The costs of reducing PM_{10} and NO_2 emissions and concentrations in the UK: Part 1: PM_{10}

A report produced for DEFRA and DTI

October 2001

AEA TECHNOLOGY
ENVIRONMENT

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Executive Summary

Total PM_{10} concentrations in the UK are a mixture of particles from several sources:

- Primary PM_{10} emissions from UK industry, traffic, etc. – particles emitted directly from combustion and other processes
- Secondary particles – those generated through chemical reaction in the atmosphere following emission of SO_2, NOx and other pollutants in the UK
- Particles naturally generated in the UK, including soil particles and salt spray
- Primary, secondary and natural particles generated in other countries.

This report focuses on the control of primary emissions in the UK. Secondary particles are being actively addressed through, for example, the UNECE's Gothenburg Protocol which sets national emission ceilings for all European countries for SO_2, NOx, NH_3 and VOCs. There is currently no Europe-wide legislation equivalent to the Gothenburg Protocol on primary particles, though it is under consideration for the next round of activities under the UNECE's Convention on Long Range Transboundary Air Pollution.

Conventional cost-effectiveness analysis of air pollution controls expresses each abatement technique in terms of pounds spent per unit mass emission reduced (e.g. £/tonne PM_{10}). This study has gone further, by combining these data with pollutant dispersion models. By doing this it is possible to express cost-effectiveness in terms of pounds spent per unit reduction in exposure for an average member of the population (i.e. £/$\mu g.m^{-3} PM_{10}$). This provides better guidance on which options will not just reduce concentrations of air pollutants, but will do so in a way that maximises benefits to human health. So, options (such as those concerning transport) that reduce emissions in towns and cities become more prominent, whilst those relating to sources such as quarrying that typically occur in less densely populated areas become less prominent.

The study involved the following steps:

- Collation of emission data broken down by source category.
- Identification of possible abatement measures and collation of cost data.
- Construction of cost-curves for emission reductions.
- Atmospheric dispersion modelling to establish the contribution of each source sector to population-weighted annual average concentrations, both nationally and in a number of UK regions – Glasgow, Greater London, Greater Manchester, Neath-Port Talbot, West Midlands and West Yorkshire.
- Derivation of cost-curves for the reduction of the annual average population-weighted concentrations.
- Assessment of the effects of uncertainty on the costs of reaching particular targets.

The most important sources of PM_{10} emissions in the UK, are as follows:

Source	1998 kilotonnes
Road transport (tailpipe, tyre and brake)	39.2
Residential plant (combustion)	34.5
Power stations	23.5
Quarrying	23.3
Other combustion in industry	19.9
Processes in industry	12.4
Animal wastes	11.4
Off-road sources	9.1
Commercial, public, agricultural combustion	5.3
Other combustion and transport	4.3
Refineries (combustion)	3.7
Other sources	10.7
TOTAL reported by IGCB	197.3
Additional marine sources with negligible impact on terrestrial air quality	5.9
TOTAL in the full NAEI inventory	203.2

Existing measures, for example improved vehicle technologies, and trends affecting industry will lead to a significant reduction in emissions in many of these sectors over the next 20 years.

Options identified for further abatement include:
- An extension of the fuel switching that has been observed since the 1950s (e.g. from coal to smokeless fuels for residential use, or from coal or oil to natural gas)
- Technological modifications
- Use of end-of-pipe abatement technologies (principally bag filters, ceramic filters, electrostatic precipitators, wet scrubbing)
- Various options for controlling dust generation at quarries (e.g. minimising drop heights, restricting vehicle speeds, use of wind shielding)

A number of options have not been included in the cost-curves. Improvements in energy efficiency might well be expected to occur without further government action on the grounds that many such options lead to cost savings over a reasonably short period of time. However, the fact that there still remains extensive scope for improvements in energy efficiency reflects the existence of market barriers. These barriers are under investigation elsewhere, for example in relation to efforts being made to reduce greenhouse gas emissions.

A number of options for reducing emissions from transport have also not been considered as these need to be assessed and implemented locally rather than nationally. These options are currently under consideration by many Local Authorities in the UK during the development of air quality action plans under the National Air Quality Strategy, and may be more cost-effective than some of the options considered in the cost-curve. They include:
- Promotion of public transport (e.g. development of park and ride schemes, bus prioritisation, integration of systems, fare subsidies).

- Use of vehicles running on cleaner fuels such as LPG and CNG (this is included in the cost-curve, but only to a limited extent).
- Development of low emission zones.
- Congestion charging, parking fees.
- Traffic management options such as speed regulation, use of high occupancy vehicle lanes, SCOOT systems.

The costs and effectiveness of these measures are too dependent on local characteristics to be included here. In any event, whilst they will be useful for dealing with localised pollution hot-spots, their effect on emissions and population-weighted exposure at the national level is likely to be negligible.

The marginal cost-curve for PM_{10} emission reductions (as opposed to changes in population exposure) for the UK as a whole in 2010 is shown in Figure 2, selected for this summary because:

1. 2010 is the year of greatest policy relevance at the present time
2. EPAQS[1] has concluded that PM_{10} is the most useful fraction of particulate matter for the purposes of standard setting.

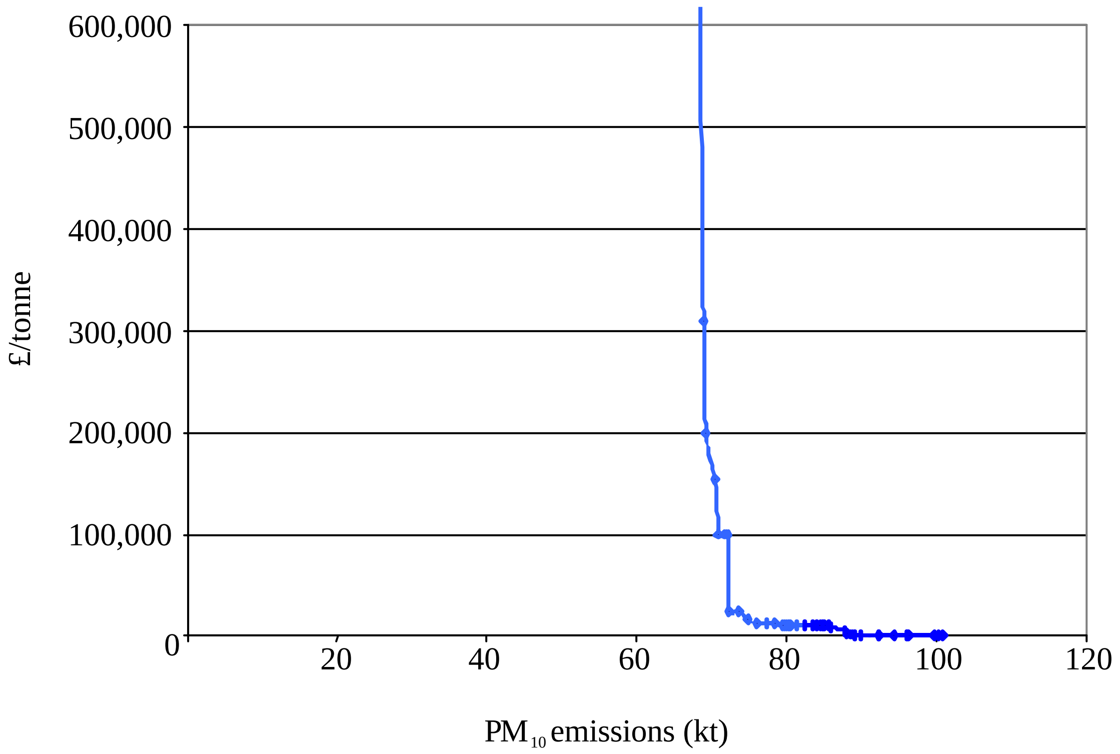

Figure 2 – Marginal cost-curve for PM_{10} emission reductions, 2010

The most cost-effective options contained within the cost-curve shown in Figure 2 are in sectors such as quarrying, refineries, iron and steel, and cement production. Overall, Figure 2 suggests that about 30% of the UK primary PM_{10} emission could be controlled by the measures identified here.

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[1] EPAQS – the UK's Expert Panel on Air Quality Standards

The transport options considered (use of 10ppm sulphur fuel, particulate traps, conversion of vehicles to run on compressed natural gas) are the least cost-effective measures of those contained in the curve. However, this is to some extent misleading. Firstly, any reduction in transport emissions is likely to have a greater benefit for human health than a similar reduction from (e.g.) quarrying, because of the proximity of people to the emission source. Secondly, the benefits of the transport options do not relate solely to reductions in PM_{10}, but also to abatement of other pollutants. [It should be noted that this applies in a larger way to many of the local options for transport that are not included in the cost-curve: for example, the promotion of public transport may have benefits extending to reduced congestion, noise and accidents, and improved accessibility, as well as pollution abatement.]

Expressing the cost-curve in terms of reductions in exposure to particles leads to some changes in the order of the options. However (albeit bearing in mind the caveat above regarding their additional benefits), the transport options again fall towards the bottom of the cost-curve.

The secondary effects of particle control measures on other pollutants are widespread for both stationary and mobile sources. In some cases, where end-of-pipe options are used, emissions of other combustion-related pollutants such as CO_2, NOx and SO_2 may increase through reductions in overall system efficiency. At the same time, however, the control of what we loosely refer to as 'particles' or 'PM_{10}' will often lead to reductions in emissions of some particularly aggressive constituents of the general particle mixture, such as heavy metals, dioxins and PAHs. In other cases, for example concerning fuel switching and efficiency options emissions of all pollutants are likely to fall. An overview of these effects is provided in the report.

The main results of this study are therefore:

1. Identification of abatement options and associated costs for reducing particle concentrations in the UK over the next 20 years.
2. Identification of the potential to reduce UK primary PM_{10} emissions by about 30%.
3. Advancement of methods for developing cost-curves that will improve the basis of future debates on air quality policy, through combining cost-curve analysis with dispersion modelling.
4. As a result of [3], assessment of how different abatement options contribute to a reduction in exposure of the population to different sources of primary particle.

Authors

This project was finalised by the following team from AEA Technology:

Mike Holland	Data checking and report finalisation
Keith Vincent	Derivation of emission/air quality relationships
Howard Rudd	Definition of options, initial report writing
Claire Handley	Finalisation of cost-curves
Tim Murrells	Analysis of transport related abatement options
Justin Goodwin	Review of emissions data, uncertainties and abatement potential
John Stedman	Co-ordination with other studies feeding into the Review of the NAQS
Daniel Forster	Uncertainty analysis

Earlier work on the study (to March 2001) was led by Ian Marlowe.

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Appendices **A1**

1 Introduction

1.1 OBJECTIVES OF THE STUDY, AND OVERVIEW OF THE METHODS USED

NETCEN, under contract reference EPG 1/8/59 "Cost of PM_{10} and NO_2 abatement", has prepared this report for the Department of the Environment, Food and the Rural Affairs (DEFRA) and the Department of Trade and Industry. The study has quantified the costs of reducing concentrations in the UK of PM_{10} (this volume) and NO_2 (in a companion volume).

