of technological change historically. Section 3 describes the mixed methods research approach combining interviews with plant R&D managers, case study evidence and econometric analysis. Sections 4 and 5 examine the evidence. Section 6 discusses findings and implications.

2. Literature: knowledge, technology, environment

This section reviews three strands of literature concerned with the role that 'new' technical knowledge and technologies play in the technological change that leads to cleaner states of production. It looks at the role of new knowledge and technology in energy-saving technological change, pollution-saving technological change, and technological change as represented in climate policy models. It argues that the empirical findings in these literature strands do not substantiate the level of importance typically given to the role that new-to-the-world knowledge and technologies are expected to play in this kind of technological change.

Figure 1 gives some conceptual structure to the relationship of interest here. The input of interest is the environment itself, proxied for by pollution emissions. Emission-saving technological change is the change in emissions per unit of output (Nordhaus 1994), or symmetrically, the change in 'environmental efficiency' brought about by the transition from one production method to another (Perkins and Neumayer 2008; Mazzanti and Zoboli 2007). Figure 1 represents this relationship schematically.

Figure 1: Emission-saving technological change

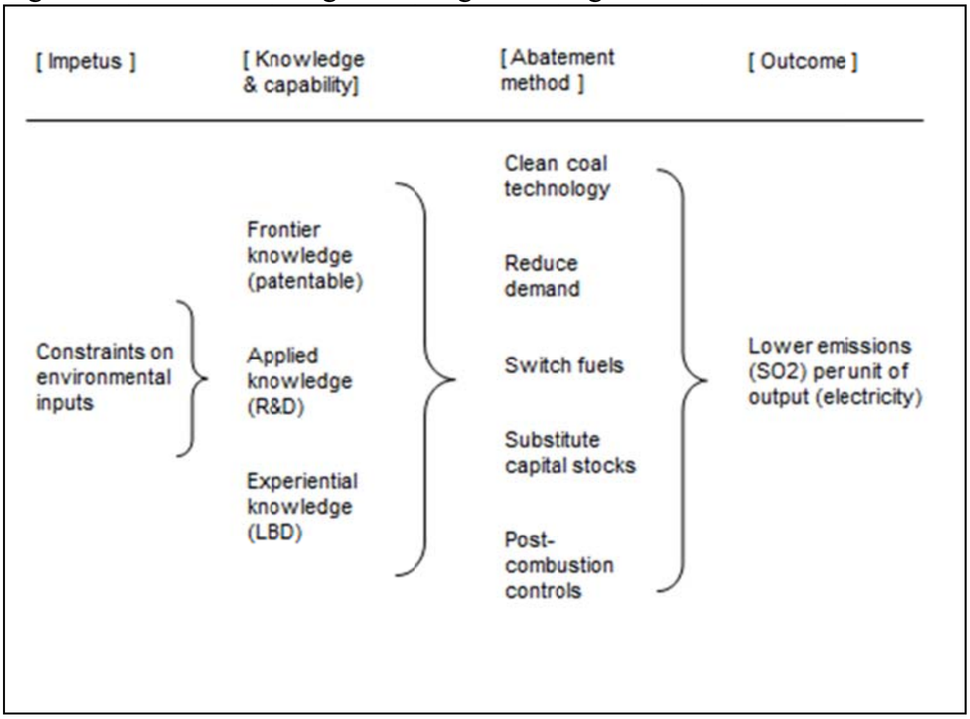

Figure 1 illustrates how different kinds of technical knowledge might figure in an emission-saving technological change process. The process is illustrated by a change process with respect to SO2 emissions. In the first column, an impetus of some kind modifies the producer's production environment in a way that motivates the producer to adapt its prior production method or technology choice to the new production environment. The impetus is typically a regulatory event or constraint. In the case of SO2 control, the impetus was the arrival of the SO2 cap and trade programme in the 1990 CAAA.

The second and third columns are of main interest. The second column sets out the different kinds of technical knowledge that the producer consults and possibly acquires anew, and on which the producer deliberates and eventually bases its technical change response to the impetus or event. Here the producer inventories what it knows and evaluates how or if its knowledge is useful in getting from the now-unsatisfactory production method to the new, satisfactory method. This is where research and learning would take place. Column 3 shows the actual physical-technical changes the producer might make to its production method once it has decided on a specific technical response. In the SO2 or GHG context, these would be abatement methods. Adopting clean coal technology, reducing the demand for electricity, switching to cleaner fuels, and/or retiring aging capital stock were some of the technical options available to the managers of coal-fired electric power plants trying to conform to the requirements of the 1990 CAAA. Each abatement method or technical change 'channel' would have required different qualities of technical knowledge to implement. Column 4 describes the outcome from the changes the plant managers did indeed choose. The outcome denotes the direction and extent of the technological change that has occurred. This is given by the ratio of output (electricity) produced per unit of the input (environment) in the new production method relative to the old one.

The juncture of interest in this process is the space between columns 1 and 4. This is where producers bring their different kinds of technical knowledge to bear on the deliberative process that leads to the choice of abatement methods. This is where one is most likely to be able to identify which qualities and kinds of knowledge articulate the technical change process. The next three sub-sections look at prior studies concerned with the role that technical knowledge has been found to play in energy-saving technological change, emission-saving technological change, and technological change in climate policy models.

a. Energy-saving technological change

Energy-saving technological change is also emission-saving technological change to the extent that it reduces emissions from fossil fuel combustion. Studies that have investigated the role of technical knowledge in energy-saving technological change have generally found that knowledge creation and new technology uptake exert a small impact relative to knowledge and technology-unintensive factors. Newell, Jaffe and Stavins (1999) found that government regulation and energy price changes explained up to 62 per cent of the change in the energy intensity of a selection of energy-using household appliances during the period 1958 – 1993, but they did not find statistically significant evidence that either the rate or direction of technological progress explained the remaining 38 per cent of the energy intensity change of these appliances. They suggest that the residual in their model may be explained by technological progress but they do not test this explicitly. They attribute the unexplained residual variation to technological progress essentially by default. They do not find positive evidence that technological progress accounted for the gains in the energy intensity level of the household appliances in question (969 - 970).

Pakes et al. (1993) study the effect of technology adoption and new technical knowledge on the change in automobile fuel efficiency in the US after 1977. Fuel efficiency of new automobiles increased 50 per cent in the eight years after 1977, spurred on in part by government regulation. Pakes et al.'s evidence shows that the way that the automakers achieved these efficiency gains was primarily by changing the mix of vehicle models offered for sale in the market, rather than by inventing new high-efficiency vehicle models from scratch. The vehicle manufacturers introduced more pre-existing small and medium sized vehicles to the market while retiring larger, less fuel efficient models. Pakes et al. also describe a sharp rise in the number of applications to the USPTO after 1977 for patents on inventions dealing with internal combustion engine performance. But similarly to Newell, Jaffe and Stavins (1999) above, the association Pakes et al. draw between technological progress and efficiency improvements is more an assertion than a definitive finding. Pakes et al. regard the contemporaneous increase in fuel efficiency and patenting activity as evidence that new-to-the-world technical knowledge causally explains a significant amount of pollution-saving technological change, but they do not explicitly test this relationship (245 – 246).

Linn (2008) found that technology adoption accounted for less of the variation in energy demand for a group of US manufacturing firms than expected. Linn investigated the effect of technology adoption on energy demand by manufacturing plants during 1963 – 1997. Linn found that a ten per cent increase in the price of energy associated with plants adopting energy-saving technologies sufficient to reduce their plant-level energy demand by one per cent. Linn concluded that the effect of technology adoption on energy demand is smaller than expected. Popp (2001) looked at the effect of energy technology-related knowledge stocks on energy demand and also found that the effect was not as large as expected. Popp constructed knowledge stocks from patent data for 13 industries and examined the effect of these stocks on industry-level energy demand. He found that while induced innovation accounted for 1/3rd of the total elasticity in energy demand across the industries in his sample on average, the remaining 2/3^{rds} was due to simple factor substitution.

Sue Wing (2008) conducted one of the most detailed decompositions to date of the change in the energy intensity of output in the US economy. He found that new technical knowledge and technological progress accounted for a minor proportion of the change in energy intensity relative to other factors. Sue Wing observes that the energy intensity of aggregate US output steadily declined during the period 1958 - 2000. He decomposed the sources of these productivity gains. Sue Wing found that new knowledge creation and technological progress accounted for the smallest portion of this change (-8.8 per cent). Inter-sectoral structural change accounted for the most (-32.6 per cent), changing capital stock structures accounted for -16.1 per cent, and input substitution accounted for a four per cent increase. *Inter-sectoral structural change therefore accounted for over five times as much of the decline in the energy intensity of output as new knowledge and technological progress created in response to higher energy prices.*

b. Emission-saving technological change

The group of studies looking at the causes of emission-saving technological change reach similar but slightly more mixed conclusions. Levinson (2009) decomposed the decline in the pollution (NOx, SOx, CO and VOC) intensity of 450 four-digit US manufacturing sectors for the period 1987 – 2001. He decomposed the decline into effects from changes in the scale of output, sector composition including international trade, and what he calls 'technique'. Scale and composition together account for a 30 per cent increase in emissions but 'technique' accounted for a 60 per cent fall in emissions. The migration of pollution intensive manufacturing overseas accounted at most for a minor part of the overall decline. Interestingly, Levinson's 'technique' effect accounted for a decreasing share of the variation in pollution intensity of US manufacturing over time. But the most important point about Levinson's study is that, much like Newell, Jaffe and Stavins (1999) and Pakes et al. (1993), the technique effect is just the unexplained residual that remains after controlling for scale and composition. Levinson does not necessarily attribute the technique effect to technological progress through knowledge accumulation. This leaves open the possibility that knowledge and technology-unintensive methods of pollution control could underlie this 'technique' effect.

Popp (2010) used US and foreign patent data to investigate the effect of technological progress, regulatory stringency and a set of adopter characteristics on the adoption of two NOx control technologies (post-combustion and combustion modification) at coal-fired power plants in the US. Popp constructed knowledge stocks from patent data and included them as an independent variable in a hazard likelihood function where the outcome was technology adoption. Popp found that regulatory stringency was by far the most important predictor of technology adoption. The knowledge stocks effects were more mixed. One specification showed that the anti-adoption effect of foreign knowledge effectively offset the pro-adoption effect of domestic knowledge, for a net effect on technological advance of near zero (2010: 24). For post-combustion technology adoption, knowledge played the more important role, increasing the expected adoption rate by over 20 per cent in the most complete model. For combustion modification technology adoption by contrast, knowledge increased the adoption rate by less than one per cent. Popp therefore found that frontier knowledge played a bigger role in the uptake of post-combustion technology than in the uptake of process-modification technology.

Another group of studies investigates the sources of changing emission intensities across countries, rather than across industries within countries. These studies tend to find that cross-border knowledge flows do not have the effect of reducing emission intensity that one might expect. Perkins and Neumayer (2008) tested the idea that the linkages that facilitate contact, communication and exchange between countries lead to the uptake of environmental friendly technologies, which in turn lead to improved environmental efficiency in the adopting (particularly developing) country. The idea is that human-to-human communication and trade in knowledge-embodying manufactured goods are conduits for knowledge flows. Perkins and Neumayer find evidence that import ties with more pollution-efficient countries improve domestic SO2 and CO2 efficiency. They do not find evidence that exports, inward FDI or telecommunications linkages improve domestic pollution efficiency.

Popp (2006) also finds a weak effect of transnational knowledge flows on domestic environmental outcomes. Using patent data from Japan, Germany and the US, Popp finds that tighter SO2 and NOx limits in the US led to more patenting by US-based inventors but not more patenting by foreign inventors. Domestic inventors innovated in pollution control technologies that had already reached a relatively advanced state abroad. This suggests that domestic inventors needed to perform 'adaptive' innovation to make foreign frontier knowledge relevant to the domestic production context. Popp also found that electric utilities purchased pollution abatement equipment largely from domestic firms rather than foreign firms.

Finally, Stern (2002) decomposed the change in sulphur emissions for 64 countries (1973 – 1990) into scale effects, inter-industry composition effects, input effects, and 'technical change' effects. He decomposes technical change effects into emission-specific and general effects. They include 'both cleaner production and the effects of shifts of output composition within each of the four broad industry sectors' (217). Stern finds that both types of technical change exerted a strong negative effect on cross-country emission intensity. In terms of the general technical change effect, he finds that agriculture, manufacturing, non-manufacturing and energy were the sectors that made the biggest contributions. Stern does not actually test the effect of frontier or any other kind of knowledge in the sulphur-saving change he observes. Technical change happened, but his evidence implies that it happened through channels other than frontier knowledge and technological progress.

c. Technological change in climate policy models

Climate policy models (CPMs) are tools for predicting the costs and benefits of climate policy interventions over very long term time horizons of typically between 50 and 150 years. These models employ structures and assumptions about the effect of frontier knowledge and technological progress that give insights into how these factors may influence climate policy outcomes, or at least give insights into how the modellers *think* these factors may influence climate policy outcomes. CPMs model technological change in three basic ways (Gillingham, Newell and Pizer 2008; Popp, Newell and Jaffe 2009): exogenously, as a process initiated and carried forward by events and factors external to the variables in the model; endogenously, as a process determined by events and factors captured fully within the variables of the model; and semi-endogenously, as a combination of the two. CPMs do not usually distinguish materially between the effect of technological change and the effect of technological progress on climate outcomes. CPMs show how policy, knowledge and technology may impact on GHG emissions in not-unrealistic ways over the very long term.

The earliest CPMs represented GHG-saving technological change exogenously with the equivalent of an exogenously-determined, time-based technological progress trend. This reflected the assumption that the GHG intensity of output would become steadily cleaner over time, even in some models in the absence of policies limiting GHG emissions. The objective of Nordhaus' original DICE model (Dynamic Integrated model of Climate and the Economy) (1994) was to maximise social welfare defined as the discounted sum of utility of per capita consumption over a 100 year time horizon. Nordhaus captured the impact of technological 'progress' on the GHG intensity of production in two ways. First, technological progress in the use of all inputs generally was captured through an exogenously-determined constant improvement in total factor productivity. Second, technological progress specific to the use of environmental inputs (GHG emissions) was captured through an exogenously-determined rate of decarbonisation of economic output. Nordhaus derived the decarbonisation rate of -1.25 per cent per year empirically. This came from the historic rate of change in the ratio of CO2 emissions to GNP for a range of mostly OECD countries for the period 1929 – 1989. This second parameter is the so-called autonomous rate of energy efficiency improvement

(AEEI – originally Manne and Richels 2004). Nordhaus' primary conclusion from later simulations with the DICE model was that 'induced innovation' is likely to be a less powerful factor in reducing the GHG intensity of output over the long term than the substitution of relatively clean inputs for relatively dirty inputs. Nordhaus also finds that induced innovation is likely to be less important than substitution between different types of capital stock (1994, 2002; Popp, Newell and Jaffe 2009).

Semi-endogenous representations of technological change and progress in CPMs attempt to overcome the insensitivity of the AEEI to the factors that cause production methods to change and new technologies to emerge and diffuse in the first place. Jakeman et al. (2004) partially endogenised some of these factors by including the possibility for fuel switching alongside energy efficiency improvements and the 'adoption of new technologies and management practices' (940) in their simulations. Jakeman et al. find that a major source of uncertainty in the semi-endogenous approach is the problem of distinguishing between the effect of substitution and the effect of technological 'progress' on the emission intensity of output.

Others have modelled the emergence of 'backstop' technologies. Backstop technologies are technologies which are known and which exist today, but which are latent and unused on a large scale because economic conditions have not called them into widespread use. Bosetti and Tavoni (2008) modelled the widespread emergence of nuclear fusion technology in response to large-scale R&D investment. Bosetti and Tavoni found that the uptake of nuclear fusion technology in the electric power sector reduced the emission intensity of electricity production and lowered the long term cost of GHG abatement. Cost reductions were especially large when gains from R&D were characterised as uncertain. Bosetti and Tavoni's findings imply that the scaling up of technologies that already exist today may play a bigger role in GHG emission reductions than technologies which have yet to emerge.

Also related to backstop technologies, Paltsev et al. (2005) modelled the emission reduction effect of coal gasification and shale oil technologies (synthetic fuels) in simulations using the Emission Prediction and Policy Analysis (EPPA) model. They 'switched on' the capital stocks that were able to use these synthetic fuels when the price of the synthetic fuels relative to the price of petroleum crossed a threshold. Paltsev et al. found that the 'malleability' of capital stocks was a decisive factor in the most cost-effective long run GHG abatement scenarios. Malleability refers to the flexibility of the capital stock to burn different fuel types without requiring major alterations. A malleable capital stock leads to cost-effective GHG reductions because it prevents plant operators from having to scrap and replace existing capital stocks. A malleable capital stock is probably also a cost-effective way to abate GHGs because it prevents plants from having to scrap and replace their technical knowledge stocks as well.

A recent group of fully endogenous representations of technological change and progress in CPMs centres on the effect of producing and accumulating advanced knowledge through formal R&D. In these models, R&D is the source of knowledge useful for reducing emissions. The knowledge stock is usually treated as a productive asset whose changing size is determined by the rate of investment in R&D, adjusted for the rate at which knowledge becomes obsolete (Sue Wing 2006). In these representations the crowding out issue emerges. R&D, in creating 'environmental' knowledge, may crowd out R&D to create 'ordinary' knowledge because the same pool of scientific and engineering labour is used to create both (Goolsbee 1998). Goulder and Schnieder (1999) found that specifying the entire pool of scientific and engineering capacity as inelastic so as to force these trade-offs in the labour pool, led to a lower cost of achieving a given abatement target but a necessarily higher carbon tax to reach the target. Goulder and Schnieder's findings imply that crowding out effects figure importantly in this change process.

Other endogenous representations rest on the accumulation of lower order forms of experiential and applied knowledge through experience with using discrete technologies. These are the 'learning curve', 'progress curve' or 'experience curve' studies. In these representations the cost of either producing a unit of output or installing a unit of capacity declines as a function of experience (not time). Dutton and Thomas (1984) summarise over 200 separate empirical and theoretical studies of this relationship between experience and cost. They find that a doubling of cumulative output generally leads to a decline in the cost per unit of between 70 and 90 per cent. Similarly but more specific to the interests of the present paper, McDonald and Schrattenholzer compiled the results of 41 separate energy technology learning curve studies. Across all these studies they finding a mean learning rate of 15.7 per cent (2001: 257 – 258) meaning that for each doubling of total capacity, the cost of producing a unit of electricity (or installing a unit of capacity) falls by 15.7 per cent. With respect to technologies dedicated to emission control, Riahi et al. (2004) estimated a learning curve function for an end-of-pipe technology to control SO2 emissions from coal-fired power plants, flue gas desulphurisation (FGD) technology. The learning curve for FGD was estimated as a function of global installed capacity. Riahi et al. found that a doubling of global capacity led to a 13 per cent decline in the cost of installing scrubber capacity sufficient to control SO2 emissions from a typical 500 megawatt (MW) plant requiring 90 per cent SO2 removal efficiency.

These kinds of learning curve-based estimates tend to assume-away important differences in the role that different kinds of knowledge play in the transition between production methods. Learning curve functions tend not to be sensitive to the difference between knowledge that is intended for environmental protection and knowledge that is intended for 'ordinary' purposes. They also tend not to be sensitive to the differences between frontier, applied and experiential knowledge. Learning curve representations do go some way to endogenizing technological progress in CPMs with respect to whatever the modelled technology produces. However, they tend to represent technological progress as a constant with respect to experiential knowledge accumulation, albeit an empirically-derived constant. This does not go much further than the fully exogenous AEEI in explaining the role that knowledge of different kinds plays in emission-saving technological change.

This section summarised a range of studies looking at the role that technical knowledge played in energy-saving technological change, emission-saving technological change, and in representations of technological change in CPMs. Few of these studies refute the idea that frontier technical knowledge and technologies have played a smaller role in pollution and energy-saving outcomes than might have been expected. Most of these studies support the idea that the channels leading to these outcomes have been characterised more by technological 'change' than by technological 'progress'. Switching from dirty fuels to relatively cleaner ones tends to account for more change than the development of altogether new fuels (Nordhaus 1994; Paltsev et al. 2005). Changing the mix of vehicles on the market seems to have accounted for a considerable amount of change alongside the development of cleaner vehicles (Pakes et al. 1993). Structural change in the distribution of output across sectors accounted for five times more of the decline in the energy intensity of output in the US than new technical knowledge and technological progress (Sue Wing 2008). Maybe emission-saving technological change is driven less by frontier technical knowledge related to environmental protection and more by frontier knowledge for ordinary purposes. Maybe this kind of technological change is driven more by abatement methods and technologies that do not involve acquiring that much new technical knowledge at all.

This all motivates the following hypothesis tested in the next sections:

When market forces are left to decide how technological change with respect to pollution emissions proceeds, frontier technical knowledge for the purpose of *environmental protection tends to play a small role in that process while knowledge for all other 'ordinary' purposes plays a bigger role, and pre-existing methods and techniques for reducing emissions that involve little or no new frontier knowledge at all play the dominant role.*

3. Research approach

Title IV of the 1990 Clean Air Act Amendments established the Sulfur Dioxide Allowance Trading Program (the Programme). The Programme is the impetus for the technological change process that makes it possible to test the hypothesis above.[5] The Programme initially established a national cap on SO2 emissions of 8.95 million tons per year. It targeted coal-fired electric power plants to achieve approximately 85 per cent of the reduction to meet this cap (Reitze 2001: 264). The Programme proceeded in two phases: Phase 1 ran from 1st January 1995 to 31st December 1999 and mandated the participation of only the plants with the highest-emitting generation units in the country. Note that a single utility often operates many plants, and a single plant often comprises several generation units. Operators of the dirtiest plants were required to reduce emissions from the affected units by approximately four million tons per year. Phase 2 of the Programme began on 1st January 2000. In Phase 2, Programme coverage was extended to 2,300 additional generation units and to all generation units that had yet to be built. Under Phase 2, a further four to five million tons of SO2 per year were to be eliminated. The Programme was the regulatory impetus behind the fall in the SO2 emission intensity of electricity production from affected plants during the period 1996 - 2001.

The hypothesis is tested in this case context for three methodological reasons. First, it exhibits a change process with respect just to a pollution externality; second, the lessons from it are as generalizable to GHG-saving technological change as are the lessons from any other US environmental policy experience or more so; third, the SO2 cap and trade programme was a policy success by almost all accounts, and it makes sense to look at the role of frontier knowledge in a technological change process that led to a desirable outcome rather than one where the outcome was more questionable.

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[5] Only the aspects of the case relevant to investigating the hypothesis are discussed here. For a detailed discussion of Title IV (Acid Deposition Control) and the Programme itself, see Reitze (2001). For evaluations of the Programme's effectiveness see Schmalensee et al. (1998). For an exposition of the role of tradable permits in the Programme, see Tietenberg (1999). For an estimate of the financial gains of the Programme attributable solely to permit trade, see Carlson et al. (2000).

First, the pattern and process by which emission-saving technological change proceeds is deeply influenced by the form of the regulation that seeks to address the pollution problem (Kemp 1997). Regulation of one form or another is, however, necessary to even observe the process since firms tend not to act deliberately to reduce emissions in absence of regulation. *The researcher's problem therefore is to identify the characteristics of a technological change process that tends only to occur in response to a regulatory stimulus, net of the effect of the nature of the regulatory stimulus which inevitably shapes that process, and which often must exist for that process to exist.*

Regulators have prescribed in the past through their policy design choices control strategies that are immature, unnecessarily expensive and/or which impair emitters' production process competitiveness (Davis et al. 1977; Seskin, Anderson and Reid 1983). The suitable methodological characteristic of the SO2 cap and trade programme as a regulatory stimulus, is that it comes as close as possible to inducing a technological change response without unduly determining the characteristics of the process itself. Cap and trade induces technological change while exerting minimal influence on technology and knowledge acquisition choices. It only intervenes in those choices insofar as setting the quantity of the pollutant to be reduced. Cap and trade leaves emitters and market forces to decide the actual abatement channels, including the quantity, newness, advancedness and type of knowledge involved. The pattern of change arising from these individual decisions should be relatively free of the distortive influence of the technology preferences of regulators.[6]

The second reason for the suitability of the Programme is that the case comes as close as any other environmental policy experience in the US to what is likely to be a market-based approach to controlling GHG emissions there. Market-based instruments tend to have strong cost advantages over more conventional command and control instruments at least in the short and medium term (Tietenberg 1999; Hahn and Hester 1989; Barakat and Chamberline Consultants 1991: 18).[7] It is unlikely that a policy to deal

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[6] This has definitely not been the case historically. Under the SO2 control regime of the 1970s the EPA decided both the quantity of emissions to be reduced and the technical method emitters would use to achieve those reductions. In the initial 1970 Amendments to the Clean Air Act, quantity was controlled by requiring that boilers beginning construction after 17th August 1971 emit no more than a maximum 1.2 pounds of SO2 per million btus of heat input. When it became apparent that the standards alone were failing to achieve adequate national ambient air quality standards, Congress strengthened them by passing the 1977 Amendments. The 1.2 pound per million btus standard prevailed but additionally, all sources were regardless of their emission rate or construction vintage to categorically reduce their SO2 emissions by 70 per cent, and for sources emitting at a rate of .6 pounds of SO2 per million btus to reduce their emissions by at least 90 per cent (Reitze 2001: 234). Since there were few technical methods of achieving standards this strict besides post-combustion control, the 1977 Amendments and the 1979 New Source Performance Standards effectively mandated the use of scrubbers.

with GHG emissions in the US that does not minimise costs to the extent that market-based instruments have been shown to minimise costs in the recent past, would be politically viable. Understanding the role of knowledge in SO2-saving change is likely to tell us something about the role of knowledge in the GHG-saving change. The regulatory designs to control the two pollutants are likely to be similar from an instrument design point of view for power plants at least, after allowing for the considerable differences between the two pollutants.[8]

Third, the Programme was an unprecedented success. It yielded the emission reductions quickly, at low-cost, and without the legal battles that have characterised US environmental policymaking elsewhere. Electricity generation units participating in Phase 1 of the Programme were able to reduce their emissions to levels below the required limit well in advance of the deadline because the provisions in the tradable permit rules allowed them to perform the lowest-cost reduction immediately and bank the credit for future use (Schmalensee et al. 1998; White et al. 1997). Studies conducted prior to the start of the Programme estimated that the average marginal abatement cost to the plant operator would be between $291 and $760 per ton of SO2, but once the Programme got underway the price of an SO2 allowance at auction did not exceed $252 per ton until 2005 (Burtraw and Palmer 2003; Carlson et al. 2000). Another illustration of policy success is that the rules the Environmental Protection Agency (EPA) established to control SO2 during the 1970s were repeatedly weakened, undermined and delayed by court cases brought by industry groups challenging EPA's interpretation of Congress' intent, and the extent of EPA's regulatory authority. Legal challenges to Title IV of the 1990 CAA Amendments were almost non-existent partly because industry saw such considerable cost-saving opportunity

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[7] Because inflexible command-and-control instruments are unnecessarily expensive. Tietenberg (1999) for example shows how cost considerations have underpinned the steady progress in the US toward more flexible policy regimes over time. Hahn and Hester (1989) documented the cost reduction effect of intra-firm 'netting' alone in the US. Barakat and Chamberline Consultants (1991: 18) document dozens of empirical policy examples where cost savings were achieved by implementing flexible policies relative to an inflexible baseline.

[8] See Perkins and Neumayer (2008) for a summary of these differences. Another difference between the two pollutants is the possibility that deep cuts in GHG emissions will require larger amounts of frontier technical knowledge and wider deployment of advanced technologies than was needed to achieve deep cuts in SO2 emissions. This may be true. Deep cuts in GHG emissions would appear to be a more costly and more complicated undertaking. But this difference does not necessarily invalidate the predictive insights of SO2 for GHGs that are based on the other similarities between the two pollution control situations: both are air pollutants, both are emitted in large quantities from stationary sources, both are or were emitted from the exact same US electric power plants with their unique geographic characteristics, and both are likely to be subject to similar regulatory instruments. The dissimilarity in terms of frontier knowledge requirements is not so much a challenge to the methodological suitability of the SO2 case to this investigation, but more a challenge to the generalizability of the findings of this investigation to GHG control policy. The claim here is not that the SO2 cap and trade experience is perfectly generalizable to GHG control policy. This would be asking too much of case-based research (Yin 2009). The claim here is that the role that knowledge played in SO2-saving technological change may shed some light on the role that knowledge is likely to play in GHG-saving technological change, for the reasons discussed here.

in emissions trading (McLean 1997). The only lawsuits filed in connection with Title IV to the knowledge of the author concerned the rules for 'substitution' units and other issues surrounding EPA's allocation of allowances to utilities (Swift 2001). These lawsuits were far less obstructive than past lawsuits had been.

Prior to the present investigation, at least two studies have examined the role that technological change played under the Programme. Carlson et al. (2000) looked at the extent to which the unexpectedly low cost of abating SO2 to comply with the Programme could be explained by the allowance trading provision alone. Their study was done in the spirit of evaluating the cost reductions attributable to the greater degree of flexibility in the Programme, relative to a less flexible counterfactual policy approach. Carlson et al. concluded that the combination of 'technological change'[9] (also 'technological improvements') and the fall in the cost of low-sulphur coal lowered the marginal abatement cost curves faced by emitters by over 50 per cent from 1985. The allowance trading provision allowed plant operators to exploit these cost curve shifts. Carlson et al. estimate that technological change accounted for about 20 per cent of these cost reductions while fuel switching accounted for 80 per cent, holding output and all non-fuel input prices constant.

The other study is Ellerman et al. (1997) who estimate that, in terms of abatement methods, 45.1 per cent of the total emission reduction achieved under the Programme came from installing flue gas desulphurisation (FGD) units, and 54.9 per cent came from switching to lower sulphur fuels. Their treatment of the role of technological change is more circumspect. In their concluding remarks on trying to explain the unexpectedly low price of SO2 emission credits as of 1998, they write:

> There certainly was some induced innovation. For example, the observed per-ton cost of scrubbing in 1995 was substantially below earlier estimates, and our investigation indicates that this difference reflected unanticipated improvements in instrumentation and controls that reduce personnel requirements, innovative sludge removal techniques, and higher than expected utilization of scrubbed units (which reduces capital cost per ton of sulfur removed). Moreover, new ways were found to adapt midwestern boilers to blends of local and Powder River Basin coals. Although such adaptation was underway prior to 1990, it may well have been accelerated by the passage of Title IV. *However, the dramatic gap between actual and expected allowance prices is simply too large to be accounted for by the observed technological improvements* [emphasis added]. (1998: 65)

[9] Carlson et al. use 'technological change' interchangeably with 'technological improvements' and 'technical progress'.

The kinds of technical changes that Ellerman et al. flag up here as innovative, like improved instrumentation, improved sludge removal techniques and higher utilisation of scrubbed (FGD) units, are discussed in detail in the next section. Indeed it would not seem as though the emergence of these new-to-the-world techniques would be enough to account for the unexpectedly low cost of abatement. The next section considers the qualitative evidence on the role of 'environmental' and 'ordinary' frontier knowledge, and on the role of pre-existing method and techniques, in the change in SO2 intensity undergone under the Programme.

4. Case evidence

The evidence base for the next three subsections includes: nine extended primary interviews conducted in 2009 with research managers, engineers, fuel purchasers and compliance specialists who worked on SO2 emissions issues during the 1980s and 90s; research reports from the Electric Power Research Institute (EPRI) into the economic and engineering implications of SO2 control legislation for US electric utilities; the original text of the Clean Air Act Amendments of 1970, 1977 and 1990 and the rulemaking actions promulgated by the EPA that implemented them; government documents; and generation unit-level SO2 compliance strategy data from the Energy Information Administration (EIA) for the period 1996 - 2005. The analysis begins at the level of the electric power plant before moving back up through the supply chain to the production method changes undergone in industries that supply those plants, including coal mining, railroad transport and the mechanical and engineering service providers of FGD systems.

a. Patterns in plant-level compliance

Owners and operators of the generation units affected by Title IV were free to choose from all compliance strategies virtually without restriction, to meet their emission reduction obligations. The EIA monitored these choices by collecting data on the frequency of use of the 14 most common compliance strategies in its annual survey of steam-power electric power plants (EIA-767)[10]. The survey instructed respondents to 'Select the existing and/or planned strategies to meet the sulphur dioxide requirements of

[10] The form EIA-767 'Steam-electric plant operation and design' gathers information on plant characteristics, plant configuration, boiler operations and fuel use, FGD unit design characteristics and FGD unit operation.

the Title IV of the Clean Air Act Amendments of 1990'. The EIA-767 questionnaire is mailed out each year to every steam-powered electric power plant in the United States with a generator name plate rating greater than 10mW. Plant managers have a statutory duty to respond to the questionnaire. This survey procedure gives some assurance that the survey data analysed directly below and in the regressions to follow is not grossly unrepresentative or incomplete.

Table 1 summarises the responses for all affected units over all reported years from 1996 - 2005.[11] The frequency column gives the total number of 'declarations' for a generation unit that it was using a particular compliance strategy in one year. Respondents had the option to state up to three compliance strategies, and the table includes all strategy declarations regardless of primacy, e.g. whether each was stated as the first, second or third strategy. The last column labelled 'FKR' is the author's own assessment of the amount of frontier knowledge the operator of the plant would have required to implement the strategy. The values 0 – 3 denote, respectively, 'zero or negligible amount of frontier knowledge required', 'small amount', 'medium amount' and 'large amount'. A hyphen means 'unknown'. Values are assigned on the basis of the author's understanding of what each compliance strategy involved technically, some of which is conveyed in the footnotes.

[11] Data come from form EIA-767, schedule III, section B, question 3(g). Data do not appear for 1998, 1999 and 2000. The response rate for the compliance strategy question in the survey was 91.9 per cent for all other years.

Table 1: Unit level compliance strategies with Title IV, 1996 – 2005

	Label	Freq	Perc	FKR
Allocated allowances and/or purchase allowances	WA	7129	42.86	0-1
No change in historic operation of unit	NC	3812	22.92	0
Switch to lower sulphur fuel	SS	3206	19.27	1-2
Not determined at this time	ND	488	2.93	0
Designate Phase II unit(s) as substitution unit(s)[12]	SU	474	2.85	1
Other	OT	330	1.98	-
Decrease utilisation – designate sulphur-free generator(s) to compensate	US	308	1.85	1
Transfer unit under Phase I extension plan[13]	TU	304	1.83	0-1
Install FGD unit (other than under Phase I extension plan)	IF	294	1.77	3
Control unit under Phase I extension plan[14]	CU	119	0.72	2
Decrease utilisation – rely on energy conservation and/or improved unit efficiency[15]	UE	56	0.34	2
Decrease utilisation – purchase power	UP	43	0.26	0
Repower unit[16]	RP	42	0.25	3
Decrease utilisation – designate Phase II units as compensating units	UC	28	0.17	1
Total		16,633	100	

The 'FKR' column shows considerable difference across compliance strategies in the amount of frontier knowledge plant operators would have needed to acquire for implementation. A pattern that emerges is that the strategies one might expect to involve acquiring and applying the most new technical knowledge received the *least* uptake out of the 14 options, while the compliance strategies one might expect to involve acquiring and applying the least amount of new technical knowledge received the *greatest* uptake. For example, 'repowering' a unit is arguably the strategy that would have stretched the plant furthest given the meaning of 'repowering' in the 1990 CAA Amendments. 'Repowering' meant:

[12] This involved shifting the unit's emission reduction obligation to a different unit under the operator's control. The emission reduction requirement could be reassigned to a unit with a lower compliance cost for example (CAAA 1990: 2593 – 2594).

[13] Same as 'designate Phase II unit(s) as substitution unit(s)', except instead of controlling unit emissions directly using a 'qualifying' technology the operator transferred the emission reduction obligation to a unit employing a qualifying technology.

[14] Under a Phase 1 extension plan a plant operator was allowed to extend the compliance deadline for a unit by up to two years provided that the operator held valid allowances for all emissions from the unit during the two years and that the operator either employed a 'qualifying Phase 1 technology' or transferred the emission reduction obligation for the unit to a unit employing a qualifying Phase 1 technology. A qualifying Phase 1 technology is 'a technological system of continuous emission reduction which achieves a 90 per cent reduction in emissions of sulphur dioxide from the emissions that would have resulted from the use of fuels which were not subject to treatment prior to combustion' (CAAA 1990: 2588).

[15] For each ton of SO2 emissions an operator avoided through energy conservation measures, the EPA awarded an equivalent number of emission allowances.

[16] See definition in-text.

> … replacement of an existing coal-fired boiler with one of the following clean coal technologies: atmospheric or pressurised fluidized bed combustion, integrated gasification combined cycle, magnetohydrodynamics, direct and indirect coal-fired turbines, integrated gasification fuel cells… or a derivative of one or more of these technologies and any other technology capable of controlling multiple combustion emissions simultaneously with improved boiler or generation efficiency and with significantly greater waste reduction relative to the performance of technology in widespread commercial use as of the date of enactment of the Clean Air Act Amendments of 1990 …. (CAA 1990: 2587)

Repowering can be considered one of the most knowledge-intensive strategies because it involved production methods ('atmospheric or pressurised fluidized bed combustion… magnetohydrodynamics, integrated gasification fuel cells') that were not in widespread use among affected plants at the time. If a plant operator had chosen to repower an affected unit then it is likely that the plant would have had to do the following: undertake considerable research into how to integrate the new unit into the existing electricity generation system; investigate the suitability of manufacturers to source the technology from; oversee the installation of the unit; learn how to operate the new unit; and maintain considerable practical on-site expertise to maintain and operate the new unit. Plant operators chose repowering as a compliance strategy in 42 out of 16,633 total declarations, amounting to one-quarter of one per cent of all declarations. Repowering ranked the 13th most popular strategy out of 14 possible strategies.

Choosing FGD units (scrubbers) might also have involved acquiring a considerable amount of new frontier knowledge, though perhaps less of it, or knowledge of a less advanced degree, compared to repowering since many scrubbers were already in use at the time. Scrubbers had been in widespread use in the US from the mid-1970s (Taylor 2001). Table 1 shows that scrubber uptake under the 1990 Amendments was comparable in extent to repowering. Installing new scrubber capacity would have involved committing significant plant engineering staff resources to expanding and especially maintaining new stocks of environmental knowledge, whose only narrow purpose would have been to control SO2 emission. This is because a scrubber has no other purpose for existence than to remove sulphur particles from the plant's flue gas stream. Installing new scrubber capacity accounted for less than two per cent of all compliance strategy declarations.

