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Industrial characteristics, environmental regulations and air pollution: an analysis of the UK manufacturing sector

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Abstract

This paper examines and quantifies the complex linkages between industrial activity, environmental regulations and air pollution. Couched in terms of the demand for, and the supply of, environmental services we utilize a new dataset of UK industry specific emissions for a variety of pollutants between 1990 and 1998. Our analysis allows us to investigate the role played by different determinants of emissions intensity. We find pollution intensity to be a positive function of energy use and physical and human capital intensity. Conversely, we find pollution intensity to be a negative function of the size of the average firm in an industry, the productivity of an industry and the industry's expenditure on capital and research and development. Our results also indicate that regulations, both formal and informal, have been successful in reducing pollution intensity.

JEL classification: O13; L60; Q21; Q25; Q28

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1. Introduction

In recent years environmental economists and policy makers have continued to strive for a more comprehensive understanding of the relationship between industrial activity and pollution.

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To date, a large majority of the research in this area has been undertaken for the US (see e.g. Kahn [25] and Gray and Shadbegian [13–16]).

The lack of studies outside of the US is largely a consequence of a scarcity of data on pollution emissions at the sub-national level and particularly at the industry and plant level. A recently produced dataset for the UK appears to have partially rectified this problem however, and provides industry specific pollution emissions for a range of pollutants between 1990 and 2000. By merging these pollution data with industry and regional data we are able to examine industry-specific determinants of air pollution emissions employing regional characteristics to take account of regional differences in the stringency of regulations (Gianessi et al. [11]).

This objective differs somewhat from the existing US literature that has tended to concentrate on the effect of regulations on plant location, productivity and pollution abatement expenditures, usually for a small number of selected industries. Gray and Shadbegian [15], for example, examine measures of environmental regulatory activity and levels of air and water pollution in the Paper and Pulp industry, finding that emissions are affected both by the benefits from pollution abatement and the characteristics of the people exposed to the pollution. Moreover, building on the earlier micro-level studies of Bartik [4], Levinson [27], Henderson [21], Gray and Shadbegian [14] examine whether a firm's allocation of production across its plants responds to the level of environmental regulation faced by those plants. In a related literature, Hamilton [17], Kahn [25] and Helland and Whitford [20] provide estimates of the impact of political boundaries, demographics and political activism on the exposure to pollution.[1]

In this paper, we concentrate on the determinants of pollution for a large number of industries in the UK and aim to provide a greater understanding of the linkages between industrial characteristics, environmental regulations and pollution intensity. Such an analysis permits us to assess the relative importance of each determinant of pollution intensity and will indicate how pollution intensity is likely to be influenced by government policy (environmental or otherwise). We couch our analysis in terms of the demand for, and supply of, environmental services where the characteristics of an industry determine its demand for such services, whilst society, through environmental regulations, supplies environmental services at a price. The equilibrium level of emissions for a given industry will reflect both demand and supply side considerations. This provides us with a theoretical framework to explore the possible determinants of industry specific emissions intensity.

Our new dataset allows us to make the following contributions. First, we consider the role played by an industry's factor intensities and assess whether industries that use physical and human capital intensively generate more pollution per unit of output. Several studies have suggested a positive link between physical capital and pollution intensity in US industries (Antweiler et al. [2] and Cole and Elliott [6]), but this has never been demonstrated for a country other than the US. Furthermore, to the best of our knowledge no link has ever been claimed to exist between human capital intensity and pollution intensity, yet we find strong evidence of such a relationship. We also examine the relation between industrial energy use and air pollution and

[1]One strand of this literature has concentrated on the characteristics of the population affected by pollution, in particular whether ethnic minorities are adversely affected by pollution. The results to date are somewhat mixed once the time the plant was established is taken into account (for further discussion, see e.g. Hamilton [18], Kriesel et al. [26], Arora and Cason [3] and Jenkins et al. [24]).

investigate whether it is stronger for some pollutants than others; whether the size of the average firm in an industry affects pollution (do large firms benefit from economies of scale and hence emit less per unit of output than smaller firms?); whether more productive firms are more resource efficient and hence less pollution intensive and whether levels of innovation and the age of plant and machinery within an industry affect pollution intensity. We are also able to estimate the relative magnitude of these effects and the extent to which they vary across different pollutants.

Second, this paper investigates the role of UK regulations with emphasis given to the relationship between regional and national regulations. We also argue, following Gianessi et al. [11] and Pargal and Wheeler [30], that there may be both a formal and an informal component to regional regulation levels with formal regulations defined as those that operate through national government or local authorities. Where formal regulations are weak or perceived to be insufficient however; it is argued that communities may informally regulate firms or industries through lobbying and petitioning. Our results suggest that throughout the UK there may be an element of both forms of regulation in operation.[2]

The remainder of the paper is organized as follows: Section 2 provides background information on UK industrial pollution sources and patterns. Section 3 discusses the supply and demand of pollution and the concept of an equilibrium level of pollution while Section 4 outlines the econometric specification including data considerations. Section 5 provides results and Section 6 discusses the policy implications and concludes.

2. Background

In common with many other developed countries, the UK has experienced falling emissions of local air pollution since the 1970s. Local air pollutants are defined as those that have a direct impact on the locale in which they are emitted, ranging from smog and respiratory problems to the blackening of buildings. These pollutants include sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and fine particulate matter (pm10). SO_2 and NO_x are also acid rain precursors and hence can have a significant transboundary or regional impact in the form of acid rain. The primary source of SO_2 is electricity generation by power stations with the second largest source being industry. The single largest source of NO_x and CO is road transport. Emissions of pm10 and CO_2 stem fairly evenly from transport, industry and power stations, with no single dominant source (OECD [29]). Unlike many other developed countries however, the UK is experiencing falling emissions of carbon dioxide (CO_2)—a pollutant with no local impact but believed to be responsible for approximately 60% of enhanced global warming (IPCC [23]). One explanation for the observed reductions in UK air pollution emissions has been the switch from coal to gas fired power stations and their increased use of abatement technology. As a result,

[2]Pargal and Wheeler [30] investigate the role of informal regulations in plant level emissions of water pollution in Indonesia. They find water pollution to be an increasing function of output and state ownership and a decreasing function of productivity and local (informal) environmental regulations. Whilst interesting, Pargal and Wheeler's study differs from ours in that it examines a single pollutant for a developing country using cross-sectional data only. Nevertheless, some interesting commonalities are found between our results and those of Pargal and Wheeler.

emissions from this source have fallen more rapidly than emissions from other sources. The attention of policy makers has therefore become increasingly focused on transport and industry.

The focus of this paper is on industrial pollution. Table 1 presents the average pollution intensities for six pollutants for each UK industry between 1990 and 2000 based on the two-digit UK Standard Industrial Classification (SIC 92). Each industry's share of total manufacturing value added is also presented. For each column, the five largest values are highlighted in bold. Coke Oven Products, Refined Petroleum Products and the Processing of Nuclear Fuel (SIC 23), Other Non-Metallic Mineral Products (SIC 26) and Basic Metals (SIC 27) are consistently amongst the five dirtiest industries for all pollutants.

Although not presented for reasons of space, the emissions intensity of the UK manufacturing sector as a whole has fallen over the period 1990–2000. However, whilst SO_2 and pm10 have fallen rapidly, CO_2 intensity has fallen very slightly, reflecting the absence of any notable decrease in total energy intensity. Such aggregated data however, mask different trends at the individual industry level. Whilst emissions intensities are falling for some industries and some pollutants, for others we observe notable increases. Such disparate trends indicate the presence of industry specific determinants of pollution intensity, which we now investigate in more detail.