The study is principally concerned with the development of ‘cost-curves’. Cost-curves provide a list of measures ranked in order of effectiveness in reducing emissions or concentrations of an individual pollution against money spent. The development of such cost-curves assists the development of policy on air quality in three ways:

1. By highlighting the most cost-effective abatement options.
2. By defining the existing technical limits on abatement in any year.
3. By showing how expensive it will be to attain certain environmental quality goals.

Development of the cost-curves produced for this study has proceeded through the following stages:

- Estimating emissions from all major sources now and into the future.
- Identifying emission reduction measures and their costs.
- Establishing the extent to which these measures are already implemented, and the extent to which they may be additionally implemented.
- Ranking measures in terms of cost-effectiveness for emission reductions.
- Using dispersion modelling to convert the emission cost-curves into cost-curves based on concentration.
- Using the results of this modelling to rank measures in terms of cost-effectiveness for reductions in pollution concentration and population exposure.
- Developing these curves for different years into the future, with particular interest for 2010.
- Carrying out the analysis both nationally and for a number of carefully chosen regions in the UK.
- Undertaking an assessment of the component uncertainties.

In addition a brief review of the effect of abatement measures on emissions of other pollutants is provided.

1.2 REASONS FOR CONCERN

PM_{10} is of concern mainly because of its effects on human health. Particles are associated with a range of acute health effects, including effects on the respiratory and cardiovascular systems, asthma and death. Following detailed review of US data [Hurley et al, 2000], COMEAP has recently concluded that the chronic health effects of particle air pollution may have a significantly greater impact than the acute effects [COMEAP, 2001]. As well as effects on health, particles in the atmosphere can also soil and corrode building materials and reduce atmospheric visibility.

EPAQS recommended an air quality standard for particles (PM_{10}) in 1995 of 50µg/m^3 measured as a 24-hour average. The air quality objective set in the 1997 National Air Quality Strategy was for this standard to be achieved as the 99th percentile. This in effect provided for the standard to be met on all but 4 days of the year. The new Air Quality Strategy for England, Scotland, Wales and Northern Ireland was published in January 2000. This was produced following a 12 month review of the original strategy. The new 2000 Strategy includes as the air quality objective for particles for 2004 the EU Stage 1 limit values in the first Air Quality Daughter Directive (see table below). The 24-hour mean limit value is for a concentration of 50µg/m^3 to be met on all but 35 days each year. However, the Strategy explains that the new objective is seen as a staging post and not a final outcome.

The European Directive 1999/30/EC [EC, 1999] on "limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air" (the 1st Air Quality Daughter Directive) was agreed in April 1999. Limit values for PM_{10} are shown in Table 1. The Table also includes indicative limit values for PM_{10} for 2010 from the Directive, which are subject to review.

Table 1 - 1st Air Quality Daughter Directive Limit Values for PM_{10}

Stage 1		
Concentration	*Specification of Limit*	*Date to be achieved by*
50 µg/m^3	Mean over fixed 24-hour periods- not to be exceeded more than 35 times a year	1 January 2005
40 µg/m^3	Annual mean	1 January 2005
Stage 2 (indicative)		
Concentration	*Specification of Limit*	*Date to be achieved by*
50 µg/m^3	Mean over fixed 24 hour periods- not to be exceeded more than 7 times a year	1 January 2010
20 µg/m^3	Annual mean	1 January 2010

The limit values specified in the directive are referenced to gravimetric measurements. As explained above, the UK Air Quality Strategy [DETR, 2000a] has adopted the Stage I limit values as objectives, also specified gravimetrically.

The Interdepartmental Group on Costs and Benefits, Air Quality (IGCB/AQ) published a preliminary economic analysis of the NAQS objectives [IGCB, 1999]. This assessed the costs and benefits of additional measures to achieve the NAQS objectives. This interim report recognised that transport measures alone would not be sufficient to meet the current PM_{10} objectives and recommended that further work should be put in place to estimate the costs of reducing PM_{10} emissions from non-transport sources. This has been the rationale for the current study. The information provided by this study is one of the main inputs to the economic analysis provided by the IGCB which looks at the costs and benefits of additional measures to achieve current and proposed alternative PM_{10} objectives [IGCB, 2001].

1.3 DEFINITIONS

1.3.1 PM_{10}

PM_{10} is airborne particulate matter with a diameter of less than or equal to 10 micrometres[1]. The diameter in question is the "aerodynamic diameter". This is defined operationally according to the type of apparatus used to measure it. Aerodynamic diameter is a function of the density and shape of the particles as well as of their size, and can be thought of as the diameter of a hypothetical spherical particle of a specified density whose aerodynamic behaviour is the same as that of the particle in question.

PM_{10} is measured by drawing air or stack-gas through a separator device that removes particles greater than 10 µm while allowing smaller ones to pass through for collection and subsequent determination. For stack monitoring, a small cyclone is used to perform this function and for ambient monitoring a device called a PM_{10} head. Ideally these devices should have zero removal efficiency for particles < 10 µm and 100% removal efficiency for particles > 10 µm. Unfortunately they do not. Figure 1 shows a typical plot of removal efficiency as a function of particle size for an ambient monitoring PM_{10} head. This shows that a significant portion of the PM_{10} in the inlet air is trapped in the impactor before it reaches the filter, and a significant portion of the particles larger than 10 µm are able to pass through the impactor without being stopped. These particles will therefore end up on the filter and will contribute to the mass of particles that are weighed. Depending on the particle size distribution in the inlet air, the two effects may cancel each other to some extent, although they are unlikely to do so exactly.

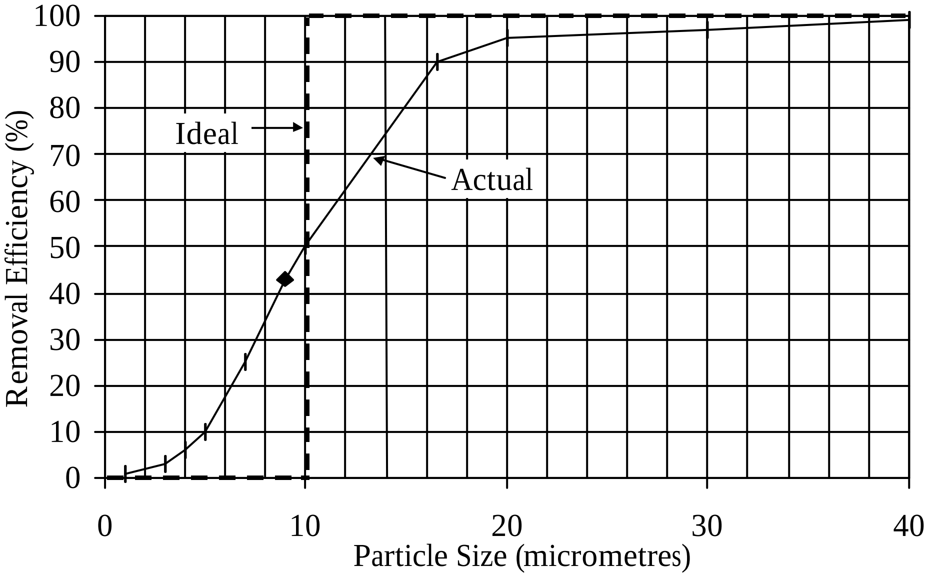

Figure 1 - Experimentally determined efficiency curve for a PM_{10} head

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[1] 1 micrometre = 1 micron =1µm = 0.000001 metre

1.3.2 Total Suspended Particulate (TSP)

Many reported emission factors refer to “total suspended particles” or TSP. This is the mass of particles collected on a filter without any upstream classification. TSP is often measured in stacks but not in ambient air. To convert emission factors expressed as total particulate it is necessary to know the particle size distribution for the source. The USEPA have published particle size distributions for many sources but there is no UK specific particle size distribution data for any of the sources of interest.

1.3.3 Filterable & Condensable Particles

Stack monitoring for particulates usually involves the sample probe, cyclone (if used) and filter housing being heated to the same temperature as the stack gas (up to 200°C), either by locating them in the stack or in a heated housing outside it. Some material that is in the vapour phase at stack temperature (and which would therefore pass through a filter) may condense to form particles as the plume disperses in the atmosphere and cools to ambient temperatures.

The particles collected on the filter are the “filterable” component. Substances that are in the vapour phase at stack temperature but later condense to form particles as the plume cools to ambient temperatures are the “condensable” component. USEPA emission factors often split the emission into filterable and condensable components.

Methods for measuring the condensable component are less well developed than are methods for the filterable component.

1.3.4 Inhalable & Respirable and Fine & Coarse Particles

When people breathe particle-laden air, the nose will usually stop particles larger than PM_{10}, whereas those of size PM_{10} or smaller can enter the respiratory system and are consequently often called “inhalable”. Particles smaller than PM_{10} but larger than $PM_{2.5}$ can generally get as far as the larynx, and those smaller than $PM_{2.5}$ can penetrate into the lungs and are often called “respirable” [McAughey, 2001]. The $PM_{2.5}$ fraction is therefore the most damaging part of the particulate matter in the atmosphere[1]

Table 2 lists these fractions and their behaviour in the human respiratory system.

Table 2 - PM size fractions and their behaviour in human respiratory system

Fraction	**Size range**	**Behaviour in human respiratory system**
non-inhalable	> 10 µm	stopped by nose
inhalable	≤ 10 µm	stopped by larynx

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[1] Noting the problems identified in Section 1.3.1 regarding the mechanical separation of particle fractions, this summary of the fate of inhaled particles is clearly general, rather than absolute.

respirable	≤ 2.5 µm	enters lungs

The terms “fine” and “coarse” are commonly, though not exclusively, used (for example by APEG[1]) with the following meanings:

Table 3 - Definitions of coarse & fine particles

fine	≤ 2.5 µm
coarse	> 2.5 µm and ≤ 10 µm

That is fine = respirable, coarse = inhalable but not respirable.

EPAQS has recently considered whether PM_{10} is still the most appropriate measurement on which to base a standard. As part of this the Panel considered whether a smaller fraction of particles ($PM_{2.5}$ for instance) might be a more appropriate standard. In its report[2] published on 3 April, the Panel concludes that, on the present evidence, measurement of particle air pollution as PM_{10}, which includes essentially all respirable particles, provides the most appropriate basis for an air quality standard in the UK.

1.3.5 Primary and secondary particles

As well as particles emitted directly into it, the atmosphere also contains so-called secondary particles. Many of these are produced through reaction of ammonia with sulphuric and nitric acids in the atmosphere forming an aerosol of ammonium sulphate and nitrate crystals. The acids are formed by the oxidation of sulphur dioxide and nitrogen oxides. These originate mainly from combustion sources and the ammonia mainly from agriculture. Secondary particles have a long atmospheric lifetime and their concentration is more uniform across the UK than primary particles. In the UK secondary particle concentrations are highest in the Southeast and lowest in the Northwest, with a continuous gradient between the two, partly as a consequence of particles brought in from continental Europe. Typical secondary concentrations range from 12 $\mu g/m^3$ in SE England to 8 $\mu g/m^3$ in NW England. Concentrations in the north of Scotland can be as low as 4 $\mu g/m^3$.