By contrast, the strategies that received the most widespread uptake involved preserving, extending and repurposing existing physical capital stocks *and also preserving, extending and repurposing existing technical knowledge* stocks, to the extent plant operators depend on 'knowledge capital' to run the physical capital. Switching to lower-sulphur fuels for example accounted for 19.27 per cent of all declarations by affected generation units. Plant operators were probably not able to switch fuels without learning anything new at all. For example switching from burning the common anthracite coal to burning the lower sulphur lignite coal for sustained periods of time tended to lead to problems with pulverisation, erosion, fouling, slagging, derating and electrostatic precipitators in the affected units (EPRI 1990). Many boilers manufactured prior to 1990 had not been engineered to burn coal with the properties of lower sulphur coals, and plant operators tended to have to alter their coal grinding equipment, update their fuel testing and handling systems, and implement measures to monitor and control what was happening in the combustion chamber (EPRI 1990). *Making these changes to existing generation systems probably required plant operators to develop and apply at least some new technical knowledge.* This would have been required at least to make boilers based on older coal combustion technology run reliably on lower sulphur coal.

This is interpreted as evidence that the operators were involved in at least some learning in switching to lower sulphur coals. What they seem to have learned though was a kind of technical knowledge one might primarily associate with 'ordinary' aims, e.g. making coal combust better, and not with primarily 'environmental' aims of lessening emissions. Nor does switching between coal types, or co-firing different coal types, or blending coal types together, qualify as either frontier or universally 'new' technologies in this interpretation. All these methods were technically feasible and existing in practice prior to 1990 (EPRI 1990; Joskow 1998; National Acid Precipitation Assessment Program 1989; Taylor 2001), they just were not in as widespread practice as they came to be after 1990.

Again referring to Table 1, after fuel switching, the next most frequently stated compliance strategy was 'no change in historic operation of unit' and the most frequently stated compliance strategy of all was using 'allocated and/or purchased allowances'. Neither of these on its own involved any physical change to the operation of the generation unit at all. Allowance using/buying accounted for 7,129 compliance strategy declarations, 42.86 per cent of the total.

There was of course the possibility that the compliance strategies that one would expect to require relatively more frontier knowledge to implement (repowering and scrubbing) accounted for a larger part of SO2 reductions than the 'declarations' in Table 1 imply. They might have been implemented at the largest units, or the dirtiest units, or the most egregiously out-of-compliance units, therefore accounting for disproportionately more SO2 reduction per declaration. This was checked by weighting the declarations in the frequency column in Table 1 in three different ways: by the unit's heat input capacity, by the unit's SO2 emissions, and by the primacy of the compliance strategy declaration (recall that primacy is whether the plant reported the compliance strategy as its first, second or third strategy, as discussed above). The detail of the weightings is included in the Appendix. None of the three weighting schemes changed the ranking of the four most frequently occurring strategies (allowances (WA), no change (NC), fuel switching (SS) and not determined (ND)). Together these four strategies never accounted for less than 93 per cent of all declarations under any weighting scheme. The only shift with respect to repowering was the same under all three weighting schemes: repowering moved from the 13^{th} most frequently occurring strategy to the 12^{th}.

Two other aspects of the data in Table 1 support the idea that plant operators are generally averse to technical learning in their compliance method choices. First, there was almost no variation in declared compliance strategy *across units within plants*. For example, in the entire dataset, it was extremely rare that a plant with six boilers (units) under its control chose to burn lower sulphur fuel for five of its boilers, but buy emission allowances for the sixth. At the plant level, the strategy a plant operator used for one generation unit was highly likely, almost without exception, to be the strategy the plant operator used for all its generation units. Also, there was extremely little variation in declared strategy *within units over time*. Over the full ten year period the compliance strategy did not change once, in any year, for 85.7 per cent of all generation units affected by Title IV of the CAA Amendments in the entire country. For example there was no significant evidence of generation units transitioning between compliance strategies or systematically 'evolving' from one strategy to another as might be expected from the effect of learning with time. Of the remaining 14.3 per cent of generation units that did change their strategy at some point during the ten years, the great majority changed their strategy just once from 'not decided' (ND) to 'allocated and/or purchased allowances' (WA).

The lack of variation in compliance method both within individual plants and within generation units over time is consistent with the idea that plant operators specifically and utilities more generally are extremely averse to new capital spending, by extension it is argued here, to technical learning and new knowledge acquisition. One employee who had worked on his utility's Title IV compliance approach explained how his utility essentially used allowance-buying and fuel switching as strategies to delay new capital spending on dedicated emission control technologies (scrubbers):

> In the early 1990s we were looking at ways to comply [with Title IV]… Our executives said taking a derating [reducing power output] at some of our units was an unacceptable option, so that ruled out a lot of possibilities… but we had other units that were built in the late

> 80s… they had big blower boxes, lots of excess mill capacity, they were fully capable of using PRB [low-sulphur Powder River Basin] coal… We eventually saw it would be possible to avoid paying a huge premium, and that we could build up a bank of allowances [by buying and burning low-sulphur coal]. Now this was Phase 1, covering 1995-1999. We did that at every Phase 1 unit we had. We thought we could build up 1.7 to 2 million tons of allowances so when the law got stricter we could turn in those credits and buy time until the scrubber technology was mature. You have to understand… utility guys are hugely averse to large capital spending. What our executives basically wanted was a strategy to delay capital spending while FGD matured.

What is significant here is that the utility chose to exploit spare capacity and tweak already obligated capacity within its existing capital stock by switching fuels and banking allowances, rather than immediately investing in new FGD units (more capital). This should not be surprising. What is interesting though is that the centrepiece of the utility's compliance strategy was to use allowances and fuel switching to *deliberately delay as far into the future as possible* new investment in capital dedicated specifically to emission control and, to the extent that capital spending is inseparably bundled with new knowledge acquisition, also delay the technical learning burden that would have been needed to operate that new capital. The utility made use of its pre-existing financial accounting expertise to use allowances in such a way as to avoid these commitments. Among utilities the practice of accumulating excess allowances by over-complying through fuel switching then banking the credits for future use was a very common approach among Title IV affected utilities (EPRI 1990; Schmalensee et al. 1998).

It would be useful to know how much, and what kind, of R&D each plant operator performed in connection with each of the 14 compliance strategies, but the EIA data do not report this information. Instead the question of R&D was raised with the utility employees, particularly what role it played in their Title IV compliance strategies and how much of the R&D that was needed to implement the compliance strategies they actually performed themselves. One manager explained how many electric utilities in the US essentially outsource the bulk of their R&D function to the Electric Power Research Institute (EPRI) in Palo Alto, California, an industry organisation which performs the bulk of low-grade, large-scale, routine R&D (what he refers to as 'the base-load topics') on behalf of its fee-paying membership:

> EPRI is a leviathan in the industry as far as R&D is concerned… We are different from the typical utility because we tend to be out in front of the EPRI membership. It's typical for the other large companies to have one guy in an engineering function who attends the EPRI meetings. It's almost a hobby for these owner-engineers to do R&D. Most of them just turn

> the R&D over to EPRI… We tend to let EPRI do the base-load topics. They've already sold their membership on everything they're going to do in 2010 [a year after the date of the interview]… For the topics that are highest value to us, we do them ourselves and get funding from EPRI and DOE [US Department of Energy]. If you want a military metaphor, EPRI is the heavy infantry… When we do work with EPRI on scrubber options, stuff has to be published and we typically leave the dissemination up to EPRI and other EPRI members… Sometimes we hold back the detail of our [scrubber] design work but most of the time we just don't think there's much patentable stuff there. Or there may be patentable stuff but we're not vigilant enough to find and patent it. We're in the business of supplying electricity, not selling this scrubber equipment… Really the value for us of the R&D is rolling up our sleeves and physically doing it. This brings us a lot of value that doesn't find its way into the final report. Our R&D work does get out to help the industry when we have the right partners [DOE and/or EPRI], and they [the industry] will get some benefit from it, but for us we feel the trade secrets is where we get our value even though most of its published.

In the first part of the passage the respondent explains how EPRI, as the 'heavy infantry' of the electric power industry's collective R&D function, essentially frees its members from having to perform the same R&D projects themselves individually. EPRI aggregates member interests into an industry-wide research agenda, carrying out the agenda on its members' behalf and disseminating the results back to them. This illustrates how EPRI is an institution which exists in part to capture economies of scale in the performance of electric power R&D, including emission control R&D, and to avoid the expense of duplicating R&D that would have been born by individual plants. Reliance on EPRI for R&D came up with several other interviewees. With respect to Title IV, it seems that EPRI acted as an institutional device to minimise the amount of emission control R&D electric utilities needed to perform. This is consistent with the understanding that R&D of any type is expensive to invest in as a lone organisation; that it is intensive in the skilled R&D labour needed to perform it; and that it is uncertain in whether it will ever yield anything useful (Antonelli 2002).

In the second part of the passage the respondent reflects on the nature of the remaining R&D that his utility did perform on its own to deal with SO2 emissions. He discusses the applied quality of this R&D. He emphasises several times that what is valuable for his utility is the knowledge that comes from the *performance* of hands-on ('rolling up our sleeves') emission control R&D rather than from the codified, crystallised end result of R&D in the form of patentable discoveries. The reason for the lack of interest in the formalisation of that knowledge is clear: 'We're in the business of supplying electricity, not supplying this scrubber equipment'. This sentiment is reinforced by the respondent's general willingness to freely share the formal research outputs (reports) with other utilities ('We typically leave the dissemination up to EPRI and other EPRI members').

Overall what this passage suggests is that the newly acquired technical knowledge that did play a role in plant-level emission control, at least at this respondent's utility, tended to be more pragmatic and applied rather than frontier and scientific in nature. Recall the respondent's comment that '…most of the time we just don't think there's much patentable stuff there. Or there may be patentable stuff but we're not vigilant enough to find and patent it'. This implies that R&D spending would be a better indicator of knowledge creation for dealing with SO2 emissions than patents. An indicator of input into the SO2-reducing innovation process probably captures more relevant learning than an indicator of output from that process (Griliches 1990). This is one reason for using R&D spending rather than patents in the model estimates in the econometrics section to follow.

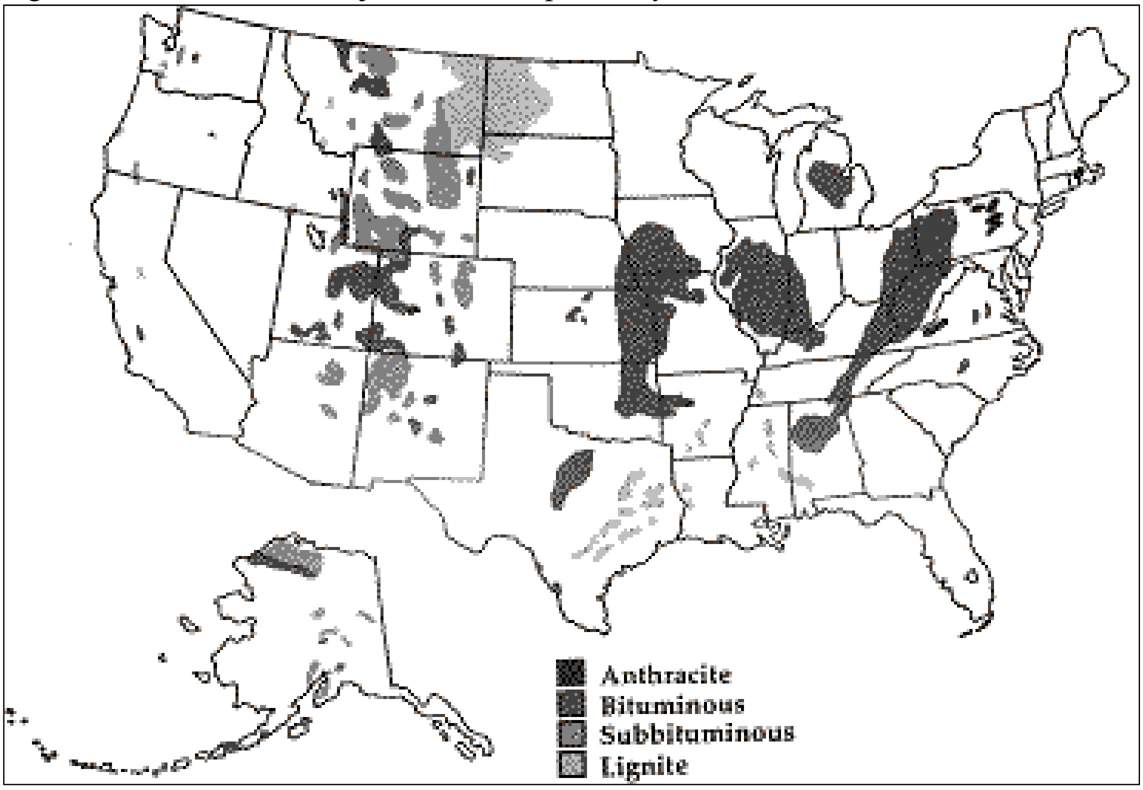
b. Productivity gains in coal mining

The pattern in plant-level compliance strategy choices belies very significant production pattern changes in the upstream industries that supplied goods and services to the electric power plants themselves. These changes fundamentally shaped the technical and economic viability of the compliance strategy choice set available to plant operators. By extension these changes strongly influenced the overall technology parameters in which SO2 reductions occurred.

One of the most pronounced effects of Title IV was to accelerate the geographic shift that was already under way in American coal mining from the high-sulphur coal deposits in the Midwestern and Eastern regions to the low-sulphur coal deposits in the Western states of Montana, Wyoming and North Dakota. Historically, the majority of US coal production by volume had come from the Midwestern and Eastern Appalachian regions. This was partly because Western coal was geographically distant from, and expensive to ship to, the power plants serving major population centres in the Eastern regions. Figure 2 depicts the geographic distribution of major coal deposits by coal rank.[17]

[17] Coal rank is determined by the degree of alteration in the process of peat transforming into anthracite coal through burial pressure, heat and time. High-sulphur bituminous coal is dense, hard, black, shiny and dry. It has high carbon content and releases the greatest amount of energy when burned. Lignite coal is browner, softer, more crumbly, earthier and contains more moisture and less carbon. Lignite coal tends to contain the least amount of sulphur by weight. The sulphur content of coal varies by weight from .5 per cent to over ten per cent, but the majority of coal types found in the United States are between one and three per cent.

Figure 2: Distribution of major US coal deposits, by coal rank



Source: American Coal Foundation (2005)

Figure 2 shows that the Midwestern and Eastern states are generally abundantly endowed with high-sulphur bituminous coal. The Western states are generally well endowed with sub-bituminous and lignite coal, both of which contain significantly less sulphur by weight. What Title IV essentially did was put a price on the sulphur content of coal. The Western states of Montana, Wyoming, North Dakota and South Dakota soon found that the large, predominately lignite coal deposit in the Powder River Basin (PRB) straddling their borders, had become a much more desirable commodity. At the same time the Midwestern and Eastern Appalachian states found that their higher sulphur content coals had become significantly less desirable (Joskow 1998). It is important to emphasise that Title IV and the cap and trade programme *accelerated* a geographic distribution coal mining activity in the US that was very much already underway. Title IV was not itself the sole reason for the shift. Other factors contributing to the shift are discussed below.

From around 1990 the Powder River Basin and surrounding region rapidly became the most important source of low-sulphur coal by volume in the country, and the rapid expansion of mining activity there was marked by the signs of technological progress (and not just technological change). Western coal deposits presented new technical challenges and opportunities to extraction because they were closer to the surface and thicker-seamed. Eastern coal deposits by contrast tended to be thinner-seamed, deeper and more difficult to access. But Eastern coals also had more energy content by weight. Sufficiently thick and continuous coal seams like the ones in the Powder River Basin could be harvested using a large rotating mechanical shearing device called a longwall shearer that grinds the coal away from the face of the coal seam. Figure 3 illustrates.

Figure 3: Longwall shearer

Prior to the opening of the Powder River Basin, the typical longwall shearer in the US cut into the face of coal seams to a depth of 24 inches. This was typically the maximum cut depth possible given the natural features of the coal deposits in Eastern coal mines. With the help of industrial equipment suppliers, mining companies were able to introduce into the Powder River Basin longwall shearers capable of cutting up to 37 inches in depth, and at the very largest mines, up to 42 inches in depth (Flynn 2002).

Once the coal had been cut away from the seam face underground it needed to be transported to the surface to be processed, loaded and shipped. Larger, more powerful conveyer motors were installed on PRB mine sites to move the harvested coal to the surface than had previously been commonly used in Eastern mines. The width of coal-moving conveyor belts increased from 48 inches to 60 inches. To move coal from the mine mouth to rail or truck shipping points, mining companies introduced trucks with the capacity to haul 240 tons in a single payload, and at the very largest mines, trucks capable of hauling 320 tons in a single payload. The use of trucks of this scale had not been widely feasible at Eastern mines due to the nature of the terrain and the scale of operations (Flynn 2002; Darmstadter 1997).

Information and communication technologies were introduced to improve the efficiency with which mining machinery was used and to eliminate waste and redundancy in transport vehicle movements. Disruption to production from broken down mining equipment was confronted with electronic sensor-enabled systems of preventative maintenance. Computer-supported automation and robotics were introduced to perform difficult or dangerous underground mining tasks, or to handle tasks requiring a high degree of precision (Darmstadter 1997). Long-wall shearers became more automated. Satellite tracking of material handling equipment was employed at the surface to monitor transport movements, to predict production bottlenecks, and to increase equipment utilisation factors (Flynn 2002). The integration of general purpose and particularly ICT-based technologies into Western coal mining operations improved financial returns to existing physical capital investments.

The share of total US coal production mined from the Western region increased from 307.9 million tons to 451.2 million short tons from 1988 to 1997, an 11 per cent change in the share (see below). By contrast the share of national production from the Eastern Appalachian region decreased by about four per cent during the same period. The share production from the Interior (Midwestern) region also decreased, by over four per cent. Again it is important to emphasise that Title IV/cap and trade was a significant *contributory* cause of this change and definitely not the only cause.

Table 2: Coal production by region, 1988 and 1997

	1988	1988	1997	1997	
	Production (million short tons)	Per cent of national total	Production (million short tons)	Per cent of national total	Average annual per cent change in production
Appalachian	449.4	47.3	467.8	42.9	.4
Interior	193.0	20.3	170.8	15.7	-1.3
Western	307.9	32.4	451.2	41.4	4.3
US Total	950.3	100.0	1089.9	100.0	1.5

Source: Energy Information Administration (1997)

Recall from Table 1 that switching to lower sulphur fuels accounted for about 19 per cent of the compliance responses declared by the operators of plants affected by Title IV. One employee at an electric utility who worked in environmental compliance at the time his utility was devising its strategy to deal with Title IV, discussed how the geographic, technological, regulatory and productivity change factors in the upstream supplier industries came together in what presented itself as a very low-cost compliance strategy for his employer:

> Low-sulphur coal burn was fairly minor for us in the pre-1990 era… Up until the mid-90s the common coal for most of our [utility] system was West Virginia or Illinois 2.5 [per cent

sulphur content coal]. Our response was a wholesale fuel switch to low-sulphur coal. We found low-sulphur fuel was available with very little premium. We had to buy our way out of some long term high-sulphur contracts we'd signed, but it was worth it. Essentially the coal materialised from the Powder River Basin. The first thing we did was switch two of our largest generating sites. Today [2009] a third of the entire utility's tonnage is PRB coal. That switch had tremendous fuel price benefits as well as being low-sulphur coal. PRB coal was very close to the surface. It turned out you could mine it a lot easier [than Appalachian coal] because the terrain is flat out there and you can use huge machinery. So the mining companies could invest in capital equipment and the manpower needed to run it was very low, maybe 10 per cent compared to the East's deep mines with smaller, thinner seams. But let's go back to the late 90s. For coal here [a Southern US state] that was deep-mined we were paying 65 dollars a ton. The at-the-mine-price in Wyoming was 5 dollars a ton. These are the late 90s. Then it cost another 25 dollars to ship it all the way to Alabama and Georgia. Per ton is a bad way compare but it's [PRB coal] not quite half the price on an energy basis.

What is significant about this passage is that some plant operators themselves were surprised by the unexpected attractiveness of the strategy of switching to low-sulphur Western coal made possible by these upstream changes in the supply chain ('We had to buy our way out of some long term contracts… it turned out you could mine [PRB coal] a lot easier because the terrain is flat out there…'). Plant operators expected that low-sulphur coal would be part of the answer, but they did not anticipate the extent to which the geographic shift, automation and mechanisation, and rail network investment factors would converge to push down the low-sulphur coal price to the extent that they did.

The respondent further alludes to the fact that a very significant part of the delivered price of any kind of coal from almost any source is transport cost. This had been the great disadvantage of low-sulphur PRB coal prior to the Title IV era (Carter 1996). The other critical factor in the shift toward Western coal besides Title IV, but which also shaped the technological parameters in which SO2 reductions occurred at plant-level, was the US railroad industry's heavy investment in the railroad network to serve what quickly became high-volume, high-frequency coal shipments leaving the Powder River Basin and travelling cross-country to Eastern electric utilities.

The rapid capital investment in the cross-country haulage routes that lowered the price of low-sulphur coal was also caused by the process of deregulating the US railroad industry. Deregulation had been underway at least since 1976.[18] Three mega-carrier

[18] Prior to 1976 American railroad companies had been locked in what had become a crippling relationship with the Interstate Commerce Commission, the Federal body responsible for regulating railroad companies. This relationship was contributing to the physical deterioration of the national rail infrastructure and the financial ruin of the railroad companies that used it. Since around 1890 the ICC's had attempted to cross-

railroad companies eventually emerged from a wave of consolidation. These companies invested heavily in the rail network serving the PRB region: Burlington-Northern, Santa-Fe (these two later merged into what is now called BNSF), Union-Pacific (UP), and Chicago & North Western (which itself was purchased by UP in 1995). BNSF and UP heavily expanded their infrastructure and operations to capitalise on PRB region coal traffic growth. BNSF spent around 100 million dollars each year during the mid-1990s on coal-related expansion, which amounted to about 1/3rd of its annual facility expansion budget. UP spent 187 million dollars on 'coal corridor' projects alone in 1999, which was about half the company's facility budget (Heller and Kaplan 1996).

The railroad company UP built a heavily-computerised 'National Operations Center' in Fort Worth, Texas to improve the efficiency of the dispatch of freight movements from the PRB region and elsewhere, and to coordinate freight traffic across its network. Several of the rail companies purchased new high-horse-power locomotives to haul coal trains of 100 cars or more in length across the country. Bigger locomotives raised the maximum number of cars possible for cross-country movements and sped up arrival times. The companies double-tracked lines that had been only single-tracked, and triple-tracked lines that had only been double-tracked. It is not unreasonable to think that the companies together spent over a billion dollars during the 1990s upgrading their rail transport infrastructure to meet PRB coal demand. These investments pushed down the delivered price of low-sulphur coal even further. These supply chain changes heavily influenced which compliance methods were technically and economically viable at the level of the electric power plant.

Several of the railroad companies entered the PRB region with huge capital investments and zero initial market share, and bid aggressively for new coal haulage business from the utilities. One utility employee interviewed for this study, a fuel

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subsidise rail service rates throughout the country to ensure no company abused the power of natural monopoly, and to ensure the regions of the country that were expensive to serve were not denied service.

These policy goals led the ICC to repeatedly deny railroad company requests to merge and consolidate. These mergers would have facilitated new capital investment in the rail network and allowed companies improve their parlous finances by reducing waste and efficiency through consolidation, but the ICC apparently felt that the risk of the abuse of market power was too great. This policy position became still more untenable with the rise of trucking in the 1950s. With the expansion of the interstate highway system and the emergence of direct competition in haulage services with the railroads by trucking, the decline of the railroad industry accelerated. All this made the ICC's obstruction of company mergers increasingly bad industrial policy.

To fix this, the Federal government began deregulating the industry in 1976 with the Railroad Revitalisation and Regulatory Reform Act of 1976, and continued to do so in 1980 with the Staggers Rail Act. A wave of consolidation ensued through the 1970s, 80s and 90s in which new railroad companies disposed of redundant labour and assets and improved their financial health. They began to offer more continuous single-haul lines that were faster and more direct. To get a sense of the extent of consolidation, in 1971 there were 71 Class 1 railroads companies operating in the country; by 1996 there were nine. In 1971 they were operating 206,000 route-miles of track; by 1996 they were operating 108,000 miles of track (Heller and Kaplan 1996).

purchasing manager, described the treatment he received from the main railroad companies as they attempted to win a new low-sulphur coal supply contract with his utility:

> As PRB started to develop, Burlington Northern [BN] and Union Pacific [UP] saw these rail routes were going to become huge business. In the East you have Norfolk Southern [one of the largest railroad companies in the East] which does relatively short hauls… The railways in the East had been charging extortionate tariffs. But because you now had direct competition in the West, you got cut throat competition between BN and UP.
>
> I've never been treated like a king before. I was working with the environmental compliance guys [at our utility] at the time. The Western rail companies would fly us out to the Powder River Basin, give us a tour of the mines, they fed us on the trains, they brought in special cars to rail us from Gillette [Wyoming] to Montana. They made a big presentation about the capital investments they were planning to triple track their lines. We had salesmen all over us. Just a few of our plants alone, that would have been 24 million tons of brand new business a year for these rail companies. They were practically crucifying themselves cutting their prices. There was just cut throat competition between these two big Western railroads because they wanted to compete against Eastern coal… Initially they didn't even have enough cars to get [the coal] out of there. Eventually they started shipping it in 110-car-long trains. These things were so long… they would never stop moving. The cars would just run underneath the coal silos moving at 1 mile an hour and the ladies would sit up in the towers filling up the cars with the computer joy sticks, then the train heads off 1,800 miles toward the East. You can imagine the volume of coal. They were triple tracking east and west and trying to figure out who was going to build more cars.

The passage conveys how acute the competition became between the railroad companies to sign Western coal transport contracts with the utilities ('… you got cut throat competition …. They were practically crucifying themselves cutting their prices …. You can imagine the volume of coal'). The intensity of competition was the result of the combined effect of railroad industry deregulation and Title IV. This passage shows that the railroad companies responded to this competition and to the new legal restrictions in their industry more broadly, in similar ways to the coal mining companies. The railroad companies made deep changes to their geography of production and distribution in the form of new lines to serve the PRB. Also like the mining companies they invested in new forms of physical capital that conformed to and exploited the new legal restrictions in the industry and therefore expanded production capacity in a relatively clean direction. Like the mining companies they rapidly up-scaled aspects of their existing operations (triple tracking, high-horse-power locomotives, the computerisation of transport logistic functions). They also integrated general purpose technologies ('filling up the cars with computer joysticks') to increase production scale and eliminate waste and inefficiency.

These upstream supply chain changes in the coal mining and railroad industries fundamentally shaped the compliance strategy response at the level of the electric power plant. Neither the nature of these changes nor their depth or extent was fully anticipated by regulators, plant operators or even the upstream supplier industries themselves immediately prior to the enactment of Title IV. What ushered forth these upstream changes was the fact that the cap and trade programme left the compliance method choice pretty much up to plant operators and the broader market forces they did business with. Technological 'progress' did play a role in the broad industrial response to Title IV, but this progress tended to occur far away from the electric power plants themselves through mechanisation, computerisation, and up-scaling in the supply industries. This analysis showed that some of the most important production method changes to lowering SO2 emissions at plant level occurred upstream of the plants in old, heavy, traditional, stereotypically 'dirty' industries.

These examples from the railroad and coal mining industries also underline how the knowledge and technology that facilitated emission reductions at plant level did not look like the kind of knowledge and technology one might expect to play a big role in environmental protection. These examples raises basic questions about the USPTO policy (discussed in Section 1) aiming to prioritise 'green' inventions in the patent approval process at the expense of non-green ones. One might suggest that faced with a patent application for a new coal harvesting device capable of cutting 42 full inches into the face of the coal seam, the patent examiner would have put this application into the 'non-green' pile. The same would go for a modified boiler designed to burn a different kind of coal without slagging or fouling problems. A patent application on a coal-harvesting invention would almost certainly have fallen outside of the USPTO's ideas about what qualifies as a 'green technology' despite the fact that this device played an important role in the technological change process and in lowering the cost of SO2 control. A patent application on a new coal harvesting device would most likely have been delayed by the USPTO programme, not accelerated. The other examples in this subsection (computerisation and automation, triple tracking of railroad beds, scaled-up coal transport equipment) also suggest that the knowledge and technology that will be useful for environmental protection is not easily categorised as 'green' from the policy outset.

c. Scrubbers: the exception?

There is a thorn in the side of the argument so far that plant-level SO2-saving technological change was characterised by minimal amounts of frontier knowledge that did not look characteristically 'environmental'. The thorn is the flue gas desulphurisation (FGD) unit, the scrubber. As a technology, flue gas desulphurisation has two characteristics that the pattern of evidence up until now would predict plant operators to systematically avoid: (1) it is capital-intensive and therefore probably entails significant technical learning to build and operate, and (2) since its sole purpose for existence is to remove sulphur particles from the flue gas stream, it is a technology which is 'environmental' in the sense of having no other purpose than pollution-saving. This leaves one wondering why scrubbers were the most widely-used SO2 control technology for two full decades prior to 1990, and why some plants chose to install scrubber units even after 1990 (Taylor 2001). If this anomaly cannot be explained satisfactorily then maybe the plant-level response was actually more frontier knowledge intensive, more 'technological' than has appeared to be the case so far.

Flue gas desulphurisation emerged in the early 1970s out of a rancorous and divisive process of political and social compromise. When Federal legislation first placed limits on stationary source SO2 emissions in the early 1970s, Federal regulators were unwilling to leave the choice of compliance method to electric utilities. *This was because regulators feared that a widespread switch to low-sulphur coal would trigger heavy distributional consequences for the states that mined and burned large amounts of high sulphur coal* (Joskow 1998). Scrubber systems avoided disrupting established geographic patterns of industrial activity because they protected mining jobs in states with companies that held long term supply contracts with electric utilities. If power plants would only control their SO2 emissions using a post-combustion method like scrubbing, the distributional consequences from the political process of cleaning up the nation's air quality could be avoided. The states with a vested interest in coal mining could be converted away from their position as opponents to those environmental goals.

Beginning in the early 1970s the US Environmental Protection Agency almost singlehandedly forged the flue gas desulphurisation technology pathway against very considerable technical, economic and political opposition. EPA spent hundreds of millions of dollars on laboratory R&D, field experimentation, demonstration projects, collaboration with utilities, capacity building and knowledge dissemination to bring scrubbing technology into the mainstream. The following except comes from a publication produced by the Air Pollution Prevention and Control Division (APPCD) of the EPA's Office of

Research and Development, dated 1995, documenting the Agency's accomplishments developing FGD systems during the 1970s and 1980s:

> The workhorses of these [flue gas desulphurisation] control technologies, wet lime and limestone systems, better known as 'scrubbers,' have been, to a great extent, pioneered, developed, and demonstrated by EPA's Air Pollution Prevention and Control Division (APPCD)… Over a 20-year period, APPCD has established FGD as a commercially accepted technology, through dissemination of program results at regularly sponsored symposia, sponsoring a number of commercial-scale demonstrations, publishing numerous journal articles, and holding industry seminars at the conclusion of successful demonstrations to ensure that vendors are able to offer FGD innovations, commercially… To foster the development and implementation of cost-effective SO2 control technology, APPCD has:
>
> - Conducted 15+ years of pilot wet lime and limestone FGD tests at RTP [EPA's facility at Research Park Triangle] and TVA [Tennessee Valley Authority] to improve the technology to a universal acceptance.
> - Sponsored a number of commercial demonstrations to show high reliability, 90 per cent SO2 control wet FGD operation.
> - Sponsored laboratory and field evaluation studies of power plant and FGD waste disposal
> - Sponsored SO2 control technology symposia on a regular basis since 1971; conducted industry briefings to transfer successful technology demonstrations to the private sector.
> - Published over 100 reports and hundreds of journal articles on FGD performance and economics.
> - Published an economic model for evaluation of alternative SO2, NOx, and PM control technologies.
> - Received 11 patents in SO2 control technology with several more pending.
> - During the 1970s and early 1980s, provided leadership through international forums such as NATO – Critical Challenges to Modern Society (NATO_CCMS) to transfer FGD technology to Europe
>
> (US EPA 1995: 1-3).

The significance of this passage is to show that flue gas desulphurisation was a technology that emerged from the powerful top-down backing of a government establishment intent in part on protecting some economically vulnerable sections of society from the distributional consequences of environmental policy. Scrubber technology did not emerge from the market forces that gave rise to the highly decentralised production method changes observed under Title IV/cap and trade. In one sense the accomplishments described in these eight bullet points testify to a heroic technology success. Without this effort, SO2 control in the early years would probably have been politically unfeasible. Yet in another sense these bullets demonstrate how far from the market-led technological change pathway industry needed to be made to stray, in order for government to avoid economic disruption and political gridlock. EPA's work to promote scrubber technology therefore took care of the supply side. The relatively rigid regulatory regimes put in place by the 1970 and 1977 CAA Amendments and the 1979 New Source Performance Standards took care of the demand side, by essentially mandating that plant operators choose scrubbers (Reitze 2001; also see the footnotes in Section 3 about the rigid regulatory approach that the cap and trade programme replaced).

If this is a correct interpretation of the reasons scrubber technology played such a strong role in the emission-saving change prior to 1990, then one should expect scrubber uptake to be very limited in a regulatory environment where both government technology supports and technology forcing policies fall away. The post-1990 regulatory world left (mainly) only a quantity requirement for firms to meet collectively as they wished. This is what Title IV did: it *replaced* the preceding scrubber-forcing regulatory regime.

Prior to 1990, engineering service suppliers that did business with coal-fired power plants had high expectations for the number of scrubbers electric utilities would choose to install under the post-1990 regime. They among others were disappointed by the extent of actual scrubber uptake under the new regime. In 1995 when the cap and trade programme began, 17 per cent of all generating units in the nation were using scrubbers. Among the generators using scrubbers, 86 per cent had installed them because the plant operator was required to do so by law, either to satisfy pre-1990 Federal NSPS requirements (the case for 61 per cent of these) or pre-1990 state laws (the case for 24 per cent). The remaining 14 per cent of all installed scrubbers were installed as choices to comply with Title IV (Carlson et al. 2000). *These numbers are consistent with the observation in Table 1 above that the compliance strategy of installing scrubber capacity in response to Title IV accounted for less than two per cent of all compliance strategy declarations for plants affected by cap and trade*.

The two per cent minority of plant operators that did choose to install FGD systems in response to the 1990 CAA Amendments came to regret their decision when it became apparent that they had seriously underestimated the fall in the delivered price of low-sulphur coal (Schmalensee et al. 1998). These plant operators had failed to predict how upstream supplier industries would respond to the restrictions of Title IV (and other events). Once the fall in the delivered price of low-sulphur coal from these upstream changes had become apparent, the decision to scrub looked very expensive indeed. Further factors besides bad information biased the technology choice of some plant operators toward scrubbers. One such pro-scrubber factor was the rewards built into the rules under Title IV. These rules authorised EPA itself to award free allowances from a reserve pool of 'bonus' allowances to operators who chose to install a 'qualifying phase 1 technology,' which was essentially a scrubber (CAA 1990; also see the relevant footnote under Table 1). The fact that incentives for scrubbing technology were built into the legislation is not surprising given the amount of resources that EPA had invested in scrubbing technology under the old regulatory regime.

Nor is there very much secondary evidence that scrubber technology made much appreciable technological progress in the post-1990 regulatory environment. Using data on the design, performance and cost of scrubber units installed at plants in the US before and after 1990, Bellas (1998) found no significant technological progress had occurred in the technology. In a follow up study, Lange and Bellas (2005) found that scrubbers installed under Title IV were cheaper to purchase and operate than older scrubbers, but that the cost reductions were a one-off drop rather than a continual decline. Taylor et al. (2005) found that scrubber technology improved in terms of cost and performance, but that the improvements occurred *before* Title IV came into force in 1995, in the anticipation years. This is consistent with the idea that scrubber manufacturers accustomed to a technology forcing regime prior to 1990 misjudged the response to the new market-based design of Title IV. Keohane (2007) found that the installed cost of a unit of scrubber capacity remained nearly constant throughout the period 1995 - 2000. The evidence from these papers does not suggest that the post-1990 regulatory regime created significant incentives that favoured the further development and uptake of scrubber technology.

All this is consistent with the interpretation of the scrubber as a technology that benefitted from heavy government promotion for two decades prior to 1990: promotion that was necessary to avoid the geographic-distributional consequences of enacting environmental policy in that era. This promotion took the form of extensive technology supports on the supply side, and rigid scrubber-forcing regulation on the demand side. These forces effectively steered the course of SO2-saving technological change off of the pathway that market forces would have compelled it to follow if distributional concerns had not been an issue. There is little reason to believe that, in absence of technology-forcing intervention, SO2-saving technological change prior to 1990 would not also have been driven by techniques involving limited frontier technical knowledge dedicated to environmental protection, and more widespread use of methods and techniques for reducing emissions that involve little or no new frontier knowledge.

5. Econometric evidence

This section tests the effect that frontier knowledge and other less knowledge-intensive methods and techniques for reducing SO2 emissions, had on the extent of SO2-saving technological change undergone by electric power plants affected by the cap and trade programme. These formal tests complement the qualitative analysis in method and in data. The last section looked at the quantity, the advancedness, the newness, and the type of knowledge embedded in the techniques used to reduce SO2 emissions under the Programme. The last section focused on the 'middle' of the emission-saving technological change process between the initial regulatory event and the eventual end result of less SO2-intensive electricity production. The analysis in this section starts at the 'end' of that process by taking the extent of change undergone by electric power plants as the dependent variable. Starting from that end point, this section tests the role that different kinds of frontier technical knowledge and other factors played for plants in arriving at that changed state of production.

a. Dependent variable and model

The regressions separately test two different dependent variables measuring the extent of change undergone in each plant in the production of electricity with respect to SO2 emissions. The dependent variable is first calculated as the *change in the SO2 intensity of electricity production between 1997 and 2001* for each plant. This measure is consistent with the outcome from the change process described in Figure 1. Figure 1 described (a) an initial policy impetus, (b) the knowledge and capability that producers bring to bear on the problem of having to respond to a changed production environment, (c) the physical technical changes producers actually implemented and (d) the change in the SO2 intensity of production rendered by those physical changes. Measuring the dependent variable this way corresponds with the last element of Figure 1, the change in the SO2 intensity of production undergone by each plant. Different types and quantities of technical knowledge become independent variables explaining that outcome, alongside technical changes implemented by the plant.