Table 1
Average pollution intensities and share of total manufacturing value added, 1990–2000

SIC	Industry	% VA	SO_2	NO_x	Tot. acid	CO	pm10	CO_2
15	Food and beverages	**12.8**	2.2	2.1	3.8	1.9	0.2	0.6
16	Tobacco products	1.0	0.2	0.2	0.3	0.2	0.02	0.1
17	Textiles	2.8	2.2	1.3	3.2	1.6	0.2	0.6
18	Clothing manufacture	2.0	0.9	0.5	1.3	0.6	0.04	0.2
19	Leather, luggage, footwear	0.7	0.5	0.5	0.8	0.9	0.1	0.2
20	Timber	1.4	0.6	**4.1**	3.4	**11.4**	**1.0**	0.6
21	Pulp and paper	3.0	**5.1**	2.6	7.0	2.9	0.4	**1.2**
22	Publishing and printing	**9.4**	0.1	0.2	0.2	0.5	0.02	0.1
23	Coke and refined petrol prods.[a]	2.0	**51.0**	**17.2**	**63.1**	**14.9**	**1.8**	**8.6**
24	Chemicals and chem.prods.	**10.4**	**5.7**	2.6	**8.7**	4.1	**0.4**	**1.1**
25	Rubber and plastic products	5.0	3.2	1.8	4.5	2.3	0.3	0.7
26	Other non-metallic min. prods.	3.4	**17.7**	**17.2**	**29.8**	**12.2**	**2.6**	**3.8**
27	Basic metals	3.7	**17.4**	**8.9**	**23.5**	**110.8**	**3.5**	**6.6**
28	Fabricated metal products	**7.5**	0.3	0.7	0.8	1.8	0.1	0.2
29	Machinery and equipment	**8.5**	0.4	0.6	0.8	1.5	0.05	0.2
30	Office machinery, computers	2.2	0.2	0.1	0.3	0.2	0.01	0.04
31	Elec. machinery and apparatus	3.7	0.7	0.4	1.0	0.6	0.04	0.2
32	Radio, television and comms.	3.6	0.3	0.3	0.6	0.5	0.03	0.1
33	Medical and other instr.	3.1	0.2	0.3	0.4	0.9	0.02	0.1
34	Motor vehicles and trailers	5.8	0.5	0.8	1.1	1.6	0.1	0.3
35	Other transport equipment	4.3	0.9	0.6	1.3	1.2	0.1	0.3
36	Manufacture of other products	3.5	1.6	**4.5**	4.7	**18.0**	0.4	0.8

%VA reports each industry's share of total manufacturing value added. Pollution intensities are measured as tonnes per thousand pounds sterling of value added. For each column, the industries with the five highest values are highlighted in bold. Tot. Acid denotes total acid rain precursors, the weighted sum of SO_2, NO_x and ammonia).

[a]Coke oven products, refined petroleum products and the processing of nuclear fuel.

3. Pollution demand and supply

In line with Pargal and Wheeler [30] we consider pollution emissions as the use of 'environmental services', an additional input in an industry's production function. The equilibrium level of these services reflects the interaction of an industry's demand for such services with the quantity which society is prepared to supply.

3.1. Pollution demand

There are a number of factors that may determine an industry's environmental demand schedule.

Energy use: Most air pollutants stem at least in part from the combustion of fossil fuels. The greater the use of fossil fuel in an industry's production process the greater the industry's demand for pollution.

Factor intensities: The pollution level of an industry may be influenced by its factor intensities. Using US data, several recent studies have suggested that those sectors that face the largest abatement costs per unit of value added also have the greatest physical capital requirements (Antweiler et al. [2] and Cole and Elliott [6]). It therefore appears that, *Ceteris paribus*, those industries that are the most reliant on machinery and equipment generate greater volumes of pollution than those that rely more heavily on labor. In part, this is likely to be due to the link between physical capital intensity and energy intensity, but there may also be a positive relationship between physical capital use and pollution even once energy use is controlled for. It may be the case that certain complex industrial processes, which would tend to be capital intensive, generate more pollution per unit of energy than other less capital-intensive processes. We also examine whether pollution intensive sectors are more or less reliant on human capital. On the one hand it could be argued that high technology, human capital-intensive sectors are likely to be more efficient and hence less energy intensive and therefore relatively clean compared to lower skill sectors. On the other hand relatively low skilled, labor-intensive sectors could be fairly clean whilst those industries that typically generate greater volumes of pollution are more likely to be based on complex industrial processes that require greater levels of human capital (skilled labor) to maintain them.

Size: Other things being equal we would expect a positive relationship between a firm's total output and emissions, although we may expect this relationship to be diminishing at the margin. Thus, it is possible that pollution normalized by output might decline as output increases, reflecting the benefits of economies of scale in both resource use and in pollution abatement.

Efficiency: Emissions are likely to be a negative function of efficiency. One would expect a more productive industry to be better managed, more resource efficient and to produce less waste per unit of output. Furthermore, such an industry would also be better placed to respond relatively quickly to any change in pollution control incentives.[3]

[3]We acknowledge the possibility that efforts to reduce pollution may themselves influence productivity. Gray and Shadbegian [13] and Gollop and Roberts [12], for instance, find that plants with higher levels of abatement costs tend to have lower levels of productivity. However, since plants with high levels of abatement costs would tend to be those from pollution intensive industries, this finding may be driven by our explanation above, i.e. unproductive industries generate more pollution. Unfortunately, a greater investigation of this issue is beyond the remit of the current paper.

Use of modern production processes: We would generally expect a newer plant or one that uses modern production processes to be cleaner. As environmental regulations have become increasingly stringent, modern production processes have become more resource efficient and hence produce less waste per unit of output.

Innovation: It is hypothesized that the level of innovation displayed by a firm or industry may reduce its demand for pollution. Firms undertake research and development (R&D) with a view to achieving either product or process innovations. The benefit of the latter is the attainment of greater efficiency, i.e. fewer inputs per unit of output. Process innovations may also provide ways of recycling waste products so that waste is reduced and fewer raw materials are required as inputs. A firm or industry undertaking a significant amount of such investment may be expected therefore to be less resource intensive, and hence cleaner.[4]

3.2. Pollution supply

Environmental regulations: Environmental regulations will ensure that the greater the use of environmental services (i.e. the larger the emission of pollution) the higher the costs imposed on any firm or industry. The result is an upward sloping 'environmental supply schedule'.

A number of studies have distinguished between formal and informal environmental regulations. Under formal regulation, the government (or local authority) imposes pollution controls on the community's behalf. Examples of formal pollution reducing policies include traditional regulation (command and control), plus economic incentives such as pollution taxes and tradable permits. In developing countries, by contrast, formal policies may be weaker or missing altogether. In such circumstances there is significant evidence to suggest that communities 'informally' regulate polluters themselves through bargaining and lobbying (see e.g. Huq and Wheeler [22], Pargal and Wheeler [30], and Hartman, Huq and Wheeler [19]).[5] It is possible, however, for such informal regulations to exist even when formal regulations are present. If formal regulations fail to ensure that local environmental quality meets local preferences then the local community may report the violation of pollution standards to the local authority or pressure regulators and firms to raise standards and/or improve monitoring and enforcement.

Formal air pollution regulations in the UK have been operating for many years, with responsibility split between the Environment Agency and local authorities. Legislation in 1990 and 1999 gave the responsibility for smaller factories (known as 'installations') to local authorities whilst very large plants, that generate nationally significant levels of pollution, are regulated by the Environment Agency.[6] In terms of procedure, plants operating (or planning to operate)

[4]The Porter hypothesis (Porter and Van der Linde [31]) argues that the cost-savings associated with such process innovations, which may be a response to more stringent regulations, are likely to at least partially offset a firm's environmental compliance costs.

[5]Pargal and Wheeler [30] provide a number of examples of such bargaining including; a cement factory near Jakarta which, without admitting liability for its pollution, compensates local people with a monthly payment of Rs. 5000 and a tin of evaporated milk (from Cribb [8]); and an Indian paper mill which, in response to community complaints, installed abatement equipment and compensated local people for any remaining damage by building a Hindu temple (from Agarwal et al. [1]).