In this study, the main focus is on primary sources of particles; estimates of the secondary contribution have been made from ambient measurements. Table 4 lists the approximate relative contributions of different fractions to UK particulate concentrations.

Some fine particles, especially secondary ones, can travel long distances on the wind. IT is estimated that particles generated from emission in other countries may in total contribute as much as 20% to UK concentrations. This will be most marked in the southeast of the country, because of its proximity to mainland Europe.

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[1] Airborne Particles Expert Group. See APEG [1999] for information on membership and remit.

[2] Airborne Particles, Expert Panel on Air Quality Standards, EPAQS 2001.

Table 4 - Relative contribution of primary, secondary and coarse particles to ambient concentrations in the UK for 1998 and 2010

	1998	2010
Primary PM_{10}	23%	17%
Secondary PM_{10}	34%	27%
Coarse	43%	55%

1.4 MEASUREMENT ISSUES

In the monitoring of ambient PM_{10} concentrations the particles, after passing through the PM_{10} head, are collected either on a filter for subsequent gravimetric determination or on a tapered element oscillating microbalance (TEOM). This latter device can measure PM_{10} continuously but requires the input air to be heated. This drives off volatile components in the suspended particles leading to under-reporting compared with gravimetric methods by about 20% to 30%. The UK uses TEOMs to monitor PM_{10} but European air quality standards are expressed in terms of gravimetric measurements.

The current convention is to multiply TEOM data by 1.3 to enable meaningful comparison with gravimetric results. This is consistent with the recent recommendation from a European Commission working group that an interim factor of 1.3 should be applied to data from all continuous measurement methods in order to assess compliance with the limit values. Work will continue in order to demonstrate that a consistent relationship exists between the national methods and the reference methods as specified in the Directive but this process is expected to take some time.

1.5 SOURCE APPORTIONMENT OF PARTICLES

In January 1999 the Airborne Particles Expert Group (APEG) published a report on source apportionment of airborne particles in the UK [APEG, 1999]. They used both emission inventories and receptor modelling to elucidate the contribution of different sources to ambient concentrations. The report emphasised the complexity of source apportionment of particulate emissions. They concluded that:

- While road transport is the dominant source in terms of emissions, industrial sources may also have an important effect on concentrations;
- There is a great deal of uncertainty in emission inventories for PM_{10};
- Long range transport is predominantly of $PM_{2.5}$;
- Local industrial sources and residential coal burning can affect PM_{10} levels substantially;
- Biological particles contribute between 5 and 10% of airborne particles;
- Current annual average PM_{10} concentrations at urban background sites are typically made up of $^1/_3$ particles from combustion sources, slightly more than $^1/_3$ secondary particles and slightly less than $^1/_3$ coarse particles comprising of sea salt, biological materials, construction dusts and windblown dusts and soils.

Table 5 lists the sources of anthropogenic primary PM_{10} for the UK in order of importance (by mass emission) as a first step in deciding which sectors the study should focus on.

Table 5 - Sources of primary PM_{10} emissions in the UK in 1998 (NAEI)

Sector	1998 (kt)	% of total
Road transport (tailpipe, tyre and brake)	39.2	19.3%
Residential plant (combustion)	34.5	17.0%
Power stations	23.5	11.6%
Quarrying	23.3	11.5%
Livestock	11.4	5.6%
Iron & steel industry	7.6	3.7%
Other industry (combustion)	7.1	3.5%
Offshore own gas use	4.2	2.1%
In-house electricity generation in industry	4.8	2.4%
Other industry (part B processes)	4.0	2.0%
Construction	3.8	1.9%
Refineries (combustion)	3.7	1.8%
IPCC Marine	2.9	1.4%
Other UK shipping	2.9	1.4%
Cement production	2.9	1.4%
Agriculture	4.8	2.4%
Public services	2.3	1.1%
Chemical industry	1.4	0.7%
Offshore flaring	1.3	0.6%
Glass production	1.3	0.6%
Other industry off-road	5.5	2.7%
Non-ferrous metals industry	1.3	0.6%
Lime production (combustion)	1.1	0.6%
Coastal	1.0	0.5%
Other industry (asphalt manufacture)	0.7	0.4%
Agriculture power units	3.4	1.7%
Railways (inter-city)	0.6	0.3%
Coke production	0.4	0.2%
Miscellaneous	0.6	0.3%
Shipping naval	0.3	0.1%
Cement and concrete batching	0.2	0.1%
Fishing	0.1	0.1%
Smokeless solid fuel production	0.1	0.1%
Railways (freight)	0.1	0.1%
Aircraft TOL (Take Off and Landing) - international	0.1	0.1%
Aircraft TOL (Take Off and Landing) - domestic	0.0	0.0%
Domestic house & garden	0.2	0.1%
Collieries	0.0	0.0%
Gas production	0.0	0.0%
Aircraft support	0.1	0.0%
Railways (regional)	0.0	0.0%
Incineration	0.1	0.0%

TOTAL	**203.2**	**100.0%**

It should be noted that the inventory for any given year (e.g. 1998) is subject to change as more data become available in later years (e.g., if improvements are made to emission factors for any sector, emissions from that sector will be recalculated back to 1970, the start date for the inventory). Therefore, it is always necessary to refer to the most recently available version of the National Atmospheric Emissions Inventory before commencing analysis. Summary tables of emissions can also appear to vary year on year because of the way that sub-sectors are allocated to sectors, and because of differences in the list of sectors included in the overall total. On this last point, the difference between the total shown in Table 5 (203.2 kt) and the total cited by the 2nd IGCB report (197.3 kt) can largely be accounted for by inclusion/exclusion of some marine sources that have a negligible impact on terrestrial UK PM_{10} exposures.

1.6 LIMITS ON THE OPTIONS CONSIDERED IN THIS REPORT

A very broad range of measures may be introduced for controlling primary particle concentrations. This report largely concentrates on those that may be introduced or promoted at a national level – for example in relation to emission standards for boilers of various standards, fuel switching, etc.

The report does not deal in detail with a large number of options that may be attractive for complying with air quality legislation locally, principally, though not exclusively, in relation to traffic emissions. This would include (and is not limited to):

- Traffic management measures – phasing of traffic lights, introduction of one way systems, low emission zones, etc.
- Financial incentivisation – scrappage subsidies, congestion charging, parking levies, etc.
- Promotion of public transport – introduction of bus lanes, use of improved information systems, introduction of park and ride schemes, etc.
- Infrastructure options – construction of bypasses, pedestrianisation, etc.
- Compulsory purchase of properties in affected areas (this is being actively considered with respect to compliance with NO_2 limits by at least one local authority at the present time).

Assessment of the need for these options to deal with local air pollution ‘hotspots’ can only reasonably be done using a much more localised analysis of concentrations than has been conducted for this work. Also, assessment of the applicability and effectiveness of these local measures needs to take account of local conditions. Such detailed analysis is being undertaken by Local Authorities in response to their obligations under the NAQS.

The report also excludes options for dealing with secondary particles. Options for dealing with these have been described elsewhere [Holland, 2000; Handley, 2001] in other reports to DEFRA.

The main output of this report therefore provides data useful for demonstrating the costs of general reductions in particle emissions. At individual locations additional or alternative strategies may be preferable.

2 Methods for Deriving Cost-curves

2.1 OVERVIEW

In the context of air pollution control, a cost-curve is a list of options ranked in terms of increasing marginal cost[1] per unit emission abated. Figure 2 shows the steps involved in the derivation of a cost-curve.

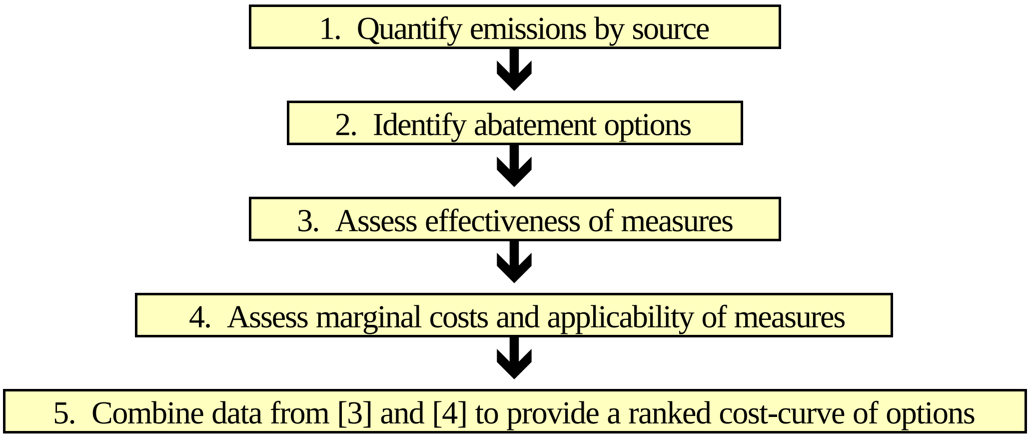

Figure 2 - Steps in the construction of a cost-curve

2.2 QUANTIFYING EMISSIONS

Quantification of emissions at the present time is relatively straightforward, drawing on the data held in the National Atmospheric Emissions Inventory [Goodwin et al, 2000; Murrels, 2000]. Development of estimates of future emissions is, however, more complex, needing to take account of (for example) industrial (and other) trends, uptake of available abatement techniques under IPPC, and government policy.

Derivation of the baseline used here for 2010 is described in a separate report [Stedman et al, 2001]. Baseline emissions for other years (to 2020) were derived similarly. Key sources of data for these projections were as follows:

Traffic activity

- DETR, 2000b: Traffic projections for England and Wales from the National Road Traffic Forecast, incorporating the impact of the 10 Year Plan for Transport.
- Scottish Executive: Traffic projections based on the Central Scotland Transport Model.
- Northern Ireland Roads Service: Traffic projections for Northern Ireland.

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[1] Marginal cost is the additional cost for an extra unit of emission reduction.

- DETR, 2000b: Estimates of changes in emissions from railways are based on data given in the 10 Year Plan for Transport.

Other factors influencing traffic emissions

- AEA Technology and DTLR: Increased penetration of diesel vehicles in the new car market; timescales for introduction of cleaner fuels, Euro-IV vehicles and particle traps.

Stationary sources

- DTI, 2000: Energy Paper 68 (Central-High Scenario), providing activity drivers by sector.

According to Energy Paper 68, electricity generation in non-FGD coal-fired stations is expected to decline to zero by 2010 in most scenarios studied, and by 2020 in all scenarios. Table 6 shows the projected changes in plant capacity. These are derived from the EP 68 “CH” scenario (C = central GDP growth, H = high energy prices).