To be concrete, values for the SO2 intensity of output are first calculated for each plant-year as tons of SO2 emitted divided by megawatt hours (mWh) of electricity generated. Intensity in 1997 is then subtracted from intensity in 2001 to arrive at a change-in-intensity value for each plant *i*:

$$Change_i = \left(\frac{\text{Tons SO2}_{2001}}{\text{mWh electricity}_{2001}}\right) - \left(\frac{\text{Tons SO2}_{1997}}{\text{mWh electricity}_{1997}}\right)$$

This gives change-in-intensity values ranging from -62.5 to 25.7 pounds of SO2 per mWh. Notice that the values range from negative to positive. This negative to positive range shows that technological change with respect to SO2 was not unidirectional. Technological change which *saved* SO2 occurred at the majority of plants but technological change which *augmented* SO2 occurred at others. About 63 per cent of plants in the sample underwent SO2-*saving* technological change. Negative values denote SO2-*saving* technological change. Any independent variable that associates with a decrease in the dependent variable means that that variable contributes to more SO2-*saving* technological change (over the range of negative values) or less SO2-*augmenting* technological change (over the range of positive values). Independent variables with negative coefficients are exerting an effect that is 'good' for the environment.

The dependent variable is also calculated a second way. It is also calculated as the *average annual growth in SO2 intensity of electricity production over the period 1997 to 2001*. This is calculated as a per cent for each plant. This measure is also consistent with the framework in Figure 1 since what is being measured is the extent of change away from an initial state of production. Whereas the first version of the dependent variable expresses the extent of change away from an initial state of production in SO2 intensity units, this version expresses the extent of change away from an initial state of production as an annual growth rate averaged over the years in the study period.

Generally, an average annual growth for can be calculated as:

$$Y_t = (1 + growth)^{x} \cdot Y_{t-x}$$

where Y_t is output in the final period, Y_{t-x} is output in the initial period, *growth* is the average annual growth rate of interest, and *x* is the number of time periods. Adapting this general growth equation to the technological change outcome of interest here, growth in emission intensity over time, gives:

$$Y_{i\,(2001)} = (1+growth_i)^4 \cdot Y_{i\,(1997)}$$

where $Y_{i\,(2001)}$ is final year intensity for each plant *i, growth* is the plant-specific growth rate in SO2 intensity of interest, the exponent is the length of the study period in years, and $Y_{i\,(1997)}$ is SO2 intensity in the initial year for each plant.

This average annual growth rate in SO2 intensity is calculated for each plant in the sample. As before, the range of final values extends from negative values implying SO2-*saving* technological change, to positive values implying SO2-*augmenting* change. The calculation is illustrated here with initial and final SO2 intensity values for a hypothetical plant. The growth rate for this hypothetical plant is sensitive to the central tendency measure of the initial and final intensity values. The modal initial intensity value in the sample is about 3.335 tons of SO2 per mWh. The modal final intensity value is about 3.940. Plugging in these values gives an annual average growth rate which is positive:

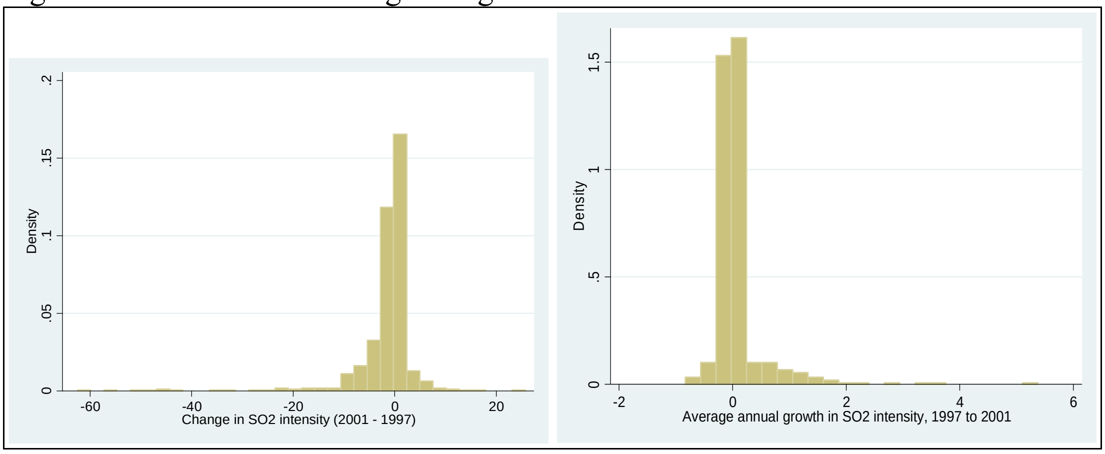
$$3.940_{\,(2001)} = (1 + g)^{4} \cdot 3.335_{\,(1997)}$$
$$g = .0426$$

This means that SO2 intensity at this hypothetical plant grew by 4.26 per cent on average during the study period. The growth rate is negative when calculated from initial and final intensities derived from other central tendency measures. Calculating the average annual growth rate from the mean initial intensity value and the mean final intensity value (10.214 and 8.467 respectively) gives -.0459 for an average annual growth rate of -4.59 per cent. For this hypothetical plant, by contrast, emission intensity did not grow as before but contracted. The calculation can also be performed on the basis of the median initial intensity and the median final intensity (7.710 and 6.568 respectively). By this measure the average annual growth rate for a hypothetical plant with these characteristics is -.0396 for an average annual growth rate which is again negative, of -3.96 per cent. These differences derive from a degree of skewness in the data, discussed below.

The analysis above describes how the intensity growth rate can be calculated for a single hypothetical representative plant. Table 3 below by contrast gives descriptive statistics for intensity growth calculated for all plants together in the sample. Table 3 gives the mean intensity growth rate for this variable as 7.87 per cent. This is based on the mean annual average growth rate as calculated immediately above for all plants in the sample. That figure is the *average of the average annual growth rate* for all plants. The average annual growth rate for each plant *i* is calculated from its own plant-specific initial and final intensity values, then the average of those growth rates is presented as the mean for the variable in Table 3 (Table 3 is given at the end of the next subsection).

Figure 4 gives distributions for both versions of the dependent variable. The spread of the values around zero shows again that technological change across plants relative to the initial state of production was not unidirectional. Plants underwent both SO2-saving and SO2-augmenting change. Again, negative values in either version of the dependent variable are 'good' for the environment. Both versions show signs of skewness but this skewness lies in different directions according to the dependent variable measure. The change-in-intensity measure is skewed by the relatively few plants that reduced their SO2 intensity by over 20 pounds per mWh. The growth measure is skewed by a few plants with average annual SO2 intensity growth of over 200 per cent. Table 3 gives skewness statistics. The regression estimates to follow deal with these outlying values in different ways.

Figure 4: Distribution of change and growth measures



Note: The measures of the extent of technological change with respect to SO2 are skewed in opposite directions. The left panel shows outliers beyond -20 (fewer pounds SO2 per mWh). The right panel shows outliers beyond two (an annual average growth rate in intensity of 200 per cent or more).

The plant is the unit of observation in the regressions. The dependent variable is the extent of technological change undergone by the plant with respect to SO2 over the study period 1997 – 2001. The dataset has a cross-sectional structure. The estimation method is OLS. The two dependent variable versions are separately estimated by the reduced-form equation:

$$D_i = \alpha + \beta \mathbf{K'}_i + \beta \mathbf{A'}_i + \beta \mathbf{C'}_i + \varepsilon_i$$

where i denotes the plant, α is the intercept interpretable as the value of the dependent variable D when all independent variables are zero, and ε is a classical error term. The variables in vectors ***K'*** and ***A'*** are the variables of main interest. The variables in vector ***K'*** relate to the quantity and type of technical knowledge available to each plant. The variables in vector ***A'*** relate to the compliance-related methods and techniques implemented by the plant, such as switching to cleaner fuels and scrubbing. The variables in vector ***C'*** control for plant-level characteristics. All independent variables are discussed in the next subsection.

In the regressions, the knowledge variables and the compliance technique variables are included additively in the single model. Recall the schematic description of emission-saving technological change in Section 2 above. That diagram showed technical knowledge and abatement techniques in separate columns, both leading to a productivity change outcome with respect to SO2. The regressions to follow treat those groups of variables as if they shared a single column that mediates the relationship between the policy impetus and the technological change outcome. The knowledge and compliance technique variables are here treated together in this way because the aim of the hypothesis is to test the effect of different knowledge types separately from one another, and to test the comparative effect of frontier knowledge against knowledge-unintensive abatement strategies. Testing the effect of each individual variable separately in this way makes a test of this hypothesis possible. This approach also follows other empirical research that has sought to estimate the technological change effect of pure knowledge (Peri 2005; Popp 2001; Popp 2002; Sue Wing 2006).

b. Independent variables

There are two variables in the first group ***K'***, the *environmental knowledge stock* and the *ordinary knowledge stock* available to the plant over the study period. The knowledge stock available to each plant *i* is calculated from environmental R&D expenditure and all other ordinary R&D expenditure performed at the level of the utility during the period 1990 - 2001. R&D expenditure is a proxy for frontier knowledge creation. The data come from mandatory reports made by US electric utilities to the Federal Energy Regulatory Commission (FERC) on FERC Form 1. FERC Form 1 defines R&D spending as:

> … costs incurred and accounts charged during the year for technological research, development, and demonstration (R, D &D) projects initiated, continued or concluded during the year… [as well as] support given to others during the year for jointly-sponsored projects … (FERC 2010: 352)

One of the subcategories on the reporting form for reporting R&D expenditure is 'Environment'. The stock of 'environmental' knowledge is calculated from all R&D expenditure falling into this category. The stock of 'ordinary' knowledge is calculated from all remaining R&D expenditure falling into all the other categories combined, which include 'Generation', 'Transmission', 'Distribution', 'Regional Transmission & Market Operation', and 'Other'. The original R&D expenditure figures are adjusted for inflation using the US Bureau of Labor Statistics' Producer Price Index for Utilities.

These variables are calculated as stocks rather than flows because it is not realistic to think about the amount of knowledge available to a plant as disappearing at the end of each year. It is more realistic to think of the ideas gained from R&D carried out in past years as being available to the plant or utility in the current year. Stocks are calculated by the perpetual inventory method where most of the knowledge created through R&D in one year carries over to the next year, so that most knowledge accumulates over time (Nadiri and Prucha 1993). Since knowledge also tends to lose its relevance over time, the stock of knowledge retained from a previous year depreciates in each subsequent year at a fixed rate of ten per cent following Popp (2010). This means that if the depreciation rate is ten per cent then only 90 per cent of the stock in year t carries over to year $t+1$.

Stocks are calculated not just from the R&D performed in the years 1997 - 2001 but also from the R&D performed in all years back to 1990. From 1990 is when plants and utilities could reasonably have been expected to begin to invest in R&D to respond to the new SO2 control requirements under the entirely new form of regulation ushered in by Title IV. Constructing stocks from the starting point of 1990 does not assume that plants were devoid of initial knowledge stocks gained through R&D performed prior to 1990. Rather, constructing stocks from 1990 assumes that the R&D performed prior to 1990 yielded a characteristically different kind of knowledge that was geared toward helping the plant comply with a different set of regulatory requirements under an entirely different regulatory regime (Reitze 2001; Taylor 2001; Kemp 1997). It assumes that it was the R&D performed in the post-1990 years that was most relevant and useful to the task of reducing the SO2 emissions under cap and trade.

The environmental and ordinary knowledge stock variables are expected to perform in the model in line with the findings from the literature in Section 2, and in line with the industrial change process that was shown in Section 4 to have facilitated productivity improvements in electricity production with respect to SO2 at plant level. These variables are expected to perform in line with the hypothesis tested in this paper, restated here:

When market forces are left to decide how technological change with respect to pollution emissions proceeds, frontier technical knowledge for the purpose of environmental protection tends to play a small role in that process while knowledge for all other 'ordinary' purposes plays a bigger role, and pre-existing methods and techniques for reducing emissions that involve little or no new frontier knowledge at all play the dominant role.

The second group of independent variables ***A'*** captures compliance-related changes the plants made in response to the new emission constraint, including methods and techniques that were relatively unintensive in frontier knowledge and technology.

The variable *total scrubber operating hours* captures the extent to which a plant dealt with its SO2 emissions under the Programme by scrubbing. The variable is measured as the total number of operating hours over all years in the study period of all scrubber units at the plant combined, in thousands of hours. More scrubbing should reduce SO2 emissions, giving a negative coefficient.

Change in coal sulphur content measures the extent to which plants chose to burn lower sulphur coal. This variable measures the difference between the per cent sulphur content of coal in 1997 and the per cent sulphur content of coal in 2001. If sulphur content was lower in 2001 then the difference is positive. It is expected that the larger the difference, the less SO2 emitted. The variable should take a negative coefficient.

Change in coal consumption measures the extent to which a plant chose to burn less coal altogether. It may have burned natural gas or petroleum in its place for example. This variable is measured as the difference between total coal consumption in 1997 and 2001. If coal consumption was lower in 2001 then the difference is positive. The larger the difference, the less SO2 emitted. This variable should take a negative coefficient.

Expand clean capital stock captures the extent to which plants built new gas-fired generation units to produce electricity in place of coal-fired generation units. This variable is measured as the proportion of all new boiler units built at the plant whose primary fuel was gas. A larger proportion of clean capital stock should reduce SO2 intensity of electricity production. The expected sign is negative.

Use or buy allowances (WA) is the extent to which a plant used or bought emission permits to comply with its obligations under the Programme. Greater use of permits should substitute for physical production method changes. Using allowances equates roughly to the right to emit SO2. Greater use of permits should associate positively with the dependent variable.

Repower with clean coal (RP) is the extent to which a plant installed clean coal technology to deal with its obligations under the Programme. A negative coefficient is expected.

The variables *repower with clean coal (RP)* and *use or buy allowances (WA)* are measured with the compliance method data the plants reported on EIA-767, summarised in Table 1 above. These variables are not measured as dummies. Recall that a given plant often operates several generation units. These two variables are measured as the proportion of generation units in a plant for which a specific compliance strategy was declared, over all the study years. For example, if a plant comprised of ten generation units then it had ten opportunities to declare 'WA' in each year. Over the five years in the study period the plant had the chance to make 50 declarations. If the plant reported 'WA' as the compliance strategy for 25 of the 50 unit-years, then the value for the *use or buy allowances (WA)* for that plant was 0.5. These variables are measured as proportions. The values do not exceed one.

Table 3: Descriptive statistics

Variable	N	Mean	Min	Max	p50	p25	p75	S.D.	Variance	Skewness
Change in SO2 intensity, 2001 - 1997	589	-1.730	-62.500	25.700	-0.396	-2.110	0.065	6.480	42.000	-4.530
Growth in SO2 intensity, 1997 to 2001	589	0.079	-0.833	5.375	-0.017	-0.058	0.023	0.474	0.224	5.300
Ordinary knowledge stock	540	0.821	0.000	119.826	0.000	0.000	0.000	6.876	47.285	12.813
Environmental knowledge stock	540	0.017	0.000	4.940	0.000	0.000	0.000	0.269	0.072	16.218
Scrub: total FGD operating hours	540	2.552	0.000	38.450	0.000	0.000	0.000	6.351	40.332	2.793
Burn cleaner fuels: change in coal sulphur content	540	0.043	-0.985	2.544	0.000	-0.007	0.044	0.252	0.063	4.557
Burn less coal: change in coal consumption	540	0.099	-1.562	2.060	0.000	0.000	0.160	0.345	0.119	0.943
Expand clean capital stock: proportion new boilers gas	540	0.001	0.000	0.200	0.000	0.000	0.000	0.014	0.000	13.538
Use or buy allowances (WA)	540	0.415	0.000	1.000	0.438	0.000	0.714	0.374	0.140	0.312
Repower with clean coal (RP)	540	0.137	0.000	1.000	0.000	0.000	0.250	0.257	0.066	6.726
Initial plant SO2 intensity, 1997	540	10.214	0.003	74.494	7.710	0.610	15.138	11.163	124.619	2.015
Plant vintage: mean boiler in-service year	540	1966	1940	1996	1965	1958	1974	10.330	106.710	0.284
Initial capital mix: proportion boilers gas	540	0.303	0.000	1.000	0.000	0.000	1.000	0.443	0.196	0.855
Plant scale: total generation capacity	540	8.226	0.659	39.534	5.977	2.868	11.959	6.878	47.313	1.348

The third group of independent variables ***C'*** controls for plant-level characteristics. Perhaps the most important among these is *initial starting SO2 intensity in 1997*. Controlling for starting SO2 intensity means that the other independent variables in the model are more likely to pick up the extent of the change in SO2 intensity actually undergone, rather than the variation in the initial starting point SO2 intensity of the plant.

Plant vintage is the average year that all generation units at the plant came into service. This controls for the possibility that older plants contributed less to the change in SO2 intensity because of the way they were constructed or because they were less adaptable than newer plants.

Initial capital mix captures the extent to which the initial capital stock at the plant was already clean and therefore may not have needed to undergo a change in SO2 intensity, or was not able to undergo this change. This is measured as the proportion of boilers at the plant in the initial year fired primarily by gas.

Plant scale is the maximum plant generation capacity measured in megawatts. This controls for the scale of electricity production at the plant on the idea that larger plants may have been able to undergo more technological change.

Descriptive statistics for all variables are given in Table 3.

c. Data

The model is estimated at the level of the plant because technical knowledge is expected to accumulate and come to be applied at this level, rather than at the lower level of the generation unit or the higher level of the utility. This is because a plant's method of producing electricity conforms to location-specific factors: the degree of urban congestion; local electricity demand and load characteristics; local, state and Federal laws controlling the disposal of solid waste; sensitivity to down time; and restrictions on emissions of other regulated pollutants. These factors shape the way that a plant goes about producing electricity and in turn its emissions profile (National Acid Precipitation Assessment Program 1989). Plant-level analysis also follows precedents in studies of technological change in the US electric power sector, for example Yaisawarng and Klein (1994), Popp (2006) and Taylor (2001).

Data come from the EIA and the EPA and are drawn from the full population of steam-electric power plants in the US with a total organic or nuclear-fuelled steam electric generator rating of 10mW or greater, for all years 1997 - 2001. The data mainly come from EIA form 767, as discussed in subsection 4 (a). The sample is defined to include all plants having at least one generation unit affected by the Programme in any year during the period. This includes plants with units that were voluntarily 'opted in' to the Programme (Reitze 2001; Schmalensee et al. 1998). All plants with generation units affected by the Programme were required to report their SO2 emissions to the EPA. EPA SO2 emissions data from EPA's Clean Air Markets database were matched to the EIA data. The final dataset comprises 662 unique plants. Missing values reduce the number of usable observations to 540. There is no observable pattern in the missing observations.

d. Linear regressions

The functional form of the model is linear throughout because there is no strong theoretical reason to expect the extent of the change in SO2 intensity undergone by the plants to have been influenced non-linearly by frontier knowledge or by any other explanatory factor. Table 4 gives the regression results for the first version of the dependent variable, which is measured as 'change' in intensity. Specification (1) estimates the model by OLS with errors clustered on the utility company owners of the plants. Errors are clustered on utility companies because utilities frequently operate more than one plant in the sample. Specification (2) gives standardized coefficients. Standardized coefficients make is possible to interpret the magnitude of the effect of each independent variable on the change in intensity undergone, relative to the magnitude of the effect of the other independent variables. This is important for testing the idea that the knowledge variables exerted a weaker influence on the change in SO2 intensity than methods and techniques involving little frontier knowledge.[19]

[19] One purpose of the estimations is to compare the effect of pure knowledge-related variables on pollution productivity relative to the effect of knowledge-unintensive abatement techniques on the same. One way to implement this comparison would be to introduce blocks of explanatory variables in sequential specifications and compare the R-square value across specifications. This approach was experimented with. It was decided that any specification that included only one block of variables would be fundamentally mis-specified and that this would have rendered comparison of the coefficients or the R-square values not meaningful. Instead, the standardized coefficient approach was adopted. The standardized coefficient approach makes it possible to decompose the dependent variable variance across pure knowledge and knowledge unintensive abatement techniques within a fully specified model including controls, and in a way that is employs a well-established technique.

Table 4: Regressions with change-in-intensity measure

VARIABLES	(1) Change	(2) Change
Ordinary knowledge stock	-0.0111*	-0.0117
	(0.00575)	
Environmental knowledge stock	0.386	0.0161
	(0.536)	
Scrub: FGD operating hours	-0.107***	-0.1053***
	(0.0326)	
Burn cleaner fuels: change in coal sulphur content	-11.01***	-0.4298***
	(1.774)	
Burn less coal: change in coal consumption	-0.453	-0.0243
	(0.388)	
Expand clean capital stock: proportion new boilers gas	-3.877	-0.0067
	(8.327)	
Use or buy allowances (WA)	1.436**	0.0828***
	(0.595)	
Repower with clean coal (RP)	0.391***	0.0813**
	(0.130)	
Initial plant SO2 intensity, 1997	-0.366***	-0.6264***
	(0.0839)	
Plant vintage: mean boiler in-service year	-0.0583**	-0.0924***
	(0.0241)	
Initial capital mix: proportion boilers gas	-3.393***	-0.2313***
	(1.161)	
Plant scale: total generation capacity	0.00652	0.0069
	(0.0277)	
Constant	117.7**	
	(48.06)	
Observations	540	540
Adjusted R-Square	0.621	0.621

Note: Dependent variable is change in SO2 intensity (2001 – 1997). Specification (1) gives OLS estimates with standard errors clustered on utilities, (2) gives standardized coefficients. Shading delineates the three blocks of variables: frontier knowledge stocks, knowledge-unintensive methods and techniques, and initial plant characteristics. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. An F-test rejects the null of joint significance of zero at $p<0.01$ in both specifications (test values: 23.70 (specification 1), 71.99 (specification 2)).

In specification (2), notice that the standardized coefficients on the frontier knowledge stock variables are quite small relative to the coefficients on the variables capturing the effect of knowledge-unintensive compliance methods and techniques. For example, a one standard deviation increase in *ordinary knowledge stock* associates with a .011 pound decrease in SO2 emitted per mWh of electricity generated on average. But a one standard deviation increase in *change in sulphur content of coal* associates with a .429 pound decrease per mWh on average. The effect of *change in sulphur content of coal* is 39 times stronger than the effect of the ordinary knowledge stock. The standardized coefficients on the knowledge stock variables are smaller than five out of six variables capturing knowledge-unintensive methods and techniques. The standardized coefficients on the frontier knowledge stock variables are also smaller than three out of four of the initial plant characteristic control variables. This implies that frontier knowledge tended to have a weaker effect on the change in SO2 intensity undergone by plants on average than relatively knowledge-unintensive control methods and techniques. It also implies that frontier knowledge had a weaker effect on the change in SO2 intensity undergone by plants on average than the plants' own initial technical characteristics.

The substantive interpretation of the effect of the knowledge stock variables in specification (1) is also of interest. These also implement the hypothesis test. *Ordinary knowledge stock* associates negatively with the change in SO2 intensity. It is weakly significant at the ten per cent level. Since the dependent variable encompasses positive and negative values reflecting SO2-augmenting and SO2-saving technological change respectively, this implies that more ordinary knowledge led to either less SO2-augmenting technological change or more SO2-saving technological change, and in either case an environmentally beneficial outcome. Ordinary knowledge was expected to exert this effect. Specifically, the coefficient of -0.011 implies that a one million dollar increase in the stock of ordinary knowledge associates with a change in the SO2 intensity of electricity production of -0.011 pounds/mWh on average, holding all other variables in the model constant. For comparison the mean change in SO2 intensity for all plants in the sample was -1.730 pounds/mWh as in Table 3. Note also in specification (1) that the coefficient on *environmental knowledge stock* is positive. This was not the expected effect, but the significance level is such that frontier environmental knowledge is interpreted to have an ambiguous impact. The analysis returns to this variable below.

Also in specification (1) above, substantive interpretation of the knowledge-unintensive methods and techniques undertaken by the plant is also of interest. Scrubbing, burning cleaner coal, burning less coal, and expanding the stock of clean production capital all give negative coefficients as expected. This means that each of these variables associates with either less SO2-augmenting or more SO2-saving technological change. The discussion in the last section found a good deal of evidence to support the idea that one of the most important methods of compliance for plants' operators under the Programme involved the relatively technologically unsophisticated method of switching to burning lower-sulphur coal. The coefficient on *change in sulphur content of coal* in specification (1) corroborates that evidence. The coefficient on this variable is negative and strongly significant. It implies that the greater the difference between the mean per cent sulphur content of coal burned in 1997 and the mean per cent sulphur content of coal burned in 2001, the more environmentally-favourable technological change took place. Specifically, the coefficient of -11.011 implies that a one per cent increase in the change in the sulphur content of coal associates with a change in the SO2 intensity of electricity production of -11.011 pounds/mWh on average, holding everything else constant.

Several of the variables capturing knowledge unintensive methods and techniques did not involve very much physical technical change at all. In specification (1) the variables *use or buy allowances (WA)* and *repower with clean coal (RP)* both associate positively with the dependent variable. The positive sign on *use or buy allowances* implies that plants that purchased and used more SO2 emission permits underwent either less SO2-saving technological change or more SO2-augmenting technological change on average. This was expected, because an allowance is akin to the 'right' to continue to emit SO2.

However, the variable *repower with clean coal (RP)* does not give the expected negative sign. This is the only variable in the model with a significant coefficient taking an unexpected sign. Installing clean coal technology would be expected to reduce SO2 intensity in practice but the coefficient of 0.391 implies that a one per cent increase in the proportion of generation units in a plant repowering with clean coal associates with an *increase* in the SO2 intensity of production of .391 pounds/mWh. What is unexpected in this estimate is the suggestion that clean coal technology associates with environmentally *un*favourable change.

The explanation for this probably lies in the wording of the relevant question on the EIA-767 survey questionnaire. Recall that this variable measures the proportion of 'declarations' by a plant that it was complying with the Programme by repowering some or all of its generation units with clean coal technology. The best explanation for the unexpected sign is that very dirty and out-of-compliance plants reported that it was their *intention* to comply with the Programme by installing clean coal technology, but in *actuality* they had not yet installed the technology at the time of reporting. This would lead to the variable associating with the plants' unchanged state of production. The wording of the question on the EIA-767 survey questionnaire corroborates this explanation.[20]

The third group of variables in specification (1) includes variables controlling for initial plant characteristics. These variables perform as expected. Higher initial SO2 intensity in 1997 at the plant, newer plant vintage, and a higher initial endowment of clean capital stock all associate with a reduction in SO2 intensity on average, all else being equal. The scale of the plant as measured by generation capacity associates with a shift toward slightly greater SO2 intensity.

Departing now from the change-in-intensity version of the dependent variable, Table 5 below gives the regression results when the dependent variable is measured by the second method, as average annual growth in intensity, for comparison. These estimates

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[20] The wording: 'Select the existing *and/or planned strategies* to meet the sulfur dioxide requirements of Title IV of the Clean Air Act Amendment of 1990' [emphasis added] (US DOE 1995).

use the growth-in-intensity version of the dependent variable. The regressions in Table 5 include all the same independent variables as before with one exception. Specification (1) estimates parameters for all independent variables that were in the model in the last set of regressions. Specifications (2) – (4) drop the initial capital mix variable, as discussed below. In specification (2) significance levels are based on non-clustered errors. In specification (3) significance levels are based on errors clustered on utility groups. Specification (4) gives standardized coefficients.

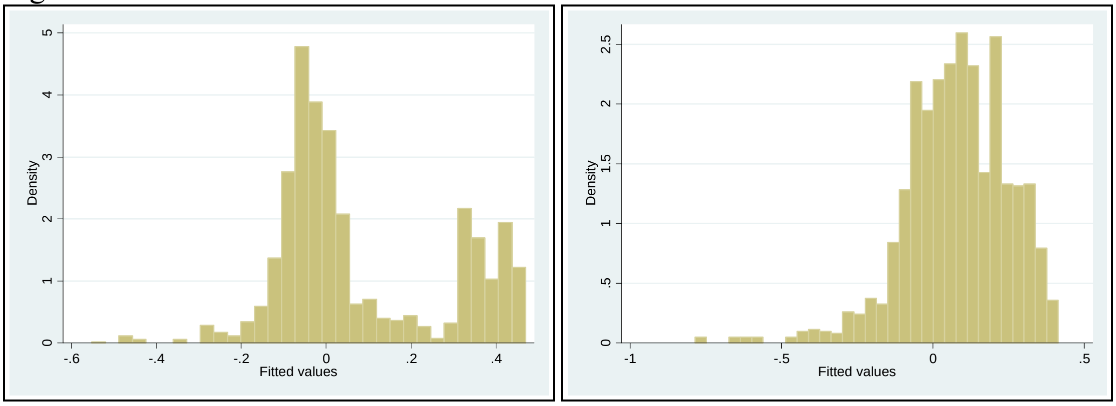
Table 5: Regressions with growth measure

VARIABLES	(1) growth	(2) growth	(3) growth	(4) growth
Ordinary knowledge stock	-0.00205	-0.00163	-0.00163*	-0.0236
	(0.00286)	(0.00294)	(0.000874)	
Environmental knowledge stock	-0.0402	-0.0367	-0.0367***	-0.0209
	(0.0776)	(0.0799)	(0.0133)	
Scrub: FGD operating hours	-0.00170	-0.00651*	-0.00651***	-0.0874*
	(0.00340)	(0.00338)	(0.00172)	
Burn cleaner fuels: change in coal sulphur content	-0.0921	-0.0250	-0.0250	-0.0133
	(0.0813)	(0.0828)	(0.0378)	
Burn less coal: change in coal consumption	-0.00734	-0.0345	-0.0345*	-0.0253
	(0.0559)	(0.0573)	(0.0198)	
Expand clean capital stock: proportion new boilers gas	-2.450	-1.867	-1.867***	-0.0441
	(1.982)	(2.036)	(0.717)	
Use or buy allowances (WA)	0.104**	0.128**	0.128	0.1010**
	(0.0505)	(0.0518)	(0.0890)	
Repower with clean coal (RP)	0.0110	0.00995	0.00995*	0.0283
	(0.0174)	(0.0179)	(0.00548)	
Initial plant SO2 intensity, 1997	-0.00503**	-0.0131***	-0.0131***	-0.3072***
	(0.00236)	(0.00193)	(0.00281)	
Plant vintage: mean boiler in-service year	-0.00198	-0.00526**	-0.00526**	-0.1140**
	(0.00218)	(0.00216)	(0.00209)	
Initial capital mix: proportion boilers gas	0.324***			
	(0.0572)			
Plant scale: total generation capacity	-0.00128	-0.00194	-0.00194	-0.0282
	(0.00300)	(0.00309)	(0.00190)	
Constant	3.906	10.54**	10.54**	
	(4.283)	(4.240)	(4.132)	
Observations	540	540	540	540
Adjusted R-square	0.179	0.129	0.129	0.129

Note: Dependent variable is annual average growth in SO2 intensity over the period 1997 to 2001. Specification (1) gives OLS estimates with standard errors in parentheses, (2) gives non-clustered standard errors, (3) gives errors clustered on utilities, (4) gives standardized coefficients. Shading denotes the three blocks of variables: frontier knowledge, knowledge-unintensive methods and techniques, and plant-level controls. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. An F-test rejects the null of joint significance of zero at $p<0.01$ in all specifications (test values: 9.58, 7.11, 7.20 and 7.11 for specifications 1 – 4 respectively.

The reason for dropping *initial capital mix* from specifications (2) – (4) is as follows. In specification (1) all the plant characteristic controls give the same signs as before, with one exception. *Initial capital mix* takes an unexpectedly positive sign. This variable measures the proportion of generation units at the plant primarily fired by gas in 1997. The positive sign implies that the more clean generation capacity the plant had in its initial capital mix in 1997, the less SO2-saving or the more SO2-augmenting change it underwent. This relationship is unlikely and unexpected. When this variable is dropped from the model, and under clustered errors, every independent variable coefficient in the model retains its same sign; but *ordinary knowledge stock* becomes significant at the ten per cent level, *environmental knowledge stock* becomes significant at the one per cent level, the scrubbing variable becomes significant at the one per cent level, and *plant vintage* becomes significant at the one per cent level. *Initial capital mix* is dropped from the model in specifications (2) – (4) *not* because it gives an unexpected sign, and *not* because omitting it raises the t-scores on these other variables. It is dropped because omitting this variable considerably improves the normality of the distribution of the residuals.

Figure 5: Residuals



Note: A comparison of growth-in-intensity model residuals with (left) and without (right) the initial capital intensity variable.

The bimodal distribution in the left panel when *initial capital mix* is in the model is only a characteristic of the residuals when the dependent variable is measured as growth, as in Table 5. When the dependent variable is measured as change-in-intensity as in Table 4, the residuals give a much more normal distribution regardless of whether *initial capital mix* is included in the model or not. This is not an 'omission of convenience' but an omission to correct an otherwise questionable specification. Specification (1) of Table 5 gives estimates when this variable is not omitted for comparison.

In Table 5 above, *ordinary knowledge stock* and *environmental knowledge stock* take negative signs in all specifications (1) – (4) implying that greater access to either type of frontier knowledge associated, on average, with either more SO2-saving technological change or less SO2-augmenting technological change. Recall from the previous set of regressions that when the dependent variable was measured as change-in-intensity that only *ordinary knowledge stock* took a negative sign. In this set of regressions by contrast both ordinary knowledge and environmental knowledge are negative.

With respect to significance, the most appropriate test comes in specification (3) when the errors are clustered on utility group. Ordinary knowledge is weakly significant at the ten per cent level as before. Environmental knowledge is significant at the one per cent level whereas it was insignificant before. This is not expected. What is more, the coefficient on *environmental knowledge stock* in specification (3) implies that environmental knowledge had a much large effect on growth in emission intensity per dollar than ordinary knowledge. These coefficients imply that a one million dollar increase in environmental knowledge associates with a growth rate change of -3.67 per cent on average, all else being equal, but that a one million dollar increase in ordinary knowledge associates with a growth rate change of just -.16 per cent on average, with all other factors remaining constant. Keep in mind however the skewed distribution of the dependent variables and the fact that estimates in OLS could be particularly sensitive to outliers. Skewness and outliers are returned to below.

The magnitude of the effect of the knowledge stock variables can be compared to the magnitude of the effect of the knowledge unintensive methods and techniques in specification (4). In standardized units, ordinary knowledge actually exerts a stronger effect on average than environmental knowledge all else equal, whereas before with the unstandardized coefficients, ordinary knowledge exerted a weaker effect. The difference may be explained by ordinary knowledge having a larger range and standard deviation in substantive units, than environmental knowledge. The standardized coefficients imply that a one standard deviation increase in the stock of ordinary knowledge corresponds to a larger change in substantive 'stock' units (dollars) than the same one standard deviation increase in the environmental knowledge variable. Descriptive statistics in Table 3 illustrate these differences.

All of the compliance-related variables (shaded) performed as expected in specification (3) in Table 5. As before, more scrubbing, greater change in the sulphur of coal, greater change in the amount of coal consumed, and an increase in the clean capital stock, all associate with an environmentally favourable outcome as expected. The coefficient on *use or buy allowances (WA)* is positive as before. The coefficient on *repower with clean coal (RP)* is positive as before, probably for the same reason discussed above.

Observe that the magnitude of the impact of the knowledge-unintensive methods and techniques again tends to be stronger than the magnitude of the impact of the knowledge variables. For example, the standardized coefficients imply that a one standard deviation increase in scrubbing activity associates with a change in intensity-growth of -8.73 per cent while the same increase in the stock of either knowledge type associates with a change in intensity-growth of about -2.0 per cent. Fuel switching exerts a moderately strong effect in standardized terms. Coal consumption exerts a slightly stronger effect than either knowledge type in standardized terms. The addition of new clean capital stock leads to about twice as large a change in intensity growth as either knowledge type in standardized terms.

The plant characteristic control variables in specifications (2) – (4) perform as expected. Greater initial SO2 intensity, newer plants, and larger plants in terms of generation capacity, all associate with more SO2-saving or less SO2-augmenting change. The standardized coefficients imply that the magnitude of the effect of a one standard deviation increase in plant age was about five times stronger than the magnitude of the effect of either type of knowledge.

e. Robust and quantile regressions

The presence of outlier observations in both versions of the dependent variable could be giving misleading estimates. The histograms in Figure 4 and Table 3 showed that outliers tended to be negative for the change-in-intensity version of the dependent variable but positive for the growth-in-intensity version. The outliers are plants that underwent the very most SO2-saving or the very most SO2-augmenting change. These outliers could bias the estimates in the change-in-intensity regressions to imply that frontier knowledge stocks and/or knowledge unintensive techniques associate with larger reductions in SO2 intensity than they really do in truth. Table 6 summarises the nature of these outliers in both versions of the dependent variable, and in the predicted values from the models in Tables 4 and 5 above. Cook's D in particular measures the extent to which these outliers might unduly bias the estimates.

Table 6: Summary statistics for skewed residuals

	Change (DV)	Change (predicted)	Growth (DV)	Growth (predicted)
Cook's D (mean)	-	0.005	-	0.001
Cook's D (max)	-	0.826	-	0.294
Skewness	-4.431	-4.012	5.272	-0.864
Variance	50.529	25.746	0.214	0.029
Min	-62.495	-42.009	-0.833	-0.786
Mean	-1.957	-1.732	0.076	0.079
Max	25.700	7.888	5.375	0.414
1st decile	-3.013	-6.069	-0.131	-0.112

Cook's D combines information on the residual of every observation and the leverage of every observation in the model. The lowest possible value of Cook's D is zero. A value above one suggests that the observation is a gross outlier exerting very strong influence on the estimates. Notice that no observation in the predicted values from either model has a Cook's D that is larger than 1. This does not mean there are no outliers, only that there are no gross outliers by this indicator. Table 6 also shows that the change-in-intensity model fits better than the growth-in-intensity model in terms of skewness and variance, but in terms of the min, mean and first decile, the growth-in-intensity model fits better.