[6]In principle, the Environmental Agency and local authorities should be equally stringent, since both have to adhere to the same national air quality guidelines. However, we acknowledge the possibility that, for instance, local authorities

certain industrial processes have to apply to local authorities or the Environment Agency for a permit. The regulator can either reject the application if it feels the environmental impact will be too great (or if there are concerns surrounding the firm's environmental competency) or a permit can be issued with conditions attached. These conditions generally take the form of emissions limits and the use of Best Available Control Technology (BACT). Regulators have to ensure that the UKs national air quality objectives are achieved and hence that nationally agreed concentrations 'ceilings' are not exceeded. Regulators therefore have to take into account the background level of concentrations when setting a plant's permit conditions. In rural areas, background concentrations of most local air pollutants are likely to be low and hence a plant can emit a greater amount of pollution without exceeding safe concentration levels. In urban areas however the background level of concentrations is already likely to be relatively high. Thus, plants' emissions limits in such areas may be more stringent to ensure safe levels are not exceeded. If the plant contravenes any of its permit conditions, for example, by exceeding its emissions limits, the first step is to serve an enforcement notice. A more extreme step is to serve a notice forcing the plant to suspend its use of the prescribed process, with the final step being prosecution—generally resulting in a fine and even imprisonment for the operator.

Despite these formal regulations, it would appear that a level of *informal* regulation of firms is also present in the UK. As suggested above, such informal regulation presumably arises when communities believe formal regulations are being breached or perceive them to be insufficient. Local and national environmental groups will often aid communities in such a position, for instance, Friends of the Earth UK have produced a 149 page manual entitled 'The Polluting Factory Campaign Guide' and host a website that names the key polluters that operate within any postcode area of the UK. Informal regulation may be 'direct' in nature (where the community directly lobbies the firm) or 'indirect' (where the community lobbies the local authority who then regulate the firm).[7]

3.3. Pollution equilibrium

With the above discussion in mind, we can summarize pollution demand and supply by defining an industry's pollution demand as:

$$e_{it} = f(p_{it}, n_{it}, pci_{it}, hci_{it}, s_{it}, tfp_{it}, mod_{it}, innov_{it}) \tag{1}$$

(*footnote continued*)
may be more sensitive to local concerns than the National Environmental Agency, raising the possibility that the stringency of regulations faced by large plants may differ from that faced by smaller plants. It is also worth noting that no new legislation was implemented during our sample period so it is not possible to compare emissions levels before and after the passage of regulations.

[7]An example of 'direct' informal regulation: In 1998 a chemical waste disposal company in Lancashire, UK applied for a licence to allow it to begin processing highly toxic waste. Since the plant was based near to residential homes and a school concerned locals began a leafleting campaign alerting the local population to the potential dangers. Press releases were sent out to the local and national media and the issue attracted a significant amount of press attention. Ultimately, the chemical company backed down and withdrew its application for the new licence. An example of 'indirect' informal regulation: following the attempt of a Lancashire power station to burn Orimulsion, a high sulfur fuel, local communities lobbied local authorities complaining about the high levels of metals and particulates associated with Orimulsion. Local authorities arranged a public inquiry that upheld the public complaint and prohibited the use of Orimulsion.

where, subscripts i and t denote industry and year, e denotes air emissions, p denotes the expected price of pollution as a result of environmental regulations, n denotes energy use, *pci* is physical capital intensity, *hci* is human capital intensity, s is the size of the average firm in the industry, *tfp* is the total factor productivity of the industry, *mod* is a measure of the vintage of production processes and, finally, *innov* represents innovation. All variables are defined in Section 4.

The industry's pollution supply schedule identifies the expected price that it will pay for pollution. This, in turn, is a function of the quantity of pollution and the stringency of formal and informal environmental regulations.

$$p_{it} = f(e_{it}, FRegs_{it}, IRegs_{it}), \tag{2}$$

where p and e are as already defined, *FRegs* refers to formal environmental regulations, whilst *IRegs* refers to informal regulations.

In equilibrium, pollution can therefore be defined as:

$$e_{it} = f(n_{it}, pci_{it}, hci_{it}, s_{it}, tfp_{it}, mod_{it}, innov_{it}, FRegs_{it}, IRegs_{it}). \tag{3}$$

4. Econometric specification and data considerations

Our estimating equation is based closely on Eq. (3)

$$\begin{aligned} E_{it} = {} & \alpha_i + \delta_t + \beta_1 N_{it} + \beta_2 PCI_{it} + \beta_3 HCI_{it} + \beta_4 SIZE_{it} \\ & + \beta_5 TFP_{it} + \beta_6 CAP_{it} + \beta_7 RD_{it} + \lambda' REG + \varepsilon_{it}. \end{aligned} \tag{4}$$

Our dependent variable, E_{it}, is pollution emissions expressed per unit of value added. We estimate Eq. (4) separately for six different measures of pollution, namely sulfur dioxide (SO_2), nitrogen oxides (NO_x), total acid rain precursors (Tot.Acid is the weighted sum of SO_2, NO_x and ammonia),[8] carbon monoxide (CO), fine particulate matter (pm10) and carbon dioxide (CO_2). The variables α_i and δ_t denote industry and year specific effects, respectively. Eq. (4) is estimated in logs for 22 manufacturing industries for the period 1990–1998.[9]

With regard to our 'demand' variables, N_{it} denotes direct fossil fuel use per unit of value added, whilst PCI_{it}, physical capital intensity, is measured as non-wage value added per worker.[10] Human capital intensity, HCI_{it}, is defined as the share of value added that is paid to skilled workers. Our size variable, S_{it}, is defined as value added per firm, within industry i. Total factor productivity, TFP_{it}, is estimated using a Cobb-Douglas production function.[11] The variable CAP_{it} is an industry's capital expenditure, scaled by value added and acts as a measure of the vintage of

[8] Emissions of these three pollutants are weighted according to their relative acidifying effects. The weights, relative to SO_2 are 0.7 for NO_x and 1.9 for ammonia.

[9] Although emissions data are available until 2000 many of our regulation variables only extend to 1998.

[10] N_{it} measures fossil fuel used *directly* by industries and hence does not include the use of electricity which is produced by power stations using fossil fuels.

[11] Due to space constraints, details regarding our estimation of *TFP* are available from the authors upon request. There was little effect on the estimated coefficient on *TFP* in Eq. (4) when *TFP* was estimated using a number of different production function specifications.

production processes, under the assumption that the greater such expenditure within an industry, the newer the industry's equipment and machinery is likely to be. Finally, we use RD_{it} to measure research and development expenditure, scaled by value added, as an indication of innovation within an industry.[12]

With regard to our 'supply' variables, *REG* in Eq. (4) denotes a vector of variables capturing formal and informal regulation. Unfortunately, direct measures of formal and informal regulations are not readily available. We argue, however, that informal regulations are locally determined and also that formal regulations are likely to have a regional component. This allows us to investigate the determinants of such regional regulations.

Although the agencies that implement formal regulations (local authorities and the Environmental Agency) have to adhere to nationally agreed guidelines, regional characteristics are likely to play a role. Regulators, for example, can take into account the local environment when deciding whether to grant a permit and will adapt the permit's conditions accordingly. As already outlined, regulators have to ensure that national air quality objectives are met at all times, thus the location of a plant and the associated background level of concentrations in that locale, will affect the stringency of the plant's emissions limits. A plant operating in an urban area, or operating in an Air Quality Management Area (an area identified as a pollution hotspot) may face more stringent permit conditions than a similar plant located in a more rural setting.

Furthermore, informal discussions with local authority pollution control officers suggest that both the stringency of the conditions attached to a permit and the enforcement of those conditions may also depend upon a local authority's priorities and the emphasis that they place on reducing air pollution. Thus, a local authority with limited resources or other more urgent priorities may be forced to devote fewer staff and other resources to the task of pollution control.

With the above in mind, in our main results we firstly attempt to capture these regional influences on an industry's pollution intensity using a measure of regional pollution prosecutions, scaled by each region's manufacturing output. In our sensitivity analysis we replace this proxy for formal regulations with variables designed to capture the background level of air pollution within a region and examine the role played by both pollution concentrations and a region's share of pollution intensive industries.