Table 6 - Projected ESI generating capacity, GW, 1999 - 2020 (DTI 2000)

	1999	2000	2005	2010	2015	2020
Coal (non-FGD)	20	19	6	1	1	0
Coal (FGD)	6	6	11	11	11	8
Oil	3	3	2	0	0	0
Mixed	7	7	6	5	3	0
GT	2	2	2	2	2	4
CCGT	16	18	24	32	36	47
Nuclear	13	13	12	10	7	4
Renewables	2	2	4	7	7	7
Other	5	5	5	5	5	5
TOTAL	73	74	72	73	73	74

These changes are already incorporated into the emission projections [Stedman et al, 2001], and so form part of the base case.

Secondary Particles

- EMEP and HARM models, basing projections around national emissions of SO_2 and NOx agreed for 2010 under the Gothenburg Protocol.

2.3 IDENTIFYING ABATEMENT MEASURES

Identification of abatement options here draws on reports written for DEFRA, DTLR, the Environment Agency, the European Commission (including the IPPC Bureau in Seville), UNECE, the USEPA and so on, and discussion with the Environment Agency and some of the industries concerned. Much of the published material is available through the internet. This section considers the different categories of abatement measures available, first for traffic sources, and then for stationary sources. More detailed consideration of abatement options is provided in the chapters that follow.

2.3.1 Options for reducing emissions from road transport

For the purposes of this report, emission reduction measures for road vehicles can generally be categorised as follows.

Technical improvements to engines
Recent years have seen a progressive improvement in engine design and engine management. There are several drivers for these improvements, including European legislation on vehicle emissions that have seen progressive change through the Euro I, II and III standards, and the forthcoming Euro IV standards.

End-of-pipe options
End-of-pipe options collect or react with pollutants in the exhaust gas stream. Here, the most notable end of pipe option is the use of particle traps on diesel vehicles. In addition to the cost of installing the necessary devices on vehicles, further costs arise through reductions in vehicle efficiency (the same applies to the use of end-of-pipe options for stationary sources). By reducing efficiency fuel use is increased, raising costs and emissions of other pollutants. These penalties clearly need to be considered in the development of policy.

Improvements in fuel quality
European legislation, particularly through the Auto-Oil programmes, has also led to improvements in fuel quality, partly in response to technical improvements on vehicles (in engines, catalysts, etc.) that require cleaner fuels either to operate at all, or reasonably effectively.

Fuel switching
Various ‘alternative fuels’ are under investigation at the present time, including compressed natural gas (CNG), liquefied petroleum gas (LPG) and the use of fuel cells. Some are already in quite widespread use – in Beijing, for example, many buses and taxis run on CNG. Penetration of alternative fuels requires the establishment of appropriate fuel distribution systems in addition to the development and sale of vehicles able to use them.

Local measures
This group covers a wide variety of options, including park and ride schemes, congestion charging, low emission zones, installation of light rail systems and infrastructure developments. As noted already, these options are too location specific to be included in this national assessment.

The different types of option are not necessarily applicable to all types of vehicle.

2.3.2 Options for reducing emissions from stationary sources

Emission reduction measures for stationary sources can generally be categorised as follows:

Management measures and improved efficiency
Also called “front end measures” and “good housekeeping”. These options tend to yield savings in costs, for example by reducing fuel inputs or waste disposal requirements. In many cases where investment is required (e.g. improved insulation), payback times may be short enough for measures to be financially advantageous. The potential for these measures to reduce burdens on the environment at the same time as saving costs is demonstrated through the continuing success of the Government’s Best Practice Programmes in Energy Efficiency and Environmental Technologies. This group of measures has not been considered within this study because data on costs, financial benefits, applicability and effectiveness in terms of particle abatement are not generalisable. Overall we consider that the emission savings to be made from these measures, whilst important, are less significant than those that would arise from the measures included in the cost-curves.

Technological measures
These involve investment in capital equipment, as well as an ongoing operating cost. Industry usually assesses such investments either in terms of the payback period or the internal rate of return. They can be further categorised as:

Process modification
This could include, for example, the use of automatic process control, or, in the case of combustion processes, the use of secondary air or flue gas recirculation. In some cases plant replacement may be necessary, though this would only be considered by industry at what they consider to be the end of the economic lifetime of a plant

Improved design of combustion and other facilities
This type of option may in many cases be considered a variation on process modification. An example concerns improvements to combustion chambers, leading to more complete combustion of fuel.

End-of-pipe options
This involves capturing and treating an emission in a dedicated plant such as a scrubber, filter or precipitator. In many cases the best solution is a combination of process modification and end-of-pipe options.

Fuel switching
Inspection of NAEI data over the last 30 years demonstrates that UK emissions of PM_{10} have fallen by about two thirds. Much of this improvement has arisen from switching from coal and oil to natural gas in both industry and the residential sector.

Whilst it is possible to draw up generic lists of measures, such as those shown in this section, it is necessary to consider the costs and effectiveness of specific abatement measures separately by sector or sub-sector (e.g. power generation, iron and steel production and associated sub-sectors).

2.4 MEASURES OF COST-EFFECTIVENESS

Cost-effectiveness studies of air quality improvements typically focus on a single measure – effectiveness in terms of £/tonne of pollutant. Determination of this measure is fairly straightforward for many measures, based on information from engineering studies or practical experience at facilities around Europe and the USA. Cost-effectiveness will certainly vary from site to site (reflecting space limitations at existing facilities, variation in fuel quality and so on), but in most cases not substantially in the context of this study.

Application of £/tonne abated data is not, unfortunately, ideal from the perspective of designing air quality improvement strategies that optimise protection of health and the wider environment against expenditure. The reason for this is that the population (and other sensitive receptors) are not distributed evenly around all sources of pollution. This study seeks to address this problem by investigating cost-effectiveness also in terms of $£/\mu g.m^{-3}$ in a number of densely populated areas. This part of the analysis necessarily takes account of a range of factors, including the location of sources, stack height, and the location at which impact is measured.

2.5 DERIVATION OF COST DATA

In interpreting cost data it is important to know when the cost information was compiled, whether the costs have been discounted over time, and what assumptions are included in the estimates of project life. Standard methods should be used in the cost analysis. In short, the data entered into a cost-curve for different measures need to be truly comparable.

Costs are usually expressed in terms of equivalent annual cost (or annualised cost). This consists of the annual operating costs of the measure plus the initial capital cost amortised over its expected economic life at an appropriate discount rate. This enables comparisons to be made between measures on an equivalent basis, in terms of cost per tonne of pollutant abated or cost per $\mu g/m^3$ reduction in the ambient concentration of a pollutant.

A summary of the guidelines produced by the European Environment Agency on cost data collection and interpretation is presented in the box below. These guidelines can be found at http://www.eea.eu.int/. Another guidance document on cost assessment is available from the US EPA at http://www.epa.gov/ttn/ecas/costguid.html.

Most cost data in the literature centres on abatement measures for large stationary sources (power plants, incinerators, etc.) and vehicle technologies (particle traps, etc.). Much less information is available on the costs and effectiveness of non-technical measures, such as many transport options (e.g. promotion of public transport, economic and fiscal instruments) and measures relevant to the residential sector. The costs of such measures tend to be strongly site specific.

Cost-Effectiveness

The EEA summary guidelines (‘Guidelines for defining and documenting data on costs of possible environmental protection measures’, EEA 2000) are:

- Pollutant definitions and assumptions regarding scope of pollutant categories should always be given wherever there is any possibility of ambiguity.
- Sufficient detail of the pollution source should be given to enable comparison with similar processes and to avoid ambiguity. It is recommended that published source sector classifications should be used wherever possible.
- Sufficient detail of the environmental protection measure should be given to avoid ambiguity, to define its performance characteristics, and to clarify any special circumstances limiting applicability of the measure.
- It is essential that reported costs are defined: what is included, what is excluded, how they have been attributed or apportioned. It is recommended that costs are also explained in physical terms, such as quantity of materials, and as unit prices. This enables cost estimates to be replicated at a later date.
- As a minimum, all data should have a background discussion of the key uncertainties related to the data.
- The year to which the following data apply should always be given:
  - cost data;
  - currency exchange rates;
  - data describing control technologies (efficiency, applicability) and process technologies;
  - emissions to the environment.
- The sources and origins of all data should be recorded as precisely as possible so that data may be traced at a later date if necessary.
- As a minimum, any discount or interest rates used should be recorded.
- If cost data are adjusted for inflation or changes in price through time, then the method used should be recorded and any index used should be recorded and referenced.
- When determining annual cost data the approach used to derive the annual costs should be recorded, along with all underlying assumptions.

The guidance recommends that all cost estimates should be presented in equivalent terms. The same base year and discount rate should be used to calculate the annualised costs of all measures, using a formula such as the following:

$$\mathrm{PVC}_0^k = \sum_{t=0}^{\mathrm{T}^k} \left[\mathrm{NRC}_t^k + \mathrm{ERC}_t^k + \mathrm{NERC}_t^k\right] \circ \left[1 + r\right]^{-t}$$

where:
PVC the present value of the total cost stream for environmental protection measure k in year zero,
NRC the non-recurring cost of environmental protection measure k in period t,
ERC the energy recurring costs to operate environmental protection measure k in period t,
NERC the non-energy recurring costs to operate environmental protection measure k in period t,
t, the operating life of environmental protection measure k, and
r = the appropriate discount rate (here taken as 6%, though sensitivity to 3% has also been carried out).

Examples are presented in the EEA guidance.

2.6 DERIVATION OF COST-CURVES

Once cost-effectiveness has been established for each option the cost-curve is generated by ranking measures in order of increasing marginal cost/tonne or unit concentration. These often show that pollution reductions are initially very cheap, but that costs rise increasingly steeply as further measures are introduced (Figure 3).