A crude solution to obtaining independent variable coefficients not unduly influenced by extreme values and skewness would be to drop the observations exhibiting extreme values and re-estimate. Besides the problem of biasing the estimates in other ways, this approach ignores the fact that observations with outlying values are actually of considerable interest in this context from a theoretical and policy point of view. The outlying negative observations in particular are the plants that underwent the very SO2-saving change. A better solution is to implement a robust regression to get around the potentially undue influence of outliers without actually omitting them. Robust regression de-weights outlying observations. It gives small weight to observations with a high Cook's D and large weight to observations with a low Cook's D. Extreme outliers with a Cook's D greater than one are dropped.

Robust regression estimates are given in Table 8 in the Appendix. In specification (1) of that table where the dependent variable is change-in-intensity, both ordinary and environmental knowledge give negative signs as expected. Neither is significant. All of the knowledge-unintensive method and technique variables in specification (1) take the expected signs. The plant characteristic control variables perform as expected. Not a great deal changes in specification (2) where the dependent variable growth-in-intensity is used. Ordinary knowledge associates positively but insignificantly. Environmental knowledge associates negatively and weakly significantly (ten per cent level). The environmental knowledge coefficient implies that a one million dollar increase in available environmental knowledge associates with a -1.98 per cent change in growth in intensity on average. This compares with a change of -3.67 per cent in specification (3) of Table 5 above, which is again the average effect across all plants in the sample.

Examination of the residuals from the robust regressions showed however that this approach was still not doing a good job of predicting the extent of SO2 intensity change undergone by the outlier plants. What would be useful is an estimation method that makes it possible to say something about the effect of the independent variables on the outlier values specifically. Ideally it would be possible to estimate the effect of the independent variables on a range of SO2 intensity change values throughout the distribution, without de-weighting or ignoring outlying cases.

Quantile regression makes it possible to distinguish the effect of an independent variable on any single quantile or any group of quantiles in the data (Hao and Naiman 2007; Koenker and Hallock 2000). Quantile regression estimates are more resistant to leverage from outlying observations partly because the effect of an outlier is 'contained' to the estimate for the quantile in which the outlying observation resides. That is, coefficient estimates are quantile-specific. Engles (1857) used quantile analysis to illustrate the relationship between working class household income and food expenditure. Quantile analysis for Engles overcame the problem that the least-squares regression line fitted to his data failed to predict food expenditure from household income with much accuracy for the households with the lowest incomes. For the poorest households, the mean relationship was misleading. Koenker and Hallock (2000) used quantile regression to analyse the birth weights of a large sample of new born babies in the US. Koenker and Hallock showed that the effect of the mother's age on the weight of the new-born baby was much stronger (positive) at the lowest quintile of the birth weight distribution than at the middle and upper quintiles. In neither of these examples would linear regression estimates of the mean conditional relationship between the dependent and independent variables have been suitable to capture the relationship of interest at the lower end of the distribution. Rather than estimating the change in the conditional *mean* that associates with a change in an independent variable, quantile regression estimates the change in the conditional *quantile* that associates with a change in an independent variable.

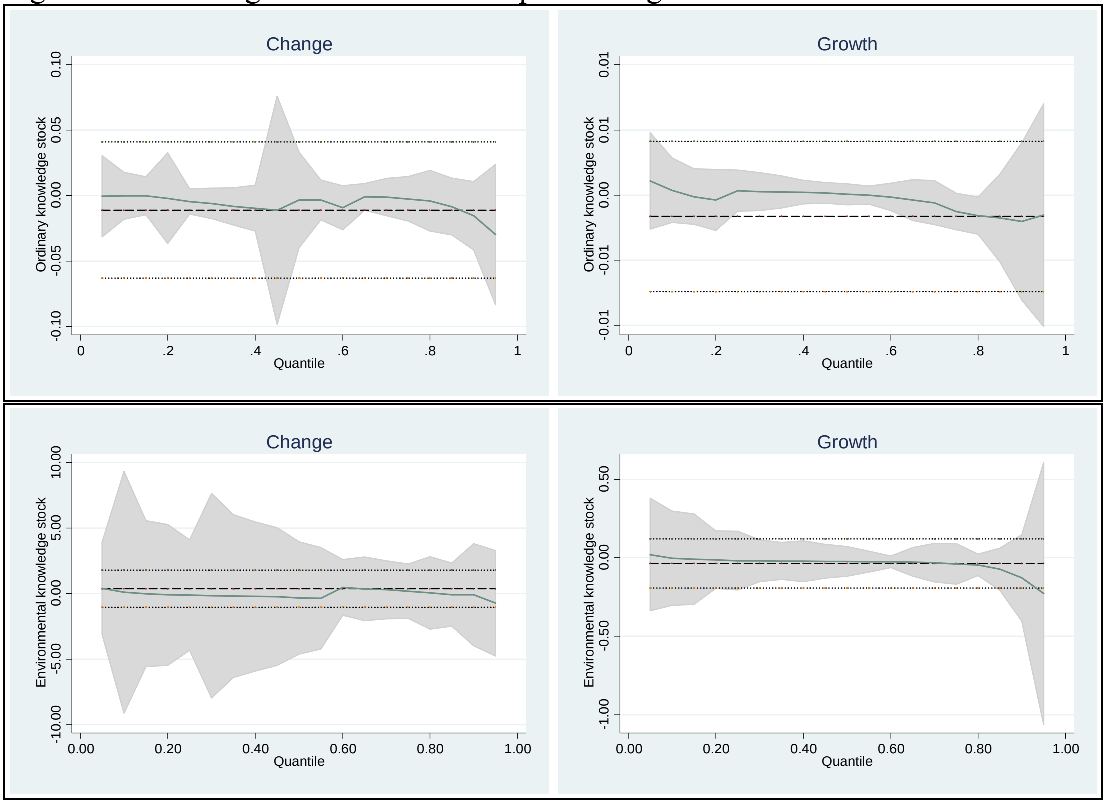
Tables 9 and 10 in the Appendix give quantile regression estimates for each of nine deciles in the present dataset, for the change-in-intensity and growth-in-intensity dependent variable versions respectively. Specifications (1) – (9) in those tables correspond to the first to the ninth deciles of the data. Significance levels are based on bootstrapped standard errors. The negative outliers flagged up above reside in the first decile.

The coefficients in Tables 9 and 10 are interpreted analogously to linear regression coefficients. The coefficient on the variable *change in sulphur content of coal* in the median regression in Table 9 specification (5) of -9.774 implies that a one unit change in this variable associates with a change in SO2 intensity *from the median* of -9.774 pounds per mWh. This compares to the estimate of the *mean* effect of scrubbing over the entire distribution given in the linear regressions in Table 4. There, a one unit increase in *change in sulphur content of coal* associated with a change in SO2 intensity of -11.011 pounds per mWh. The median estimate shows that the mean estimate was in fact being strongly influenced by the negative outliers. Outliers made the fuel switching variable look more influential than perhaps it really was. This has particular implications for the interpretation of the effect of the knowledge variables.

Figure 6 graphs all of the estimated decile coefficients for the two knowledge variables, for each version of the dependent variable. These coefficients are estimated in the same way as in Tables 9 and 10. Actual point estimates for each decile are given in those Tables. In each panel in Figure 5, the heavy dashed line is the mean linear regression estimate for the entire distribution. The light dashed lines are confidence intervals for the linear regression estimate. Of main interest is the curving line bounded by grey shading.

This line graphs all of the quantile regression coefficient point estimates by decile. The grey shading is the confidence interval. The y-axis gives the value of the coefficient at a given decile and the variable name.

Figure 6: Knowledge coefficients from quantile regressions



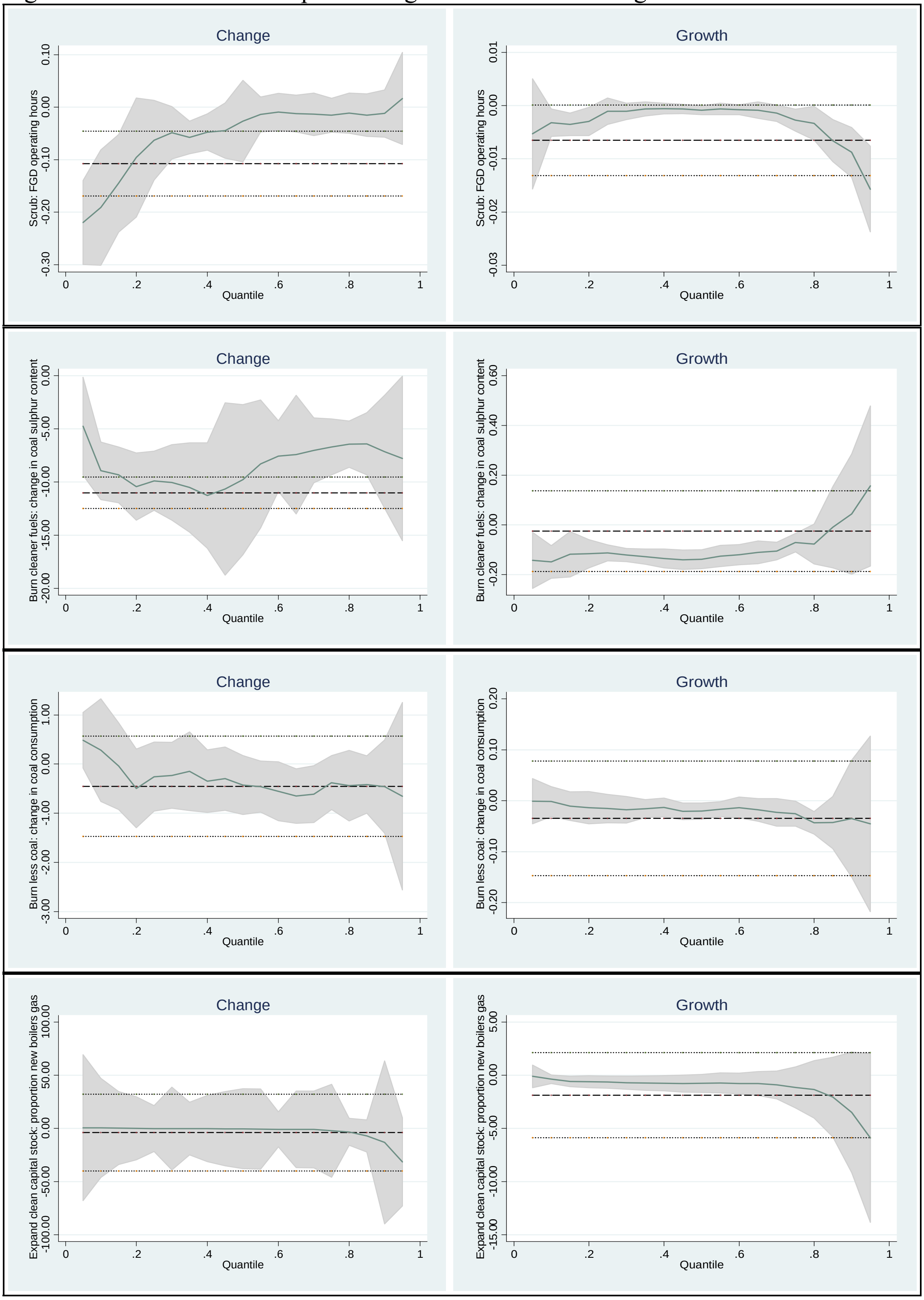
Note: In each panel the solid curving line is the estimated coefficient for the variable on the y-axis across quantiles. Grey shading indicates confidence intervals. Point estimates for each decile are given in Tables 9 and 10. The heavy dashed line is the linear regression estimate and the light dashed lines are confidence intervals.

There are some commonalities in the effect of the knowledge variables on the dependent variable across all four panels in Figure 6. First, the knowledge coefficients tend to be stable across deciles. This implies that the effect of knowledge on the change in SO2 intensity is not all that different for plants whose emission intensity dramatically improved (first decile) and for plants whose emission intensity dramatically deteriorated (tenth decile). The knowledge effect does not vary a great deal across deciles. What the four trends also have in common is that none of the point estimates are statistically significant, as seen in Tables 9 and 10. This is true for both types of frontier knowledge against both versions of the dependent variable. *That is, at no single decile of the data does quantile regression detect a statistically significant effect of frontier knowledge on change in SO2 intensity undergone, for either 'environmental' or 'ordinary' knowledge.* A further commonality across the four panels is that the point estimates tend to become more negative at higher deciles. This implies that the effect of frontier knowledge is weaker for plants that underwent the most SO2-saving technological change but stronger for the plants that either underwent little SO-saving change or which underwent SO2-augmenting change. This implies that the role of frontier knowledge may be to *reduce the extent of SO2 augmenting change that would otherwise have taken place*, rather than to deepen the extent of SO2-saving change that actually takes place.

Figure 7 below plots decile coefficients for the knowledge unintensive method and technique variables for comparison. These variables show much more variation across deciles in the strength of the effect they exerted on the dependent variable. Most are also consistently negative. Most are statistically significant at least at some deciles.

Reading across the change and growth dependent variables in Figure 7 shows that the strength of the effect of scrubbing might be shaped something like an inverted U. Scrubbing appears to have exerted a strong negative effect for the plants undergoing the deepest SO2-saving change, a moderate negative effect for the middle plants, and again a strong negative effect for the plants whose SO2 intensity increased. The effect of scrubbing is statistically significant across several deciles, as shown in Tables 9 and 10. This stands in sharp contrast to the effect of the knowledge variables in Figure 6. Also in contrast to the frontier knowledge variables, the coefficients on *change in sulphur content of coal* are always negative in the change-in-intensity quantile regressions and always, across every decile, strongly statistically significant (one per cent level). This holds largely true in the growth-in-intensity quantile regression, except that the effect of the variable becomes positive and statistically insignificant around the eighth decile, as shown below.

Figure 7: Coefficients from quantile regressions for knowledge unintensive methods



Note: As above, the solid line curving line gives quantile regression coefficients, grey shading denotes confidence intervals, the heavy dashed line is the linear regression coefficient, the light dashed lines are linear estimate confidence intervals.

Even the effect of the variable *change in coal consumption* is more consistently negative and more often statistically significant than the knowledge variables. The third row of graphs in Figure 7 above shows that the effect of this variable was negative across almost the entire range of deciles in both change and growth versions of the dependent variable. The increasingly negative effect across deciles implies that the strength of the effect of *change in coal consumption* was weaker for the plants undergoing the most SO2-saving change and stronger for the plants undergoing SO2-augmenting change. For this variable, the decile coefficients which are statistically significant tend to fall in the middle and upper deciles of the distribution. The knowledge variable coefficients by contrast were only variably negative and never statistically significant at any decile.

6. Analysis and contributions

This paper set out to investigate the role that frontier and other kinds of knowledge play in the kind of technological change that leads to greater productivity with respect to pollution emissions. It compared the role that frontier knowledge and technologies play in that change process, relative to the role that pre-existing, well-known, relatively knowledge-unintensive techniques play. From a critical reading of the literature it developed the hypothesis that under regulatory conditions that leave market forces to determine the kind of knowledge and technologies used to facilitate this change, such transitions might not be very ‘technological’. By this it meant that the factors that account for the biggest part of the change in the state of production with respect to pollution, the factors which account for the biggest productivity gains, are determined more by knowledge unintensive methods and techniques than by new ‘frontier’ knowledge and technologies. Insofar as frontier knowledge does play a role, knowledge originally intended for ‘ordinary’ purposes was expected to play a bigger role than knowledge originally intended for dedicated ‘environmental’ purposes.

This hypothesis was tested in the context of the change in SO2 intensity of electricity production undergone by US electric power plants under the SO2 cap and trade programme set up by the 1990 CAA Amendments. Methodologically, the SO2 cap and trade programme was chosen because it came as close as practically possible to penalising the pollution externality without influencing the technology choices of plant operators in how they went about dealing with that externality. Under cap and trade it was mainly market forces that shaped technology choice. Within this case context, and unusually for the environmental technological change literature, a mixed methods approach combining regression analysis with qualitative case evidence (interviews, government documents, research reports, policy analysis) was used. The evidence considered within this mixed methods framework tended to support the hypothesis.

This paper makes several contributions. One contribution is the multi-levelled understanding of knowledge in environmental technological change that this mixed methods approach made possible. The paper went beyond testing how knowledge and technology affect the change in emission intensity at plant level, which has been the single-level approach of many studies in this field (Bellas 1998; Carlson et al. 2000; Ellerman et al. 1997; Lange and Bellas 2005; Popp 2010; Yaisawarng and Klein 1994). This paper looked behind the plant-level responses to the considerable and unexpected changes that occurred in the upstream supply chain industries. This upstream analysis showed how plant operators' options for complying were influenced, if not framed by, production method changes in stereotypically 'dirty' supplier industries. These included changes to the design of coal-fired boilers by the boiler manufacturers, changes in the type of coal the coal mining industry mined, improvements in the techniques the coal mining industry used to harvest coal, and the up-scaling and extension of cross-country rail routes by the railroad industry. This paper with its multi-level analysis contributes a deeper and more complete understanding of the role of knowledge and technology in the plant-level response than would have been possible without recognising these supplier industry-level changes.

Another contribution of the multi-level analysis has been to show that knowledge and technologies not easily recognisable from the outset as having an environmental protection application, tended to influence the change in SO2 intensity even more strongly than knowledge and technologies intended for environmental protection. This idea was implemented quantitatively through an explicit test of the relative effect of 'environmental' and 'ordinary' knowledge types. The qualitative analysis illustrated several times how types of knowledge and technology that eventually became influential for dealing with SO2 emissions would have been very difficult to predict.

Consider the implication of this unpredictability. Recall the US Patent and Trademark Office's policy of advancing 'green technology' patents to the front of the cue in the patent approval process. The unpredictability identified in this study casts doubt on the idea that a patent examiner working at the USPTO in 1989 on the eve of the 1990 Clean Air Act Amendments, would have been able to recognise the potential for very cheap SO2 control in a patent application for a longwall coal seam shearer enlarged to perform a cut to a depth of 42 inches. The findings in this paper suggest that this is not a patent application that the patent examiner, keen to implement the procedures of the Green Technology Pilot Program, would likely have moved to the 'green technology' pile.

This suggests not just that programmes that try to identify and prioritise promising 'environmental' technologies can be ineffective at doing this. It also suggests that technology-picking programmes can actually retard the development of technologies that truly do, or will someday, have an environmental protection application, by delaying the award of intellectual property to what are perceived to be 'non-environmental' technologies, or by diverting scarce R&D resources away from these technologies. Without the analysis of the changes undergone in boiler manufacturing, coal mining, and railroad industries, it might not have been possible to see that the technical knowledge that becomes useful for environmental protection can be hard to identify at the outset.

This paper also contributes a detailed quantitative analysis of the frontier knowledge intensity of plant operators' compliance approaches to dealing with the cap and trade programme. The compliance strategy 'declarations' data, supported by utility employee interview material, found that plant operators tended to avoid frontier knowledge-intensive compliance strategies, like repowering with clean coal technology. Out of over 16,000 generation unit-year declarations examined in this paper, only one quarter of one per cent chose to repower with clean coal technology. Instead the great majority chose methods involving little or no new technical learning: 42 per cent used or bought emission allowances, 22 per cent made no change at all to the historic operation of the unit, and 19 per cent switched to lower sulphur fuels. This is consistent with the idea that the compliance strategies that involved the least technical learning saw the biggest uptake, while the strategies that involved the most technical learning saw the least uptake.

This is the first contribution to the environmental technological change literature to the knowledge of the author to therefore directly test the idea that frontier knowledge does not play the driving role in raising productivity levels with respect to pollution. If frontier knowledge has not been the big driver historically during this period, then it is worth looking at drivers that have been. This idea was tested statistically under OLS and then, to deal with high-leverage outlier observations, robust and quantile regression.

The change-in-intensity OLS regressions found that in standardized terms, the strength of the frontier knowledge effect was about eight times smaller than the allowance-using/buying effect, ten times smaller than the scrubbing effect, and 39 times smaller than the fuel switching effect. These effects were directionally consistent but less pronounced in magnitude in the growth-in-intensity regressions. In standardized terms, the effect of frontier knowledge was weaker than the effect of these pre-existing, relatively knowledge-unintensive techniques in 11 out of 12 instances.

Since outlier plants might have been biasing these mean estimates in OLS, robust regression was used to down-weight the effect of plants in the estimates whose SO2 intensity had dramatically increased or decreased. The robust estimates also found that burning cleaner coal, burning less coal, and expanding the clean capital stock all contributed to SO2-saving technological change with significance levels better than five per cent. The effect of frontier knowledge on SO2 intensity was insignificant in three out of four instances. But even the predictions from the robust regressions were not accurately predicting SO2 intensity change for the outlier plants.

Quantile regression was used to investigate how the effect of the independent variables in the model influenced SO2 intensity change across the full range of technological change outcomes in the data distribution. The graphs of the coefficients across this full range of outcomes showed that frontier knowledge increased the amount of environmentally-favourable technological change undergone across nearly the entire distribution. But, interestingly, pure frontier knowledge led to more environmentally-favourable change at the upper quantiles than at the lower quantiles. That is, *frontier knowledge of either type was more influential in reducing the amount of SO2-augmenting change undergone than it was in increasing the amount of SO2-saving change undergone*. Yet at the same time, at no decile of the distribution was this frontier knowledge effect statistically significant. Rather, the knowledge unintensive techniques were statistically significant across a range of deciles. In terms of explaining the observations that underwent the absolute most SO2-saving change, scrubbing appears to have been influential. In the change-in-intensity quantile regressions, scrubbing exerted a strong and significant effect at the lowest deciles of the distribution but a weaker and less significant effect at the upper deciles. This might be taken as evidence against the hypothesis, and as evidence that is inconsistent with the broader pattern found in this study, if this apparent discrepancy was not in fact explained away by EPA's extensive scrubber 'boosting' discussed at length in Section 4 (b). Regardless, the contribution of quantile regression has been to point-point the causes of these observations lying at the upper and lower ends of the distribution.

Future research looking at the comparative effect of advanced and unadvanced pollution control techniques on pollution productivity would do well to note the limitations of the estimation strategies employed in the regressions in this study. Although the test variables and control variables were carefully selected in line with theoretical expectations and constructed from the available data as carefully as possible, there is always the possibility that the observed relationships are attributable to endogeneity of these variables to the dependent variable, rather than to the substantive real-world relationship expected. Recall that the sample was defined to include every plant that had a boiler affected by the 1990 CAA Amendments. This sampling criterion means that frontier technical knowledge could have had a negligible effect on pollution productivity for the regulation-affected plants in the sample, but a large effect for regulation-unaffected plants. Frontier knowledge could have been the very force that kept regulation-unaffected plants out of the sample by reducing their pollution levels to the point that they were left unaffected by the 1990 Amendments.

Another estimation consideration is that the pollution abatement response of a plant manager with respect to technical knowledge may be multi-staged. This multi-staged response might be possible to represent econometrically. It is plausible to think that in the first stage a plant manager might take stock of its portfolio of potential technical options. The plant manager might inventory the plant's technical knowledge level. Based on this inventory the plant manager then selects a pollution abatement strategy. Plants rich in knowledge and capability might be more inclined to adopt advanced abatement methods while plants with limited knowledge and capability might be drawn toward unadvanced ones. This process could potentially be estimated by a two-stage estimation strategy using existing knowledge stocks in the first stage and chosen pollution abatement strategy in the second. This might show for example that advanced abatement strategies are not inherently uneconomical but simply that they are unviable for low-knowledge plants regardless of the economic benefits relatively advanced methods might promise.

Another important caveat to these findings is the relatively short time frame of the study period. The econometric analysis looked at the years between 1997 and 2001 only. While it is reasonable to conclude from these data that frontier knowledge and technologies did not play the driving role in the change in SO2 intensity during this period, it might not be prudent to generalize this finding to a cap and trade programme for GHGs for example, beyond the short to medium term. One could interpret these findings to say that low-technology approaches drive the transition in production methods away from GHG emission in the short to medium term, but once these approaches have been exhausted, higher-technology responses emerge to drive the transition in the longer term. This might especially be the case if mandated cuts to GHG emissions are deeper than cuts mandated to SO2 emissions have been. These deeper cuts might in time give rise to a bigger role for frontier knowledge of all kinds.

Another contribution of this paper is the finding that the 'knowledge richness' or 'technical learning burden' across compliance approaches is itself an important explanatory factor behind their variation in uptake. We already knew that low-cost abatement opportunities distinguish themselves from high-cost in part by being more plentiful and more accessible (Hanley, Shrogen and White 2006). The findings in this study imply that low-cost abatement opportunities are more plentiful and accessible in part *because* they entail less technical learning and knowledge-acquisition than high-cost opportunities. The learning burden embedded in the different opportunities is *itself* a cost and *itself* a reason why these opportunities locate in different places along the abatement cost curve.

These findings also suggest a new reason why the preponderance of studies concerned with the innovation effects of the different policy instrument types tend to find that 'market-based instruments induce the most innovation' (Jaffe, Newell and Stavins 2002; Vollebergh 2007). Market-based instruments may be the best policy choice for a range of reasons, but it does not appear from these findings that one of those reasons is that they reward the creation or application of frontier technical knowledge. *The big advantage of market-based instruments with respect to innovation, rather, seems to lie in the fact that they give firms the freedom to dismiss knowledge-intensive strategies in favour of well-known, well-tested techniques that do not involve a big technical learning burden.* Whether or not a policy induces firms to invest in R&D or adopt new-to-the-world technologies should be a less important evaluation criterion than it has been, at least in the literature debate. The real cost-saving benefit of market-based instruments appears to lie in part in letting polluters comply by whatever means they choose, knowledge intensive or otherwise.

When policymakers do find justification to boost or prescribe what they perceive to be pro-environment technologies, they should acknowledge that the most inexpensive technologies for reducing emission can come from the dirtiest industries and from supplier industries well upstream of the entities that are often directly beholden to regulation. If policymakers must stray from technology neutrality then they should try to work with whichever industries believe they have low-cost abatement technologies to offer, and let these industries inform the choice government takes to decide which technologies to boost. Programmes should focus on developing technological competence around grounded, pragmatic strategies. These might include fuel switching capability, multi-fuel capacity, modified combustion methods, supply chain related changes and other approaches identified by the industries themselves (Ogden, Podesta and Deutch 2008). This approach would be consistent with the finding in this study that when plant operators are not unduly influenced by the technology preferences of government, they tend to resist the 'environmental' technologies governments might have envisioned for them beforehand.

7. References

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8. Appendix

Table 7: Weighted compliance strategy declarations

	S1	S2	S3	All	All (%)	Rank	Weighted by heat input (%)	Rank	Weighted by SO2 (%)	Rank	Weighted by strategy primacy (%)	Rank
Decrease utilisation - designate phase II units as compensating units	0	7	21	28	0.17	14	0.00	14	0.00	14	0.08	14
Repower unit	13	7	22	42	0.25	13	0.02	12	0.00	12	0.17	12
Decrease utilisation - purchase power	0	21	22	43	0.26	12	0.00	13	0.00	13	0.14	13
Decrease utilisation - rely on energy conservation and/or improved unit efficiency	35	21	0	56	0.34	11	0.24	10	0.05	11	0.33	11
Control unit under Phase I extension plan	65	54	0	119	0.72	10	1.58	7	0.49	9	0.69	10
Install FGD unit	140	125	29	294	1.77	9	1.87	5	0.58	8	1.58	7
Transfer unit under Phase I extension plan	73	192	39	304	1.83	8	0.77	9	2.37	5	1.46	8
Decrease utilisation - designate sulphur-free generator(s) to compensate	76	159	73	308	1.85	7	0.09	11	0.22	10	1.40	9
Other	222	89	19	330	1.98	6	1.71	6	1.69	6	1.96	6
Designate Phase II unit(s) as subst. unit(s)	252	178	44	474	2.85	5	1.56	8	1.30	7	2.62	5
Not determined at this time	400	86	2	488	2.93	4	3.13	4	4.94	4	3.12	4
Switch to lower sulphur fuel	1,730	1,161	315	3,206	19.27	3	16.76	3	24.39	2	17.75	3
No change in historic operation of unit	3,184	587	41	3,812	22.92	2	26.67	2	16.79	3	24.42	2
Allocated and/or purchase allowances	5,436	1,518	175	7,129	42.86	1	45.60	1	47.18	1	44.27	1

Column titles above are interpreted as follows:

- ‘S1’, ‘S2’ and ‘S3’ give the number of compliance strategy declarations stated as the first, second and third strategies respectively.
- ‘All’ and ‘All (%)’ give the same data as in Table 1 on unweighted declarations.
- ‘Rank’ refers to the preceding column.
- ‘Weighted by heat input’: the weighting was performed by multiplying the number of compliance strategy declarations in each compliance strategy category by the per cent of the heat input that all generation units falling into that compliance strategy category accounted for.
- ‘Weighted by SO2 (%)’: the weighting was performed by multiplying the number of compliance strategy declarations in each compliance strategy category by the per cent of the SO2 emissions emitted by all generation units falling into that compliance strategy category.
- ‘Weighted by strategy primacy (%)’: the weighting was performed by multiplying the number of declarations in each compliance strategy category by .5 if the declaration was given as the ‘first’ strategy, .333 if it was given as a ‘second’ strategy, .166 if it was given as a ‘third’ strategy.

Table 8: Robust regression estimates

VARIABLES	(1) d0197intens	(2) growth
Ordinary knowledge stock	-0.00422	0.00000432
	(0.00849)	(0.000392)
Environmental knowledge stock	-0.276	-0.0198*
	(0.231)	(0.0107)
Scrub: FGD operating hours	0.00855	-0.000176
	(0.0101)	(0.000452)
Burn cleaner fuels: change in coal sulphur content	-4.372***	-0.132***
	(0.242)	(0.0110)
Burn less coal: change in coal consumption	-0.507***	-0.0157**
	(0.166)	(0.00764)
Expand clean capital stock: proportion new boilers gas	-1.281	-0.581**
	(5.892)	(0.272)
Use or buy allowances (WA)	0.124	0.0110
	(0.150)	(0.00691)
Repower with clean coal (RP)	0.157***	0.00867***
	(0.0518)	(0.00239)
Initial plant SO2 intensity, 1997	-0.116***	-0.00155***
	(0.00700)	(0.000257)
Plant vintage: mean boiler in-service year	-0.00598	-0.000785***
	(0.00647)	(0.000288)
Initial capital mix: proportion boilers gas	-0.153	
	(0.170)	
Plant scale: total generation capacity	-0.00803	2.06e-05
	(0.00893)	(0.000412)
Constant	12.02	1.536***
	(12.73)	(0.566)
Observations	540	540
R-squared	0.702	0.361

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 9: Quantile regressions - change in intensity

VARIABLES	(1) change	(2) change	(3) change	(4) change	(5) change	(6) change	(7) change	(8) change	(9) change
Ordinary knowledge stock	-0.000140	-0.00205	-0.00592	-0.00960	-0.00335	-0.00929	-0.00106	-0.00396	-0.0154
	(0.0168)	(0.0370)	(0.0425)	(0.0250)	(0.0207)	(0.0140)	(0.0145)	(0.00703)	(0.0109)
Environmental knowledge stock	0.108	-0.0952	-0.162	-0.219	-0.333	0.476	0.294	0.0703	-0.0818
	(5.496)	(5.870)	(6.230)	(3.652)	(2.315)	(1.774)	(1.441)	(0.252)	(0.355)
Scrub: FGD operating hours	-0.191***	-0.0957**	-0.0486***	-0.0472**	-0.0263	-0.00904	-0.0134	-0.0112	-0.0119
	(0.0540)	(0.0417)	(0.0147)	(0.0190)	(0.0219)	(0.0151)	(0.0147)	(0.0225)	(0.0464)
Burn cleaner fuels: change in coal sulphur content	-8.941***	-10.43***	-10.04***	-11.27***	-9.774***	-7.554***	-7.019***	-6.439***	-7.148***
	(2.212)	(1.480)	(1.594)	(2.571)	(2.907)	(2.220)	(2.181)	(0.536)	(1.266)
Burn less coal: change in coal consumption	0.282	-0.497	-0.230	-0.347	-0.427	-0.556*	-0.611**	-0.440	-0.457
	(0.496)	(0.659)	(0.294)	(0.389)	(0.339)	(0.313)	(0.274)	(0.356)	(0.725)
Expand clean capital stock: proportion new boilers gas	0.515	0.108	-0.0568	-0.119	-0.303	-0.791	-0.955	-3.287	-13.09***
	(19.78)	(16.23)	(14.68)	(18.78)	(20.24)	(10.58)	(19.77)	(3.265)	(4.955)
Use or buy allowances (WA)	0.343	0.101	0.0408	0.0213	0.0369	0.0744	0.0818	0.246	0.133
	(0.227)	(0.154)	(0.0870)	(0.0728)	(0.0573)	(0.0513)	(0.166)	(0.364)	(0.709)
Repower with clean coal (RP)	0.248	0.176	0.381	0.377	0.302	0.231	0.203	0.188***	0.203***
	(0.530)	(0.266)	(0.232)	(0.238)	(0.311)	(0.292)	(0.316)	(0.0499)	(0.0741)
Initial plant SO2 intensity, 1997	-0.550***	-0.396***	-0.326***	-0.272***	-0.186***	-0.137***	-0.115***	-0.0982***	-0.0274
	(0.0975)	(0.0488)	(0.0401)	(0.0392)	(0.0491)	(0.0284)	(0.0307)	(0.0167)	(0.0394)
Plant vintage: mean boiler in-service year	-0.00789	-0.00409	-0.00217	-0.000809	-0.00169	-0.00593	-0.00414	-0.0165	-0.0304
	(0.00815)	(0.00665)	(0.00529)	(0.00424)	(0.00494)	(0.00361)	(0.00661)	(0.0158)	(0.0310)
Initial capital mix: proportion boilers gas	-2.145***	-1.580***	-1.329***	-1.453***	-1.004*	-0.826**	-1.004**	-1.147***	-0.172
	(0.675)	(0.447)	(0.366)	(0.402)	(0.523)	(0.353)	(0.423)	(0.411)	(0.877)
Plant scale: total generation capacity	0.0197**	0.00873	0.00611	0.00195	-0.000198	-0.00245	-0.00198	-0.00292	-0.0388
	(0.00919)	(0.0117)	(0.0115)	(0.00856)	(0.00494)	(0.00503)	(0.00745)	(0.0224)	(0.0428)
Constant	17.14	9.461	5.536	3.031	4.333	12.52*	9.198	33.79	62.01
	(16.37)	(13.24)	(10.55)	(8.444)	(9.994)	(7.318)	(13.07)	(31.06)	(61.04)
Observations	540	540	540	540	540	540	540	540	540

Table 10: Quantile regression – growth

VARIABLES	(1) growth	(2) growth	(3) growth	(4) growth	(5) growth	(6) growth	(7) growth	(8) growth	(9) growth
Ordinary knowledge stock	0.000371	-0.000371	0.000258	0.000221	5.70e-05	-0.000148	-0.000588	-0.00158	-0.00203
	(0.00168)	(0.00122)	(0.000724)	(0.000593)	(0.000459)	(0.000240)	(0.000746)	(0.00124)	(0.00270)
Environmental knowledge stock	-0.00361	-0.0125	-0.0200	-0.0224	-0.0236	-0.0266	-0.0318	-0.0455	-0.129
	(0.0762)	(0.134)	(0.0850)	(0.0962)	(0.0686)	(0.0463)	(0.0638)	(0.138)	(0.299)
Scrub: FGD operating hours	-0.00320	-0.00297*	-0.00107	-0.000552	-0.000865*	-0.000762	-0.00142**	-0.00330**	-0.00876***
	(0.00317)	(0.00155)	(0.000840)	(0.000574)	(0.000475)	(0.000463)	(0.000607)	(0.00153)	(0.00311)
Burn cleaner fuels: change in coal sulphur content	-0.149***	-0.117***	-0.122***	-0.135***	-0.139***	-0.120***	-0.106***	-0.0772*	0.0436
	(0.0376)	(0.0271)	(0.0108)	(0.0135)	(0.0145)	(0.0176)	(0.0150)	(0.0407)	(0.112)
Burn less coal: change in coal consumption	-0.00159	-0.0136	-0.0177*	-0.0132*	-0.0204***	-0.0134**	-0.0230*	-0.0435***	-0.0354
	(0.0215)	(0.0194)	(0.0107)	(0.00747)	(0.00745)	(0.00636)	(0.0124)	(0.0157)	(0.0588)
Expand clean capital stock: proportion new boilers gas	-0.359	-0.607	-0.709	-0.740	-0.759	-0.773	-0.907	-1.331	-3.489
	(0.562)	(0.661)	(0.802)	(0.899)	(0.902)	(0.689)	(0.811)	(1.195)	(6.031)
Use or buy allowances (WA)	0.0485	0.0178	0.0182	0.0136	0.0224*	0.0245	0.0320	0.0757**	0.145*
	(0.0322)	(0.0170)	(0.0145)	(0.0116)	(0.0136)	(0.0155)	(0.0195)	(0.0348)	(0.0816)
Repower with clean coal (RP)	0.0116*	0.00836	0.00740	0.0114	0.0114	0.0104	0.0102	0.0106	0.0165
	(0.00667)	(0.00842)	(0.00779)	(0.00912)	(0.0111)	(0.00809)	(0.00862)	(0.0106)	(0.0664)
Initial plant SO2 intensity, 1997	-0.00279	-0.00319***	-0.00262***	-0.00214***	-0.00217***	-0.00276***	-0.00416***	-0.00796***	-0.0203***
	(0.00184)	(0.000768)	(0.000549)	(0.000454)	(0.000432)	(0.000472)	(0.00122)	(0.00301)	(0.00532)
Plant vintage: mean boiler in-service year	-0.000213	-0.000618	-0.000822**	-0.000869**	-0.000765**	-0.00127***	-0.00192**	-0.00439**	-0.0187***
	(0.00108)	(0.000455)	(0.000381)	(0.000341)	(0.000363)	(0.000352)	(0.000789)	(0.00213)	(0.00441)
Plant scale: total generation capacity	0.00219	0.000734	0.000368	0.000255	0.000152	5.08e-05	7.62e-05	-0.000826	-0.00409
	(0.00155)	(0.000588)	(0.000444)	(0.000357)	(0.000425)	(0.000357)	(0.000591)	(0.00135)	(0.00488)
Constant	0.307	1.176	1.593**	1.695**	1.503**	2.512***	3.833**	8.805**	37.45***
	(2.155)	(0.898)	(0.749)	(0.670)	(0.717)	(0.696)	(1.573)	(4.252)	(8.725)
Observations	540	540	540	540	540	540	540	540	540

Paper 3: What makes a pollution-saving invention technologically influential?