Since the emphasis placed on formal pollution regulation by local authorities may depend upon the social problems within a region, we also include a region's unemployment rate as a measure of such problems. Ceteris paribus, we would expect a region with a high unemployment rate to devote fewer resources to pollution control.[13]

Turning to informal regulations, we also believe these are likely to be a function of regional characteristics. A number of studies have posited a link between income and regulations (Dasgupta et al. [9]), with more affluent countries/regions typically shown to demand a cleaner environment. More affluent regions of the UK may be more concerned with the impact of pollution intensive factories on property prices and may have fewer other social problems to serve

[12]Table A1 in the appendix provides the source and more information on our variables. Table A2 provides summary statistics.

[13]Deily and Gray [10] find evidence to suggest that the regulation of US steel mills by the Environmental Protection Agency is responsive to local economic and political conditions.

as distractions. Furthermore, communities with a greater proportion of professional workers may be better placed to mobilize opposition to such pollution intensive plants.

Regional informal regulations may also be a function of a region's population density. On the one hand, a densely populated area may mean there are more people adversely affected by pollution and hence opposition to such plants may be greater. Conversely, a pollution intensive plant may be less 'visible' in a densely populated, urban area and hence may escape the attentions of the local population.

Demographic factors may also influence the extent to which a region lobbies for cleaner industrial activity. We may expect, for instance, that a younger population would be more concerned about pollution issues and better placed to lobby against polluters.

With the above arguments in mind, we rely on the unemployment rate to capture the role played by the wealth of a region. We also include regional population density and the share of a region's population under the age of 44 to capture our other suggested determinants of regional informal regulation.[14] In a sensitivity analysis we also consider the role played by per capita income. Finally, note that since both regional formal and informal regulations are potentially subject to the same determinants (e.g. the unemployment rate), we are unable to separate the two effects in our analysis.

Although our emissions data are industry specific as opposed to region specific, we are still able to capture these regional determinants of regulations and include them as determinants of an industry's emissions intensity. For instance, we define our pollution prosecution variable as follows:

$$REGpros_{it} = \sum_{r} (s_{irt} * PROS_{rt}), \tag{5}$$

where subscripts i, r and t denote industry, region and year, respectively, s is the output of industry i in region r as a share of total national output of industry i, and $PROS$ is pollution prosecutions scaled by manufacturing output. Therefore, industries that have a higher share of their output in regions with high pollution prosecutions will have higher values of *REGpros*.

Equivalent variables for regional unemployment rate, population density and population under the age of 44 are also calculated and denoted by *REGunem*, *REGpd*, and *REGagepop*, respectively. These variables are calculated using data for 37 NUTS2 regions in the UK.[15] See Table A1 in Appendix A for more information.

A potential problem with the use of the regional unemployment rate as a determinant of pollution intensity is the direction of the causality between these two variables. Thus far we are assuming that regions with fewer social problems will be able to devote more resources to pollution control and, being wealthier, will also exert a greater demand for environmental regulations. It could be argued, however, that high-income, employed individuals will choose not to live in a highly pollution intensive region and hence such a region will become the domain of low-income and/or unemployed individuals. In such a situation causality moves from pollution

[14]The UK Office for National Statistics reports data on population under the age of 44 and population under the age of 16. Both variables were tested and gave similar results. Note that other potential regional characteristics that could influence informal regulation, such as level of educational attainment, political ideology and voter turnout, are not included due to the non-availability of data.

[15]The exception is pollution prosecutions that are only reported for 12 UK regions.

intensity to income and unemployment rather than the other way around. Econometrically this problem is not easy to overcome since the use of any alternative measure of affluence, as an instrument for unemployment, will be subject to the same endogeneity concerns.

In principle, our regional population density variable could also suffer from endogeneity concerns. It could be argued, for instance, that the greater the pollution intensity of a plant, the lower the surrounding population density will be as individuals would choose not to reside in close proximity to such a plant. There is little evidence to support this causality however. Historically populations have expanded most rapidly in industrial areas, particularly following the industrial revolution as workers embraced increased employment opportunities. Hence, the most densely populated areas have always been the most industrialized. Secondly, land for new property development in the UK is scarce and casual observation suggests it is readily developed almost irrespective of its location. Furthermore, developers are under increasing pressure to develop the so-called 'brownfield' sites. Thus, we believe endogeneity is less of a concern for population density than unemployment. Davidson-Mackinnon exogeneity tests are nevertheless performed to assess the exogeneity of regional unemployment and population density and are discussed in Section 5.

Although we have thus far outlined the regional aspects of UK air quality regulations, the UKs formal regulations are by no means entirely regional in nature. Decisions as to which industrial processes are to be regulated as well as general guidance on how and at what level to set regulations are all determined at a national level. We rely on our industry and year specific fixed effects (α_i and δ_t in Eq. (4)) to capture these national formal regulations. The former will capture regulations which are specific to each industry but which have not changed over time, whilst the latter will capture effects which are common to all industries but which have changed over time.

Referring back to Eq. (4), we expect the sign of β_1, the coefficient on energy use per value added and β_2, the coefficient on physical capital intensity, to be positive. β_3 could be positive or negative depending on whether human capital intensive sectors are cleaner or dirtier relative to lower skill sectors. β_4, the coefficient on value added per firm within industry *i*, β_5 the coefficient on total factor productivity, β_6 the coefficient on capital expenditure and β_7 the coefficient on R&D expenditure, should be negative. We expect the sign on *REGpros* to be negative, whilst that on *REGunem* should be positive. The sign on *REGpd* may be negative due to the lobbying power of a densely populated region, but may be positive if a plant in a densely populated area is less visible and hence escapes informal regulation. Finally, we expect the sign on *REGagepop* to be negative.

5. Results

5.1. Estimation results

Table 2 presents our results estimated using both fixed and random effects specifications.[16] The Hausman specification test suggests that there is some correlation between the explanatory

[16]All estimations use heteroscedastic robust standard errors. We also estimate a simple OLS model without controlling for industry effects. The sign and significance of the estimated coefficients are very similar to those estimated using fixed and random effects. That said, industry effects are jointly significant within our fixed effects model,

variables and the error terms, suggesting that greater emphasis should be placed on the fixed effects results.

The first point to note is that, across all 12 models, energy intensity is a positive and highly significant determinant of pollution intensity. Physical capital intensity is also found to be a positive and significant determinant of SO_2, total acid rain precursors and CO_2 for both fixed and random effects, even though energy intensity is being controlled for. This is consistent with the results of a number of US studies (see e.g. Cole and Elliott [7] and Levinson and Taylor [28]). Furthermore, although our prior expectations for human capital intensity were uncertain, it would appear that high skill, human capital intensive industries are dirtier than low skill, labor-intensive industries, even once *PCI* and energy intensity are controlled for; additionally, an increase in the human capital intensity *within* an industry will increase that industry's pollution intensity. This finding has not, to our knowledge, been previously demonstrated.

Table 2 also indicates that, for many pollutants, pollution intensity is a negative function of the size of the average firm in an industry. We also find total factor productivity to be a negative and often significant determinant of pollution intensity.[17] However, capital expenditure intensity, our proxy for the vintage of production processes, is not found to be statistically significant. Finally, research and development expenditure is found to be a negative and significant determinant of pollution intensity in the majority of our 12 models.[18]

With regard to our regulation variables, our pollution prosecution variable, *REGpros*, is consistently negatively signed, although not always significant. We therefore find some evidence to suggest that the greater an industry's concentration in regions with high levels of pollution prosecutions (relative to manufacturing output) the lower its pollution intensity. The estimated coefficient on regional population density is also negative and is statistically significant in most models. This suggests, ceteris paribus, that the greater an industry's concentration in densely populated areas, the lower its pollution intensity. This finding is consistent with the notion that the *informal* regulation of industries will be greater in densely populated areas as the number of people who would be adversely affected by pollution would be greater and hence so too would be their lobbying pressure. However, *REGpd* may also be capturing the regional nature of UK *formal* regulations. Since a plant's permit conditions (i.e. emissions limits) are set in accordance with the background level of concentrations in a region, it is to be expected that those operating in urban (densely populated) areas will have to be cleaner per unit of output. Thus, whilst these effects are

(*footnote continued*)
suggesting that such effects do play a role. Their influence would appear to manifest itself in the magnitude of the coefficients rather than in the sign and significance of the coefficients. The OLS results are available from the authors upon request.