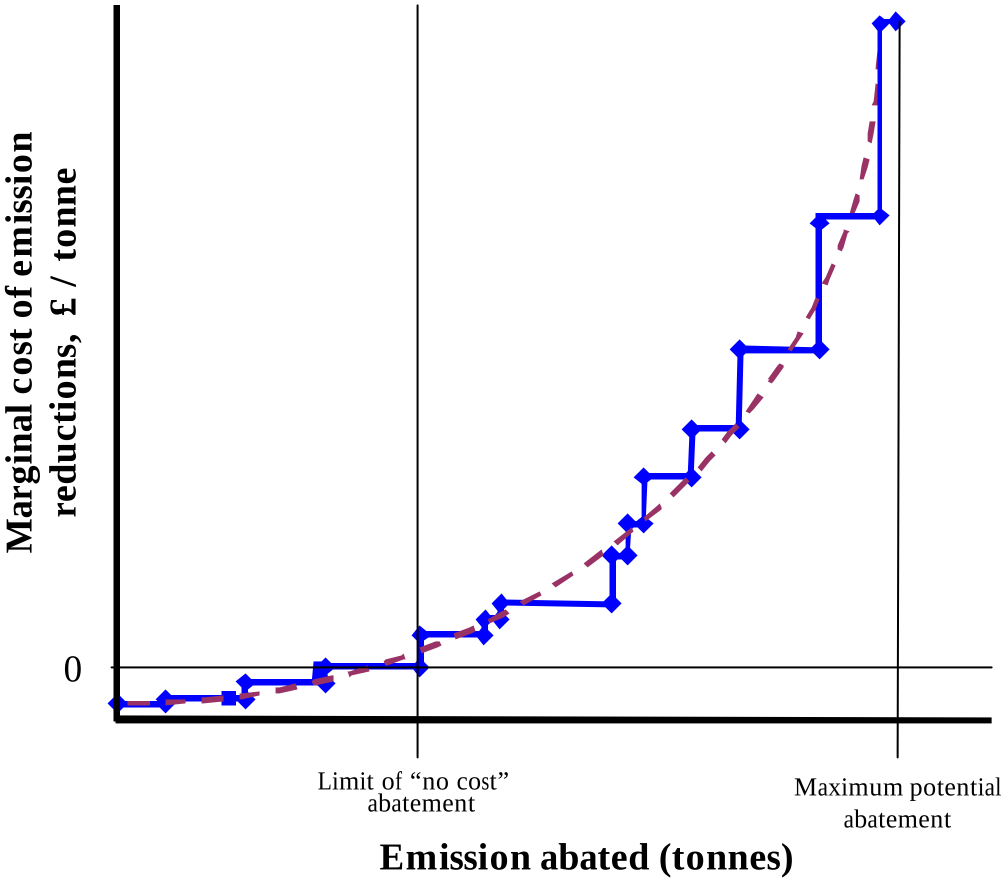

Figure 3 - Example of a marginal cost-curve

Marginal cost-curves are variously plotted as a series of discrete steps, or as a smoothed line, both being shown in Figure 3. The figure also demonstrates some other issues. First, and most obviously, there are limits to the extent to which abatement options can control emissions or concentrations, this being referred to as the maximum potential abatement or maximum feasible reduction. Secondly, there are a number of measures that reduce pollution whilst saving money. Excellent examples are the energy efficiency options already referred to that save money by reducing fuel bills, with short payback times. It might be thought that the potential for additional implementation of these measures must be very limited by now, though observations made for example on the national housing stock tend to suggest otherwise. There would certainly seem to be some market barriers in place that prevent the full uptake of these apparently money-saving measures, and so this report has not included them in the cost-curves. This clearly provides a possible source of bias towards the cost-curves presented in this report being pessimistic – that greater emission reductions may be possible at lower costs than we have estimated. The issues behind sub-optimal penetration of efficiency measures have been extensively researched over many years, and further progress in this field was beyond the scope of this study.

Cost-curves need to be treated with care by policy-makers for several other reasons:

- All known or quantifiable measures are included up to the point at which emissions from a sector are reduced to their minimum. However, some of the later measures on the cost-curve may negate the need for some earlier options (i.e. any option for a given source that is cheaper in terms of £/tonne than a second option, but which in total abates a smaller amount of pollution than the second option and is not complementary to it). For example, it would be illogical to upgrade bag filters or electro-static precipitators on a combustion plant *and* to convert the system to run on natural gas (which alone would effectively reduce emissions of particles to zero), simply because it is interpreted that the cost-curve suggests that both measures are needed to reach a particular level of emission. This is taken into account in development of the curves showing cumulative costs.
- The response of industry to the introduction of new environmental and non-environmental policy may differ to that anticipated in the cost-curve.
- Some policies that at first appear unrelated to emissions control may have significant impacts on air quality. Good examples are liberalisation of the energy sector (leading to the ‘Dash for Gas’ in the 1990s) and de-regulation of bus services.
- Many measures control more than one pollutant. Hence a measure that appears expensive for controlling PM_{10} but which controls a broad range of other emissions also, may be preferable to a cheaper option that perhaps deals with PM_{10} alone in the context of wide ranging initiatives such as the National Air Quality Strategy.

2.7 CONVERTING EMISSION COST-CURVES INTO CONCENTRATION COST-CURVES

The Government's policy objectives are framed in terms of ambient concentrations rather than emissions. Consequently, the relationship between reductions in ambient concentration and the cost of achieving them is of more interest than is the cost of emission reduction *per se*.

Ambient concentration objectives are usually expressed in terms of the fraction of the time that the concentration of the pollutant is above its limit value, and usually apply at every point in the country. The functional relationship between the statistics in terms of which the standard is expressed and the cost of achieving it is therefore complex and multi-factorial.

However, the main effects of airborne particulates about which people are concerned - health effects and the soiling and erosion of buildings (although not the reduction of atmospheric visibility) - are such that their rate is approximately proportional to the concentration. Consequently, the cumulative effect of the pollutant on a receptor (person or building) is proportional to the exposure of that receptor to the pollutant.

2.7.1 Basis of the dispersion and exposure modelling

If X is the total exposure (in receptor.year.µg/m^3) that the population has accumulated in the year in question, P is the total population of receptors, and $\overline{c}$ is the population-weighted annual average concentration, then $X = \overline{c}P$[1]. $\overline{c}$ is therefore the average exposure of the population. For any member of the population taken at random $\overline{c}$ is their expected exposure in (µg/m^3) years.

$\overline{c}$ has a number of properties that make it ideally suitable as a parameter in terms of which cost-curves can be constructed. These are:

1. It is a single valued function of emissions
2. It can be expressed as the sum of the contributions of individual sources
3. These contributions can be estimated by dispersion modelling
4. It scales linearly with emission from individual sources[2]

Other statistics related to ambient concentrations, such as the number of exceedences of a standard, do not possess these properties.

$\overline{c}$ is most strongly influenced by changes in concentrations in large cities such as London. These are also the areas that are at greatest risk of exceedences of air quality standards due to the presence of emissions associated with urban activities.

The contribution ($\overline{c}_i$) of source i to the total population-weighted average ($\overline{c}$) is proportional to the emission (E_i) from that source. That is, $\overline{c}_i = k_i E_i$, where k_i is a constant characteristic of the source sector. If the application of an emission reduction measure to source i gives an emission reduction of ΔE_i then it will produce a reduction in $\overline{c}$ of $k_i \Delta E_i$. The set of factors k_i, which are equal to the population-weighted annual average concentrations that each source would produce if it emitted 1 tonne per year, thus allow us to convert an emission cost-curve into a concentration cost-curve.

A cost-curve expressed in terms of $\overline{c}$ only predicts the cost of reducing $\overline{c}$. While this allows us to relate costs to benefits, such as reductions in adverse health impacts, it does not allow direct prediction of the cost of achieving the air quality standards as set out in European Directive 1999/30/EC. However, it does produce a first estimate of these costs, which can then be refined by

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[1] If the country is divided into 1 km×1 km grid squares and the population in square (i,j) is $p_{i,j}$ and annual average concentration in square (i,j) is $c_{i,j}$ then the population-weighted annual average concentration is:

$$\overline{c} = \frac{\sum_i \sum_j c_{i,j} p_{i,j}}{\sum_i \sum_j p_{i,j}}$$

However, $\sum_i \sum_j c_{i,j} p_{i,j}$ is X, the total exposure (in person.year.mg/m^3) accumulated in the year in question and $\sum_i \sum_j p_{i,j} = P$ the total population, so $\overline{c} = X/P$ and $X = \overline{c}P$.

[2] That is, $\overline{c}_i(\alpha E_i) = \alpha \overline{c}_i(E_i)$, where E_i is the emission from source sector i and α is a constant.

mapping emissions and concentrations. For example, the set of measures required to achieve $\bar{c}$ = 40 $\mu g/m^3$ and their associated emission reductions can be used to map instantaneous and annual average concentrations. If the standards are exceeded, then the source emissions can be adjusted, in order of increasing cost per tonne, to determine the least cost set of measures needed to meet the standards.

Although in theory the population-weighted annual average concentration could be modelled for all receptors, in this study we have only modelled it in terms of the human population. This is because:

- People are the most important receptors,
- Population data for other receptors are not available,
- The density of building materials is likely to follow the human population density, and so is effectively taken into account.

It is evident from the results of the analysis presented below that the total contribution of anthropogenic sources of primary PM_{10} to $\bar{c}$ is small - being approximately 2 to 4 $\mu g/m^3$. This means that even if all anthropogenic sources were completely switched off concentrations of PM_{10} would only be reduced by this much.

2.7.2 Choice of regions

Case study regions have been chosen based on current and projected assessments of air quality across the UK. The regions are those that have been found to have exceedences of the Air Quality Strategy Objectives for PM_{10} and/or NO_2. The regions chosen are defined by Local Authority Districts (Appendix 8) and are:

- Glasgow
- Greater London
- Greater Manchester
- Neath Port Talbot
- West Midlands
- West Yorkshire

Figure 4 shows the location of the regions. The populations within each region are presented in Table 7.

Table 7 - National and regional population totals

Region	Population
UK	56,882,000
Glasgow	576,000
West Yorkshire	1,520,000
Manchester	2,678,000
West Midlands	2,509,000
Neath - Port Talbot	140,000
London	6,808,000

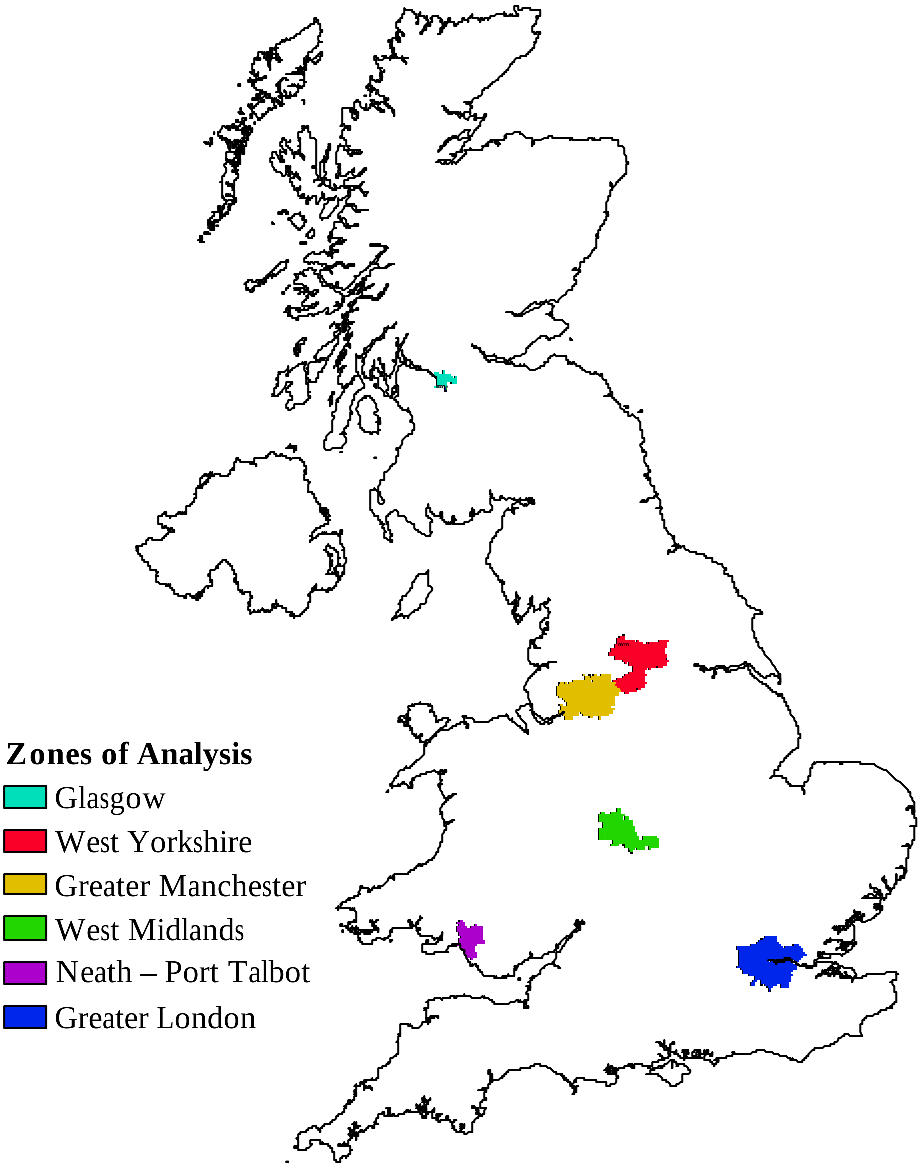

Figure 4 - Case study regions

2.7.3 Treatment of sources outside regions

Sources outside a region also contribute to ambient concentrations inside the region, reducing the scope for local control of ambient concentrations. In particular, the effect of controlling sources in a region may be very small compared with the costs of controlling them because of the contribution of sources outside the region and also because of the fact that only part of the impact of sources in the region falls within the region.