Abstract

This paper investigates why a relatively small group of pollution-saving inventions have ended up exerting a very strong influence on the state of the art in pollution control technology, while the great majority of inventions have ended up exerting only a very weak influence. A new dataset of 4,007 pollution abatement-related patents from the global motor vehicle industry is developed out of the NBER Patent Citation Datafiles. After analysing patterns that emerge in the characteristics of the most influential of these inventions, two hypotheses are formally tested in a negative binomial model. The first states that the prevailing cost of polluting increases the technological influence of pollution-saving inventions because the technical knowledge that these inventions embody is in greater demand. The second states that when the knowledge stock that an inventing company brings to bear on the inventive process exhibits greater technical breadth, that is when the stock is compositionally more diverse, the pollution-saving inventions that emerge are likely to be more influential. Evidence is found to support both hypotheses. The findings inform the design of future climate and energy R&D programmes by identifing the conditions under which the most influential pollution-saving inventions have emerged. The patent selection procedure suggests ways that patent data can be used in econometric analysis more precisely. The findings imply that what matters for pollution-saving technological progress at least is more than simply the size of the technical knowledge stock brought to bear on the inventive process: the breadth, structure and composition of the knowledge stock also seems to matter.

1. Introduction

The climate policy discussion in the United States and elsewhere has been circling in on the idea that a large-scale, government-led R&D programme for greenhouse gas (GHG) abatement and clean energy technology development, will be central to any technically and politically-viable GHG reduction strategy (Hoffert et al. 2002; Ogden et al. 2008; Duderstadt et al. 2009; Freed et al. 2009; Hayward et al. 2010; National Academy of Sciences 2009). The scale of R&D spending put forth in these proposals is on par with the scale of funding the US once devoted to the Manhattan Project of the early 1940s to develop the atomic bomb, and with the Apollo programme of the 1960s and 70s to land a man on the moon (Mowery, Nelson and Martin 2009). With this much public spending potentially at stake it makes sense to think about which kinds of inventions have been technologically influential in advancing the state of pollution control historically, and what can be learned from this past experience about the design of tomorrow's R&D programmes for GHG control.

This paper uses US patent citation data to examine the variable technological influence of pollution abatement inventions that emerged between 1976 and 2006 to control conventional pollutant emissions from motor vehicles. It describes the considerable heterogeneity in the influence these inventions exerted on technological progress in motor vehicle pollution control. It tests two hypotheses about the factors that cause a select few pollution control inventions to be so much more technologically influential than the great majority. The first states that the prevailing cost of using the environment as a pollution disposal sink increases an invention's technological influence; the second that the breadth and composition of the technical knowledge the inventor company brings to bear on the pollution control problem does the same. In the most applied sense these findings shed light on what policymakers and inventors 'should be looking for' with respect to advancing the state of the technological art in pollution control cheaply. They also shed light on the role of invention and inventiveness in pollution-saving technological change as compared to input substitution, technological diffusion and resource conservation.

Section 2 critically discusses what we know about why some pollution-saving inventions are so much more technologically influential than others, looking for clues in the attributes of inventors, the attributes of their inventions, the state of demand for technical knowledge and the pool of available knowledge the inventor has to draw on. Section 3 explains why the US automobile industry is an appropriate context for testing the hypotheses and describes how the patent citation dataset is constructed. The quantitative analysis in Section 4 draws out patterns in the characteristics of the most influential inventions in the dataset, constructs a negative binomial regression model to estimate the causes of variation in the number of citations each patent received, and tests the two hypotheses. Section 5 analyses the results and draws conclusions about the role of invention and inventiveness in environmental technological change.

2. Literature: the causes of influential inventions

This section looks at why a select few inventions end up exerting such a strong influence on the state of pollution control technology while the large majority of inventions exert little or only very weak influence. It examines the attributes of inventors, the attributes of inventions, the demand for technological possibility, and the type of technical knowledge available to inventors.

A ‘pollution-saving’ invention is an invention that deliberately effects a different state of production in whole or in part to avoid, mitigate, suppresses the formation of, treat or inoculate at least one socially undesirable substance. The extent of an invention’s technological ‘influence’ is proportional to the extent to which it advances the state of the technological art in pollution control. The ‘state of the technological art’ is characterised by the relationship between what is usefully possible from a product or process and the amount of an input consumed by that product or process. The input of interest here is the amount of the atmosphere’s assimilative capacity vehicles use as a disposal sink for pollution. An invention advances the state of the art in motor vehicle pollution control if it makes technically possible a reduction in the use of atmosphere inputs (emissions) with all else remaining equal (Sue Wing 2006).

a. Attributes of inventions and inventors

The intrinsic technical qualities of the invention itself and/or the attributes of the inventor that bring the invention into existence, partly explain why some inventions are more technologically influential than others. A group of studies using patent data has investigated the characteristics of high-influence patented inventions. An invention’s ‘generality’ is one such characteristic. By generality these studies mean the breadth of an invention’s usefulness across users, applications and industries. Moser and Nicholas

(2004) tested whether inventions in the field of electricity bore out this generality characteristic given the popular perception of electricity as the archetypal general purpose technology. Moser and Nicholas found that electricity-related inventions actually exhibited lower generality levels than a broad group of inventions related to agriculture, heating, pipes and joints, and other purposes. Lerner (1994) looked at the effect of the scope of patents owned by biotechnology start-up firms on the valuations of those firms, as valued by potential venture capitalist investors. Lerner found that the scope of the patents held by start-up firms associated positively with the venture capitalists' valuations. Hall and Trajtenberg (2006) analysed the characteristics of general purpose technologies using US patent data. Hall and Trajtenberg found that the most highly cited patents had higher generality scores and that patents with higher generality scores took longer to be issued, made about twice as many claims, and were more likely to be assigned to a US corporation.

'General' inventions may be more influential because they embody technical knowledge that is more basic or scientific in nature (Gibbons and Johnston 1974), which in turn predisposes them to a wider range of uses. The more basic in nature the knowledge embodied in the invention, the more readily the invention lends itself to uptake and elaboration across a range of products, processes and industries (Helpman 1998; Lipsey et al. 1998). Inventions embodying more basic knowledge might stand in contrast to inventions embodying knowledge which is more 'engineering' or commercially-oriented in nature (Antonelli et al. 2006). Inventions embodying engineering knowledge may have a more restricted range of possible elaborations because they are only capable of solving narrow problems in limited contexts. The scope for applying them widely across industries is limited.

Other studies have found that simply the location of an invention in some regions of technology space associates either with more valuable patent protection or with more technologically influential inventions. Jaffe (1987) used US patent data to investigate the technology region effect by operationalising a patent's position in technology space by its US Patent and Trademark Office (USPTO) assigned technology classification. Jaffe found that the position of an invention in technology space independently impacted on the owning firm's performance, even after controlling for firm attributes and the effect of knowledge spillovers from adjacent firms. Schankerman (1998) also used technology classification as an indicator of the technology space location of patented inventions, but for French patent data. Schankerman found that patent protection was likely to be more valuable when the underlying invention falls into the technology fields of mechanical devices or electronics. Bessen (2008) found that patent protection is likely to be more valuable if the patented invention falls into the technology fields of computers and communications.

These studies give convincing evidence of an association between invention influence and technology classification and/or location of the patented invention in technology space. Their weakness lies in the theoretical justification for these associations, which do not always give a compelling reason for why an invention should be more influential simply, and only, because it happens to dwell in one region or another. This suggests that technology region effects may be masking more fundamental factors, such as: the amount of inventive activity co-locating with the invention in the technology region; the extent of demand for the technical knowledge arising out of the technology region; and fertility differences across regions made possible by differently sized and differently configured pre-existing stocks of knowledge.

The attributes of the inventor, including the type of organisation and national origin, have been observed to affect invention technological influence. Griliches (1990) observed that patents assigned to individual inventors were on average less valuable than patents assigned to firms. Jaffe, Trajtenberg and Henderson (1993) observed that the technological influence of patented inventions, as measured by forward citations, varied across organisational types. Inventions assigned to universities were about 30 per cent more influential on average than those assigned to blue-chip firms. Inventions assigned to universities were about 50 per cent more influential on average than those assigned to ordinary (non-blue chip) firms. The 'blue chip effect' suggests that large corporations bring more resources to bear on technical problems, including more highly skilled labour, better access to prior scientific knowledge and superior research facilities. The finding that university inventions tend to be more influential may be true for the same reason inventions scoring more highly in measures of generality tend to be more influential: both are likely to be comprised of ideas that are more basic or scientific in nature.

Several studies have found that the nationality of the inventing organisation matters. Schankerman's (1998) findings using renewal fee data on French patents implied that inventions assigned to French inventors and Japanese inventors were more influential on average than inventions assigned to inventors from other countries. Similarly, Bessen's (2008) findings implied that inventions assigned to an inventor of any foreign country at all relative to the patent-granting country, were more influential. Again the econometric evidence is convincing but the underlying theoretical explanation is not. A case for why one country's inventors should be better at identifying more promising ideas than others, all else being equal, is not convincingly made. The extent of national R&D subsidies and state support for quasi state-owned companies is one possible explanation for differences across nations. Another more prosaic explanation is that nationality effects are really an artefact of the tendency of companies to seek patent protection abroad only for the most valuable inventions in their portfolios (Popp 2006; Griliches 1990).

The idea that invention influence is wholly explained by intrinsic invention characteristics and/or the attributes of the inventor are substantially weakened by the dozens of examples of inventions possessing 'superior' technical qualities that come to exert a much weaker influence on technological progress than inventions with 'inferior' technical qualities (Katz and Shapiro 1994; Arthur 1988). The classic example is the QWERTY keyboard arrangement designed in the late 1800s to deliberately slow the key strokes of typists in order to prevent the mechanical typewriters of that era from jamming. The jamming problems are now gone but the QWERTY arrangement remains, despite being the inferior arrangement in today's technological context. The so-called DHIAT-ENSOR arrangement would permit 70 per cent of the words in the English language to be composed with just the ten letter positions in the home row (Shermer 2008), probably increasing the achievable typing rate in widespread use. David (1993) and others explained the extensive technological influence, indeed dominance of such 'inferior' inventions in terms of historical and contextual factors that set these inventions on dominant path-dependent trajectories and made their dominance resistant to technological 'challengers' (David 1993; Antonelli et al. 2006; Ruttan 1997). The effect of contextual factors on the technological influence of inventions is explored next, starting with demand-side factors.

b. Demand for technological possibility

Hicks' (1932) induced innovation framework attempted to explain the rate and direction of inventive activity as a response to changes in the price of inputs. Hicks predicted that inventors would adapt the direction of their inventive effort to conform to the relative scarcity or price changes of the inputs used by the would-be adopters of their inventions. Griliches (1960) found that a prominent explanation in the rate of uptake of hybrid corn varieties in the US was the different profit expectations from uptake of farmers and seed producers across crop growing regions. The induced innovation framework has been an important framework in the environmental technological change literature for explaining the emergence of inventions for environmental protection (Popp, Newell and Jaffe 2009). These demand-side forces are indeed expected to affect the quantity and direction of inventive activity with respect to motor vehicle pollution control, but also the extent of the influence of individual inventions in that field, as discussed in turn.

Empirical work in the environmental technological change literature tends to find evidence that input prices play a role in inducing inventive activity to address the scarce or expensive input. Popp (2002a) used US patent data to test whether inventive activity in 11 energy-related technology classifications responded to energy price changes. Popp found that the quantity of inventive activity responded positively to an increase in the energy price. Newell, Jaffe and Stavins (1999) investigated whether the energy-using features of a range of domestic appliances responded to changes in the price of energy. Newell, Jaffe and Stavins found evidence that when the price of energy increased, models of domestic appliances that used less energy tended to emerge. Both of these studies looked at the responsiveness of inventive activity to energy inputs, not purely environmental inputs.

Other studies have come close to testing the induced innovation hypothesis with respect to environmental inputs, but data limitations have tended to undermine the directness of these tests. In these tests, inventive activity is typically measured as counts of patents related to the protection of a range of environmental media from a range of pollutants (Brunnermier and Cohen 2003). The input constraint is typically measured by pollution abatement and control (PAC) expenditure (Lanjouw and Mody 1996; Jaffe and Palmer 1997). These studies find that inventive activity for environmental protection generally, across this wide range of domains and in response to an imprecise spectrum of environmental policy stimuli, tends to associate positively with environmental input constraints.

None of these studies has looked at the effect of environmental input price changes on the variable technological influence of individual inventions. The closest is Popp (2002b) who examines a related paradox. The paradox is that, despite the theoretical expectation that market-based environmental policies induce more 'innovation' than command and control instruments (Magat 1978), the switch-over in the United States in 1990 from a command and control regime to a market-based regime for SO2 control was followed by a measurable *decline* in SO2 control-related patenting activity. Popp finds that this discrepancy can be explained by the change in the nature of inventive activity before and after 1990. Before 1990, SO2-related inventions focused mainly on reducing the installed cost of scrubber capacity since installing scrubber capacity was really the only way to achieve compliance. After 1990, the inventive focus shifted to raising the removal efficiency of scrubbers, since SO2 reductions in excess of compliance were rewarded under a tradable permit regime. The post-1990 regime may have induced less inventive activity, but the inventive activity it did induce was of a higher 'quality' because it responded to a policy context that gave larger rewards to technical knowledge that reduced just pollution input, rather than knowledge that reduced the cost of scrubbers generally. Popp's finding implies that the exact same invention could exert a very different degree of technological influence depending on the nature of the prevailing regulatory context.

This prior work about the effect of contextual demand-side factors on the quantity and direction of inventive activity underpin the first hypothesis. The first hypothesis takes the induced innovation idea that the changing cost of inputs affects the quantity of inventive activity and extends it to the idea that the changing cost of inputs affects the quality or technological influence of pollution-saving inventions. It states that: *the cost of using environmental inputs (polluting) increases the technological influence of pollution-saving inventions since technical knowledge for dealing with pollution should be in greater demand when discharging emissions is more expensive.* Heightened demand in the surrounding technological context should reward more strongly an invention that emerges to reduce emissions, regardless of the intrinsic technological features of the invention, all else being equal. Inventions emerging under these conditions should satisfy stronger and more widespread demand for the technical knowledge they embody.

c. Supply of technical knowledge

Hicks also theorized in his 1932 *Theory of Labour* that the portion of inventive activity that is not induced by changing relative input prices is brought about by general 'autonomous' progress in science and technology. The idea of autonomous technological progress implies that inventive activity occurs because individuals and firms possess technical capabilities built up from prior experience, and that they bring these capabilities to bear on the present day technical problems they face. As discussed below, prior work has tended to find a positive relationship between prior technical capability and the quantity of inventive activity, but these studies have little to say about the effect of this prior capability on invention quality or influence.

Theoretical work modelling growth and long-run technological change implies that prior technical capability should positively affect the influence of pollution-saving inventions. The macro endogenous growth literature represents the effect of technical capability in the long-run growth process using stocks of 'knowledge capital' within regions and countries (Romer 1990; Aghion and Howitt 1998). Nordhaus (2002) represented the effect of technical capability on economic output as the knowledge created by investing in energy sector R&D. He then estimated the effect of this knowledge on the long-run carbon intensity of economic output. Nordhaus found that technical knowledge had only a small positive impact on the carbon intensity of output. His finding is sensitive to assumptions about how the knowledge stock is calculated, and others have found much stronger knowledge stock effects under different assumptions (Popp 2004).

The strength of these studies is the way they bring prior technical capability effects into models of economic growth and change, by representing capability as knowledge capital and R&D spending respectively. A weakness of these studies is that they treat the stock of knowledge as if the only aspect of this stock that mattered for growth and technological change was the size of the stock. They do not go very far in representing the effect of different mixes or compositions of knowledge within those stocks, meaning they effectively treat within-stock heterogeneity as if it were unimportant. Nor do these studies deal with the effect of these stocks on the quality or influence of inventions.

At least two studies have represented prior technical capability as a stock of knowledge that shows some degree of heterogeneity in its composition. These studies also analyse the effect of these varied knowledge stocks on economic outcomes. Goulder and Schneider (1999) divided the stock of knowledge available to an economy into appropriable knowledge, whose benefit was enjoyed only by the firm undertaking the R&D, and non-excludable knowledge, whose benefit was enjoyed by all firms within the same industry. The purpose for Goulder and Schneider of employing these different levels of appropriability of knowledge types within the stock in their model, was to understand the effect of the appropriability characteristic of knowledge on output. Knowledge of both appropriability levels had a positive impact on output. The second study is Gerlagh (2008) who represents compositionally-varied knowledge stocks by setting up a model in which firms choose among investing in carbon-based energy R&D, carbon-saving energy R&D, or neutral R&D. Gerlagh used this heterogeneity in knowledge type by end use to investigate the effect of crowding out between knowledge types on the optimal carbon tax. Gerlagh finds that carbon-saving energy R&D crowds out carbon-based energy R&D under a carbon tax. Both of these studies imply that the variation in the type of knowledge that comprises the stock is likely to influence inventive activity and the broader course of technological change.

Empirically, two further studies test the effect of prior capability on the quantity of inventive activity, by constructing knowledge stocks from patent data. Popp (2002a) constructed knowledge stocks for 11 energy technologies from US patent data. The size of the stock changed over time according to the level of inventive activity in the technology area and a rate of decay to capture knowledge obsolescence. Popp found that knowledge stocks exerted an impact on inventive activity in energy technologies that was several times stronger than the demand-side inducement effect of the price of energy. Popp's study pertained only to the US. Verdolini and Galeotti (2009) by contrast compared the effect of knowledge deriving from two different sources on inventive activity in energy efficient technologies for 17 countries. They calculated a domestic knowledge stock from patents granted to inventors based within the patent-using country, and a foreign knowledge stock from patents granted to inventors in all countries abroad, the latter adjusted by a diffusion parameter for each pair of countries based on geographic proximity and language barriers (also see Peri 2005). Verdolini and Galeotti found that the portion of the knowledge stock available to domestic inventors that originated from other countries had twice as strong an effect on inventive activity in the using country as the portion of the stock deriving from domestic sources. Foreign knowledge mattered more. Both studies validate the idea that greater prior technical capability increases the quantity of inventive activity undertaken. The second study validates the observation that heterogeneity in the knowledge stock, here delineated by geographic origin, affects the quantity of inventive activity.

If variation in the composition of prior technical knowledge affects the learning and knowledge-application process at the centre of the inventive activity, then it should be possible to observe this at the level of the learning process of the individual. At the level of the individual, Cohen and Levinthal (1990) observed that studies of the learning process find that accumulated prior knowledge increases the individual's ability to store new knowledge into memory, as well as their ability to recall that knowledge and put it to use. They found that knowledge acquisition is self-reinforcing: the more knowledge one has, the more knowledge one is able to absorb. Bower and Hilgard (1981) found that the more objects, concepts and patterns the individual has stored in memory, the easier it is for the individual to acquire additional information that gives detail or elaboration to those structures, and the easier it is for the individual to recall those new, more elaborate structures and use them. In a different study of memory and cognition, Bower and Hilgard (1981) found that individuals acquire external information more easily when the nature of the incoming information is closely related to what they already know, since understanding is frequently achieved through associative learning. Cohen and Levinthal (1990: 131) found that in a learning context where there is uncertainty about what needs to be learned to solve a problem, greater diversity in the knowledge already possessed provides a more robust basis for learning, because greater knowledge diversity increases the likelihood that the incoming information relates to what is already known. Pirolli and Anderson (1985) studied the way individuals go about solving novel and difficult technical problems by observing how they learned recursive programming procedures in the computer programming language, LISP. Pirolli and Anderson found that individuals compiled an increasingly advanced knowledge of the programme almost exclusively by 'analogizing' from programming examples they already understood.

The individual's capacity to learn and absorb new information seems to be improved by the *quantity* of knowledge the individual already possesses, namely the size of the stock. This is consistent with the representation of the effect of knowledge in the endogenous growth and technological change frameworks above. But the *diversity* of what the individual already knows, namely the composition of the stock, as well as the *proximity* of what the individual already knows to what the individual is trying to learn, both bear importantly on the same learning and knowledge application process that is at the heart of inventive problem solving.

At the level of the firm and the nation, several studies have elaborated on the compositional aspect of the knowledge stock in conceptual terms. Breschi, Lissoni and Malerba (1998) draw a distinction between the aspect of knowledge which is 'cumulative' and the aspect of knowledge which makes some ideas more or less 'proximate' to others. For Breschi, Lissoni and Malerba, 'cumulativeness' refers to the position or primacy of a new idea relative to an old idea, with new ideas stacking up on top of old ideas in a building block-like way. Certain foundational ideas already need to be in place at the base of the structure for more advanced ideas at the top of the structure to be absorbed, and for some concepts and understandings of some phenomena to ever be attained.

In contrast, the 'proximity' of knowledge tends to refer to the distance between fields of technical knowledge in technology space (Jaffe 1987) or the distance between individual ideas residing within a single region of technology space. The distance between two fields of knowledge is smaller if an inventor who is a specialist in field A would find it easy to absorb knowledge from field B which is not his own, or to apply that knowledge or invent within field B. Cincera (2005) adds to this that the distance between ideas or knowledge fields is asymmetrical: the inventor who normally invents in knowledge field A can have an easier time inventing in knowledge field B than vice versa.

At least two studies have applied these knowledge composition concepts empirically at the level of the firm. Breschi, Lissoni and Malerba (1998) investigated the extent of the distance between the components of the knowledge stock held by the typical firm, using data for about 10,000 patents granted to firms by the European Patent Office.

They found that almost 80 per cent of the firms to which these patents were assigned held patents in between one and three technology fields. Most firms' knowledge stocks were positioned in quite narrow areas of technology space. They found that despite the advantages that knowledge stock diversity seems to confer for learning and technical problem solving, diversity in the stock of knowledge within firms was the exception, not the rule. In a related study, Cohen and Levinthal (1990) investigated why firms exhibit sharp differences in their ability to recognize useful information in the surrounding technological context and assimilate this information for solving technical problems of their own. Some firms are very good at appropriating knowledge from the external environment, others are not. Using firm-level R&D spending data, Cohen and Levinthal found that a firm's absorptive capacity is largely determined by the firm's level of prior related knowledge and the breadth or diversity of that prior-held knowledge.

These findings about the positive effect of knowledge stock composition on learning and inventive problem solving motivate the second hypothesis. It states that: *the greater the breadth of technical knowledge stock the inventing firm brings to bear on the inventive process, in this context the problem of devising novel ways to motor vehicle pollutant emissions, the more technologically influential will be the resulting inventions, all else being equal*. This is because greater knowledge breadth should increase the likelihood that what needs to be known to extend the technology frontier for pollution control is related to something the company already knows. This improves the company's ability to identify relevant information in its surrounding environment, assimilate it into new technical knowledge and render that knowledge into pollution-saving inventions that in turn have superior intrinsic technical characteristics relative to other comparable inventions.

3. Research approach: patents for motor vehicle pollution abatement

The two hypotheses are tested in the context of the inventive response of 31 global automobile companies to restrictions on conventional pollutant emissions from light duty passenger vehicles in the United States between 1976 and 2006. This section explains the suitability of this test case, describes the procedure for selecting the dataset, and identifies some prominent trends in the dependent variable.

a. Case choice

The motor vehicle pollution control case is characterized by a set of relations between environmental regulators and the automobile companies. These relations essentially forced the automobile companies to comply with regulators' demands by inventing new-to-the-world methods of pollution control, rather than by allowing the companies to comply through simpler methods. These conditions resulted in a large amount of inventive activity in motor vehicle pollution control documented formally in the US patent record.

The formal account of the legal history of motor vehicle pollution control in the US usually proceeds as follows. The US Federal government first became significantly involved with the motor vehicle air pollution issue when Congress passed the Motor Vehicle Pollution Control Act in 1965 (White 1976; Reitze 2001) but this legislation was weak in many ways. A few years later Congress addressed the issue firmly in the 1970 Clean Air Act (CAA) Amendments. The 1970 legislation mandated that nearly all new vehicles sold in the US achieve 90 per cent reductions in carbon monoxide (CO), oxides of nitrogen (NOx) and hydrocarbon (HC) emissions on a grams-per-mile basis by the mid-1970s. Sulphur dioxide (SO2) emissions were also regulated for diesel engines. These standards were modified several times in the years to come in terms of timing, stringency and enforcement (Davis et al. 1977). During the 1980s little new was done to tighten standards. The 1990 CAA Amendments provided for significant further tightening of the CO, NOx and HC standards beginning in 1994. The 1990 Amendments also authorized the Environmental Protection Agency (EPA) to require further reductions after 2003 (Waxman et al. 1991; NESCAUM 2000). To the credit of all parties involved, conventionally powered passenger vehicles sold today in the United States satisfying the most stringent standards emit 97 per cent less CO, 95 per cent less NOx and 98 per cent less HC on a grams-per-mile basis than new vehicles sold in 1965 without any emission control (NESCAUM 2000)[21].

This formal legal history belies a complicated set of relations between automobile companies and state and Federal environmental regulators. These relations gave rise to the defining features of the regulatory approach to motor vehicle pollution control. Those features put the regulatory focus squarely on the harmful substances and a continual ratcheting-down of standards. Prior to 1970, state environmental regulators in California had initially tried to get the automobile companies to reduce motor vehicle emissions voluntarily in the 1950s and 60s, but the automobile companies had consistently

[21] Average 1965 emissions rates were 10 g/mi for VOC, 80 g/mi for CO, and 4.1 g/mi for NOx. Federal Tier II standards for these pollutants will be 0.125 g/mi, 1.7 g/mi, and 0.20 g/mi, respectively.

rebuffed those efforts (Nader 1965; Bittlingmayer 1987). The regulators accused the automobile companies of resisting even the most minor and inexpensive technical changes to vehicle design despite compelling emerging evidence of the adverse health effects of emissions (Doyle 2000). Eventually the Federal government also assumed the position that the automobile companies were not responding quickly enough to requests that they deal voluntarily with the emissions issue. The automobile companies for their part said they were developing pollution control technology as quickly as they could even though nothing much about their vehicles seemed to be changing. Government-industry relations reached a low point in the mid-1960s when the US Department of Justice filed a formal suit against the four major US automobile companies at the time, charging that they had violated anti-trust law by colluding among themselves to retard the development and deployment of motor vehicle pollution control technology (Bittlingmayer 1987; Goldstein and Howard 1980). These events set the stage for Congress' hard line approach to regulating motor vehicle emissions at the Federal level in the early 1970s.

When Congress acted on the issue in the 1970 CAA Amendments, the 90 per cent mandatory reductions set out for all new vehicles was partly retaliation against the automobile companies for their persistent and, it was felt, dogged unwillingness to deal with the issue on their own. Despite testimony from the automobile manufacturers that it would be extremely difficult and expensive, if not impossible, to meet the 90 per cent reductions by the given deadline, Congress wrote into the 1970 Amendments extremely strict enforcement provisions. One enforcement clause stated that any seller of a non-conformant vehicle or engine would be liable to a civil penalty of up to $10,000 for each vehicle sold, despite the fact that the retail price of a small car in the US in the mid-1970s was about $4,000. Congress and the EPA insisted that the stringency of the standards and the strength of enforcement provision were necessary to safeguard public health. By mandating emission standards that Congress knew were unreachable with the present state of technology, Congress acknowledged that it was effectively forcing the automobile companies to develop the pollution control technology they should have been developing voluntarily throughout the 1950s and 60s (Gerard and Lave 2005). As a result, R&D spending in the automotive industry spiked in the mid and late 1970s as the automobile manufacturers scrambled to meet the standards (US Department of Commerce 1980).

These events gave rise to two features of the US regulatory approach that make the motor vehicle case useful from a methodological point of view for understanding the causes of highly technologically influential pollution-saving inventions. First, the repeated ratcheting-down of emission standards over time essentially forced the automobile companies to continually invent at the outer boundary of the technological frontier with respect to pollution control to stay in conformance with the standards. The inventions that came out of automobile company research laboratories played a central role in standards attainment because other potential lower-tech abatement strategies like fuel switching or reducing underlying transportation demand were either out of the automobile companies' control or commercially unattractive given the regulatory approach. New-to-the-world pollution control technology in new vehicles was largely responsible for standards attainment. It was largely technological advance that offset the adverse environmental impact of a more than two-fold increase in automobile use in American society over the 30 years from 1970. The data show for example that during the period 1970 to 1997, annual vehicle miles travelled in the United States increased from 1.1 trillion to 2.56 trillion miles (Reitze 2001: 270) but aggregate emissions by weight from all mobile sources actually *decreased* from 209.5 to 114 million short tons during the same period (US EPA 2008). That is, the number of vehicle miles travelled *increased* by 133 per cent, but emissions from all regulated vehicles in aggregate providing those transportation services *decreased* by 46.6 per cent. The first reason this is an appropriate case is that new inventions played an unusually influential role in this technological change outcome.

Second, the fact that the regulatory effort came to focus squarely on reducing emissions of the problematic substances makes it easier to identify inventive activity whose sole purpose was pollution abatement. The standards were concerned almost solely with CO, NOx and HC. Identifying inventive activity with the sole purpose of pollution abatement would be more difficult if regulators had prescribed that the automobile companies adopt whole cleaner-burning engine technologies for example. Under this condition the automobile companies' inventive response would have had more mixed aims. Inventions would have been aimed at reducing pollution emissions perhaps but also at incorporating the new engine designs into their vehicles. This would have made it more difficult to separate out inventions dedicated solely to saving pollution. If it can be said that all the inventions in the sample came into existence to solve more or less the same problem then it becomes easier to identify factors that make individual inventions more technologically influential than their peers.

b. Dataset construction

The patent dataset was extracted from the National Bureau of Economic Research (NBER) Patent Citation Data Files. These files contain information on 3.3 million patent records granted by the USPTO between 1976 and 2006. A group of global automobile industry patents was extracted by a two-step procedure. First, 71,658 patents were extracted on the basis of having been granted to any of 31 companies involved in the manufacture of automobiles or the supply of automobile-related components. Second, 4,007 of these patents were identified as having been intended for the purpose of abating conventional pollutants from motor vehicles. The two steps are explained here in detail.

The full dataset for the automobile industry as a whole was selected on the basis of patent assignee. All the companies that sold passenger vehicles in the United States between 1976 and 2006 were identified by consulting the industry trade publication, Ward's Automotive Yearbook. Patents assigned to any of these 26 automobile manufacturers[22] were extracted from the NBER file. According to Ward's, these 26 companies produced 99.68 per cent of all vehicles sold in the United States during that 30 year period, meaning the dataset very closely approximates the full population of patented inventions filed by the automobile manufacturing industry in the United States during that period. Selecting patents on the basis of company assignee eliminated the variation in invention quality connected to assignee type, since patents assigned to individuals are held to be less technologically influential than those assigned to corporations (Griliches 1990; Bessen 2008). Patents assigned to the global automobile *manufacturers* accounted for 57,665 of the 71,658 patents in the dataset (80.4 per cent).

The other 13,993 patents were assigned to a representative group of automobile component and services *supplier* companies. Supplier companies were not themselves generally liable to emission control standards in the US, but they helped the manufacturers meet the standards. Haasic (2010) analysed 102,000 patents related to automotive engine design, vehicle design and alternatively fuelled vehicle development granted by OECD countries during the period 1998 – 2007. He found that out of the top 30 most frequently occurring patent assignees, ten were parts and service supplier companies and the rest were automobile manufacturers. Neumayer and Perkins (2012) include both exports of automobiles and automobile parts and components in their study of the 'California hypothesis', that countries are more likely to have more stringent emission standards if they export more of their automobile sector output to countries that themselves have stricter standards. Sperling (2001) looked at the distribution of Federal government spending under the Partnership for a New Generation of Vehicles (PNGV), the government-industry R&D partnership set up in the US in 1993 to develop highly fuel

[22] Which included American Motors Corporation, BMW, British Leyland, Chrysler, Daimler-Chrysler, Fiat, Ford, GM, Honda, Hyundai, Isuzu, Jaguar, Kia Motors, Land Rover, Mazda, Mitsubishi, Nissan, PACCAR, Peugeot, Porsche, Renault, Saab, Subaru, Suzuki, Toyota, Volkswagen, and Volvo.

efficient, low polluting vehicles. Sperling found that out of the $300 million spent on R&D under the PNGV each year, about $100 million went to automotive parts and service suppliers, $100 million went to the three major US automobile makers who in turn subcontracted about three quarters of this to suppliers, and the remaining $100 million went to government energy research laboratories (2001: 253). Haasic's findings were used to identify five representative global supplier companies.[23] Patents assigned to supplier companies therefore account for 19.6 per cent of the 71,658 patents.

Selecting patents on the basis of corporate assignee alone would have contaminated the dataset with thousands of patents that were irrelevant to the automobile industry, since several of the 26 automobile manufacturers produce goods and services unrelated to automobiles. Mitsubishi Group for example produces insurance services, banking services, chemicals, foods, heavy industry machinery, consumer goods and electric power equipment, as well as automobiles. The same 'diversified conglomerate' problem pertains equally or more so to the supplier companies. On the supplier side, Siemens AG holds hundreds of patents related to communications systems, power generation, medical technology and home appliances, in addition to those it holds for automotive parts and components.

In order to restrict the dataset to the automobile sector patents mostly likely to be relevant to Federal emission control regulations (Neumayer and Perkins 2012), only the patents assigned to the passenger automobile manufacturing division(s) of the companies were selected. Patents assigned to 'Mitsubishi Motor Corporation' were retained but patents assigned to 'Mitsubishi Chemicals Industries Ltd,' 'Mitsubishi Atomic Power Industries, Inc.,' and 'Mitsubishi Paper Mills, Ltd.' were discarded. The same procedure was used for the supplier companies. For Siemens AG, patents were retained if they were assigned to 'Siemens Automotive Electronic Ltd' and 'Siemens Automotive Corp' but discarded if they were assigned to 'Siemens Business Communication Systems Inc,' 'Siemens Electromechanical Components Inc' and 'Siemens Med Solutions Inc'. Selecting patents at the level of the corporate division or subsidiary increased the likelihood of being able to identify factors related to high-influence inventions by reducing the statistical noise created by inventions unrelated to automobile production.

The second stage of the selection procedure identified those patents within the 71,658 automotive industry patents that the assignees had intended to be used solely or partly for controlling HC, CO, NOx or any combination of these pollutants from passenger vehicles. In the following way 4,007 such patents were identified.

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[23] Allied Signal, Bendix Corporation, Bosch, Hitachi and Siemens.

Telephone interviews were conducted with automotive engineers who had worked in emission control R&D in the automotive industry during the 30 years. The engineers were asked about the main technology strategies the companies they and their contemporaries had focused on to reduce vehicle emissions.[24] Based on these responses and a reading of the automotive engineering literature, a Boolean search term[25] was developed to identify patents potentially relevant to pollution abatement. The search term was used to search the abstracts of all patents in the USPTO's searchable online patent database. This returned 8,524 patents of 'potential' relevance to pollution abatement.

The abstracts of a systematic sample[26] of 609 of these 'potentially relevant' patents were read through on-screen. Each of the 609 patents was assigned into one of three groups based on the content of the abstract: those intended 'only' for pollution abatement (PA-only), those intended 'partly' for pollution abatement (PA-partly), and those intended for some other non-pollution abatement purpose. Pre-defined criteria were applied to the categorization decision, shown in the appendix. Through this sorting process it was possible to discard 53.7 per cent of the potentially relevant patents returned by the Boolean search term as irrelevant to automobile pollution control (even though these patents had satisfied the requirements of the search term).[27] The remaining 46.3 per cent of patents were categorized as PA-only or PA-partly patents.

Patents 'only' for pollution abatement were those where the underlying invention was intended only and solely for controlling pollution and for no other purpose. Patents 'partly' for pollution abatement were those where the underlying invention was at least partly intended for controlling pollution, but also intended to improve some other aspect of the vehicle including fuel efficiency, engine performance, engine durability, the

[24] These included: (1) 'leaning out' the combustion process to burn fuel more completely and minimize the formation of problem gasses; (2) re-circulating pollution-laden gasses back to the engine combustion chamber to be re-burned and the problem substances therein destroyed; (3) configuring the flow of exhaust gasses to pass across substrates that catalyse noxious substances into innocuous ones; (4) and using electronic sensing and feedback equipment to monitor the composition of exhaust gasses and signal other parts of automobile, particularly the engine, to adjust accordingly. See Faiz, Weaver and Walsh (1996) for a detailed discussion of the progress in automotive engineering techniques to deal with conventional pollutants over the time period.

[25] Using key words to represent in sequence the host technology ('automobile', 'vehicle,' 'car', 'engine'); the by-product or pollutants from the host technology ('carbon' and 'monoxide', 'oxides' and 'nitrogen', and 'hydrocarbons'), an indication that these by-products were problematic ('pollutant', 'emissions', 'toxic', 'harmful'), and a remedy to the problem ('abate', 'control', 'clean', 'purify'). I tested and adjusted the search phrase iteratively until the patents returned contained the greatest number of potentially relevant patents judging by a sample of patent titles.

[26] Defined as every fifth patent for the years 1976, 1979, 1981, 1986, 1990, 1993, 1997 and 2000.

[27] The irrelevant patents turned out to be intended for controlling pollutants from sources other than passenger vehicles (jet engines, watercraft, construction machinery), for controlling substances other than HC, CO or NOx (particulates from diesel engines) or for creating, managing, transforming or handling these substances in industrial processes unrelated to pollution control.

combustion process, fuel composition or the routing or management of exhaust gasses. An example of a patent intended partly for pollution abatement is patent number 4159701 entitled ‘System for controlling fuel supply in internal combustion engine’. According to the abstract, this invention controls and interrupts the supply of fuel to the engine when the vehicle is braking in order to reduce fuel wastage during vehicle deceleration and to suppress the creation of harmful exhaust gas components. For all such ‘partly’ patents there was evidence that the underlying invention was motivated into existence by more objectives than just pollution abatement.