[17]In principle, a firm that does not abate pollution appears to use less labor and capital to produce the same amount of output. There may therefore be an inherent positive correlation between emissions intensity and *TFP*. This would imply that the magnitude of our estimated coefficient on *TFP* is smaller than it perhaps should be. Whilst we believe such bias to be small, we acknowledge this possibility.

[18]The impact of R&D expenditure on emissions intensity may be subject to a lag. In unreported results we therefore test one, two and three-year lagged values of R&D but found no systematic difference in either the magnitude of the estimated coefficient or its significance. Using lags is costly given our short time series and hence we continue to use contemporaneous R&D expenditure in our reported estimations.

Table 2
Determinants of industrial pollution (fixed and random effects)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	SO_2	NO_x	Tot.Acid	CO	pm10	CO_2	SO_2	NO_x	Tot.Acid	CO	pm10	CO_2
	Fixed effects						Random effects					
Energy	0.94***	0.65***	0.77***	0.24***	0.65***	0.93***	1.10***	0.92***	1.0***	0.60***	0.94***	0.96***
	(0.11)	(0.033)	(0.063)	(0.088)	(0.052)	(0.013)	(0.071)	(0.030)	(0.051)	(0.14)	(0.075)	(0.017)
PCI	0.13	−0.021	0.12**	0.034	0.047	0.015*	0.24**	0.030	0.18***	0.023	0.076	0.028**
	(0.091)	(0.024)	(0.050)	(0.069)	(0.044)	(0.009)	(0.11)	(0.042)	(0.056)	(0.094)	(0.056)	(0.013)
HCI	0.35***	0.11***	0.22***	0.075	0.16***	0.038***	0.41***	0.025	0.22***	−0.002	0.097*	0.045***
	(0.082)	(0.023)	(0.043)	(0.051)	(0.033)	(0.009)	(0.10)	(0.040)	(0.051)	(0.088)	(0.052)	(0.012)
SIZE	−0.077	−0.067***	−0.096**	−0.081	−0.12***	−0.006	0.030	−0.098**	−0.10**	−0.15*	−0.12**	−0.016
	(0.080)	(0.023)	(0.039)	(0.055)	(0.037)	(0.007)	(0.098)	(0.038)	(0.049)	(0.087)	(0.051)	(0.012)
TFP	−0.60*	−0.42***	−0.33*	−0.54**	−0.70***	−0.072**	−1.018**	−0.29*	−0.35*	−0.12	−0.59***	−0.071
	(0.34)	(0.088)	(0.18)	(0.24)	(0.13)	(0.030)	(0.40)	(0.15)	(0.20)	(0.34)	(0.20)	(0.045)
CAP	0.056	0.018	0.024	0.040	0.010	0.004	0.048	0.036	−0.001	0.097	0.048	0.012
	(0.076)	(0.017)	(0.038)	(0.045)	(0.025)	(0.006)	(0.093)	(0.035)	(0.044)	(0.074)	(0.044)	(0.010)
RD	−0.20**	0.067**	−0.12**	0.23**	0.011	−0.015	−0.20***	−0.004	−0.097**	0.25**	−0.12**	−0.025*
	(0.077)	(0.029)	(0.058)	(0.10)	(0.050)	(0.012)	(0.075)	(0.030)	(0.043)	(0.11)	(0.048)	(0.013)
REGpros	−0.32	−0.43***	−0.42***	−0.53***	−0.45***	−0.044*	−0.53	−0.22	−0.37**	−0.44	−0.27	−0.077*
	(0.25)	(0.079)	(0.14)	(0.19)	(0.12)	(0.025)	(0.39)	(0.15)	(0.19)	(0.32)	(0.20)	(0.042)
REGpd	−1.74***	−0.063	−0.84***	−0.16	−0.34**	−0.085**	−1.74***	−0.23	−0.88***	−0.066	−0.72***	−0.15***
	(0.38)	(0.090)	(0.2)	(0.24)	(0.17)	(0.036)	(0.40)	(0.15)	(0.21)	(0.37)	(0.22)	(0.052)
REGunem	3.14***	2.059***	1.75***	4.69***	1.75***	0.26**	2.22	1.57***	1.88***	5.92***	1.34*	0.17
	(0.87)	(0.28)	(0.53)	(0.78)	(0.44)	(0.11)	(1.49)	(0.56)	(0.69)	(1.15)	(0.69)	(0.15)
REGagepop	−9.034*	−4.47**	−2.60	−14.42***	−4.17	−0.36	−14.87	−2.80	−6.63	−16.75**	−1.92	0.59
	(5.37)	(1.79)	(3.42)	(4.55)	(3.10)	(0.74)	(9.13)	(3.42)	(4.22)	(6.99)	(4.21)	(0.92)
R^2	0.81	0.94	0.91	0.68	0.87	0.99	0.93	0.93	0.97	0.86	0.97	0.99
D–M Exog.	1.86	0.086	1.32	0.0045	2.91	1.65						
(REGpd)	(0.17)	(0.77)	(0.25)	(0.94)	(0.091)	(0.20)						
D–M Exog.	0.024	2.72	1.99	1.06	0.20	0.55						
(REGunem)	(0.88)	(0.10)	(0.16)	(0.31)	(0.65)	(0.46)						
Hausman							69.1	110.7	83.2	68.4	36.7	84.5
(FE vs. RE)							(0.000)	(0.000)	(0.000)	(0.000)	(0.008)	(0.000)
N	198	198	198	198	198	198	198	198	198	198	198	198

Our dependent variables are expressed as pollution intensities, measured as emissions per unit of value added. Standard errors in parentheses (p values for the exogeneity tests). The $D-M$ exogeneity test cannot be performed for random effects estimations.
*Significant at 10%.
**Significant at 5%.
***Significant at 1%.

consistent with both formal and informal regulations we are unfortunately unable to separate the two.

Table 2 also indicates that the regional unemployment rate is a positive, and almost always significant, determinant of an industry's pollution intensity. This finding is consistent across both our 'within' fixed effects models and our random effects models. This is in accordance with our prior expectations and suggests that environmental regulations are more stringent in regions with fewer social problems such as unemployment. Finally, *REGagepop*, which captures the effects of a young population, is found to be consistently negative across models, but is only significant in four cases.[19]

To test for the potential endogeneity of *REGpd* and *REGunem*, we employ a Davidson-Mackinnon exogeneity test. The null hypothesis states that an ordinary least squares estimator would yield consistent estimates. A rejection of the null indicates that endogenous regressors' effects on the estimates are meaningful, and instrumental variables are required. Lagged values of *REGpd* and *REGunem* are used as the instrumental variables. Whether we use one, two or three year lags, the null of exogeneity cannot be rejected (at the 5% level) for either *REGpd* or *REGunem*, for any pollutant. Table 2 reports the test statistics based upon one-year lags.

The estimated coefficients on the year dummies, although not reported for reasons of space, are negative for all pollutants (1990 is the omitted year dummy) suggesting that all industries have been influenced by environmental policy and/or benefited from the introduction of new technologies. For all pollutants, the time path of the estimated coefficients is generally smooth, with little evidence of major jumps. We examine the magnitude of these effects below.

Since all variables are expressed in natural logarithms our estimated coefficients are elasticities allowing us to make a direct comparison across variables and pollutants. Considering the non-regulation variables first, perhaps not surprisingly, we find the largest elasticities to be estimated for energy use. Thus depending on the pollutant, across our 22 industries a 1% increase in energy use is associated with an increase in pollution intensity of between 0.25% and 1.1%. For most pollutants, the next largest elasticities are estimated for productivity (*TFP*), followed by human capital intensity, R&D and size. Whilst the sign and significance of the independent variables do not vary a great deal across pollutants, generally speaking the results for CO show the least statistical significance. Estimated elasticities also vary across pollutants. It is particularly notable that estimated elasticities for CO_2 are very small with the exception of energy use. This concurs with prior expectations since the relationship between energy use and CO_2 emissions is stronger than for the other pollutants, suggesting that the role played by other variables is minimal.