In this study, sources in a "buffer zone" outside each region have been taken into account in the dispersion modelling. These zones are different for area and point sources. Define three sets of geographical locations:

R = the set of all locations in the region itself (i.e. R *is* the region)

T = the set of all locations outside R and less than or equal to 15 km away from the boundary of R (i.e. T is a 15 km wide annulus surrounding R)

U = the set of all locations outside R and less than or equal to 100 km away from the boundary of R (i.e. U is a 100 km wide annulus surrounding R)

In the modelling, the contribution of point sources in U and area sources in T are included.

The buffer zones of some regions overlap. However, the potential complications this could cause are ignored. The regions are treated as if the others did not exist.

2.7.4 Results of the initial dispersion modelling

Ambient concentrations have been predicted for emissions from all major processes and for source sectors like road transport, residential gas and coal combustion (see Table 8). Sources for which the PM_{10} emission is a significant amount of the national total such as power stations, iron and steel plant and refineries are modelled individually. Other emission sources for which the emission is more diffuse or less well characterised are modelled by considering the emission from each of the individual 1-km squares of the disaggregated inventory.

Table 9 lists values of k_i for the source sectors modelled. This factor relates emission in tonnes to population-weighted exposure in $\mu g.m^{-3}$ and has been used to derive concentration cost-curves both nationally and for the case study regions. So for example, for road transport nationally, the k_i factor is 2.54×10^{-5} $\mu g.m^{-3}$/tonne (from column 3 of the top row of data in Table 9). Multiplying this by the national emission of PM_{10} from transport gives the total population-weighted concentration (i.e. exposure) attributable to transport.

Table 8 - Summary of source sectors modelled, showing the nature of the source and the resolution of each respective receptor area

NAEI Source Sector	Source description	Nature of source modelled	Receptor area	Receptor resolution
Road Transport	Includes combined exhaust and brake and tyre wear	Volume	UK	1 km
Residential Combustion	All solid fuel combustion in domestic grates	Volume	UK	1 km
Residential Combustion	Gas consumption in domestic grates	Volume	UK	1 km
Power Stations	Assumes stations 24 operating in 2005 and 2010	Point	UK	5 km
Quarrying	Only total aggregate is considered	Volume	UK	1 km
Agriculture	Emission (2.28 kt) relates to straw burning	Volume	UK	1 km
Agriculture	Off-road vehicles	Volume	UK	1 km
Other industry (Combustion)	Includes industrial in-house electricity generation	Volume	UK	1 km
Construction	All construction activities	Volume	UK	1 km
Refineries (Combustion)	Includes process and combustion sectors	Point	120 km square centred on plant	2 km
Other Industry (Small Processes)	Non -fuel processes	Volume	UK	1 km
Cement		Volume	UK	1 km
Iron & Steel	Sinter Plant	Volume and point	120 km square centred on plant	2 km
Iron & Steel	Blast Furnaces	Volume and point	120 km square centred on plant	2 km
Iron & Steel	Basic oxygen Furnaces	Volume and point	120 km square centred on plant	2 km
Iron & Steel	Coke Production	Line source	120 km square centred on plant	2 km
Public Services	Building Services- coal	Volume	UK	1 km
Public Services	Building Services – gas	Volume	UK	1 km
Other Industry (Large Processes)	Non -fuel processes	Volume	UK	1 km
Lime Production	Rotary kiln	Volume	UK	1 km
Lime Production	other kilns (e.g. shaft kiln)	Volume	UK	1 km
Lime Production	lime hydrator	Volume	UK	1 km
Lime Production	Fugitive	Volume	UK	1 km
Non-ferrous metals	Aluminium	Volume	UK	1 km
Non-ferrous metals	Copper	Volume	UK	1 km
Non-ferrous metals	Lead and zinc	Volume	UK	1 km
Non-ferrous metals	Other non-ferrous metals	Volume	UK	1 km
All other sources	A combined emission grid	Volume	UK	1 km

Table 9 - Contributions to population-weighted annual average concentrations of PM_{10} by source sector when each source sector emits 1 tonne per year (blank cells are sources whose contribution is too small to model)

Source	**Subsource**	**National** μg/(m^3-tonne)	**Glasgow** μg/(m^3-tonne)	**W. York** μg/(m^3-tonne)	**Manchester** μg/(m^3-tonne)	**W.Mid** μg/(m^3-tonne)	**Neath PT** μg/(m^3-tonne)	**London** μg/(m^3-tonne)
Road Transport		2.54×10^{-5}	1.89×10^{-3}	8.04×10^{-4}	6.65×10^{-4}	6.63×10^{-4}	1.28×10^{-3}	4.97×10^{-4}
Residential Combustion	All solid fuels	4.64×10^{-6}	2.75×10^{-4}	1.22×10^{-4}	9.36×10^{-5}	1.02×10^{-4}	4.30×10^{-4}	2.96×10^{-5}
Residential Combustion	Gas	4.51×10^{-5}	2.10×10^{-3}	1.13×10^{-3}	8.49×10^{-4}	9.95×10^{-4}	1.24×10^{-3}	7.17×10^{-4}
Residential Combustion	Oil							
Power Stations	Coal	1.12×10^{-6}	4.32×10^{-6}	3.48×10^{-6}	3.52×10^{-6}	4.35×10^{-6}	6.24×10^{-6}	7.61×10^{-6}
Power Stations	Other fuels							
Quarrying	Mineral Extraction	8.55×10^{-6}	2.32×10^{-4}	3.57×10^{-4}	1.20×10^{-4}	6.32×10^{-5}	1.99×10^{-4}	6.98×10^{-5}
Quarrying	Conveyors	8.55×10^{-6}	2.32×10^{-4}	3.57×10^{-4}	1.20×10^{-4}	6.32×10^{-5}	1.99×10^{-4}	6.98×10^{-5}
Quarrying	Crushing & Screening	8.55×10^{-6}	2.32×10^{-4}	3.57×10^{-4}	1.20×10^{-4}	6.32×10^{-5}	1.99×10^{-4}	6.98×10^{-5}
Quarrying	Haulage	8.55×10^{-6}	2.32×10^{-4}	3.57×10^{-4}	1.20×10^{-4}	6.32×10^{-5}	1.99×10^{-4}	6.98×10^{-5}
Quarrying	Mounds & Stockpiles	8.55×10^{-6}	2.32×10^{-4}	3.57×10^{-4}	1.20×10^{-4}	6.32×10^{-5}	1.99×10^{-4}	6.98×10^{-5}
Agriculture	Intensive Livestock Production							
Agriculture	Combustion	4.83×10^{-6}	3.80×10^{-4}	2.53×10^{-4}	1.88×10^{-4}	1.39×10^{-4}	7.21×10^{-4}	6.98×10^{-5}
Agriculture	Power Units	5.97×10^{-6}	3.88×10^{-4}	2.31×10^{-4}	1.85×10^{-4}	1.36×10^{-4}	1.36×10^{-3}	7.34×10^{-5}
Other industry (Combustion)		2.14×10^{-5}	8.74×10^{-4}	5.85×10^{-4}	2.47×10^{-4}	4.49×10^{-4}	2.30×10^{-3}	2.20×10^{-4}
Offshore Own Gas Use								
In-house electricity generation								
Construction		3.94×10^{-5}	2.03×10^{-3}	1.07×10^{-3}	8.26×10^{-4}	9.57×10^{-4}	1.15×10^{-3}	7.06×10^{-4}
Refineries (Combustion)		1.47×10^{-6}						
Other Industry (Small Processes)		3.16×10^{-5}	1.88×10^{-3}	1.28×10^{-3}	8.12×10^{-4}	9.50×10^{-4}	1.72×10^{-3}	3.90×10^{-4}
Cement		6.49×10^{-6}				6.82×10^{-6}		1.40×10^{-5}
Iron & Steel	Sinter Plant	9.85×10^{-6}					1.23×10^{-3}	
Iron & Steel	Blast Furnaces	7.83×10^{-6}					1.29×10^{-3}	
Iron & Steel	Combustion							
Iron & Steel	Electic Arc Furnaces							
Iron & Steel	Basic oxygen Furnaces	1.17×10^{-5}					1.15×10^{-3}	
Iron & Steel	Coke Production	1.11×10^{-5}					9.36×10^{-4}	
Iron & Steel	Flaring							
Public Services	Building Services							

Source	**Subsource**	**National** µg/(m^3-tonne)	**Glasgow** µg/(m^3-tonne)	**W. York** µg/(m^3-tonne)	**Manchester** µg/(m^3-tonne)	**W.Mid** µg/(m^3-tonne)	**Neath PT** µg/(m^3-tonne)	**London** µg/(m^3-tonne)
Other Industry (Large Processes)		3.17×10^{-5}	2.03×10^{-3}	1.10×10^{-3}	6.85×10^{-4}	9.75×10^{-4}	1.15×10^{-3}	7.05×10^{-4}
Offshore Flaring								
Other Industry Offroad								
Lime Production	Rotary kiln	2.24×10^{-5}	1.76×10^{-3}	9.26×10^{-4}	2.56×10^{-4}	8.32×10^{-4}	9.60×10^{-4}	6.24×10^{-4}
Lime Production	other kilns (e.g. shaft kiln)	2.20×10^{-5}	1.76×10^{-3}	9.26×10^{-4}	2.56×10^{-4}	8.32×10^{-4}	9.60×10^{-4}	6.24×10^{-4}
Lime Production	lime hydrator	2.24×10^{-5}	1.76×10^{-3}	9.26×10^{-4}	2.56×10^{-4}	8.32×10^{-4}	9.60×10^{-4}	6.24×10^{-4}
Lime Production	fugitive	2.20×10^{-5}	1.76×10^{-3}	9.26×10^{-4}	2.56×10^{-4}	8.32×10^{-4}	9.60×10^{-4}	6.24×10^{-4}
Coastal								
Other Nonindustrial								
Other Industry (Asphalt manufacture)								
Nonferrous Metals	Aluminium Production							
Nonferrous Metals	Primary Lead & Zinc Production							
Nonferrous Metals	Copper Refining							
Nonferrous Metals	Other							
Railways (intercity)								
Miscellaneous								
Shipping Naval								
Cement and Concrete batching								
Fishing								
SSF Production								
Railways (Freight)								
Aircraft Take Off&Landing (international)								
Aircraft Take Off&Landing (Domestic)								
Domestic House&Garden								
Collieries								
Gas Production								
Aircraft Support								
Railways (Regional)								

Table 10 presents the national populated weighted mean concentrations for 2005 and 2010 derived by adding together the PM_{10} concentration resulting from each of the individual source sectors.