The 282 pollution abatement ‘only’ and ‘partly’ patents identified through abstract reading were ‘scaled up’ to the full automobile industry dataset on the basis of primary USPTO-assigned patent subclass. The subclass of each PA-only or PA-partly patent was identified. All patents within the full 71,658-patent automobile industry dataset falling into those subclasses were marked as pollution abatement ‘only’ or ‘partly’ patents accordingly. Table 1 summarizes the number of patents falling into each group. The patents of main interest are the 4,007 pollution abatement-related patents which constitute the dependent variable though patents from the other groups are used as controls.

Table 5: Structure of automobile industry patent dataset

All NBER patent citation data file patents (1976-2006)	3.3 million
Automobile industry patents	71,658
For pollution abatement (PA-related)	4,007
Only (PA-only)	2,301
Partly (PA-partly)	1,706
For all other purposes (non-PA)	67,651

4. Quantitative analysis

In this section the data for the 4,007 pollution abatement patents are fitted to a model in which the dependent variable is the raw number of citations received by each patent, a measure of technological influence. The unit of observation is the patent. Given the novelty of the dataset, key trends are analysed in the characteristics of the most heavily cited pollution abatement patents. Model estimates are given along with substantive interpretation. Robustness checks are performed.

a. Dependent variable

The dependent variable is the raw number of citations each pollution abatement-related patent received from all other patents in the US patent system. A single citation received is also called a 'forward citation'. For any focal patent, a forward citation originates from a patent granted later in time. A 'backward citation' originates from the focal patent and is made to a patent granted earlier in time. The same citation linking two patent documents can be both a forward citation and a backward citation simultaneously, depending on which patent is the focal patent. The dependent variable here, raw forward citations received, is referred to throughout as 'citations received' or just 'citations'.

The number of citations received is used as a measure of the technological influence of the invention underlying the patent. This follows studies that have used citations as an indicator of the value of patent protection on an invention (Harhoff et al. 1998; Bessen 2008) and the technological influence of the invention itself (Moser and Nicholas 2004; Jaffe, Trajtenberg and Henderson 1993). Trajtenberg (1990) for example showed a positive relationship between citations received and the social value of the invention in terms of the level of consumer and producer surplus the invention created. Harhoff et al. (1998) showed a positive correlation between citations received and the economic value of the patent in money as reported by the patent owner. Hall and Trajtenberg recognize citations received as an indicator of a patent's 'importance' relative to other patents because applicants have a legal duty to disclose any knowledge of the prior art in a patent application (2006: 391). If a patent applicant fails to make all appropriate backward citations to prior art then the applicant fails to fulfil this legal duty. Applicants also have an incentive to make the minimum number of backward citations to prior art to avoid giving existing patent holders undue claim to the applicant's intellectual property. The US Office of Technology Assessment and several courts of law recognize citations as an intellectual property boundary marker in the adjudication of disputes over the scope of patent rights (Trajtenberg 1990). This paper follows these precedents by using citations received as an indicator of a patent's technological influence.

Using citations received as measure of technological influence also presents some challenges. Additional factors within the patenting system can artificially inflate or deflate citations received away from the 'true' number indicative of a patent's technological influence. These factors include *truncation effects*, *cohort effects*, and *citation proliferation* effects. These factors are discussed below and control variables are developed to account for the influence of each.

b. Descriptive analysis

This subsection examines key trends in the dependent variable and uses these trends to substantiate the hypotheses in Section 2. This subsection analyses an 'adjusted' version of the dependent variable. As discussed above, other factors are at play in determining the number of citations received by a patent that have little to do with the patent's own technological influence. An adjusted version of the dependent variable is calculated to remove some of these influences. The adjustment is performed by multiplying raw citations received by an adjustment coefficient developed by Hall, Jaffe and Trajtenberg (2001: 31). This strips out the heaviest influences arising from truncation effects, cohort effects and citation proliferation effects, thus giving a more accurate picture of pure technological influence. The correlation coefficient between the adjusted and raw citations is .886. To the extent that the trends described here might be sensitive to differences in whether or not citations received is adjusted, or attributable to the adjustment method itself, comparison is made to raw citation and alternate adjustment method measures.

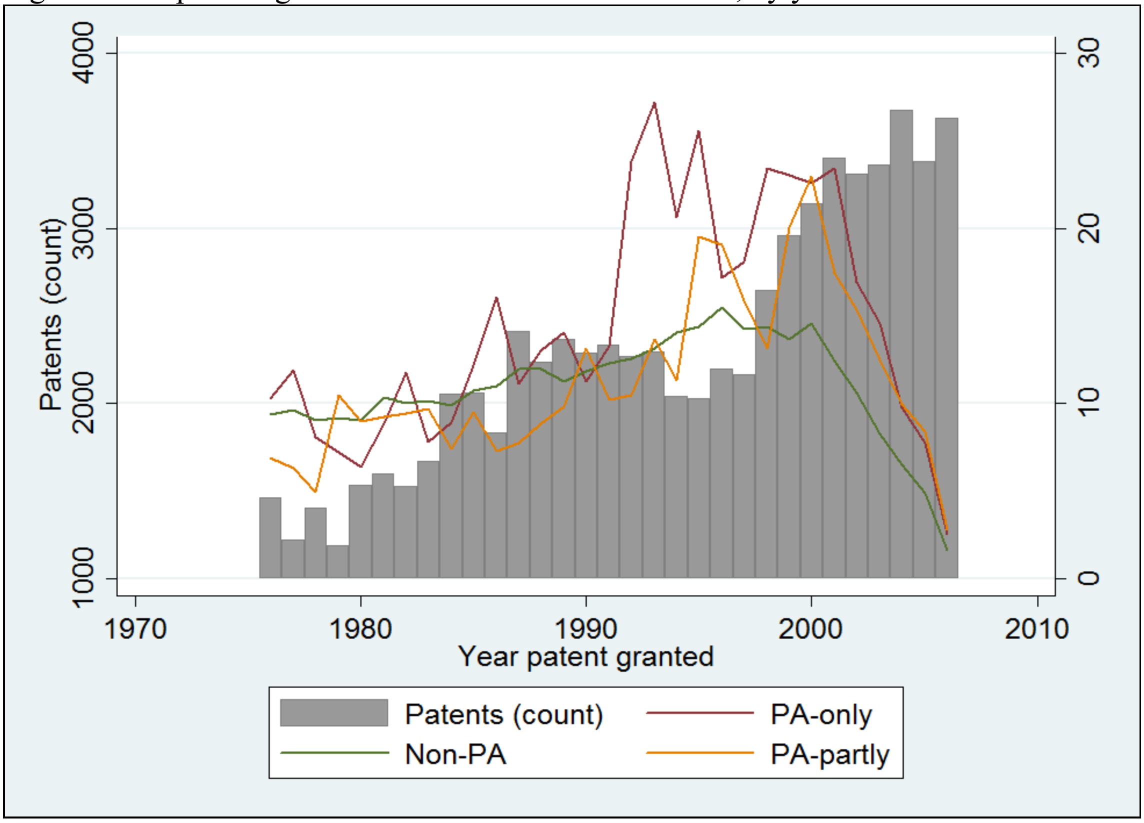
Table 2 gives the adjusted citations received by the three groups of patents in the automobile industry dataset: PA-only patents, PA-partly patents and Non-PA patents. Table 2 shows that PA-only patents received about 25.5 per cent more citations on average than PA-partly patents, and that PA-only patents received about 32.4 per cent more citations on average than Non-PA patents (that is, all other general automobile patents). This pattern persists to a lesser extent in the comparison of the medians. Also observe that for all three patent groups, the means and variances are consistently unequal and that the variance is always larger the mean. This signals over-dispersion.

Table 2: Descriptive statistics for citations received, by patent type

	N	Mean	Median	S.D.	Variance	Min	Max
PA-only	2,301	15.811	9.057	23.957	573.977	0	308.064
PA-partly	1,706	11.798	7.408	16.283	265.144	0	180.961
Non-PA	67,651	10.748	7.144	13.694	187.548	0	341.180
All	71,658	10.936	7.255	14.234	202.607	0	341.180

Why did PA-only patents receive so many more citations on average than PA-partly and Non-PA patents? The answer seems to lie in a spike in citations received by patents in the PA-only group that occurred around 1990. This spike was probably caused by the 1990 Clean Air Act Amendments. Figure 1 gives the annual number of patents granted to the entire automobile industry on the left axis and the mean number of citations received in each year by PA-only, PA-partly and Non-PA patents on the right axis. This figure shows that mean citations received by PA-only patents shot up around 1990. Mean citations received by PA-partly patents did the same to a lesser extent and with a lag of about five years. Mean citations received by PA-only and PA-partly patents remained elevated until around 2000 when truncation effects start to set in.

Figure 1: All patents granted and mean citations received, by year

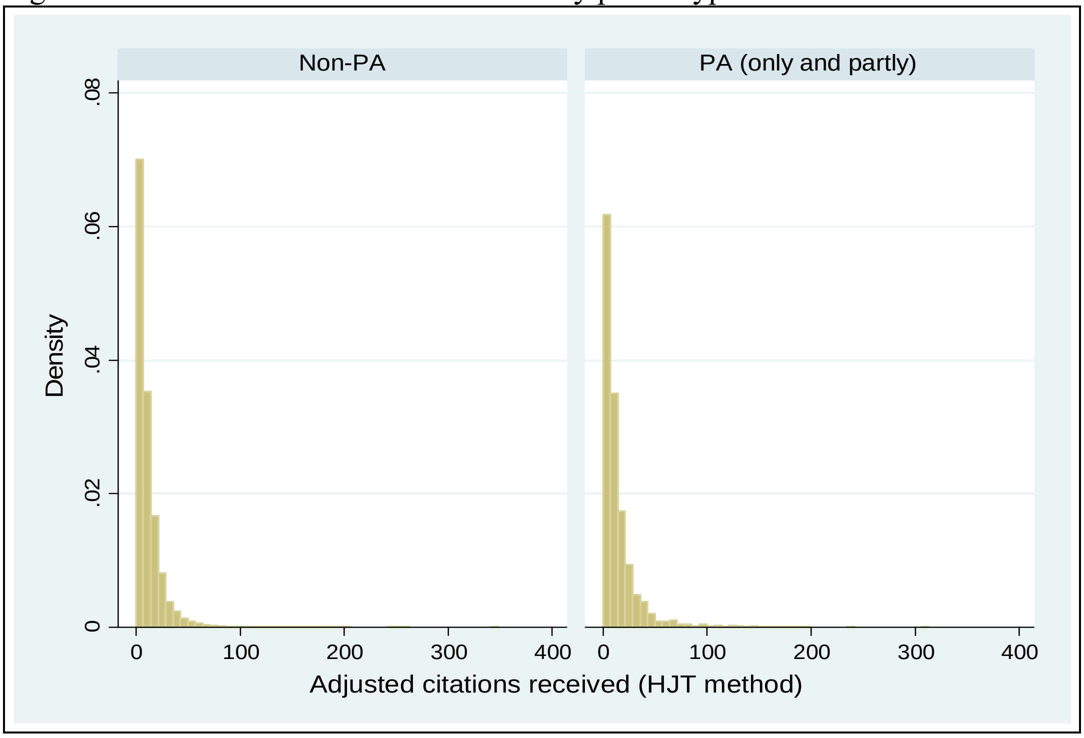


Note: Bars are number of patents granted to entire automobile industry in each year. Long dashes are mean citations received per year by PA-only patents, short dashes by PA-partly patents, solid line by Non-PA patents.

The spike in Figure 1 is interpreted as the response to a shock in the level of demand for technical knowledge for controlling motor vehicle emissions to new, stricter standards. This shock occurred around 1990. This interpretation is consistent with the idea in Section 2 (b) that an invention's technological influence is not merely a function of the invention's intrinsic technical characteristics but also a function of the demand environment for the knowledge and technological possibility that the invention embodies (Arthur 1988; Katz and Shapiro 1994; David 1993). Figure 1 implies that PA-only and PA-partly inventions tended to be more influential if they came into existence close in time to the emergence of the problem they purported to solve. The pollution abatement inventions that came first in time relative to this demand probably became building blocks for all future inventors working on similar problems. Future inventors in turn made numerous backward citations to the initial prior art in their own patents. There is also likely to be a 'low-hanging-fruit' effect here in the sense that the inventions that respond quickest to the knowledge demand shock exploited the intellectual property for achieving the easiest, cheapest abatement possibilities. This post-1990 divergence in citation received between PA-related and Non-PA patents accounts for most of the difference in mean citations received across patent groups in Table 2.

Although the purpose of the model is to test for technological influence determinants within the PA-related patent group, there is another comparison of interest to be drawn between the PA-related and Non-PA groups. Figure 2 below gives the distribution of patents by citations received for each patent group. The strong right hand skew in both distributions indicates a relatively large proportion of low-influence patents receiving zero or very few citations to the left, and a relatively small proportion of high-influence patents receiving ten or more citations to the right. This skew is consistent with studies of the distribution of patent value or importance (Bessen 2008; Harhoff et al. 1998; Griliches, Hall and Pakes 1993; Trajtenberg 1990). For the patents in the PA-related group in the right panel, 20.4 per cent received zero citations, 64.9 per cent received between one and five citations, and the remaining 14.7 per cent received over five citations.

Figure 2: Distribution of citations received by patent type



The interesting patents from a technological influence point of view lie in the long right tail. These are the inventions that some might refer to as 'breakthrough' inventions. In the right hand tail in right panel in Figure 2 is the most highly cited pollution abatement-related patent in the dataset. Patent number 5974791 is titled 'Exhaust gas purification device for an internal combustion engine' which received 308 adjusted citations. This patent received over 19 times more citations than the mean pollution abatement patent. It was granted to Toyota in 1999. The abstract of the patent filed with the USPTO sheds light on the characteristics of the invention which may have caused it to be so highly cited.

> In an exhaust gas purification device, an exhaust gas passage of a diesel engine diverges into two branch pipes and a particulate filter (DPF) is disposed in each of the branch pipes. The DPF uses a metallic substrate and NOx absorbent is attached to the wall of the paths in the DPF [sic]. Therefore, the DPF act as both a normal particulate filter and a NOx absorbent. During the operation of the engine, SOx, as well as NOx, in the exhaust gas is absorbed in the NOx absorbent in the DPF. An electronic control unit (ECU) monitors the amount of SOx absorbed in the DPF during the operation and, when the amount of SOx absorbed in one DPF increases, switches the exhaust gas flow to the other DPF. The ECU further performs the SOx recovery operation to release the absorbed SOx from the DPF. After completing the SOx recovery operation, the ECU performs the regenerating operation of the DPF in which the particulate matter trapped in the DPF is burned. Since SOx in DPF [sic] is already released by the previous SOx recovery operation when the regenerating operation of the DPF is performed, the growth of sulfate particle in the DPF does not occur even if the DPF is exposed to a high temperature lean air-fuel ratio atmosphere of the regenerating operation. (Hirota and Tanaka 1999)

Patent 5974791 was granted on an invention that simultaneously modifies at least four different subsystems of a vehicle in a way that leads to the abatement of two pollutants, NOx and SOx. The scope of this invention is not constrained to one vehicle subsystem or component like many others in the dataset. Many others modify just the combustion timing device or just the substrate on the catalytic converter for example. The invention described here makes a range of small, harmonizing modifications across at least four areas of the vehicle. Those changes are elaborated in less technical language as follows.

First, the invention modifies the exhaust gas handling subsystem when it re-routes the flow of exhaust gasses exiting from the engine. Gasses are re-routed to pass through one of two branch pipes. Second, it modifies the vehicle's electronic engine control system when it devotes part of the electronic control unit's (ECU) capacity to monitoring the amount of NOx absorbed from the exhaust gasses by the substrate and the amount of particulate matter trapped by the filter. Third, the invention modifies the existing pollution control system by altering the diesel particulate filter (DPF) so that it becomes essentially two devices in one: both a filter for trapping particulates in the exhaust gasses and a NOx adsorber. Fourth, these changes all work together to accommodate a combustion process that has already been engineered to eliminate the formation of HC and CO. To appreciate this fourth aspect requires an appreciation of the way automobile manufacturers have historically dealt with HC and CO.

Historically, one of the most prominent areas of pollution control technology development has been to burn the fuel within the combustion chamber in the engine more leanly, that is in the presence of an excess of air. Burning fuel with excess air raises the combustion temperature high enough to incinerate the HC and CO gasses that are a by-product of the combustion process even before they become harmful emissions (Faiz, Weaver and Walsh 1996; Nader 1965; Reitze 2001). The problem with this approach is that running the engine with excess air raises the temperature of the remaining exhaust gasses. A high exhaust gas temperature tends to deactivate the substrate that deals with the third pollutant that needs controlling, NOx. The combustion process modification approach therefore leads to a trade-off where control of HC and CO is good but control of NOx suffers. An elegant and appealing aspect of patent 5974791 is that it regulates the temperature of the NOx-adsorbing substrate by switching the flow of exhaust gasses to a second branch pipe when the substrate in the first branch pipe gets too hot. This partly overcomes the trade-off.

A chief characteristic of this patent is therefore that it harmonizes and modifies all four of these vehicle subsystems at once. This characteristic is consistent with the second hypothesis set out in Section 2 about the causes of high-influence inventions. That hypothesis stated that the breadth or diversity of the knowledge stock that the inventor brings to bear on the pollution abatement problem should associate positively with high-influence pollution abatement inventions. Since a narrow, specialized knowledge stock is the opposite of a broad, diverse one, this hypothesis also implies that the more specialized the knowledge stock the inventor brings to bear on the problem, the less influential should be the resulting pollution abatement inventions. Patent number 5974791 is interpreted as evidence that is consistent with this hypothesized relationship. It does its job by modifying four vehicle subsystems simultaneously in a way that would have been difficult without a broad, diverse stock of technical knowledge.

This most highly cited invention could of course be an anomaly in the data set. But closer inspection of a group of highly influential patents shows that it has a lot in common with other high-influence inventions. Table 3 presents a range of characteristics of the top 20 most highly cited inventions by the adjusted citations measure. The top 20 have some common features. Fourteen out of 20 were applied for in or after 1995. Sixteen out of 20 were assigned to Japanese companies. Fourteen out of 20 were assigned to Toyota. Not a single patent in the top 20 was assigned to a supplier company meaning every single one was assigned to a manufacturer. Nineteen out of 20 were intended only for pollution abatement and for no other purpose. There are also distinct trends in the technology classification of these patents, discussed shortly.

Table 3: Characteristics of highly-cited pollution abatement patents: HJT method

Rank	Citations received	Application year	Patent class/subclass	Inventor country	Company	Manufacturer	PA-only	PA-partly
1	308	1998	60/276	JP	TOYOTA	1	1	0
2	239	1998	60/285	JP	TOYOTA	1	1	0
3	192	1998	60/285	JP	TOYOTA	1	1	0
4	191	1993	60/276	JP	TOYOTA	1	1	0
5	187	1996	60/274	DE	DCHRYSLR	1	1	0
6	181	1998	60/277	JP	TOYOTA	1	0	1
7	176	2001	60/285	JP	TOYOTA	1	1	0
8	174	1996	60/276	JP	TOYOTA	1	1	0
9	170	1999	60/285	JP	NISSAN	1	1	0
10	169	1994	60/276	JP	TOYOTA	1	1	0
11	163	1994	60/274	US	FORD	1	1	0
12	157	1996	60/278	JP	TOYOTA	1	1	0
13	156	1995	60/274	US	FORD	1	1	0
14	151	1992	60/276	JP	TOYOTA	1	1	0
15	149	1996	60/276	JP	TOYOTA	1	1	0
16	147	1996	60/276	JP	HONDA	1	1	0
17	144	1999	60/274	DE	VW	1	1	0
18	143	1994	60/276	JP	TOYOTA	1	1	0
19	142	2001	60/285	JP	TOYOTA	1	1	0
20	138	1996	60/276	JP	TOYOTA	1	1	0

The number of citations received in column 2 in this table is based on the adjustment method discussed above. It is possible that the adjustment itself could be determining which patents occupy the top 20 slots. Perhaps the raw number of citations received or the number of citations received adjusted by a different method would change the top 20 and therefore change what appear to be common characteristics of highly influential patents. To check this, Table 4 compares the top 20 when measured by raw citations, when measured by citations adjusted in a different way, and when measured by citations adjusted in the present way. The main difference with the alternate 'fixed effects' adjustment method compared to the one used so far is that it strips out all time-based influences.[28]

[28] It divides the number of raw citations a patent received by the mean number of citations all patents in its cohort received. This strips out all time-based effects on citations regardless of whether these effects are artificial (arising from sources like greater search capability) or real (patents arriving later in time are genuinely more valuable or influential) (Hall, Jaffe and Trajtenberg 2001).

Table 4: Characteristics of highly-cited pollution abatement patents: other measures

	1995 or later	Japanese	Toyota	Manufacturer	PA-only	Technology class 60
Raw citations received	14/20	14/20	12/20	18/20	19/20	18/20
Adjusted (FE method)	20/20	14/20	4/20	19/20	12/20	8/20
Adjusted (HJT method)	14/20	16/20	14/20	20/20	19/20	20/20

Even when measured in terms of raw citations and citations adjusted by the fixed effects method, the 20 most highly cited patents still tend to have in common the same characteristics as before. The majority were still applied for in or after 1995, assigned to Japanese inventors, assigned to manufacturers and not suppliers, and intended for no other purpose than pollution abatement. The one exception is that under the fixed effects adjustment method, a smaller proportion of the top 20 were assigned to Toyota. The difference is accounted for by other Japanese manufacturers: Honda and Nissan together account for 9/20 while General Motors accounts for 3/20. The citation measurement method does not substantially alter the common characteristics of the most highly cited pollution abatement inventions.

There are also important patterns in the USPTO technology classification of the most influential patents. The technology classification that occurred most frequently in the top 20 across all three citation measures was technology classification 60, ‘Power plants.’ According to the USPTO this technology classification refers to inventions for the purpose of ‘converting energy into mechanical motion’.[29] Depending on the citation measure, between 40 and 100 per cent of the top 20 fell into this classification.

This is curious because not nearly the same proportion of patents fall into technology classification 60 when the data set is considered in terms of patent *counts*. By patent *counts*, only 31.7 per cent (1,272) of all pollution abatement-related patents fall into technology classification 60. This means that there are proportionally more ‘Power plant’ patents in the top 20 by *citations* than there are in the entire data set by patent *counts*. This means that the proportion of patents in the whole dataset classified as ‘Power plant’ patents is a poor predictor of the proportion of ‘Power plant’ patents that occupy the top 20 by citations.

[29] ‘This is the residual class concerned with the driving of a load by the conversion of heat, pressure, radiant, or gravitational energy into mechanical motion. It includes a motor in combination with its energy supply or its exhaust treatment. It also includes the motors, per se, combinations of motors, and elements specialized for use in such energy conversion that are not specifically provided for elsewhere’ (USPTO 2011).

The opposite is true for technology classification 123, 'Internal combustion engines'.[30] Between zero per cent and 35 per cent of the top 20 patents by *citations* fall into this classification, yet 52 per cent (2,069) of the full data set falls into this classification by *counts*. This means that for technology classification 123, the proportion of patents in this technology class in the dataset as a whole does a poor job of predicting the proportion of patents in this technology class to occupy the top 20. Whereas with classification 60 patent counts under predict the number in that classification in the top 20, with classification 123, patent counts over-predict. This implies that prior studies testing the effect of independent variables on inventive activity measured in patent *counts* may not be generalizable to the effect of the same factors on patent *value* or *technological influence*.

Patterns also emerge in the distribution of a larger group of influential patents across technology classes, particularly over time. Table 5 considers a subset of merely 'influential' pollution abatement patents defined as those receiving 15 or more citations. There were 1,173 pollution abatement patents in the dataset receiving 15 or more citations (29.2 per cent). Table 5 gives the proportion of these 'influential' patents by technology class and time period. The first row shows that 17.32 per cent of influential patents applied for during the period 1973 – 1985 were classified as 'Power plant' patents whereas 40 per cent of influential patents applied for during the period 1986 – 1995 were classified that way. The first period begins in 1973 because the patents are organized on the basis of application date.

[30] 'This class contains inventions relating to prime movers or engines in which a combustible material is burned within an inclosed [sic] space or chamber and the heat energy thus developed converted into work by permitting the resulting products of combustion to act upon and through mechanical powers, the engine in question including suitable mechanism whereby the functions above enumerated are continually and automatically carried out, and such engine being designed to communicate power to some machine or device exterior to itself' (USPTO 2011).

Table 5: Proportion of pollution abatement patents by technology classification and time period

Technology classification	1973-1985	1986-1995	1996-2006
60: Power plants	17.32	40	42.79
73: Measuring and testing	0	1.07	1.35
123: Internal combustion engines	73.23	47.73	38.74
180: Motor vehicles	0	3.73	7.96
239: Fluid sprinkling, spraying and diffusing	0	1.33	3
261: Gas and liquid contact apparatus	1.57	0	0
340: Communications: electrical	0	0.27	0.45
422: Chemical apparatus, process disinfecting, deodorizing or sterilizing	7.09	1.87	0.75
423: Chemistry of inorganic compounds	0	2.13	1.2
477: Interrelated power delivery controls, including engine control	0	0.27	2.25
502: Catalyst, solid sorbent: product or process of making	0.79	0.53	0.15
701: Data processing: vehicles, navigation and relative location	0	1.07	1.35
Total	100	100	100

Note: 'influential' patents defined as those receiving more 15 or more citations. Of interest is the change in proportion of patenting activity in each technology class over time.

This table shows that the distribution of patents across technology classifications changes quite considerably across time periods. Internal combustion engine patents (123) for example accounted for 73.2 per cent of influential pollution abatement patents in the first period, but by the third period had come to account for only 38.7 per cent. This implies that the importance of Internal combustion engine patents (123) relative to all other abatement related technology strategies waned over time. On the other hand Power plant patents (60) accounted for 17.3 per cent of the inventive effort in the first period, but by the third period had come to account for 42.7 per cent. This implies that technology strategies related to Power plants (60) became relatively more important over time.

Table 5 also shows that for influential patents, seven technology classifications had no patenting activity at all in them during the first period (73, 180, 239, 340, 423, 477 and 701). Technology classifications within the USPTO organisational system do in fact change over time, but every one of these classifications existed in 1973. The fact that there was no patenting activity in these classifications is therefore not because these classifications did not exist. Rather it seems that the majority of inventive activity initially concentrated in a few core classifications (60 and 123) before progressively diversifying outward into adjacent and additional classifications. Table 5 shows that classifications 73, 340, 477 and 701 came to account for proportionally more of these influential inventions over time. These later-entering classifications tended to relate to technology strategies that involved using electrical and electronic devices to measure, control, signal and adjust the vehicle's combustion and exhaust gas management and treatment systems. Electronic controls were a significant source of technological advancement in motor vehicle pollution control beginning in the mid-1980s (Faiz, Weaver and Walsh 1996; National Academy of Sciences 2006; NESCAUM 2000).

One can interpret these changes in technology class over time as the inventive effort behind the influential inventions adapting its location in technology space in order to exploit changing levels of technological opportunity over time. Table 5 can be interpreted as an informal test of this adaptability hypothesis. If the inventive effort did not adapt to the changing location of technological opportunity then the distribution of patenting across technology classifications would have remained more or less the same over time. Table 5 gives evidence to reject the idea that the most influential inventions failed to adapt their technological approach to abatement over time. This interpretation is consistent with Jaffe (1987) who found that the most profitable firms tended to adapt the technology region of their inventive effort to changing technological opportunity over time. Unprofitable firms kept chasing diminishing returns in over-exploited technology regions. Similarly, Podolney and Stuart (1995) found that 'dead end' inventions that never received any citations were the ones that failed to exploit new knowledge emerging in related technology areas that would have been useful to solving the focus problem.

The ability of an inventor to adapt to an emerging technological opportunity is closely linked to the second hypothesis set out in Section 2 about the impact of the diversity of the inventor's knowledge stock on the technological influence of its inventions. If the richest technological opportunities are constantly changing over time with the emergence of new knowledge in adjacent technology fields and shifting levels of demand for certain types of knowledge and technologies, then an inventor needs to possess a degree of adaptability in order to shift location in technology space as the location of technological opportunity changes. The hypothesis states that the inventors that face this changing and unpredictable technological opportunity with a diversity of existing knowledge and experience should be better able to exploit these opportunities than inventors with a narrow range of knowledge and experience (Cincera 2005).

c. Test variables

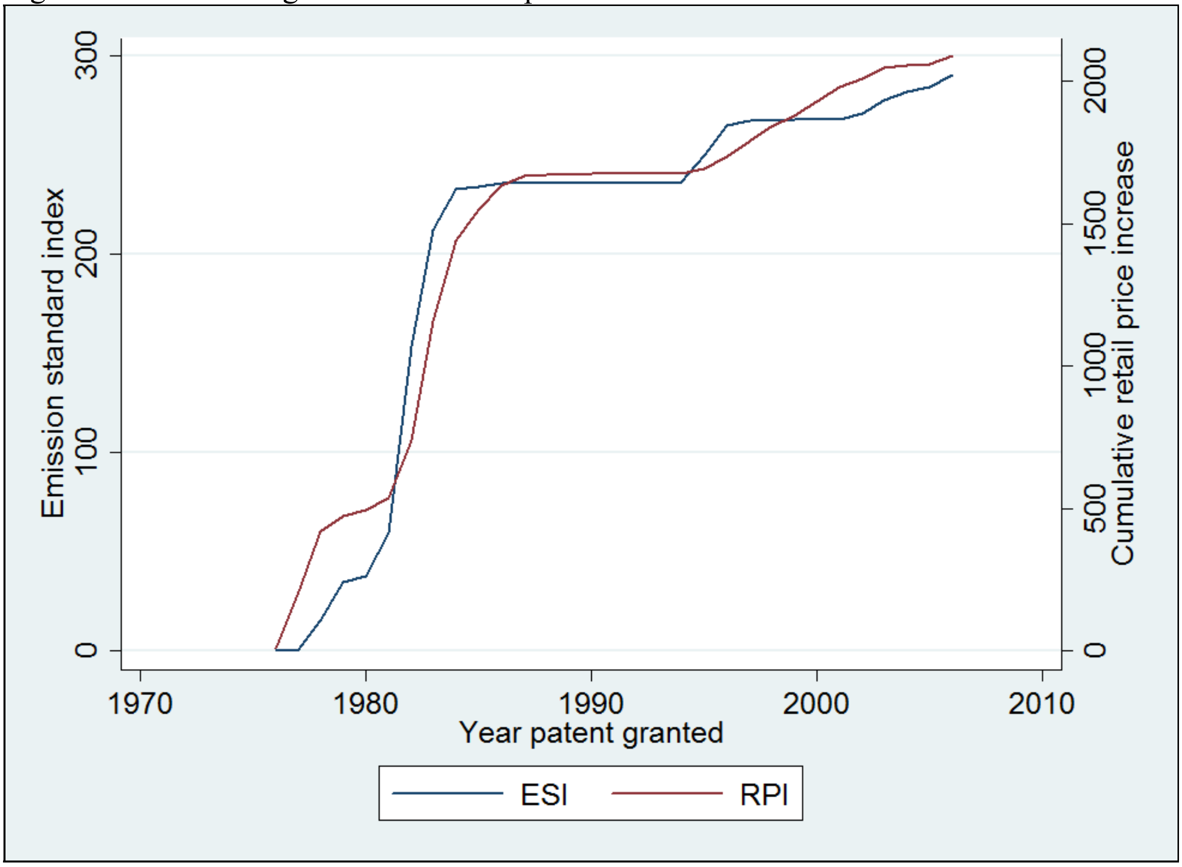
The first hypothesis stated that the technological influence of a pollution abatement-related invention should associate positively with the prevailing cost of using environmental inputs, that is, the cost of polluting. Technical knowledge for dealing with pollution should be more in demand and more influential when environmental inputs are more expensive. This hypothesis is implemented through a variable that captures the cost to automobile companies of using the environment as a disposal sink for conventional motor vehicle pollutants.

The variable is an *index of Federal emissions standards* for CO, HC and NOx from new light duty passenger vehicles. The allowable emission standard for each pollutant in each year is originally measured in grams per mile for all years 1976 - 2006. The raw data come from NASCAUM (2000) and National Academy of Sciences (2006). The standard for each pollutant is then combined into a composite Federal emission standard index (ESI) measuring the level of allowable emissions in aggregate in each year. Each pollutant is assigned equal weight. Then, since the hypothesis aims to test the effect of the changing *cost* of using environmental inputs, the index is inverted so that the least stringent emission standard approximates the lowest cost of using these inputs and the most stringent standards approximates the highest cost. This transformation is consistent with the idea that the cost of pollution control should increase at the margin on the approach to zero (Kahn 1998; Tietenberg and Lewis 2009). This variable should associate positively with invention technological influence.

Since Federal emission standards are a proxy for the cost of using environmental inputs, a second variable is used to separately test the same hypothesis. This alternate test variable is the *annual increase in the retail price of a new automobile sold in the United States that is due to meeting Federal emission control and fuel efficiency standards*. The major automobile manufacturers report this annual retail price increase (RPI) to the Bureau of Labor Statistics, which are in turn reported in Ward's Automotive Year Book (2009). The variable is calculated as the cumulative cost of meeting Federal emission standards in each year, beginning in 1968 when the Federal government first became seriously involved in the regulation of motor vehicle emissions (Bittlingmayer 1987; La Pierre 1976; White 1976). This variable more directly measures the annual cost to the automobile companies of manufacturing vehicles that use different levels of environmental inputs. This variable should associate positively with technological influence.

Figure 3 compares the two measures of the cost of using environmental inputs over time. The biggest jump in both occurs in the wake of the CAA Amendments of the late 1970s and notably not in the wake of the 1990 CAA Amendments.

Figure 3: Cost of using environmental inputs over time



The upward trends in Figure 3 introduce the possibility that these test variables associate with citations received on account of time-related unobservable influences affecting both variables. Interestingly, the simple bivariate correlation between citations received and each of these two test variables is *negative.* For the Federal ESI it is -.116 and for the Retail Price Increase it is -.147. The hypothesized direction of association is positive however. Other checks on the possibility that unobservable time-related influences are influencing the result of the hypothesis test are performed in the robustness checks section. The next subsection also goes to length to develop control variables that account for all known time-related influences on citations received.

Recall that the second hypothesis predicted a positive relationship between the breadth or diversity of the inventor's knowledge stock and the technological influence of the inventor's inventions. Greater knowledge stock diversity should make the inventor more able to perceive and exploit opportunities in the changing technological context. Knowledge breadth should increase the likelihood that what needs to be learned in the changing location of technological opportunity relates to something the inventor already knows (Cohen and Levinthal 1990). Conversely, the inventor with a less diverse (more specialized) knowledge stock should be less capable of exploiting changing technological opportunity. The narrower knowledge stock precludes or limits the possibility for associative learning (Breschi, Lissoni and Malerba 1998).

The second hypothesis is implemented through two test variables. The first measures the degree of diversity in the automobile company's knowledge stock while the second measures the degree of specialisation. Diversity and specialisation are inversely related (Cantwell 2006). *Knowledge stock diversity* is measured by the number of USPTO-assigned primary technology sub-classifications an automobile company had patented in, by a given year. This variable is calculated cumulatively within automobile companies. Two versions of the knowledge stock diversity variable are calculated. The first is based on the number of pollution abatement-related sub-classifications. The second is based on the number of general automobile industry-related sub-classifications. The expectation is that, for both versions, greater diversity should associate positively with the technological influence of the company's pollution abatement patents, all else being equal.

The second test variable captures the degree of *knowledge stock specialisation* within a company in a given year. Specialisation is measured by constructing an index of Revealed Technological Advantage (RTA). The Revealed Technological Advantage index measures the ratio of the relative share of a company's patenting activity in a technology classification, to the relative share of the company's overall patenting activity in the industry, in each year (Cantwell 2006; Lee 2001). The RTA index is similar to the Revealed Comparative Advantage index used in the international trade literature to measure relative country export (or other) specialisation (Balassa 1965). The difference with the RTA index is that instead of measuring relative export specialisation it measures relative specialisation in technological competence. The RTA index lends itself naturally to patent data organized on the basis of technology classification (Archibugi and Michie 1995; Lee 2001).

The index is calculated on the basis of USPTO-assigned primary technology classification and company, for each year:

$$RTA_{ij} = [\ (\ P_{ij}\ /\ \textstyle\sum_i P_j\ )\ /\ (\ \sum_j P_{ij}\ /\ \sum_j P_i\ )\ ]$$

where P is the count of granted patents, i denotes the USPTO-assigned technology classification and j denotes the automobile company. The numerator is the number of patents granted to the automobile company in a technology classification relative to the number of patents granted to the automobile company in all patent classifications. The numerator represents the share of a company's patenting activity in each technology classification. If a company held its entire patent portfolio in a single technology classification, the value of the numerator would be one. The denominator is the number of patents in all technology classifications combined granted to a company, relative to the number of patents in all technology classifications combined granted to the automobile industry, in each year. The denominator represents the share of the company's overall patenting activity relative to the entire automobile industry. The value of the denominator would be one in a company-year when all patents granted to the automobile industry were granted to a single company.

The index is calculated for each company-year. A company has a comparative technological specialisation when its RTA index score is greater than one and a comparative technological de-specialisation when its score is less than one. Greater specialisation is expected to impact negatively on invention technological influence. As with the diversity measure of breadth, two versions of the RTA index are calculated. The first is based on counts of patents in pollution abatement-related technology classifications; the second is based on counts of patents in all technology classifications. Table 6 shows that the knowledge diversity and knowledge specialisation measures are inversely related.

Table 6: Correlation matrix for knowledge composition variables

	Knowledge diversity (all pats)	Knowledge diversity (PA pats)	RTA index (all patents)	RTA index (PA patents)
Knowledge diversity (all pats)	1			
Knowledge diversity (PA pats)	0.8336	1		
RTA index (all patents)	-0.2618	-0.2287	1	
RTA index (PA patents)	-0.0496	-0.0394	0.1596	1

d. Control variables

Other factors internal to the USPTO patent award system can inflate or deflate a patent's count of citations received. These factors can have little to do with technological influence. Controls are constructed to account for these influences.