With regard to the regulation variables, estimated elasticities can be seen to be relatively large, particularly those for *REGunem* and *REGagepop*, although the latter are often not statistically significant. These findings suggest that environmental regulations have played a significant part in reducing industrial emissions intensity.

[19]It is possible that region-specific and/or region-industry-specific shocks are influencing our regional regulation results. However, the sign and significance of our regional regulation variables are very similar whether we use 12 or 37 UK regions, and whether we rely on within industry variation (fixed effects) or both within and between-industry variation (random effects).

5.2. Sensitivity analysis

In order to assess the robustness of our results, Table 3 provides a sensitivity analysis. To enable us to provide a detailed sensitivity analysis, we are forced to focus on only two pollutants due to space considerations. We choose total acid rain precursors and CO_2, believing these to be the most representative of our pollutants. Tot.Acid includes SO_2, NO_x and Ammonia, and therefore represents both local and regional pollutants, whilst CO_2 represents global pollutants.[20] Similarly, since Table 2 indicates that fixed and random effects results are very similar, Table 3 focuses on fixed effects specifications.

Models (13) and (14) begin by testing an alternative measure of HCI. Our original measure of HCI is defined as the share of value added paid to skilled workers (see Table A1), where unskilled workers are defined as those in the textiles sector. In case our results are influenced by specific characteristics of the textile sector our alternative HCI measure, *HCImanf*, is simply measured as an industry's wage expressed relative to the average manufacturing wage. Again, *HCImanf* is found to have a positive, significant impact on industrial pollution intensity. In fact, this finding is robust across other measures of HCI based around wage rates. Also, the sign and significance of HCI is unaffected by the omission of other independent variables and the use of alternative functional forms (logs, levels, first differences, fixed effects, random effects). We therefore find robust evidence of a positive link between wage-based measures of human capital intensity and pollution intensity, suggesting that high skill industrial processes are often pollution intensive. Unfortunately, we are unable to find suitable data on non-wage measures of HCI.

But can we claim that our wage-based measures are accurately capturing HCI? It is possible that pollution intensive industries pay their workers a risk premium due to poor working conditions, risks of chemical spills, etc. If so, then higher wages in pollution intensive industries may reflect this risk premium rather than higher levels of human capital. Whilst plausible, it would seem unlikely that this effect alone could be responsible for the robust positive relationship between HCI and pollution intensity. Nevertheless, controlling for industry-level injury rates or morbidity risks would solve this problem but these variables have proved unattainable for our time period.[21]

However, a casual observation of our data indicates that our wage-based measures of HCI do accord with prior expectations of the level of human capital in many industries. For instance, if we average each industry's HCI over time (1990–1998) and rank across industries, then the highest ranked industries include SIC 31 Electrical Machinery and Apparatus, SIC 30 Office Machinery and Computers and SIC 29 Machinery and Equipment. These are all industries that we would expect to have relatively high levels of human capital. Furthermore, three of the dirtiest manufacturing industries (SIC 24 Chemicals, SIC 21 Pulp and Paper and SIC 27 Basic Metals) are found within the top 10 industries when ranked by HCI. If we now consider industries with low levels of HCI, we find SIC 17 Textiles, SIC 18 Clothing and SIC 19 Leather Products amongst the

[20] Estimating the models in Table 3 for pollutants other than Tot.Acid and CO_2 reveals them to be equally robust across alternative specifications.

[21] Some data are available on the number and rate of fatal injuries by industry for the UK. These data provide no indication of injury rates or morbidity risks through ill health. Furthermore, no patterns are discernible between pollution intensive industries and the risk of a fatal accident.

Table 3
Sensitivity analysis (fixed effects)

	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
	Tot.Acid	CO_2	Tot.Acid	CO_2	Tot.Acid	CO_2	Tot.Acid	CO_2	Tot.Acid	CO_2	Tot.Acid	CO_2
Energy	0.85***	0.93***	0.78***	0.94***	0.70***	0.93***	0.77***	0.93***	0.767***	0.94***	0.71***	0.93***
	(0.057)	(0.011)	(0.064)	(0.13)	(0.063)	(0.012)	(0.064)	(0.012)	(0.064)	(0.012)	(0.064)	(0.012)
PCI	0.13***	0.020***	0.15**	0.026**	0.15***	0.018**	0.13**	0.016*	0.13***	0.014	0.10**	0.016*
	(0.049)	(0.0086)	(0.068)	(0.012)	(0.050)	(0.009)	(0.049)	(0.009)	(0.049)	(0.009)	(0.051)	(0.008)
HCI			0.21***	0.038***	0.19***	0.033***	0.23***	0.041***	0.23***	0.040***	0.18***	0.034***
			(0.044)	(0.0086)	(0.040)	(0.008)	(0.046)	(0.009)	(0.047)	(0.008)	(0.041)	(0.008)
HCImanf	0.35**	0.13***										
	(0.18)	(0.033)										
SIZE	−0.14***	−0.0079	−0.10***	−0.0066	−0.098**	−0.011*	−0.083*	−0.017**	−0.10**	−0.010	−0.12***	−0.012*
	(0.040)	(0.0069)	(0.039)	(0.0070)	(0.043)	(0.007)	(0.045)	(0.008)	(0.042)	(0.007)	(0.043)	(0.007)
TFP	0.067	−0.071			−0.31	−0.067**	−0.32*	−0.049	−0.30	−0.059**	−0.27	−0.049*
	(0.24)	(0.045)			(0.19)	(0.029)	(0.19)	(0.031)	(0.18)	(0.028)	(0.20)	(0.028)
Lab. Prod.			−0.21	−0.060**								
			(0.17)	(0.27)								
CAP	0.042	0.019	0.025	0.0049	0.030	0.005	0.005	0.001	−0.001	0.001	0.036	0.004
	(0.040)	(0.065)	(0.038)	(0.0059)	(0.040)	(0.006)	(0.040)	(0.006)	(0.040)	(0.006)	(0.039)	(0.006)
RD	−0.11**	−0.021**	−0.12*	−0.014	−0.14**	−0.021*	−0.11*	−0.005	−0.099*	−0.013	−0.16***	−0.020*
	(0.048)	(0.0082)	(0.059)	(0.012)	(0.057)	(0.012)	(0.060)	(0.011)	(0.058)	(0.011)	(0.061)	(0.012)
REGpros	−0.24**	−0.039**	−0.41***	−0.042*								
	(0.11)	(0.019)	(0.14)	(0.026)								
REGdirtymanf							−1.16	−0.57**				
							(1.46)	(0.28)				
REGSO$_2$									0.18	−0.12**	−0.040	−0.11*
									(0.34)	(0.061)	(0.36)	(0.06)
REGpd	−0.53***	−0.077**	−0.86***	−0.089**			−0.64	−0.23***	−0.94***	−0.087**		
	(0.18)	(0.032)	(0.20)	(0.035)			(0.41)	(0.076)	(0.21)	(0.036)		
REGunem	0.34	0.12	1.64***	0.27**			1.22**	0.29***	1.36***	0.22**		
	(0.44)	(0.085)	(0.52)	(0.11)			(0.55)	(0.10)	(0.52)	(0.096)		
REGagepop	−1.79	−0.64	−2.51	−0.37			−0.34	−0.55	−1.49	0.084		
	(−2.6)	(0.48)	(3.4)	(0.73)			(3.64)	(0.71)	(3.57)	(0.71)		
REGpcY											−2.95***	−0.33*
											(0.93)	(0.19)
R^2	0.89	0.97	0.91	0.98	0.89	0.98	0.91	0.98	0.91	0.98	0.90	0.98
n	198	198	198	198	198	198	198	198	198	198	198	198

Our dependent variables are expressed as pollution intensities, measured as emissions per unit of value added. Standard errors in parentheses.
*Significant at 10%.
**Significant at 5%.
***Significant at 1%.

bottom four industries. These are all industries that we would expect to have low levels of human capital and are also industries that have very low levels of pollution intensity (see Table 1). We therefore have some confidence in our HCI data and in the positive relationship found between this variable and pollution intensity. A more detailed examination of this issue remains the subject of future work.