Table 10 - Sum of population-weighted mean concentrations in 2005 and 2010. Results are expressed on a TEOM basis. To express on a gravimetric basis results need to be multiplied by 1.3 (see Section 1.4).

	National	Glasgow	West Yorks.	Manchester	W. Midlands	Neath Port Talbot	London
2005	1.84	2.13	2.12	2.38	3.22	2.65	3.85
2010	1.67	1.91	1.89	2.16	3.04	2.53	3.49

Table 11 and Table 12 present the population-weighted concentrations for each of the individual processes for 2005 and 2010 respectively. Nationally and for each of the regions apart from Neath-Port Talbot, concentrations are highest for the road transport, residential combustion of gas, construction activities, other industry small process, other industry combustion, “other sources” and large processes. Figure 5 ranks the concentrations in descending order for all sources contributing more than 0.01 µg m^{-3} to the annual mean concentration. Emissions from the road transport sector clearly dominate the concentration profile. The role of gas combustion in the residential sector is likely to be significantly overstated through uncertainty in the emission factor (see Section 4.4).

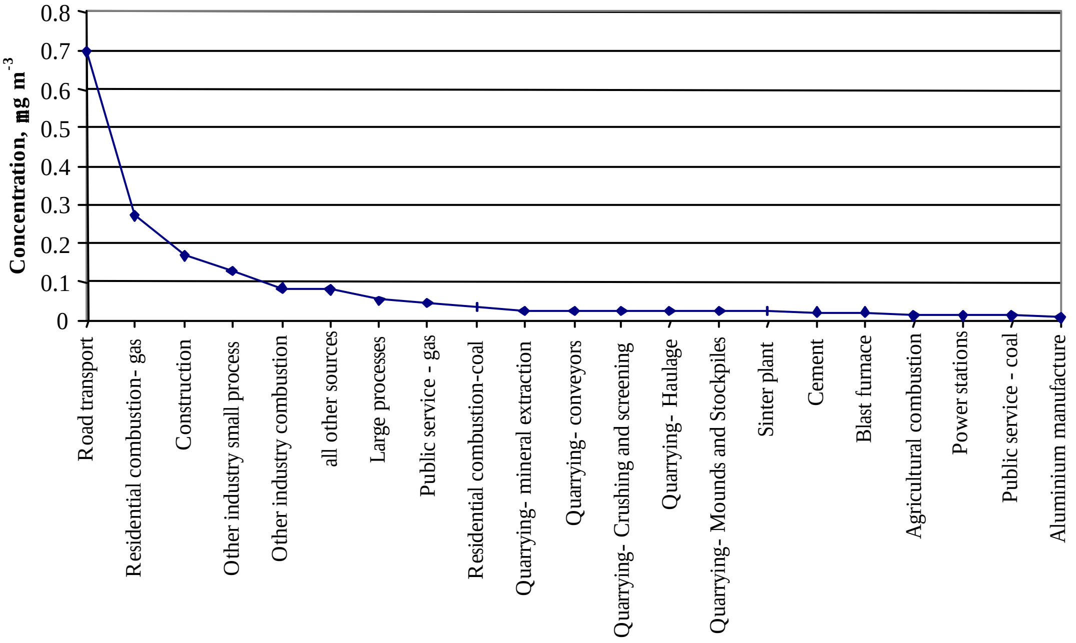

Figure 5 - PM_{10} concentrations resulting from emission from a range of different emission sources. Only concentrations greater than 0.01 mg m^{-3} are shown.

Further details of the modelling work, including validation of the approach, are provided in Appendix 10.

Table 11 - Population-weighted mean concentrations for national and regional areas for 2005 (mg m^{-3})

		Region					
Sector	National	Glasgow	West Yorks.	Man-chester	W. Midlands	Neath PT	London
Road transport	0.699	1.015	0.854	1.033	1.107	0.383	1.760
Residential combust. -coal	0.034	0.012	0.010	0.008	0.015	0.035	0.004
Resiential combust. - gas	0.273	0.396	0.307	0.375	0.436	0.1	0.813
Power stations	0.012	0.003	0.020	0.023	0.017	0.003	0.006
Quarrying♣	0.025	0.006	0.050	0.011	0.004	0.017	0.002
Agricultural combustion	0.012	0.004	0.011	0.009	0.007	0.005	0.004
Off road power units	0.002	*	0.002	0.002	0.001	0.002	0.001
Other industry combustion	0.082	0.029	0.090	0.129	0.099	0.316	0.071
Construction	0.167	0.236	0.183	0.224	0.260	0.063	0.483
Refineries	0.005	0.006	*	0.015	*	*	0.005
Other industry small process	0.127	0.139	0.183	0.211	0.653	0.124	0.132
Cement	0.019	*	*	*	0.001	*	0.003
Sinter plant	0.022	*	0.002	*	*	0.548	*
Blast furnace	0.018	*	0.002	*	*	0.697	*
Basic oxygen furnace	0.005	*	*	*	*	0.163	*
Coking plant	0.004	*	*	*	*	0.048	*
Public service – coal	0.011	0.008	0.013	0.014	0.009	0.007	0.013
Public service – gas	0.045	0.075	0.046	0.051	0.055	0.01	0.169
Large processes	0.050	0.060	0.054	0.059	0.070	0.016	0.125
Lime-Rotary – Kiln	0.007	0.008	0.007	0.009	0.009	0.002	0.018
Lime- other kilns	0.004	0.005	0.004	0.005	0.005	0.001	0.010
Lime- lime hydrator	0.007	0.008	0.007	0.009	0.009	0.002	0.018
Lime – fugitive	0.002	0.002	0.002	0.003	0.003	0.001	0.005
Aluminium	0.010	*	*	0.044	0.069	*	*
Zinc and lead	0.006	*	*	*	0.116	*	*
Copper	0.003	*	*	*	0.075	*	*
Other non ferrous metals	0.008	*	*	0.001	0.086	0.007	0.004
All other sources	0.079	0.088	0.072	0.105	0.1	0.036	0.201

♣ For the purposes of this study, emissions from quarrying are assumed to be evenly distributed among the following processes: mineral extraction; conveyors; crushing and screening; haulage and mounds and stockpiles. The concentrations predicted for each sector are the same and is the value presented in the table.

* Represents a concentration value less than 0.001 µg m^{-3}.

Table 12 - Population-weighted mean concentrations for national and regional areas for 2010 (μg m^{-3})

		Region					
Sector	National	Glasgow	West Yorks.	Man-chester	W. Midlands	Neath PT	London
Road transport	0.526	0.764	0.643	0.777	0.833	0.288	1.324
Resdiential combust. -coal	0.024	0.008	0.007	0.005	0.011	0.025	0.003
Residential combust - gas	0.276	0.401	0.311	0.379	0.441	0.101	0.823
Power stations	0.007	0.002	0.013	0.015	0.010	0.002	0.004
Quarrying♣	0.021	0.005	0.041	0.009	0.003	0.014	0.001
Agricultural combustion	0.012	0.004	0.011	0.009	0.007	0.005	0.004
Off road power units	0.002	*	0.001	0.002	0.001	0.001	0.001
Other industry combustion	0.083	0.029	0.090	0.130	0.099	0.317	0.071
Construction	0.181	0.257	0.200	0.244	0.284	0.068	0.526
Refineries	0.006	0.006	*	0.015	*	*	0.005
Other industry small process	0.139	0.151	0.199	0.230	0.712	0.135	0.144
Cement	0.019	*	*	*	0.001	*	0.003
Sinter plant	0.022	*	0.002	*	*	0.551	*
Blast furnace	0.018	*	0.002	*	*	0.676	*
Basic oxygen furnace	0.005	*	*	*	*	0.166	*
Coking plant	0.004	*	*	*	*	0.046	*
Public service – coal	0.009	0.007	0.011	0.012	0.008	0.006	0.011
Public service – gas	0.047	0.079	0.048	0.053	0.058	0.010	0.177
Large processes	0.055	0.065	0.060	0.065	0.076	0.017	0.136
Lime-Rotary – Kiln	0.008	0.009	0.007	0.010	0.010	0.002	0.019
Lime- other kilns	0.005	0.005	0.004	0.006	0.006	0.001	0.011
Lime- lime hydrator	0.008	0.009	0.007	0.010	0.010	0.002	0.019
Lime – fugitive	0.002	0.003	0.002	0.003	0.003	0.001	0.006
Aluminium	0.011	*	*	0.046	0.073	*	*
Zinc and lead	0.006	*	*	*	0.117	*	*
Copper	0.003	*	*	*	0.077	*	*
Other non ferrous metals	0.008	*	*	0.001	0.086	0.007	0.004
All other sources	0.076	0.085	0.069	0.101	0.096	0.035	0.194

♣ For the purposes of this study quarrying is assumed to be evenly distributed among the following processes: mineral extraction; conveyors; crushing and screening; haulage and mounds and stockpiles. The concentrations predicted for each sector are the same and is the value presented in the table.

* Represents a zero concentration or concentration value less than 0.001 μg m^{-3}.

3 Emissions and Concentrations

National and regional emissions data have been taken from the National Atmospheric Emissions Inventory (NAEI) except where otherwise stated. Information is summarised in this chapter, though more details are given in the Appendices:

- Appendix 2: Emission factors from the NAEI for PM_{10}.
- Appendix 3: Additional emission factors for livestock.
- Appendix 4: NAEI estimates of emissions of various size categories of PM in the 1990s.
- Appendix 5: Detailed view of the 1998 emissions.
- Appendix 6: Emission forecasts into the future (to 2020).
- Appendix 7: Regional inventories for PM_{10} in 1997.
- Appendix 9: Emissions from point sources.
- Appendix 10: Validation of PM_{10} modelling.

3.1 NATIONAL DATA SETS

Emissions for 1998 were summarised in Table 5 in Chapter 1. More than 50% of emissions arose from just 4 sources (road transport, residential combustion, power stations and quarrying) in 1998. Projections for the period 2000 to 2020 are shown for the major sectors in Table 13. It is evident from these data that major reductions in emission are anticipated. These come mainly from the four main sources identified above, and reflect changes in activity levels, fuel switching and technological advances.