Truncation effects refer to the period of time a focal patent has had to accumulate citations from other patents. Truncation refers to uneven 'exposure windows' across patents when it is possible to receive citations. Within this dataset a patent with a 30-year exposure window has had more time to accumulate citations than a patent with a five-year exposure window (Hall, Jaffe and Trajtenberg 2001; Lerner 1994). The patent granted in 1976 will have received more citations by 2006 than a patent granted in 2001 simply on account of exposure, all else being equal. This variable measures the number of years between the date the patent was granted and the final year of the dataset, 2006.

Cohort effects refer to the fact that the number of patents granted annually by the USPTO has been steadily increasing over time and especially since around 1984 (Kortum and Lerner 1997; Sanyal and Jaffe 2006). Figure 1 showed that this is also the case for patents granted to the motor vehicle industry generally. As the size of each annual cohort of patents grows, each successive cohort acquires greater citation 'power' to cite previous patents (Hall and Ziedonis 2001). This probably increases the potential for backward citations to be made in aggregate though not necessarily the number of forward citations received, since the number of 'citable' patents is also increasing. This variable measures the number of general automobile (Non-PA) patents granted to all the automobile companies in each year.

Citation proliferation effects refer separately to the propensity of patents granted in some years and some technology classes to make more backward citations (Hall, Jaffe and Trajtenberg 2001). Patents granted later in time may be making more backward citations because they are truly more influenced by prior art. If this were the case then the extra forward citations observed for patents granted in later years would be a 'real' influence on the dependent variable and therefore variation of interest to explain. On the other hand, patents granted later in time may be making more backward citations to prior art because patent examiners made greater use of computerized database search tools from the mid-1990s. These search tools may have increased examiners' ability to identify relevant prior art and negotiate citations to these patents into patent documents. In this case, the larger number of backward citations observed in later years would be 'artificial' variation in the dependent variable that should be controlled for. There are also likely to be substantial differences in backward citation-making practices across technology classifications due to the different examination practices across technology divisions within the USPTO (Trajtenberg 1990). This variable measures the number of backward citations made by each pollution abatement patent to all other patents. This is appropriate because most backward citations reference patents granted close to the focal patent in time and patents in closely related technology classifications (Hall, Jaffe and Trajtenberg 2001). The main regression results include this variable because citation proliferation effects are judged more likely to be artificial than real.

Company-specific factors include subsidies national governments give to domestic corporations to incentivize R&D (Hall and van Reenan 1999), differently sized company R&D budgets or knowledge stocks brought to bear on technical problems, different scientist and engineer skill levels, different qualities of research equipment, differences in the effectiveness of R&D managers at obtaining patented inventions, reputational and industry leadership factors, and the variation in any of these over time. This variable measures the number of general automobile industry (Non-PA) patents applied for by each automobile company in each year (930 unique values).[31]

The *price of petrol* accounts for the possibility that an association between an invention's technological influence and the cost of environmental inputs is really an association between a patent's technological influence and the cost of petrol. The raw data come from the Bureau of Labor Statistics. The variable is the annual retail price of a gallon of gasoline in 2006 dollars.

The variable *PA-partly patents* controls for the possibility that some of the patents in the dataset were more influential because they solved problems in the automobile industry context that had nothing to do with pollution abatement, but for which there was acute demand. The variable is a dummy for any patent intended for a purpose additional to controlling motor vehicle pollution as judged by the abstract-reading procedure discussed above.

Table 7: Descriptive statistics, independent variables

Variable	N	Mean	Std. Dev.	Min	Max
Raw citations received	4007	7.403	11.612	0	143
Federal emission index	4007	238.346	76.077	0.000	300.000
Cumulative RPI ($2006)	4007	1,698.806	515.942	0.000	2,228.650
Knowledge diversity (all pats)	4007	3,645.207	2,466.363	3.000	8,685.000
Knowledge diversity (PA pats)	4007	150.393	111.686	1.000	438.000
RTA index (all patents)	4007	8.846	28.525	0.156	1,168.000
RTA index (PA patents)	4007	6.245	12.775	0.123	302.000
Truncation effects	4007	11.945	8.562	0.000	33.000
Cohort effects	4007	2,524.430	680.331	1,087.000	3,401.000
Citation proliferation effects	4007	6.682	5.450	1.000	109.000
Company specific factors	4007	310.259	236.821	0.000	1,115.000
Petrol price ($2006/gal)	4007	1.553	0.392	0.000	2.562
PA-partly patents	4007	0.426	0.495	0.000	1.000

[31] Company specific factors are an important source of heterogeneity and several alternative approaches to controlling for these effects were experimented with. One possibility was to include a series of year dummies plus a series of company dummies, or a series of year-company dummies. Time-related dummies are problematic in patent citation data for the reasons discussed above and in the robustness subsection. Controlling for firm-related heterogeneity with company dummies would have been a viable approach and the results of this strategy are given in the Appendix. Ultimately a strategy of constructing a control from the patent record itself was selected as the more parsimonious, theoretically fitting and accurate approach.

e. Regression results

The regressions in Table 8 test the first hypothesis that the prevailing cost of polluting leads to more influential pollution-saving inventions, all else remaining equal. Standard errors are clustered on the companies. Specification (1) includes the Federal emission standard index variable corresponding to the cost of using environmental inputs, plus the controls for patent record-specific influences on citations received. Specification (1) shows that the Federal emission standard index test variable associates positively and highly statistically significantly with citations received with a coefficient of about .006. Specification (2) adds the control variables that account for influence factors originating outside the patent record including company specific factors, the price of petrol and the invention characteristic of being intended for some purpose additional to pollution abatement. The coefficient on the test variable *Federal emission index* almost doubles in size and the standard error decreases when these extra controls are added.

Table 8: Test of the cost of polluting on invention technological influence

	(1)	(2)	(3)	(4)
VARIABLES	allcites	allcites	allcites	allcites
Federal emission index	0.00595***	0.0102***		
	(0.00147)	(0.00133)		
Cumulative RPI ($2006)			0.00135***	0.00213***
			(0.000262)	(0.000308)
Truncation effects	0.0237**	0.0886***	0.0463***	0.109***
	(0.0120)	(0.0137)	(0.0156)	(0.0177)
Cohort effects	-0.00115***	-0.000898***	-0.00127***	-0.00114***
	(9.35e-05)	(7.50e-05)	(0.000112)	(8.84e-05)
Citation proliferation effects	0.0210***	0.0198**	0.0191**	0.0184**
	(0.00759)	(0.00798)	(0.00765)	(0.00798)
Company specific factors		-0.000250		-0.000213
		(0.000360)		(0.000370)
Petrol price ($2006/gal)		-1.088***		-0.931***
		(0.147)		(0.124)
PA-partly patents		-0.217**		-0.222**
		(0.100)		(0.105)
Lnalpha	0.248***	0.167***	0.231***	0.145**
	(0.0678)	(0.0627)	(0.0677)	(0.0603)
Constant	2.901***	2.272***	2.049***	1.197**
	(0.384)	(0.257)	(0.520)	(0.511)
Observations	4,007	4,007	4,007	4,007

Note: Standard errors clustered on automobile companies in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Lnalpha is the estimate of the parameter accounting for over-dispersion in the dependent variable. Its statistical significance rejects the null that dependent variable would have been better modelled as Poisson.

Columns (3) and (4) implement the additional test of the same hypothesis using the alternate measure of the cost of polluting. Rather than using the emission standard to proxy for cost, this alternate variable directly measures the cost of polluting as the cumulative increase in the retail price of a new vehicle due to meeting Federal emission and fuel efficiency standards, as reported by the major automobile manufacturers. In column (3) this alternate test variable *Cumulative RPI* also associates positively and highly statistically significantly with citations received as expected. In column (4) where the variables accounting for competing explanations for technological influence are included in the model, the coefficient on *Cumulative RPI* retains the same level of significance and the coefficient increases considerably. Specifications (1) – (4) are taken as evidence that the cost of polluting increases the technological influence of pollution-saving inventions all else being equal. This implies that the nature of demand for new technical knowledge, that is, what type of technological capability industry requires and how acutely so, can condition the economic context in a way that is favourable to the extent of a pollution-saving invention's influence.

Since the negative binomial regression model is based on a log-linear conditional expectation function, negative binomial coefficients can be interpreted as semi-elasticities. The coefficient on the test variable *Federal emission index* of .0102 in specification (2) implies that a one-unit increase in the index increases expected citations received by about 1.02 per cent on average, all else being equal. The expected increase is calculated exactly in the usual way: $(\exp^{.0102} - 1) * 100 = 1.02$ per cent. The coefficients can also be interpreted in terms of the impact on the dependent variable *in citations* rather than per cents. Discrete changes in citations associated with each independent variable are given below. For the test variables in question here, a one standard deviation increase from the mean of *Federal emission index* variable increases the expected citation count by 4.736 citations holding all other variables in the model at their means. For the alternate test variable *cumulative RPI*, a one standard deviation increase from that variable's mean increases the expected citation count by 6.474 citations holding all other variables in the model at their means.

Table 9 implements the test of the second hypothesis about the effect of the composition of the inventor's knowledge stock on the degree of influence of the inventions it patents. Companies with diverse knowledge stocks are expected to be able to adapt quickly to changing technological opportunity in new technology regions while those with narrow knowledge stocks are not. Specification (1) is the exact same as specification (2) in the previous table, the baseline. Specification (2) adds the knowledge stock diversity variable calculated from the subclasses of all of the patents held by the company, both pollution abatement patents and general automobile-related patents. Specification (3) adds the knowledge diversity measure calculated from the subclasses of just the PA-relevant patents. Both test variables give the expected positive signs indicating that greater diversity in the composition of knowledge leads to more influential inventions, but only *knowledge diversity (PA pats)* is statistically significant. The coefficient on the 'PA' version of the diversity variable is five times stronger than the coefficient on the 'all patents' version. This implies that diversity boosts invention influence but only insofar as diversity spans the technology region related to pollution abatement. Knowledge diversity that spans the whole technology region related to motor vehicles in general is not enough.

Table 9: Test of knowledge composition on invention technological influence

	(1)	(2)	(3)	(4)	(5)
VARIABLES	allcites	allcites	allcites	allcites	allcites
Federal emission index	0.0102***	0.0104***	0.0108***	0.0104***	0.0103***
	(0.00133)	(0.00136)	(0.00148)	(0.00134)	(0.00135)
Truncation effects	0.0886***	0.0997***	0.103***	0.0910***	0.0899***
	(0.0137)	(0.0160)	(0.0166)	(0.0141)	(0.0140)
Cohort effects	-0.000898***	-0.000891***	-0.000949***	-0.000873***	-0.000875***
	(7.50e-05)	(7.03e-05)	(7.48e-05)	(7.49e-05)	(7.17e-05)
Citation proliferation effects	0.0198**	0.0200***	0.0215***	0.0194**	0.0196**
	(0.00798)	(0.00765)	(0.00799)	(0.00790)	(0.00786)
Company specific factors	-0.000250	-0.000496*	-0.000420	-0.000334	-0.000427
	(0.000360)	(0.000298)	(0.000290)	(0.000351)	(0.000330)
Petrol price ($2006/gal)	-1.088***	-1.099***	-1.152***	-1.088***	-1.079***
	(0.147)	(0.156)	(0.162)	(0.148)	(0.147)
PA-partly patents	-0.217**	-0.222**	-0.219**	-0.218**	-0.207**
	(0.100)	(0.0967)	(0.0931)	(0.0993)	(0.0977)
Knowledge diversity (all pats)		5.40e-05			
		(4.08e-05)			
Knowledge diversity (PA pats)			0.00155***		
			(0.000504)		
RTA index (all patents)				-0.00240*	
				(0.00132)	
RTA index (PA patents)					-0.0106***
					(0.00275)
Lnalpha	0.167***	0.163***	0.158***	0.163***	0.153**
	(0.0627)	(0.0609)	(0.0578)	(0.0628)	(0.0620)
Constant	2.272***	1.975***	2.000***	2.204***	2.270***
	(0.257)	(0.358)	(0.324)	(0.269)	(0.262)
Observations	4,007	4,007	4,007	4,007	4,007

Note: Standard errors clustered on automobile companies in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Specifications (4) and (5) implement the same hypothesis test using the alternate indicator of knowledge stock composition, knowledge stock specialisation, measured as the index of Revealed Technological Advantage. The coefficients on *RTA index (all patents)* and *RTA index (PA patents)* are both negative implying that the more specialised the knowledge stock held by the company, the less influential were the company's pollution abatement inventions. There is a similar pattern in the level of statistical significance in the two specialisation variables in specifications (4) and (5) as there is in the diversity variables in specifications (2) and (3). When the RTA index is calculated from the classifications of all automobile-related patents held by companies in specification (4), the coefficient is weakly statistically significant, but when it is calculated from the classifications of just pollution abatement-related patents in specification (5), it is strongly statistically significant. The coefficient on the 'PA' version of the specialisation variable is 12 times larger than the coefficient on the 'all patents' version. Having a narrow breadth of knowledge in general automotive technology is bad for coming up with influential pollution abatement inventions, but having a narrow breadth of knowledge in pollution abatement-specific technology is even worse.

The direction of the signs on the coefficients on all control variables is universally stable across all specifications in Tables 8 and 9. Only the variable *company specific factors* transitions in and out of statistical significance. Recall that *truncation effects* measures the length of exposure the patent had to accumulate citations. The positive sign implies that a longer exposure window associates with more citations received as expected. *Cohort effects* controls for changing patenting rates over time with the number of Non-PA patents granted to the automobile industry in each year. The negative coefficient implies that the quantity of Non-PA patenting activity trades off with the quality of PA-related patents in terms of technological influence. The positive sign on *citation proliferation effects* implies that the more backward citations made by pollution abatement patents, the more forward citations pollution abatement patents received. The negative sign on *company specific factors* implies that the more patenting activity undertaken by an automobile company in a given year, the less technologically influential its pollution abatement patents are predicted to be. The variable *PA-partly* is a dummy for inventions intended for some purpose other than pollution abatement. The negative sign implies that inventions which are not wholly devoted to pollution abatement tend to be less influential perhaps because an attempt to solve many problems in a single invention leads to the invention solving no single problem well.

The negative sign on the variable *petrol price* implies that an increase in the real price of gasoline leads to fewer predicted citations received by pollution abatement patents, all else staying equal. The effect of this variable is rather large in relative terms with a one standard deviation increase in the price of gasoline decreasing the number of predicted citations by 2.685 holding all other independent variables at their means. An explanation for this negative relationship might be that an increase in the fuel price caused companies to divert their inventive effort away from pollution-saving inventions toward fuel-saving inventions, causing the quality and subsequent influence of the pollution-saving inventions to suffer.

Table 10 gives the discrete change in citations received predicted by the model for each independent variable holding all other independent variables at their means. These discrete change estimates are derived from specification (3) in Table 8. Table 9 reports the discrete change in citations predicted for a change of the full range of the independent variable, a one-unit change centred around the mean of the independent variable, and a change of one standard deviation centred around the mean of the independent variable.

Table 10: Discrete change in citations received

	Min to max	1 unit	1 std dev
Federal emission index	11.020	0.064	4.980
Truncation effects	49.523	0.605	5.350
Cohort effects	-20.471	-0.006	-3.868
Citation proliferation effects	47.958	0.127	0.691
Company specific factors	-2.511	-0.003	-0.587
Petrol price ($2006/gal)	-33.403	-7.169	-2.685
PA-partly patents	-1.270	-1.290	-0.637
Knowledge diversity (PA pats)	4.501	0.009	1.020

f. Robustness

The decision to parameterize the dependent variable in the negative binomial could affect the regression results. Table 1 showed that the means and variances for all three patent groups in the dataset are unequal. Figure 1 showed that the patent citation distribution for pollution abatement patents is strongly skewed. For every specification in Tables 8 and 9 a chi-square test of the hypothesis that the negative binomial adjustment parameter (lnalpha) is equal zero (which would indicate a good fit to the Poisson distribution) was rejected with a p-value never greater than .0001 (Hilbe 2007; Winklemann 2008). These are signs that the negative binomial is a better choice than the Poisson. But is the negative binomial a better choice than OLS?

Table 11 gives estimates for negative binomial, Poisson and OLS parameterizations. The comparison is based on specification (3) in Table 10 where the test variables are the Federal emissions index and knowledge diversity measured from PA-patents. For the negative binomial and Poisson parameterizations, the dependent variable remains the raw number of citations received. For the OLS parameterization the dependent variable is the log of raw citations received.

Table 11: Comparison of estimation methods

	Negbin	Poisson	OLS
Federal emission index	0.0108***	0.0077***	0.0082***
	(0.0015)	(0.0015)	(0.0012)
Truncation effects	0.1028***	0.0459***	0.0608***
	(0.0166)	(0.0115)	(0.0125)
Cohort effects	-0.0009***	-0.0010***	-0.0009***
	(0.0001)	(0.0001)	(0.0001)
Citation proliferation effects	0.0215***	0.0156**	0.0179**
	(0.0080)	(0.0063)	(0.0076)
Company specific factors	-0.0004	-0.0004*	-0.0002
	(0.0003)	(0.0002)	(0.0001)
Petrol price ($2006/gal)	-1.1524***	-0.5533***	-0.6418***
	(0.1624)	(0.0921)	(0.0744)
PA-partly patents	-0.2187**	-0.2765***	-0.1307*
	(0.0931)	(0.0901)	(0.0697)
Knowledge diversity (PA pats)	0.0016***	0.0011**	0.0007**
	(0.0005)	(0.0006)	(0.0003)
Constant	1.9999***	2.6834***	1.8544***
	(0.3242)	(0.3528)	(0.4801)
lnalpha	0.1576***		
	(0.0578)		

Note: robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

In Table 11, the signs on the coefficients for every one of the eight independent variables, test or control, are the same in OLS as they are in the negative binomial. They are also the same in the Poisson as they are in the negative binomial. The significance level on the test variable *Federal emission standard* remains positive as expected and strongly statistically significant under OLS. The significance level on the test variable *knowledge diversity (PA pats)* also remains positive as expected and significant, but decreases from the one per cent to the five per cent level. The decision to model the data as negative binomial does not substantially change the result of the two hypothesis tests compared to OLS.

Various split sample tests were performed to see how the test variables performed in different subsets of patents. If the cost of polluting and the breadth of knowledge both increase the technological influence of patents intended ‘for pollution abatement’ then their coefficients should strengthen when regressed on the group of PA-only patents intended 'only' for pollution abatement, but weaken when regressed on the group of PA-partly patents intended for 'mixed' purposes additional to but including pollution abatement. This should be particularly true for the cost of polluting variable. Table 14 implements this test, where specification (1) is the baseline, specification (2) estimates the model only for the PA-only patents and specification (3) estimates the model only for the PA-partly patents. The *Federal emission index* coefficient strengthens and weakens respectively in the test specifications relative to the baseline as expected, and the significance level remains unchanged. The *knowledge diversity (PA pats)* coefficient increases under both test specifications relative to the baseline specification. This implies that the explanations tested here for what makes a 'pollution abatement' patent technologically influential are more generalizable to patents whose underlying inventions are dedicated solely to pollution abatement.

Some patent data studies have suggested that foreign companies tend to seek patent protection abroad only for those of their inventions they know to be most valuable (Antonelli et al. 2006; Popp 2006). This might mean that patents assigned to inventors in non-US countries are over-represented in the most influential patents in this dataset. This means the results implied by the hypothesis tests might pertain more to foreign patents than to domestic ones. Specification (4) in Table 14 tests whether the results pertain to domestic patents alone by dropping all non-US patents. The coefficient on *Federal emission index* remains positive as expected and highly significant. The coefficient on *Knowledge diversity (PA pats)* becomes insignificant. When the other three knowledge breadth variables are tested in this US-patents-only subset in the same way as the knowledge diversity variable, they all give the expected sign and they all are statistically significant at the ten per cent level at least. This implies that the results in this paper also pertain to domestic patents of potentially lower technological influence generally.

Another possibility is that the test results pertain differently to patents assigned to supplier companies than they do to patents assigned to manufacturer companies. Table 14 specification (5) shows that when the model is estimated only for the patents assigned to manufacturer companies, both *Federal emission index* and *knowledge diversity (PA pats)* give the expected signs and remain highly statistically significant. When the model is estimated only for the patents assigned to supplier companies however, the results change somewhat. For supplier-assigned patents, *Federal emission index* associates positively and statistically significantly as expected but *knowledge diversity (PA pats)* becomes insignificant. This implies that technical knowledge breadth does not affect the technological influence of patents assigned to suppliers but that as above, it does affect the technological influence of patents assigned to manufacturers.

The finding that knowledge breadth does not impact significantly on the technological influence of supplier-assigned patents is probably explained by the procedure for selecting patents for supplier companies, discussed in Section 3. All of the patent classifications that a manufacturer ever patented in would have been represented in the full automobile industry dataset because all of a manufacturer's patents would have been relevant to motor vehicles. But only some of the classifications that a supplier company ever patented in would have been represented in the full data set because only some of a supplier's patents were relevant to motor vehicles. Outside the sample, the supplier companies may well have patented in more technology classifications than the manufacturer companies, but since the selection procedure was designed to extract only patents related to motor vehicles, the full breadth of supplier company patent classifications was probably constrained.

Time-related influences could compromise the test results. If there were a time-related variable that correlated with both the dependent variable and the test variable, and which was omitted from the model, then the test result might be spurious. Section 4 (d) explained how the control variables go to length to include all known time-related influences. *Truncation effects* accounted for the different exposure windows patents had to accumulate citations from the year they were granted. *Cohort effects* accounted for the changing number of patents being awarded in the US patent system over time and therefore the different citation 'power' of differently sized patent cohorts. *Citation proliferation effects* accounted for the changing propensity of patent examiners to make citations over time. These variables account for all time-related influences known to the author. If the test variable coefficients suffer from omitted variable bias, the bias arises from an influence additional to those captured by these controls.

Further tests were performed of the effect of linear and quadratic time trends. Table 15 compares the time trend specifications against a baseline. Specification (1) is the baseline, specification (2) includes the linear time trend, specification (3) includes the quadratic time trend, and specifications (4) and (5) include the linear and quadratic time trends using the RTA index measure of knowledge specialisation, rather than diversity as in the previous specifications, for comparison. The test variable results do not change in any of these specifications.

A series of year dummies was included as an alternate method of dealing with time-based influences. This approach is problematic. The problem with using year dummies when the dependent variable is measured as citations received is that they strip out nuisance influences along with influences of substantive interest. They control for the effect of changing patent examination practices over time for example but in doing so they also strip out the effect of changing emission standards that are inextricably bound up with time. This is the same problem with adjusting citations received by the so-called 'fixed effects' method discussed above (Hall, Jaffe and Trajtenberg 2001).

For thoroughness nonetheless, Table 12 gives estimates that include 29 year dummies taking 1976 as the omitted category. Specification (1) is the baseline; specification (2) adds the year dummies. The time-linked variables *Federal emission index* and *Petrol price* do not perform as they have in previous specifications once the year dummies are included in specification (2). This is expected because the time dummies strip out all time-linked variation in citations received that was previously being picked up by *Federal emission index* and *Petrol price*. Specification (2) is a poorly specified model. It has been included to illustrate the pitfall with respect to the first hypothesis of using year dummies as a strategy to deal with time-linked influences. Specification (3) drops both time-linked variables but leaves in the year dummies. Specification (4) replaces raw citations received as the dependent variable with the HJT-adjusted version of citations received discussed in Section 4. The important point to take away from Table 12 is that the coefficient on *Knowledge diversity (PA pats)*, which is a variable that is not linked to time, remains positive and significant as hypothesized in all four specifications: more diverse knowledge leads to more influential patents.

The main results are robust to two further tests in specifications (6) and (7) of Table 14. Specification (6) tests whether the results persist when the dependent variable is changed from raw citations received to citations received adjusted by the HJT method. They are not sensitive to this change for either test variable. Finally, California has almost always had stricter motor vehicle emission standards than the Federal government in place at any given point in time due that state's unique air quality challenges. Specification (7) tests whether a variable measuring the cost of polluting based on California's emission standards changes the results. It does not.

5. Analysis and contributions

This paper makes some contributions which are theoretical, some which are empirical and some which speak to the impending policy decisions related to climate and energy R&D spending that motivated the investigation to begin with.

This is the first paper to the knowledge of the author to test whether Hicks' theory of induced innovation about the effect of input prices on inventive activity can be extended to the effect of changing prices for purely environmental inputs on not just the quantity of inventive activity, but also the quality or technological influence of discrete inventions. Popp (2002a) tested Hicks' hypothesis that inventive activity responds to input price changes with respect to energy inputs, and found evidence that it does. Newell, Jaffe and Stavins (1999) tested Hicks' hypothesis with respect to whether the energy-using characteristics of a range of domestic appliances respond to energy prices, and found evidence that they do. The present paper tested whether inventive activity responds to changes in the cost of using pure environmental inputs as a disposal sink for conventional pollutants from automobiles (pollution). Testing whether induced innovation theory extends to purely environmental inputs is important because the use of pure environmental inputs is one of the core problems climate-related R&D programmes will be designed to address. Inventive activity for GHG control is likely to be more technologically influential if it occurs under conditions where there is a cost attached to emitting GHGs.

This finding is important because at least one proposal for a climate-and-energy R&D programme for the US has suggested that very large-scale government R&D investment in R&D would be an adequate *substitute* for a legal instrument that puts a price on GHG emissions (see Hayward et al. 2010). The evidence in the present paper does not tell us that R&D spending is not a valid substitute for putting a price on carbon (but the evidence in other studies does, for example Fischer and Newell 2008). The evidence in the present paper does, however, support the idea that inventive activity for pollution abatement responds positively to the cost of using environmental inputs as a disposal sink. It is wiser to design climate and energy R&D policy on the basis of economic relationships for which evidence exists, than to design policy on the basis of relationships for which no evidence exists. This is why the majority of proposals that include both ramped-up R&D spending as well as legal instruments that price the externality (Ogden et al. 2002; Duderstadt et al. 2009; National Academy of Sciences 2009), should be preferred over those that rely on R&D as a substitute for pricing.

This paper contributes to the policy interest in the design of environmental policy instruments likely to induce the most pro-environment innovation activity (Kemp 1997; Popp et al. 2009), by showing that very large variation exists in the technological influence of individual inventions *within a single policy instrument type*. This evidence suggests that there are forces influencing the efficacy of the inventive process that run deeper than the design of the policy instrument. Pollution-saving inventions seem to be more influential when a) they emerge in the immediate wake of new demand for pollution-saving technical knowledge; b) the inventing company brings a wider breadth of technical knowledge to bear on the abatement problem; and c) when the inventing company adapts its abatement strategy to the changing location and extent of inventive opportunity in technology space over time. These invention influence factors may not remain the same across policy instrument types, but to the extent that they say something about the inventive process for pollution abatement itself that underlies all policy instrument choices they can at least be taken to inform the innovation-stimulation aspect of policy design choices.

This paper contributes to the fast-growing body of environmental innovation and technological change research using patent data by offering insights into how these studies might use the patent record with more precision. Other studies have tested the association between citations received and the social value of inventions (Trajtenberg 1990) and the association between citations received and the value of patent protection (Harhoff et al. 1998). This is the first paper to the author's knowledge to use citations received as an indicator of something akin to the technological quality, impact, importance or influence of patented inventions for the specific purpose of pollution abatement, and to test explanations for the heterogeneity in invention influence that informs the design of climate and energy R&D policy. This paper found that the most highly-cited motor vehicle pollution abatement inventions were between 16 and 29 times more technologically influential than the mean invention, depending on the measure of citations received.

The technological strategies they embodied tended to span several technology regions dealing with several subsystems of the vehicle; they tended to be assigned to foreign and particularly Japanese companies; they tended to be assigned to manufacturer and not supplier companies; and they tended to fall into certain technology regions. Future studies that use patent data to construct stocks of knowledge, by technology classification for example, should therefore always consider weighting patents by a measure of influence such as citations (Griliches 1990), to guard against the potential bias of omitting the knowledge 'impact' dimension from such stocks.

This data set construction procedure in this paper also sheds light on how the patent record can be used with greater precision. Considerable effort was invested in ensuring that only patents relevant to motor vehicle pollution control wound up in the dataset. The discussion of the dataset construction process showed that manually reading through patent abstracts on-screen made it possible to discard over 53 per cent of patents returned by a carefully design Boolean search term as irrelevant to the purpose of pollution abatement. Taylor (2001) found that abstract reading made similar improvements to the precision of a dataset concerned with patents for SO2 control. Manually reading through abstracts is not the quickest way to identify a group of research question-relevant patents, but this paper finds that that technique seems to go a long way to eliminating irrelevant patents and therefore statistical noise in the regression estimates. More precise datasets can reduce the scope for mis-estimated coefficients and poorly-informed policy advice. This is not intended to suggest that the group of patents identified in this study is noise-free or that the abstract reading process managed to identify the best possible group of technology sub-classifications to analyse. What this is intended to suggest is that excess noise can arise from dataset construction techniques based only on Boolean search terms (Yeh et al. 2005) or based only on patent sub-classifications (Popp 2002b), and that this noise can obstruct researchers from reaching good answers to important questions.

The result from the second hypothesis test is the most original finding to come out of this investigation. It gives the first empirical evidence to the author's understanding that an aspect of the knowledge stock other than the stock's sheer size impacts on pollution-saving inventive activity and therefore on the broader process of pollution-saving technological change. This finding supports Verdolini and Galeotti's (2009) conclusion that the foreign and domestic components of the knowledge stock available to domestic inventors each impact on domestic inventors' inventive activity levels differently. It supports Gerlagh's (2008) finding that within the knowledge stock made available to an economy through R&D, variation in the stock by end-use (carbon-based energy R&D, carbon-saving energy R&D, or neutral R&D) leads to crowding out among components of the stock, which in turn affects the rate and direction of environment-saving technological change. It supports Goulder and Schneider's (1999) finding that a different kind of within-stock heterogeneity affects the same outcomes, namely the degree of appropriability of different knowledge stock components. It corroborates too Cohen and Levinthal's (1990) evidence that the diversity of a firm's prior-held knowledge impacts positively on the firm's ability to recognize the value of important ideas in its external environment and assimilate those ideas into its own innovation process. The finding here implies that Cohen and Levinthal's concept of absorptive capacity can be extended to firms involved in inventive activity for pollution abatement. The knowledge breadth finding contributes to our theoretical understanding of the way technological progress in a modern context proceeds, in a pollution-saving direction or otherwise, by opening up the possibility that knowledge cumulativeness, knowledge proximity (Breschi, Lissoni and Malerba 1998), knowledge origin (Verdolini and Galeotti 2009) and within-stock knowledge structures all *also* matter for technological progress, in addition to simply the size of the stock.

The knowledge breadth finding also backs up some of the patterns observed in this paper about the characteristics of highly influential pollution-saving inventions within the automobile industry specifically. These patterns shed empirical light on how, within this industry, GHG-saving technological change might proceed. This paper finds that the most highly influential pollution-saving inventions tended to be conceived from a position of technical *breadth of understanding* across technology fields rather than from a position of technical depth of understanding within any one technology field. The most highly influential inventions tended to render this understanding into physical form by *harmonizing and integrating* different sub-systems of the vehicle rather than replacing or attending to individual sub-systems in isolation. They tended to exhibit *adaptability* in the way they went about extending the technological frontier for abatement by exploiting and repurposing knowledge from adjacent fields in line with shifting technical opportunity, rather than stagnating in single knowledge areas to pursue diminishing returns. Much in the way firms go about actually physically reducing pollutant emissions within a plant or a firm by exploiting the cheap and easy abatement opportunities first (Kahn 1998; Tietenberg and Lewis 2009), they may also exploit first the cheap and easy opportunities for extending the technological possibility frontier for abatement itself. These may be among the most influential pollution-saving inventions.

Policymakers concerned with designing climate and energy R&D programmes for maximum impact should consider using the public sector's relative insensitivity to the market forces that tend to concentrate firm R&D effort in a narrow range of technical fields (Breschi, Lissoni and Malerba 1998). They should promote R&D collaboration across industry sectors, across technical knowledge areas, and across firms that might not normally collaborate. This could increase the exposure of firms to the broader variety of technical knowledge types that the findings in this paper suggest increase the role that inventive activity plays in pollution-saving technological change.

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7. Appendix

a. Criteria guiding patent categorisation by abstract

With respect to categorizing patents by the information in their abstracts according to whether they were ‘only’, ‘partly’ or ‘not at all’ intended for pollution abatement from light duty vehicles, several decision criteria were established at the outset.

All patents for processes and devices to measure the volume or composition of gasses from the combustion process or exhaust system were deemed relevant, as long as evidence existed in the patent abstract that the inventor intended the invention to measure substances classified as automobile pollutants.

Patents related to the control of formaldehyde and other ‘hazardous substances’ as defined in the 1990 Amendments to the Clean Air Act were categorically excluded. The quantity by weight of hazardous substances from the combustion process is very small compared to the quantity by weight of criteria pollutants HC, CO and NOx. Moreover, these substances were not wholly regulated throughout the full time period considered, and regulatory pressure on automakers to abate these substances was not nearly as stringent. Very few hazardous substance-related patents were encountered anyway.

The 1990 CAA did not actually set standards for other hazardous substances benzene, formaldehyde and 1,3 butadiene but rather directed EPA to study the need for and feasibility of controlling emissions of these substances from motor vehicle emissions..

Inventions with a stated purpose of reducing emissions from diesel engines were excluded because the vast majority of passenger automobiles manufactured and operated in the United States now run on unleaded fuels.

If the patent abstract did not state or imply an application to abating pollution from light duty passenger vehicles in the abstract, or this was not obvious from the abstract to someone with a reasonable knowledge of the technical means of emissions control in motor vehicles, the patent was deemed irrelevant.

Inventions to improve service station handling of gasoline vapours during the vehicle refuelling process were excluded because these do not improve emissions from the vehicle itself but rather improve emissions from the apparatus of the refuelling process.

b. Construction of Boolean search term

Search terms referring to country-specific policy terms ('Tier-1' or 'Tier-2' or 'Euro standards') were omitted which allowed for the possibility for LDV pollution abatement patenting activity to be induced by factors other than policy events.

The term 'engine' was experimented with in case technical innovations to control pollution from engines used in other non-automotive applications may have spilled over into vehicle-engine applications. Most relevant inventions were very explicit about including both the terms 'automobile' or a synonym of automobile, as well as 'engine', meaning most patents would have been caught by the first set of *host technology* terms.

A 256 character-limit on query length applies to the USPTO's online patent search tool. This forced the phrase to be kept to a reasonably short length. Search phrase length restrictions caused potentially relevant but less essential key words like 'lead', 'aromatic hydrocarbons', and 'sulphur' to be left out.

Data for granted patents were collected only until the year 2000. In the year 2000 the total number of patent *applications,* for all purposes, filed with the USPTO begins to drop off as a symptom of the truncation process. Truncation occurs partly due to the time lag between the date a patent application arrives at the USPTO and the date the patent officer takes a decision to grant, review or reject the application.

c. Supplemental regressions

Table 12: Estimates with year dummies

VARIABLES	(1) allcites	(2) allcites	(3) allcites	(4) cr_hjt
Federal emission index	0.0108***	-0.0278***		
	(0.00148)	(0.00664)		
Truncation effects	0.103***	0.188***	0.169**	0.162**
	(0.0166)	(0.0636)	(0.0819)	(0.0811)
Cohort effects	-0.000949***	-0.000558***	-0.000558***	-0.000383**
	(7.48e-05)	(0.000149)	(0.000150)	(0.000158)
Citation proliferation effects	0.0215***	0.00976	0.00977	0.00779
	(0.00799)	(0.00670)	(0.00669)	(0.00712)
Company specific factors	-0.000420	-0.000993***	-0.000993***	-0.000937***
	(0.000290)	(0.000183)	(0.000183)	(0.000191)
Petrol price ($2006/gal)	-1.152***	0.0258		
	(0.162)	(0.0745)		
PA-partly patents	-0.219**	-0.182***	-0.182***	-0.126**
	(0.0931)	(0.0635)	(0.0632)	(0.0531)
Knowledge diversity (PA pats)	0.00155***	0.00302***	0.00302***	0.00315***
	(0.000504)	(0.000397)	(0.000397)	(0.000547)
appyr_77		1.314***	0.250	0.254
		(0.232)	(0.316)	(0.310)
appyr_78		1.618***	0.533*	0.499*
		(0.0895)	(0.299)	(0.286)
appyr_79		1.980***	0.878***	0.821**
		(0.117)	(0.336)	(0.329)
appyr_80		5.905***	1.004**	0.945**
		(0.832)	(0.445)	(0.430)
appyr_81		7.778***	1.150**	1.066**
		(1.139)	(0.544)	(0.532)
appyr_82		8.078***	1.430**	1.302*
		(1.063)	(0.691)	(0.677)
appyr_83		8.431***	1.755***	1.628**
		(1.114)	(0.649)	(0.634)
appyr_84		8.516***	1.818***	1.699**
		(1.062)	(0.686)	(0.676)
appyr_85		8.920***	2.199***	2.075***
		(1.040)	(0.775)	(0.771)
appyr_86		9.188***	2.449***	2.294***
		(0.939)	(0.859)	(0.849)
appyr_87		9.493***	2.720**	2.596**
		(0.819)	(1.091)	(1.080)
appyr_88		9.433***	2.642**	2.534**
		(0.876)	(1.058)	(1.039)
appyr_89		9.939***	3.127***	3.044***
		(0.782)	(1.142)	(1.122)
appyr_90		10.01***	3.180***	3.147***
		(0.805)	(1.187)	(1.164)
appyr_91		10.44***	3.596***	3.609***
		(0.690)	(1.320)	(1.294)
appyr_92		10.59***	3.723***	3.778***
		(0.724)	(1.394)	(1.366)
appyr_93		10.59***	3.703**	3.855***
		(0.653)	(1.443)	(1.415)
appyr_94		11.56***	3.761**	3.948***
		(0.852)	(1.478)	(1.453)
appyr_95		11.60***	3.792**	4.053**
		(0.813)	(1.627)	(1.591)
appyr_96		11.89***	4.058**	4.367***

		(0.743)	(1.696)	(1.666)
appyr_97		12.02***	4.175**	4.522**
		(0.649)	(1.936)	(1.900)
appyr_98		12.43***	4.561**	4.999***
		(0.659)	(1.926)	(1.901)
appyr_99		12.52***	4.620**	5.189**
		(0.600)	(2.090)	(2.049)
appyr_00		12.11***	4.207*	5.002**
		(0.582)	(2.203)	(2.164)
appyr_01		12.06***	3.805*	4.838**
		(0.695)	(2.248)	(2.212)
appyr_02		11.75***	3.362	4.860**
		(0.662)	(2.355)	(2.318)
appyr_03		10.86***	2.459	4.314*
		(0.624)	(2.441)	(2.411)
appyr_04		10.43***	1.569	3.987
		(0.678)	(2.703)	(2.584)
appyr_05		8.553***	-0.327	2.966
		(0.970)	(2.727)	(2.618)
appyr_06			-8.888***	-13.09***
			(2.756)	(2.679)
lnalpha	0.158***	-0.179***	-0.179***	0.368***
	(0.0578)	(0.0410)	(0.0410)	(0.0696)
Constant	2.000***	-2.851	-2.245	-2.290
	(0.324)	(1.910)	(2.389)	(2.360)
Observations	4,007	4,007	4,007	4,007

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Omitted category is 1976.