Models (15) and (16) replace our measure of total factor productivity with a simpler measure of labor productivity, defined as gross value added per worker. This variable is still found to exert a negative influence on emissions intensity, although it is only significant for CO_2.

Models (17)–(24) assess the sensitivity of our results to changes in our regulation variables. Models (17) and (18) begin by dropping all regional regulations, relying on the industry and year effects to capture the effects of environmental policy. The sign and significance of the remaining variables are almost identical to those from models (3) and (6), strongly indicating that our regulation variables are not unduly influencing the sign and significance of the non-regulation variables.

Models (19) and (20) replace our pollution prosecutions variable with an alternative measure of formal regulations. Since the stringency of regional formal regulations will be influenced by the background level of pollution concentrations, *REGdirtymanf* captures the concentration of UK dirty industries within a region. Referring back to Eq. (5), *REGdirtymanf* is calculated by replacing $PROS_{rt}$ with a region's share of UK dirty production, where dirty production is classed as the production from five of the most pollution intensive industries (see Table 1).[22] Thus, an industry located in a region with a high share of national pollution intensive output, will have a high value of *REGdirtymanf*. As expected, *REGdirtymanf* is found to be a negative determinant of pollution intensity for both models (19) and (20), although it is only statistically significant in model (20).

As an alternative to *REGdirtymanf*, models (21)–(24) include an actual measure of pollution concentrations within each region. We use SO_2 concentrations, measured as the average pollution concentration across urban sites within each region. Since CO_2 concentrations are not reported, SO_2 concentrations are used for both Tot.Acid and CO_2.[23] Perhaps surprisingly, $REGSO_2$ is neither negative nor significant for Tot.Acid, but is both negative and significant for CO_2. The inclusion of *REGdirtymanf* and $REGSO_2$ in models (19)–(22) implies that *REGpd* is now capturing informal regulatory pressures alone (rather than urbanisation and hence background pollution concentrations). Thus, for CO_2 at least, our results appear to show evidence of informal regulatory pressures in densely populated areas.

Finally, models (23) and (24) replace *REGpd*, *REGunem* and *REGagepop* with regional per capita income, a more direct determinant of environmental regulations. In light of endogeneity concerns, a Davidson-Mackinnon exogeneity test was undertaken to test the null of exogeneity of *REGpcY*. For CO_2 the null of exogeneity could not be rejected, for Tot.Acid the null was rejected. Thus, lagged *REGpcY* is used in models (23) and (24). Nevertheless, *REGpcY* is found to exert a

[22]These industries are Coke Ovens (SIC23), Chemicals (SIC24), Other non-metallic minerals (SIC26), Basic Metals (SIC27) and Pulp and Paper (SIC21).

[23]We believe it is reasonable to expect a link between SO_2 concentrations, a measure of regulatory pressure for SO_2, and CO_2 emissions. Alongside a greater incentive to adopt abatement technology, an increase in the regulation of a fossil fuel-based pollutant such as SO_2 is likely to increase the pressure on a firm to reduce its use of fossil fuels. A reduction in the use of such fuels would obviously reduce CO_2 emissions.

Table 4
Change in emissions intensity, 1990−1998, resulting from the change in environmental policy, energy intensity and industrial characteristics (%)

	SO_2	No_x	Tot. acid	CO	pm10	CO_2
Regional regulations	−11.1	−10.8	−15.0	−7.5	−10.3	−3.0
Year dummies	−57.3	−22.8	−31.9	−6.3	−25.5	−7.4
Energy intensity	−7.0	−5.2	−5.8	−2.3	−4.9	−7.6
PCI	+0.9	−0.4	+0.9	+0.5	+0.5	+0.1
HCI	−1.0	−0.2	−0.7	+0.1	−0.5	−0.1
Other vars.[a]	+2.0	−0.6	+3.2	+2.5	+0.3	+3.2

Calculated using fixed effects results and industry means.
[a]Other variables refers to size, TFP, capital expenditure and R&D expenditure.

negative, statistically significant influence on both Tot.Acid intensity and CO_2 intensity. This finding may reflect both a formal and an informal element, as previously argued.[24]

5.3. *Explaining pollution changes 1990–1998*

In order to assess the determinants of trends in pollution intensity over our sample period, we examine the extent to which our key explanatory variables are responsible for the change in emissions intensity over the period 1990–1998. Specifically, using industry means, we use data for 1990 to calculate the predicted value of emissions intensity for that year using our estimated results. To examine the role played by regulations, for instance, we then replace 1990 regulation data with 1998 data, whilst holding non-regulation data constant at its 1990 level. This allows us to measure the extent to which 1990 emissions intensity would have been reduced, ceteris paribus, if regulations were at their 1998 level. The same principle is then used to examine the impact of our year dummies, energy intensity, factor intensities and our other economic characteristics. Table 4 provides the results.

Table 4 indicates, for example, that, depending on the pollutant, the change in our regional regulation proxies (as measured by our regional variables) over the period 1990–1998 had the effect of reducing emissions intensity by between 3.0% and 15.1%, relative to 1990 levels. Our year dummies, believed to be capturing national regulations, new technologies and changing tastes that are common to all industries, had an even larger impact on emissions intensities. The year dummies capture a reduction in pollution of between 6.3% and 57.3%, again depending on the pollutant.

[24]As a final check on the robustness of our results, we consider the possible role played by outliers and estimate dfbetas. Dfbetas focus on one coefficient and measure the difference between the regression coefficient when the *i*th observation is included and excluded, the difference being scaled by the estimated standard error of the coefficient. Bollen and Jackman [5] argue that an observation is deserving of special attention if $|\text{dfbeta}| > 1$, implying that the observation shifted the estimated coefficient by at least one standard error. Across all pollutants and all independent variables we find no dfbetas that exceed 1. We also estimate our results dropping one industry at a time. Again, the sign and significance of our key variables remain unaffected.

Table 4 also indicates that changing energy intensity has provided a moderate fall in pollution intensities, which is broadly consistent across pollutants. Our results also suggest that changing factor intensities within our mean industry have had only a small impact on emissions intensity, the direction of which differs across pollutants. Finally, changes to our other four industry characteristics (size, TFP, capital expenditure and R&D expenditure) over the period 1990–1998 result in a small overall increase in emissions intensity relative to 1990 levels, for all pollutants except NO_x. Whilst increases in TFP have reduced emissions intensity, during the 1990s R&D expenditure per unit of value added and the size of the average firm within our mean industry declined slightly, resulting in an increase in emissions intensity.

6. Conclusions and policy implications

The close relationship between the manufacturing sector and pollution emissions means that it is essential that both firms and pollution regulators have a detailed understanding of the processes and industrial characteristics that influence an industry's pollution intensity.

Our panel of 22 industries covering the period 1990–1998 has provided a number of insights into what determines industrial pollution intensity. For a wide range of air pollutants, we have shown pollution intensity to be a positive function of energy use, and physical and human capital intensity. Conversely, we find pollution intensity to be a negative function of the size of the average firm in an industry, the productivity of an industry and the industry's expenditure on capital and research and development. We also find the sign and significance of these effects to be generally consistent across our six pollutants.

Although there is no single measure of UK pollution regulation, we have attempted to capture the effects of regulations using industry specific fixed effects, a time trend (or time dummies) and those regional characteristics that are likely to influence the stringency of regulation. We find the time trend to be negative and consistently significant and also find evidence of a strong regional influence on pollution intensity. Whether we capture formal regulatory pressure using a measure of regional pollution prosecutions, the regional share of 'dirty' industries or the background level of local air pollution, we find a consistently negative, and generally significant, impact on pollution intensity. Our results also indicate that regional population density, unemployment rates, age structures and per capita incomes have influenced industrial pollution intensities during our sample period. This raises the possibility that an element of informal regulation may be in operation in the UK.