Table 13: Estimates with firm dummies

VARIABLES	(1) allcites
Federal ESI	0.0109***
	(7.947)
Truncation effects	0.0881***
	(6.083)
Cohort effects	-0.000940***
	(-10.21)
Citation proliferation effects	0.0191**
	(2.264)
Company specific factors	-4.48e-05
	(-0.115)
Petrol price $2006/gal	-1.107***
	(-8.246)
PA-partly patents	-0.204**
	(-2.261)
d_BENDIX	0.269
	(1.506)
d_BMW	-1.283***
	(-12.97)
d_BOSCH	-0.575***
	(-6.229)
d_CHRYSLER	-0.497***
	(-4.828)
d_DCHRYSLR	-0.371***
	(-9.996)
d_FIAT	-0.831***
	(-5.272)
d_FORD	-0.175***
	(-4.253)
d_GM	-0.279***
	(-10.66)
d_HITACHI	-0.410***
	(-3.420)
d_HONDA	-0.454***
	(-7.205)
d_HYUNDAI	-0.939***
	(-11.26)
d_ISUZO	-0.408***
	(-4.387)
d_JAGUAR	-0.262**
	(-2.071)
d_KIA	-1.880***
	(-25.01)
d_MAZDA	-0.121
	(-1.483)
d_MITSUB	-1.251***
	(-9.968)
d_NISSAN	-0.0949**
	(-2.108)
d_PACCAR	0.451***
	(2.818)
d_PEUGEOT	-1.198***
	(-9.045)
d_PORSCHE	-0.888***
	(-8.296)
d_RENAULT	-22.65***
	(-22.07)
d_SAAB	-1.371***
	(-13.88)
d_SIEMENS	-0.420***

	(-4.828)
d_SUZUKI	-0.629***
	(-6.331)
d_VOLVO	-1.998***
	(-15.85)
d_VW	-0.300***
	(-2.891)
Lnalpha	0.114*
	(1.918)
Constant	2.464***
	(7.850)
Observations	4,007

Robust z-statistics in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Toyota is omitted category.

Table 14: Split sample and other model quality checks

VARIABLES	(1) allcites	(2) allcites	(3) allcites	(4) allcites	(5) allcites	(6) cr_hjt	(7) allcites
Federal emission index	0.0108***	0.0125***	0.00909***	0.00939***	0.0102***	0.00613***	
	(0.00148)	(0.00166)	(0.00132)	(0.00131)	(0.00146)	(0.00133)	
Truncation effects	0.103***	0.106***	0.119***	0.0585**	0.0927***	0.0329**	0.0733***
	(0.0166)	(0.0177)	(0.0202)	(0.0271)	(0.0138)	(0.0146)	(0.0194)
Cohort effects	-0.000949***	-0.00106***	-0.000641***	-0.00121***	-0.000942***	-0.000473***	-0.00108***
	(7.48e-05)	(8.40e-05)	(0.000134)	(0.000109)	(7.03e-05)	(7.75e-05)	(8.34e-05)
Citation proliferation effects	0.0215***	0.0166	0.0284***	0.0227***	0.0241***	0.0215***	0.0236***
	(0.00799)	(0.0108)	(0.00689)	(0.00618)	(0.00849)	(0.00739)	(0.00785)
Company specific factors	-0.000420	-0.000310	-0.000556**	-0.000771***	6.59e-05	-0.000455*	-0.000472
	(0.000290)	(0.000386)	(0.000276)	(0.000285)	(0.000367)	(0.000246)	(0.000316)
Petrol price ($2006/gal)	-1.152***	-1.063***	-1.321***	-0.949***	-1.081***	-0.817***	-0.671***
	(0.162)	(0.165)	(0.168)	(0.191)	(0.145)	(0.136)	(0.113)
PA-partly patents	-0.219**			-0.0368	-0.194*	-0.166**	-0.285***
	(0.0931)			(0.0959)	(0.104)	(0.0792)	(0.0999)
Knowledge diversity (PA pats)	0.00155***	0.00161*	0.00161**	-0.00242	0.00129***	0.00218***	0.000772
	(0.000504)	(0.000903)	(0.000667)	(0.00262)	(0.000380)	(0.000388)	(0.000548)
California ESI							0.00833***
							(0.00212)
	0.158***	0.184***	0.0892	-0.161**	0.132**	0.497***	0.236***
	(0.0578)	(0.0580)	(0.0607)	(0.0632)	(0.0610)	(0.0651)	(0.0716)
Constant	2.000***	1.674***	1.456***	3.589***	2.044***	2.930***	2.847***
	(0.324)	(0.359)	(0.530)	(0.846)	(0.287)	(0.332)	(0.719)
Observations	4,007	2,301	1,706	569	3,355	4,007	4,007

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 15: Time trend regressions

VARIABLES	(1) allcites	(2) allcites	(3) allcites	(4) allcites	(5) allcites
Federal emission index	0.0108***	0.0107***	0.0106***	0.0102***	0.0102***
	(0.00148)	(0.00149)	(0.00150)	(0.00137)	(0.00137)
Truncation effects	0.103***	-0.0212	-0.0288	-0.0333	-0.0407
	(0.0166)	(0.0493)	(0.0491)	(0.0459)	(0.0458)
Cohort effects	-0.000949***	-0.000841***	-0.000832***	-0.000766***	-0.000758***
	(7.48e-05)	(9.68e-05)	(9.76e-05)	(9.28e-05)	(9.36e-05)
Citation proliferation effects	0.0215***	0.0230***	0.0231***	0.0211***	0.0212***
	(0.00799)	(0.00800)	(0.00798)	(0.00786)	(0.00784)
Company specific factors	-0.000420	-0.000403	-0.000402	-0.000410	-0.000408
	(0.000290)	(0.000273)	(0.000273)	(0.000314)	(0.000313)
Petrol price ($2006/gal)	-1.152***	-1.156***	-1.154***	-1.083***	-1.081***
	(0.162)	(0.164)	(0.164)	(0.148)	(0.148)
PA-partly patents	-0.219**	-0.221**	-0.221**	-0.210**	-0.210**
	(0.0931)	(0.0934)	(0.0934)	(0.0981)	(0.0981)
Knowledge diversity (PA pats)	0.00155***	0.00155***	0.00155***		
	(0.000504)	(0.000497)	(0.000495)		
RTA index (PA patents)				-0.0106***	-0.0106***
				(0.00275)	(0.00275)
Time trend		-0.132**		-0.132**	
		(0.0526)		(0.0519)	
Time trend^2			-3.52e-05***		-3.50e-05***
			(1.32e-05)		(1.30e-05)
Lnalpha	0.158***	0.152***	0.151***	0.147**	0.146**
	(0.0578)	(0.0585)	(0.0585)	(0.0630)	(0.0630)
Constant	2.000***	267.2**	143.5***	266.4**	143.0***
	(0.324)	(105.4)	(52.88)	(104.1)	(52.16)
Observations	4,007	4,007	4,007	4,007	4,007

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Conclusions: findings and implications

This research set out to investigate the singular role that technical knowledge plays in pollution-saving technological change as opposed to the many different roles that knowledge can appear to play empirically, depending on the design of the environmental policy under which that change takes place. This section discusses the patterned role for knowledge that emerges across the three papers and the implications of that pattern for theory and policy. These findings are considered to be valid only within the fairly specific empirical framework set out in the Introduction that connects the three studies. The main conclusions therefore pertain to:

- The innovation response by private firms to major pollution control regulation
- The response of these firms to conventional air pollution within the United States
- The innovation response insofar as it was concerned specifically with reducing pollution emissions and not with reducing energy or other ordinary inputs
- Episodes of pollution-saving technological change constrained to relatively short study periods occurring during relatively modern times.

The main conclusions presented here are not intended to extend beyond this fairly narrow set of historical-empirical conditions. In the strictest sense the conclusions should only be seen as valid within these conditions. However, one reason for studying these regulatory events, pollutants and industries was to generate a body of evidence that might be useful for making predictive statements about the role that knowledge, and the technologies that knowledge makes possible, is likely to play in an industrial transition away from GHG emissions in future. It cannot be emphasised enough that generalising from the evidence in these three papers to the main conclusions is an entirely different endeavour to generalising from those conclusions to the GHG emissions problem. The second endeavour is characterised by a massively larger degree of uncertainty due to the scale, pervasiveness and time frame of the GHG pollution problem. To the extent that the conclusions to this study attempt to make statements about the role of knowledge in future GHG-saving technological change, they should be seen as broad speculations based on a relevant but limited foundation of evidence.

1. A pattern for knowledge

This research finds that it may have been nearly costless for the firms in this study to acquire information in the form of patents, blueprints, books, articles, instruction manuals, formulae, and software, including information that is useful for environmental protection. However it seems to have been considerably more expensive for them to transform this information into human-embodied knowledge through learning. Learning is the process of transforming information into useable knowledge (Antonelli 2002; Arrow 1962). Information becomes knowledge when it becomes embodied in a person. People formulate knowledge by acquiring information through learning. Information may be free, abundant and easy for firms to acquire, but the process of transforming information into knowledge that is useful in improving the way things are made can be costly.

These studies suggests that technical learning for the firms in these studies was costly because firms had limited and finite capacity to undertake learning activities. The resources these firms had to devote to learning were limited. The kind of worker that is able and willing to engage in technical learning is generally in short supply. It can take 25 years to train up a new scientist or engineer. This means that the supply of scientific and engineering labour tends to be relatively inelastic to demand for it (Goolsbee 1998; Goulder and Schneider 1997). Technical learning can be difficult and unpleasant work. Firms may be aware of the productivity advantages that would flow from learning but they also seem to be constrained from fully pursuing these advantages by the limited amount of learning-ready labour they have available. There is generally much more technical learning a firm would like to undertake than its available learning resources permit (Dosi 1988; Mowrey and Rosenberg 1979).

Learning capacity constraints mean that the firms in these studies had to be selective about the kind of information they chose to use their scarce learning resources to acquire. A very large amount of potentially acquirable information surrounds the firm at any given time. This information is not in the firm's possession, although it potentially could be. In these studies, firms had to make choices about which kinds of information were worth acquiring. For the same amount of learning effort, there were larger financial returns to acquiring some kinds of information compared to other kinds. Firms dealt with this variable-usefulness-of-information problem by prioritising the kinds of information that promised the largest financial returns. They devoted their scarce learning resources to acquiring the highest-return kinds of information first. Firms were constantly looking for ways to free-up learning capacity. One way they did this was by constantly shedding learning activities concerned with low-return information and re-deploying this capacity to acquire ever higher-return types of information.

This learning prioritisation process led the firms and industries in this study to systematically demote or abandon learning activities concerned with certain kinds of knowledge. They tended to de-prioritise acquiring information and maintaining knowledge and technology possibilities that had particular characteristics. Knowledge devoted to reducing pollution emissions was one kind of knowledge that firms and industries seemed to systematically demote or abandon. They demoted pollution-saving knowledge in this learning prioritisation process to low-priority status. This was especially the case when the pollution-saving knowledge was of a high degree of newness or advancedness. Knowledge with these attributes tended to require more learning resources to acquire. Forming new pollution-saving knowledge tended to occupy more learning resource than the returns to possessing that kind of knowledge could warrant.

When information is abundant but learning capacity is scarce, firms tend to de-prioritise if not wholly jettison knowledge and learning activities dedicated to reducing pollution, for several reasons implied by this research. Dedicated pollution-saving knowledge tends to have an undesirably narrow range of applications because its sole reason for existence is to deal with the pollution externality. The usefulness of dedicated pollution-saving knowledge in real world industrial applications is wholly vulnerable to the capriciousness and unpredictability of public policy decision making. Pollution-saving knowledge is prone to rapid and unforgiving obsolescence. The precariousness of pollution-saving knowledge contrasts with knowledge that has a broader range of potential applications. Knowledge of a more general purpose by contrast is more robust to the risk of obsolescence and is less prone to the unpredictability of the outcome from collective decision making.

Firms also tend to de-prioritise or jettison dedicated pollution-saving knowledge because an abundance of substitution possibilities exist for it. An abundance of possibilities exist for achieving the productivity effect that pollution-saving knowledge it is capable of rendering. These substitution possibilities can exist through changes in the firm's supply chain as has been pointed out before in the business and environmental regulation literature by Theyel (2000), Porter and van der Linde (1995) and Konnola and Unruh (2007). One contribution of this research is to reinforce the finding that simple supply chain substitutions by firms can potentially undermine or delay deeper, more learning-intensive transformations of the production process or business model. Through substitution firms can render the same productivity gains with respect to pollution without committing nearly as much technical learning capacity to the problem of complying with pollution control requirements.

The findings from this research imply that there is a hierarchy in the desirability of ideas according to the different attributes of those ideas. Dedicated pollution-saving knowledge, and especially 'new' and 'advanced' pollution-saving knowledge, tends to feature in a low position in this hierarchy. This hierarchy interacts with the generalized scarcity of firm learning capacity. This interaction inclines firms to prefer 'no-knowledge' and 'low-knowledge' pathways to raising their productivity with respect to pollution whenever these pathways are possible. Low-knowledge pathways tend to be consistent with the incremental, gradual approach many industrial facilities have been inclined to take to reduce pollution (Kemp 1997; Murphy and Gouldson 2000; Nemet 2009). Similarly in this research, firms were found to systematically de-prioritise knowledge-, technology- and learning-intensive approaches to dealing with pollution. They tended to engage in as little dedicated pollution-saving learning as possible and to adopt as little dedicated pollution-saving technology as regulation permitted. This pattern is interpreted as evidence of learning being a costly activity for firms. From the point of view of the firm there were much more important things to be devoting scarce learning resources to than acquiring a kind of technical knowledge that is fragile, substitutable and prone to rapid obsolescence.

This is the principal finding of this research. The principle finding is that once the policy influence effect had been sufficiently accounted for, the firms and industries in this study systematically de-prioritised knowledge-, technology-, and learning-intensive approaches to complying with pollution control regulation insofar as this effort was focused solely on compliance and/or pollution abatement. When firms did in fact develop or adopt advanced knowledge and technology for pollution control in these studies, this was either because the form of environmental regulation forced them to (Gerard and Lave 2005; La Pier 1976; Stavins 1998), or because the form of regulation prescribed specific, relatively advanced abatement technologies that regulators had chosen themselves (Popp 2003; Taylor 2001), or because firms had turned to them as a last resort after exhausting all the simple options. This de-prioritisation process led firms to avoid acquiring new, dedicated pollution-saving knowledge and technology altogether if this was possible.

One way that this finding differs from common findings the business and environmental regulation literature and some aspects of the science and technology studies literature, is in withholding judgement about whether or not unadvanced compliance and abatement methods are adequate methods of pollution control. It has been argued throughout these studies that these methods have been adequate to the pollution control problem firms have faced. The knowledge unintensive abatement methods that firms in these studies favoured were very much adequate to the regulatory and broader economic conditions prevailing upon them. These approaches were inexpensive, quick to implement and effective. This 'adequacy' interpretation contrasts with the idea that because a firm merely reduces pollution to the point of compliance through small organisational changes or production process tweaks, that is somehow not mounting a sufficiently involved response to the problem (OECD 1987; Pearson and Foxon 2012; Soete and Arundel 1997). Yet if the extent of technological change is not deep or quick enough then surely some of the blame falls on weak environmental regulation as a reflection of weak social preferences for a clean environment, or on the rigour with which pollution control regulation is enforced, or on the disproportionate political strength of polluters in the regulation-setting process.

This research finds that if low-learning, low-technology approaches were not possible then firms first tried to adapt and repurpose the knowledge they already possessed to the new problem of controlling pollution. When all of the economical pollution control possibilities from the knowledge the firm already possessed had been exhausted, they began to search for knowledge that was new in the local sense, that is, new to the firm but not universally new. Firms began this search only when the cost of compliance became sufficiently high. Once learning began, firms prioritised the kind of information that they believed would provide the largest pollution cost saving per unit of learning capacity involved. The accumulation of pollution-saving knowledge through this process tended to result in incremental modifications and adjustments to prevailing technological forms, consistent with previous findings about the stubborn prevalence of incremental approaches to industrial pollution control (Kemp 1997; Murphy and Gouldson 2000; Nemet 2009). At least in the context of these three studies, and at least over the relatively short time frames considered in them, the accumulation of knowledge in reaction to the need to reduce pollution did not radically alter or displace prevailing technological forms altogether (Dosi 1988; Ausubel 1989).

Clearly there are limits to how far these findings can be generalized. The evidence here considered the role of knowledge and technology in controlling conventional pollutants. Caution must be exercised in generalizing these findings to the role that knowledge and technology are likely to play in reducing GHG pollution. More intensive technical learning and more advanced pollution control technologies may be required than these findings imply. For example, in this research, firms found ways to control conventional pollution without consuming less fuel, as by replacing high-sulphur coal with low-sulphur coal. GHG policy has not yet become sufficiently stringent to know whether comparable techniques will emerge to control GHG pollution. Cost-driven innovation can be a very powerful force (Ausubel 1989; Hicks 1932; Schmookler 1965). However, compared to conventional pollution control, some evidence implies that there are fewer technical possibilities for reducing GHG emissions that do not involve fundamentally and radically changing the way that energy is produced. This basic difference in the characteristics of conventional versus GHG pollution may limit the generalizability of these findings to the GHG control case.

The generalizability of these findings to GHG emissions is also constrained by the 22, five and 30 year time frames of the studies which place them within a similar frame of technological reference (Geels 2002). The technological change pattern observed in these studies occurred against a backdrop of potentially much deeper technological transformations occurring at much higher technological frames of reference (Geels 2002; Konnola and Unruh 2007). During the last 200 years for example the types of new energy sources that industrialised societies have come to harness have been progressively cleaner in terms of carbon content and conventional pollution emissions. Wood gave way to coal, coal gave way to petroleum, and petroleum seems to be giving way to natural gas (Ausubel 1989), at least in the some of the applications where demand for energy services is quite particular and specific. One implication of these changes constantly occurring at higher frames of reference is that ordinary consumer demand for quieter, more convenient, less expensive, safer and more abundant energy services may ultimately usurp, or at least assist, pollution control regulation as a main driver in a shift away from GHG-intensive fuels in the long term.

Before discussing the implications of this finding for theory and policy it is important to show how this pattern emerges from the evidence in the three papers.

2. Substantiation of findings

The first paper hypothesised that the level of industrial environmental R&D spending depends conditionally on the degree of flexibility built into the prevailing environmental policy regime. The paper tracked how the form of regulation became increasingly flexible from 1973 to 1994, with regulators turning over more and more discretion to firms to deal with pollution control requirements by the methods that the firms themselves saw fit. Testing found that the environmental regulatory burden motivated less environmental R&D spending the more flexible the prevailing policy regime became. No- and low-learning compliance strategies were less of an option for polluters in the 1970s because the form of regulation essentially required polluters to perform large amounts of environmental R&D. However, when policy became more flexible in the 80s and 90s, the natural inclination of firms towards low-learning compliance approaches began to show through.

The second paper used the SO2 control impetus created by cap and trade to compare the effect of knowledge intensive compliance pathways against knowledge unintensive compliance pathways. Interview evidence showed that electric power plant R&D managers tended to outsource the environmental R&D function to the third party industry association EPRI when this was possible. This outsourcing arrangement eliminated a large amount of the redundant learning and search cost that the plant would have born had it undertaken the R&D on its own.

Also in the second paper, the multi-levelled consideration of the technical changes undergone in the railroad, coal mining and boiler manufacturing industries further supported the pattern of firm reluctance to learn. From the point of view of the regulated firm, what was even better than an institutional arrangement that defrayed the cost of pollution-saving R&D was a supply chain arrangement that shifted the learning burden almost entirely to other firms upstream in the supply chain. One reason power plants were so receptive to the possibility of burning low-sulphur coal was because someone *else* radically altered the industrial geography of coal production. Someone *else* bore the cost of extending the rail infrastructure to make it suitable for transporting low-sulphur coal across the country. Someone *else* shouldered the cost of re-designing industrial boilers to handle the new properties of lower-sulphur coal. The regulated power plants themselves did not have to bear the cost of any of this.

Even the way these upstream firms went about supplying lower sulphur coal to the power plants shows that they too would have shifted the environmental learning burden to someone else, if there was anyone further upstream to shift it to. Generally there was not. The next best approach was for these suppliers to change their coal mining and boiler manufacturing methods just minimally enough to deal with the pollution-saving learning burden that had been shifted to them. Under relative policy neutrality a wide range of actors and industries brought their technical knowledge and capabilities to bear on the pollution problem. The technical response was spread diffusely across many actors. It was not concentrated on a single actor, or on a single technology, or in a single industry.

In the third paper, the very considerable effort by the automobile companies to develop new pollution-saving inventions may seem inconsistent with the patterned role for knowledge described so far. The existence of 4,007 patented pollution-saving inventions may seem to contravene the tendency of firms to systematically choose compliance pathways that require the very least amount of pollution control-specific learning possible.

The third paper does not contravene this general pattern but rather gives it depth and dimension. In the third paper, the automobile companies spent heavily on discovering and acquiring advanced pollution-saving knowledge because they had no better option. The lack of alternate low cost abatement options was the reason for choosing the automobile emissions control context as a way to examine the variability in invention impact. This is where the methods devices used to understand the role of knowledge 'net' of the effect of policy begin to bear fruit.

The possibility that the automobile companies went searching for advanced pollution-saving knowledge as their first priority can be explained by fact that they were essentially cajoled into doing so by the regulators. The third paper discussed how the rigidity of the regulators' grams-per-mile policy approach was partly a reaction to what they perceived to be foot-dragging by the automobile companies in the 1950s and 60s to 'develop new pollution control technology'. This apparent foot-dragging was more than a sign that the automobile companies were not being fully cooperative with regulators. The pattern implies that that 'developing new pollution control technology' was far from the least expensive way for the emissions issue to be dealt with. The automobile companies may have understood this better than the policymakers. The main force that compelled the automobile companies to engage in so much inventive activity was a policy design that heavy-handedly enforced learning- and knowledge-intensive compliance, rather than the automobile companies' own learning prioritisation process, which was essentially subjugated to the preference of the state for a particular regulatory design.

If the automobile companies abided by the pattern described then they should have maximised the use of pre-existing and relatively unadvanced forms of knowledge before searching for pollution-saving inventions. The third paper did not look at the effect of pre-existing knowledge and techniques in the automobile companies' technical change response. However, the learning prioritisation pattern in the first two studies would predict the automobile companies to resort to searching for frontier pollution-saving knowledge only after exploiting all available non-frontier and low-learning possibilities.

Future research will be needed to test this prediction empirically. At least one secondary source of evidence bears light on this prediction without undertaking such a test. Pakes et al (1993) looked at the effect of technology adoption on the change in automobile fuel efficiency in the US after 1977. Federal fuel efficiency requirements essentially required the automobile companies to improve vehicle fuel efficiency by 50 per cent in the eight years after 1977. Pakes et al found that the main way the automobile companies achieved these efficiency gains was by changing the mix of vehicles they offered for sale. In the years after 1977 the automobile companies offered for sale more vehicle models that were smaller and lighter -- models which had already existed before the regulations came into force -- and retired from their vehicle lines those models that were larger and heavier. Pakes et al found that automobile companies' principal compliance strategy for dealing with the fuel economy standards was to shuffle the distribution of the vehicles they offered for sale with respect to the pre-existing fuel efficiency features. They did not develop more fuel-efficient vehicles right away. Rather they exploited the fuel efficiency feature they already possessed across a larger portion of total vehicle sales. This behaviour is consistent with the patterned role for learning and R&D that emerges across this research.

The main finding of this research rests on the assumption that firms are left to choose their own compliance pathways in a way that is not unduly influenced by the learning and technology preferences of government. It is not realistic to expect that government will remain technology neutral toward firm compliance choices in future. It is important to point out the implications of government technology preferences for these findings.

The second and third studies found that government chose to impose its technology preferences on firms at least in part to protect vulnerable parts of the body politic from the distributional consequences of environmental policy. In the case of SO2 control, letting the power plants choose their own compliance methods in the 1970s would have led to a rush to low-sulphur coal. This would have had significant negative consequences for coal mining workers in US states endowed with large deposits of high-sulphur coal. Protecting these workers from unemployment was a major reason the EPA pushed SO2 scrubbing technology to the extent that it did. Scrubbing was a technological solution to a fundamentally political-distributional problem.

Distributional factors were also a motivating force behind pollution control technology development in the automobile emission control context. The grams-per-mile approach was the regulator's way of ensuring that ambient air quality standards in urban areas would be met, even though lower and looser automobile emission standards probably would have sufficed to ensure the same ambient air quality standards in rural areas. In this way also, government used 'the development of new pollution control technology' as a strategy to mitigate distributional concerns, this time between city dwellers and inhabitants of rural areas. The reality is that governments will probably continue to steer the course of pollution-saving technological change down learning- and technology-intensive change pathways, not least to mitigate these kinds of distributional concerns in future.

The findings from the third paper suggest how firms and governments should go about searching for universally new technical knowledge when political-distributional or other circumstances make this necessary.

The third paper found that some kinds of pollution-saving knowledge have a much bigger impact on pollution-saving technological progress than other kinds of knowledge, and that some ways of searching for high quality ideas may be more efficient than others. In the search for new pollution-saving knowledge firms first scoured what they already knew for ideas that could be repurposed to the pollution problem. In the 1970s and early 1980s the automobile companies relied heavily on tweaking the engine fuel combustion system as a main strategy for dealing with pollution emissions.

After exploiting all the viable technology options that existed in the 'combustion modification' region of technology space, the companies migrated their search to the 'engine controls' region where technological opportunity was more abundant. When technological opportunity arose in new or adjacent regions like 'electronic measurement devices,' firms migrated their search attention to that new region. The automobile companies' search effort generally migrated away from technology regions where the returns to learning effort were low, and migrated toward technology regions where the returns to learning were high. What appears to be important for an automobile company to exploit the most promising pollution-saving possibilities across technology space is the company's 'learning mobility'. This is the company's ability to migrate its search across technology regions as the location of technological opportunity changes. The degree of learning mobility, and therefore the effectiveness of the firm's search, appears to be affected by the composition of the knowledge the firm brings to bear on the search effort. The third paper found that a diverse stock of knowledge facilitates learning mobility across technology space and therefore the exploitation of the best ideas. A specialised knowledge stock inhibits learning mobility.

The idea that firms favour abatement approaches that involve low amounts of learning, frontier knowledge and new technology reinforce research that points to major sources of inexpensive GHG abatement out to 2030. Enkvist et al (2007) in the 'McKinsey' GHG reduction cost curve study found that almost three quarters of potential GHG reductions come from measures that are either '. . . independent of technology or rely on mature rather than new technologies.' In the conclusions to their study they write:

> The role of technology in reducing emissions is much debated. We found that some 70 percent of the possible abatements at a cost below or equal to 40 euros a ton would not depend on any major technological developments. These measures either involve very little technology (for example, those in forestry or agriculture) or rely primarily on mature technologies, such as nuclear power, small-scale hydropower, and energy-efficient lighting. The remaining 30 percent of abatements depend on new technologies or significantly lower costs for existing ones, such as carbon capture and storage, biofuels, wind power, and solar panels. The point is not that technological R&D has no importance for abatement but rather that low-tech abatement is important in a 2030 perspective. (Enkvist et al 2007: 44)

The findings of this research echo the findings of the McKinsey study by emphasising that low-technology change opportunities that require little or no technical learning are likely to account for some of the cheapest sources of GHG reductions. The three empirical studies in this volume found a general disinclination by firms toward abatement approaches that would have involved acquiring locally new or universally new technical knowledge through learning. A driver behind this disinclination is the cost of learning. The findings of this research and the findings of the McKinsey study is that this research gives a rationale for why some abatement opportunities might be much cheaper and therefore more desirable than others. The McKinsey study describes a cost curve with low-tech building insulation at the cheap end and high-tech carbon capture and storage at the expensive end. This research goes a step further to propose one contributory reason for why these different types of actions locate at different ends of the curve. That reason is the relatively low cost of learning required to implement the cheapest abatement opportunities.

3. Implications for theory and policy

This section discusses the implications of these findings for theory and policy. These implications are illustrated in the context of controlling GHG pollution although the pattern is relevant to the role that knowledge plays in technological change with respect to all kinds of pollution.

To think concretely about these findings it is helpful to consider the extent of the productivity gains that will be needed in the next 40 years to stabilise global GHG emissions. Ekins (2009) calculated the productivity gains in CO2 (not GHG) emissions to GDP that will be needed to hold the maximum global average temperature rise to an expected change pathways of two degrees. In these calculations Ekins assumed an on-going rate of population growth of three per cent and an on-going rate of economic growth of three per cent. On these assumptions he calculated that global CO2 productivity would need to increase 10 to 15 times above its present level by 2050 in order to keep to the CO2 concentration consistent with this maximum two degree change pathway. To reach this level of productivity from today's levels will require gains of about six per cent per year. To put this into perspective, the productivity of labour in the United States increased about 10-fold during the period 1830 to 1955 (Ekins 2009). This means that CO2 productivity needs to increase by at least as much in 40 years as labour productivity increased in 125 years.

The findings in this research expand the evidence base for making informed predictions about the role that different types of knowledge are likely to play in achieving these productivity gains. A challenge to climate policymaking has been the relative paucity of hard evidence about the role that technical knowledge has played in this kind of change process historically. In a recent literature review, Gillingham, Newell and Pizer (2008) surveyed the ways that knowledge, learning and R&D have been represented in long run processes of growth under climate policy. Having reviewed 94 contributions to this literature they conclude that many of the representations of the role of knowledge are not well grounded in evidence. Concluding, they write

> Perhaps most importantly, all [approaches to representing technological change endogenously in models of growth under climate policy] struggle with an inherent lack of empirical data to calibrate model parameters convincingly ... users looking to draw normative conclusions about the costs and benefits of alternate policies need to be particularly aware of the degree to which models have been ground-truthed against historic facts and trends and ensure that opportunity costs have been accounted for properly. While exceptionally promising, there is a sense that our ability to conceptually model technological change has outstripped our ability to validate the models empirically, making this an area where policymakers and other normative users need to be particularly careful. (2749- 2751)

The findings from the present research speak to this shortcoming. They imply that universally new pollution-saving knowledge has played a smaller and more nuanced role in pollution-saving technological change historically than some of the studies Gillingham, Newell and Pizer are referring to suggest. For example, in one representation of the long term cost of climate policy, Popp (2003) found that endogenising the effect of R&D activity that is induced by a carbon tax increases overall welfare gains from the policy from 1.74 trillion dollars to 1.88 trillion (2003:17). In another representation, van der Zwaan et al (2002) found that endogenising the effect of learning by doing in the form of price decreases in clean energy production led to a 20 per cent lower peak in CO2 emissions by 2040, compared to a scenario in which technological progress was modelled exogenously (2002: 12). The present research suggests that the amount of R&D and advanced technical learning that climate policy actually induces might be smaller than previously thought. To the extent that R&D and advanced technical learning do play a role in productivity change with respect to GHG emissions, their effect may be stronger at later points in time when all the low-cost, no- and low-learning change possibilities have been exhausted.

These findings also underline that theoretical representations of the role of knowledge in pollution-saving technological change would be improved by making firmer assumptions about the design aspects of the policy instrument used to control GHG pollution. Policy design aspects strongly influence the kind of knowledge involved in this kind of change (Kemp 1997; Kemp and Pontoglio 2011; Vollebergh and Kemfert 2005). The first paper found that the amount of pollution-saving R&D firms see fit to undertake is conditionally dependent on just one of these policy design aspects: the degree of flexibility. In the third paper the grams-per-mile approach induced a considerable amount of inventive activity. These findings imply that future theoretical work can represent the endogenous effect of knowledge more accurately (Grubb, Köhler and Anderson 2002; Nordhaus 2002; Popp 2004; Sue Wing 2006) by making firmer assumptions about the nature of the policy instrument.

Exogenous representations of technological progress in pollution control have been cast as somewhat simplistic and unrealistic in the endogenous technological change literature (Grubb, Carraro and Schellnhuber 2006; Popp, Newell and Jaffe 2009). The findings from the present research imply that exogenous representations may not be entirely inaccurate. Exogenous representations might approximate productivity gains that are specifically pollution-saving and which are a response to strict policy conditions. Brock and Taylor (2010) point out that a constant rate of technological progress in pollution control maps surprisingly well onto the historical experience in the US with conventional pollution (2010: 130-131). The present findings imply that firms engage in the minimum amount of learning and knowledge production possible to meet the pollution limits set by regulators. This means that the amount of new knowledge they produce is exactly as much as necessary to meet the regulators' requirements. A constant exogenous representation of the effect of knowledge that is perfectly in line with the demands of policy may not be unrealistic.

These findings imply that climate policy models should focus on representing the causes of productivity gains with respect to GHG emissions, rather than on the causes of productivity gains with respect to energy use. Energy productivity is an attractive and empirically tractable proxy for pollution productivity (Grubb, Kohler and Anderson 2002; MacCracken et al 1999; Nordhaus 1994). However these findings show that historically, firms have innovated in ways that reduced pollution emissions without reducing energy use necessarily. The electric power plants in the second paper and the automobile companies in the third showed themselves capable of finding ways to reduce pollution without necessarily reducing fuel consumption. This implies that exogenous representations of technological progress like the Autonomous Energy Efficiency Improvement parameter (AEEI) (Nordhaus 1994; Jakeman et al 2004) may not be inaccurate because of their constancy. Energy-related representations like the AEEI may be inaccurate because they are insensitive to the fact that innovation can proceed in a direction that reduces pollution without reducing energy. An empirically-validate Autonomous Pollution Saving Improvement parameter might be more realistic.

Knowledge, R&D and learning are usually represented as expanding the range of pollution-saving production possibilities available to firms (Jorgenson and Wilcoxen 1993; Loschel 2002; Nordhaus 2002). Accumulated knowledge is represented as lowering the cost to firms of dealing with pollution. The present research found that many of the production possibilities that firms actually used to deal with pollution existed prior to the performance of pollution-saving R&D under the policy impetus. Some of the production possibilities firms made use of even existed prior to the implementation of the policy itself. This means that it may not be realistic to represent accumulating knowledge as pushing out a universal production possibility frontier in abatement (Binswanger and Ruttan 1978; Nordhaus 1969; Ruttan 1959). It may be more realistic to represent firms as making heavy use of production possibilities that already exist latently before the arrival of policy. Policy 'activates' these possibilities into use. When pre-existing possibilities are depleted, firms search for 'locally' new production possibilities in order to extend their 'local' production possibility frontiers.

These findings also have implications for policy. Carraro et al (2010) recently reviewed the environmental technological change literature. Their aim was to understand the impact of environmental regulation on technological change after environmental policy has been implemented (ex-post) and to assess the likely effect of climate policy through computer simulations before policy has been implemented (ex-ante). Carraro et al's principal policy conclusion from their review of 148 contributions to this literature was that policies to address GHG pollution need to be designed to correct both the negative environmental externality arising from pollution as well as the positive knowledge externality arising from R&D activity. They write

> R&D policy and environmental policy need to be shaped considering this "double externality" problem.... Jan Tinbergen has clearly indicated the correct approach in his essays on economic policy (Tinbergen 1952). The "Tinbergen Rule" states that the number of policy tools must be equal to the number of policy objectives.... Accordingly, policy makers should address the environmental externality by means of environmental policies and the knowledge externality by means of specific knowledge policies. (209)

The findings from the present research give reason to look more closely at the second part of this policy recommendation. It is not clear whether Carraro et al are suggesting that policy should correct the positive externality from knowledge spillovers generally or whether they are suggesting that policy should correct the positive externality from knowledge related to GHG control specifically. It is common to conclude that both elements of the 'double externality' need to be corrected (Nordhaus 1990; Jaffe, Newell and Stavins 2005; Newell 2010). However, it is not always clear whether what is being recommended is a correction of the spillover from all kinds of R&D generally or from R&D relevant to pollution control specifically.

These findings question whether the positive externality from R&D relevant to pollution control specifically is something that the empirical evidence suggests needs to be corrected, at least for the time being. There were numerous examples in this research of firms finding inexpensive ways to conform to pollution restrictions that did not involve large amounts of new R&D dedicated specifically to pollution control. When firms chose to engage in significant amounts R&D, the activities they undertook were often very difficult to distinguish from R&D activities for general purposes. Firms tended to repurpose knowledge that was originally created for solving a different problem to the new problem of dealing with pollution. After exhausting the possibilities in their existing knowledge, firms then searched for ways to modify existing 'dirty' production methods in ways that made those methods viable again.

The evidence considered in this research does not provide justification for subsidizing GHG control-specific R&D over and above a subsidy to ordinary R&D. It would be very difficult for policymakers to systematically determine which R&D activities are sufficiently 'GHG control-specific' to deserve a surplus R&D subsidy. Furthermore, there no clear reason why the knowledge and technologies required to control GHG emissions in the long run would fail to be sufficiently induced into existence by a combination of strong, credible and deep GHG limits on the one hand, and appropriate subsidization of all types of R&D on the other. These findings imply that policy should continue to be used to correct the positive externality from all types of knowledge generally (Antonelli 2002; Breschi 2002; Arrow 1969; Bloom, Griffith and Van Reenen 2002; Grossman and Helpman 1991; Jaffe, Trajtenberg and Henderson 1993) and that policy should continue to be used to correct the negative externality from GHG pollution. This would be fully consistent with Tinbergen's Rule. Within these policy constraints, firms should be left to decide the nature and extent of technological change that is appropriate for their own circumstances.

4. References

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