Many of our findings are consistent with the results of other studies of industrial pollution. For example, in their study of US steel mills, Deily and Gray [10] find evidence to suggest that the US Environmental Protection Agency is responsive to local economic conditions when setting regulations. Our cross-industry study of the UK also finds industrial pollution intensity to be responsive to regional unemployment rates and incomes. Similarly, Hamilton [17], Kahn [25] and Helland and Whitford [20] find evidence that demographics, political activism and other social factors can influence environmental regulation in the US, findings now broadly supported by our analysis. In their study of plant level water pollution in Indonesia, Pargal and Wheeler [30] also find evidence of informal regulatory pressures. In common with our results, pollution is found to be a negative function of per capita incomes but, contrary to our results, a *positive* function of population density. They interpret this finding as a 'visibility' effect, i.e. plants in rural areas are more visible and are therefore held more accountable than plants in urban areas. In the UK it would appear that the lobbying power of a densely population region overcomes any 'visibility' effect. In terms of non-regulation variables, Pargal and Wheeler do not consider factor intensities or R&D expenditure, but do find pollution to be a negative function of plant level productivity, again, a finding which our results support. Finally, whilst studies such as Antweiler et al. [2] and Cole and Elliott [7] have indicated that pollution intensive industries are typically intensive in the use of physical capital, to the best of our knowledge, no link has previously been demonstrated between human capital use and pollution intensity.

Our results generate a number of policy implications. First, it would appear that environmental regulations in the UK have been successful in reducing both industrial emissions and emissions intensity.[25] Our results also suggest, however, that it may be fruitful to target regulations towards energy use. Whilst any reduction in energy use will reduce pollution intensity, pollutants such as sulfur dioxide would benefit from a differential tax that is applied to energy use in accordance with the pollution content of that energy. Industries would then have an incentive not only to reduce energy use, but to switch to less pollution intensive forms of energy, e.g. to low sulfur coal or from coal to natural gas. The UK's recently introduced climate change levy operates on a similar principle. Looking further afield, our results also have implications for the harmonization of environmental policies within the European Union. Our findings suggest that regulators will face pressure to adjust regulations to ensure that they meet local preferences. This may be pressure to partially relax regulations in economically disadvantaged regions if regulations are felt to be damaging employment prospects. Conversely, there may be demand to increase regulations if communities believe regulations are failing to protect the local environment. In the face of such pressures it may be politically difficult to rigidly implement harmonized regulations across the EU.

Turning to other policy implications, our analysis suggests that innovative firms, i.e. those that invest in research and development generally experience lower pollution intensity, as do those firms that undertake new investment. Thus new production processes and new plant and technology all appear to facilitate pollution control thereby supporting the continued or increased use of R&D tax credits as a possible government initiative. Furthermore, our results suggest that firms now have an added incentive to increase their productivity levels as 'environmental productivity' appears to be a side effect of more traditional productivity increases.

Despite these policy implications, our results suggest that certain influences on pollution are beyond the control of policymakers. The UK does not appear to enjoy a comparative advantage in labor-intensive industries and if a degree of specialization in the manufacturing sector is to be maintained, it is likely to be in those sectors that use at least moderate levels of physical and human capital. Since these characteristics appear to contribute towards pollution intensity,

[25] Successful in the sense that they have achieved a substantial reduction in emissions. We are not claiming that UK regulations have necessarily been efficient. Market instruments are still relatively scarce in the UK, with a continued reliance on command and control policies.

offsetting reductions in emissions will be necessary elsewhere. This would appear to be an obstacle that UK environmental policymakers have to accept and overcome.

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Appendix A

Table A1
Data definitions and sources

Variable	Definition/source
Pollution emissions	Emissions by industry in tonnes. Source: Office for National Statistics (ONS), UK Environmental Accounts. Emissions are calculated by applying emissions factors to a wide range of highly specific industrial processes and fuel use. These emissions factors are generally year specific. Data on relevant industrial processes and fuel use, and their mapping to industrial sectors, stem from the combination of the National Atmospheric Emissions Inventory and the UK National Accounts Input–Output tables
Pollution intensity	Emissions divided by gross value added (tonnes per thousand pounds sterling of GVA). See individual sources for emissions and GVA
Energy use	Total direct fossil fuel use by industry. Source: As above
N (Energy intensity)	Energy use divided by gross value added (tonnes of oil equivalent per thousand pounds sterling of GVA). See individual sources for energy use and GVA
Gross value added	Gross value added by industry. Billions of pounds sterling (1995 price). Source: ONS, UK Input-Output Analyses 2002 Edition
PCI	Physical capital intensity: Non-wage value added per worker ((VA-payroll)/employees). Source: payroll and employees data from OECD STAN Database
HCI	Share of value added paid to skilled workers: (payroll/VA)—(((unskilled wage*employment))/VA) where the unskilled wage is that of the textiles sector. Source: As above
HCImanf	An industry's wage rate relative to the average manufacturing sector's wage. Source: As above
SIZE	Value added per firm. Million pounds sterling (1995 prices). Source: number of firms, ONS, Annual Business Inquiry and report PA1002
TFP	Total factor productivity: see below
CAP	Capital expenditure divided by value added. Pounds sterling of capital expenditure per pound sterling of Value Added. Source: ONS, Annual Business Inquiry and report PA1002
RD	Research and development expenditure divided by value added. Pounds sterling of R&D expenditure per pound sterling of Value Added. Source: ONS
UK regional data	Source: ONS, Regional Accounts (various years) and Regional Trends (various years)

Table A2
Summary statistics

Variable	Mean	Min.	Max.	'Between' sd	'Within' sd
Energy	0.40	0.0097	4.14	0.75	0.13
SO_2	5.08	0.013	62.85	11.40	2.53
NO_x	3.07	0.070	21.34	5.01	0.98
Tot.Acid	7.29	0.077	76.33	14.57	3.00
CO	8.65	0.013	143.90	23.40	3.91
*Pm*10	0.52	0.0032	3.98	0.92	0.17
CO_2	1.19	0.025	10.71	2.24	0.39
PCI	20.04	3.13	157.79	26.67	6.92
HCI	0.14	0.32	0.79	0.17	0.10
Size	4.33	0.19	94.19	12.12	3.47
TFP	0.065	−0.02	0.71	0.33	0.085
CAP	0.11	0.012	0.36	0.058	0.027
RD	0.052	0.00077	0.23	0.058	0.014
REGpros	0.45	0.063	1.01	0.21	0.088
$REGSO_2$	80.55	46.47	128.23	15.56	9.10
REGdirtymanf	0.33	0.30	0.39	0.018	0.0051
REGpd	1135.92	857.41	2204.08	326.10	60.87
REGunem	8.17	5.50	10.60	1.47	0.19
REGagepop	61.51	57.45	63.19	1.20	0.34
REGpcY	10731.8	9552.6	13832.6	598.27	530.95

37 NUTS2 UK regions: Durham, Northumberland-Tyne and Wear, Cumbria, Cheshire, Greater Manchester, Lancashire, Merseyside, East Riding and N. Lincolnshire, N. Yorkshire, S. Yorkshire, W. Yorkshire, Derbyshire and Nottinghamshire, Leicestershire and Rutland and Northamptonshire, Lincolnshire, Hereford-Worcester and Warwickshire, Shropshire and Staffordshire, W. Midlands, E.Anglia, Bedforshire and Hertfordshire, Essex, Inner London, Outer London, Berkshire and Buckinghamshire and Oxfordshire, Surrey and Sussex, Hampshire and the Isle of Wight, Kent, Gloucestershire and Wiltshire, Dorset and Somerset, Cornwall and the Isles of Scilly, Devon, West Wales and the Valleys, East Wales, N.E. Scotland, E. Scotland, S.W. Scotland, Scottish Highlands and the Isles, N. Ireland (Tables A1 and A2).

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