Table 13 - Summary of primary PM_{10} emission forecasts for major sectors, kt/yr

	2000	2005	2010	2015	2020
Public Power	9.51	11.07	7.23	5.12	4.41
Petroleum Refining Plants	3.62	3.72	3.84	4.05	4.18
Other Combustion & Transformation	3.25	3.59	3.93	4.28	4.64
Residential Plant	17.55	13.50	11.41	10.17	9.34
Commercial, Public & Agricultural Combustion	6.00	5.70	5.64	5.58	5.45
Iron & Steel Combustion	1.09	1.42	1.87	2.21	2.46
Other Combustion in Industry	11.88	11.15	11.23	11.41	11.56
Processes in Industry	10.46	11.03	11.51	12.10	12.70
Quarrying	18.30	14.90	12.12	10.07	8.78
Construction	3.81	4.23	4.61	5.03	5.48
Road Transport Combustion	31.05	22.18	14.91	11.22	10.87
Brake & Tyre Wear	4.93	5.36	5.81	6.27	6.70
Off-Road Sources	1.87	1.93	2.00	2.15	2.31
Military	0.35	0.33	0.33	0.32	0.31
Railways	0.70	0.44	0.32	0.28	0.25
Shipping	1.18	1.18	1.17	1.16	1.16
Civil Aircraft	0.17	0.20	0.24	0.27	0.30
Non Landfill Waste Treatment & Disposal	1.44	1.59	1.75	1.90	2.07
Non Livestock Agriculture	-	-	-	-	-

Total	**127**	**114**	**100**	**94**	**93**

3.2 REGIONAL DATA SETS

Regional emission inventories have been generated using the NAEI data for 1997, which was, at the time of the analysis, the most recent data set for mapped emissions. The NAEI database is based on a 1 km resolution grid across the UK, with emission totals for sectors within each 1 km square gridcell. Point sources are mapped separately, using a grid reference for the actual location. The methodology used in the NAEI mapping is explained fully elsewhere [Goodwin and King, 2000]. The PM_{10} inventories for the six regions are summarised in Table 14.

Table 14 - Summary of regional PM_{10} inventories, t/yr

	Glasgow	**Greater London**	**Greater Manchester**	**Neath - Port Talbot**	**West Midlands**	**West Yorkshire**
Power stations	0.11	0.85	0.44	0.04	0.40	0.40
Industrial combustion	7.0	160	197	19	109	157
Residential combustion	95	1126	528	83	426	374
Industrial processes	69	689	396	27	687	233
Petrol road transport	239	2132	1352	108	890	708
Diesel road transport	296	2628	1619	126	1146	876
Diesel off-road	7.0	54	42	13	38	27
Other road transport	177	1520	891	59	696	494
Other	0.70	75	36	1.3	13	4.1
Point sources	0.03	199	1859	1734	175	51
Totals	***890***	***8588***	***6925***	***2169***	***4183***	***2925***
% of UK total	*0.48*	*4.66*	*3.76*	*1.18*	*2.27*	*1.59*

Altogether the six regions selected for analysis represent 13.9% of the national PM_{10} inventory for 1997. None of the regions contain refineries, cement works or lime works which are relatively significant sources of PM_{10} emissions on the national scale.

The relative importance of each source category varies across the regions, as demonstrated in Table 14 and Figure 6. In particular, the inventory for Neath Port Talbot is dominated by point sources, whereas point sources represent only 27% of the Greater Manchester inventory and less than 5% for the other four regions. With the point sources excluded (Figure 7), the inventories are broadly similar but still differ in the detail.

It should be noted that the sector data presented in these tables and figures do not include the point source data. Thus, for example, PowerGen's Fiddlers Ferry power station (with emissions of 1,685 t/yr) is included in the "Point sources" category for Greater Manchester and not in the "Power stations" category. The sector categories include only emissions for sources sufficiently small to be treated as area sources - readers are referred to Goodwin & King [2000] for further details of the methodologies used in the NAEI.

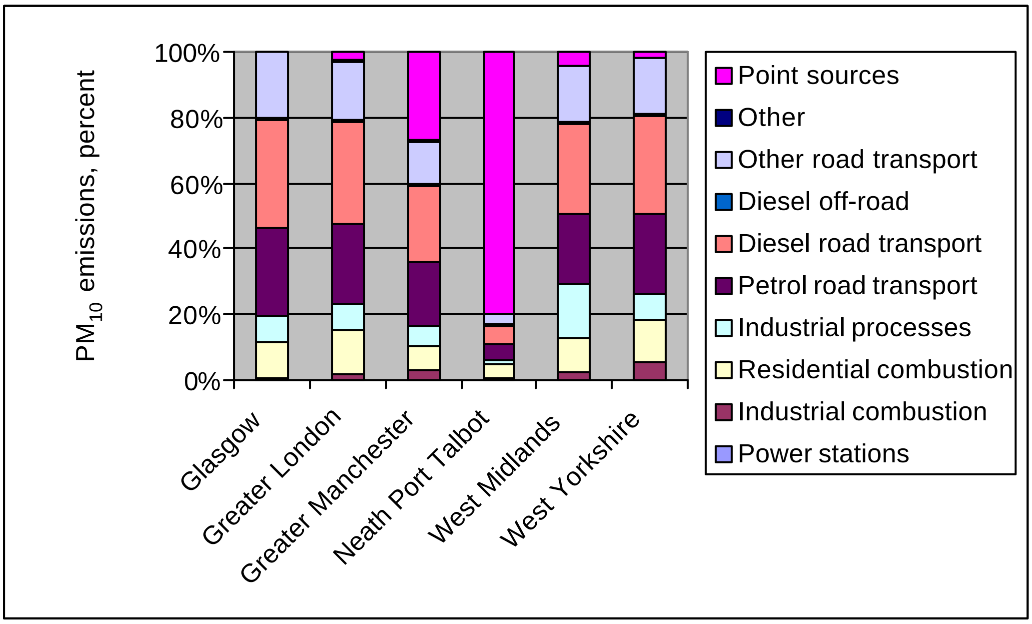

Figure 6 - % contribution of source categories to the six regional PM$_{10}$ emission inventories

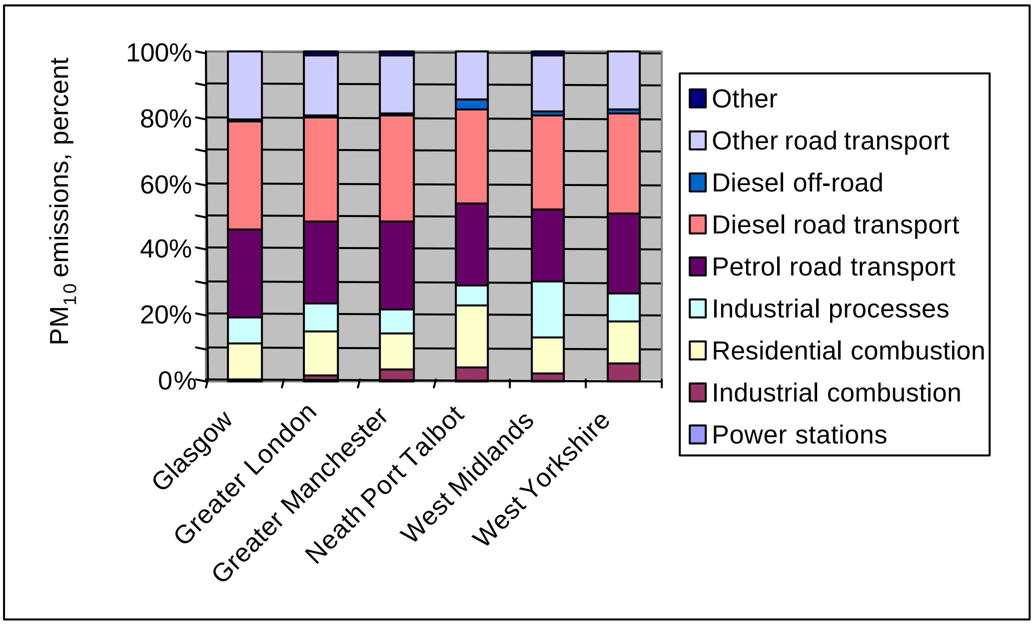

Figure 7 – As Figure 6, with point sources excluded

3.3 CONTRIBUTION OF EMISSIONS TO CONCENTRATION AND EXPOSURE

Table 15 shows the breakdown of ambient PM$_{10}$ concentrations in 1998 and 2010 expressed as the population-weighted annual mean concentration from the mapping analysis (see Chapter 2 for a description of the methodology). The table shows that primary particles contribute less than 20% in

2010 to the population-weighted annual mean concentration (which also includes a contribution from European primary particles).

Table 15 - UK population-weighted annual mean PM$_{10}$ concentration (µg.m^3, gravimetric)

Year	Total	Primary	Secondary	Coarse
1998	22.8	5.2	7.7	9.9
2010 baseline	17.9	3.1	4.9	9.9

Projected contributions of each sector to particle concentration levels in 2010 are presented in Table 16. In terms of the main national contributions to concentration levels, road transport is the most significant contributor followed by residential combustion, and “other” industry processes and combustion. The contribution of road transport emissions to population-weighted concentration levels is higher than its emissions share. This reflects the correlation between traffic movements and population. In contrast, the contribution from sectors such as power stations (which figure highly in terms of primary emission contributions) are particularly small, as they tend to be located outside of the major cities. European primary particle emissions also make an important contribution.

Table 16 – Contribution of primary PM$_{10}$ emissions to population-weighted concentrations in 2010 (baseline scenario, µg.m^3, gravimetric)

Sector	Concentration	% Total
Road transport	0.721	23.9%
Residential combustion	0.509	16.9%
Other combustion in industry	0.435	14.4%
Public services	0.155	5.1%
Other sources *	0.099	3.3%
Iron & Steel	0.064	2.1%
Off road power units *	0.052	1.7%
Non ferrous metals	0.036	1.2%
Lime production	0.03	1.0%
Cement	0.025	0.8%
Agricultural combustion *	0.016	0.5%
Power stations	0.009	0.3%
Refineries	0.008	0.3%
Quarrying **	na	na
Construction **	na	na
Total UK primary	**2.159**	**71.6%**
European primary	**0.856**	**28.4%**
Total	**3.015**	**100.0%**

* Sector not included in cost-curve; ** Area sources not in baseline maps

4 Abatement Options for Stationary Sources

4.1 INTRODUCTION

This section describes abatement options for the main stationary sources that were investigated and summarises the techniques available for emissions reduction and their associated costs. The Section starts with a discussion of widely deployed abatement techniques for particles, and is followed by discussion of additional options relevant to each of the main emitting sectors. Some updated emissions data for 1999 are referred to in the Chapter.

While most of the main sources of primary PM_{10} in the UK are covered, there are certain exceptions. Offshore sources of primary particles were not included in the analysis as the impact on mainland concentrations is likely to be limited. Sectors such as construction which could make a more significant contribution were also not included in the analysis due to a lack of information on emission factors and abatement costs[1]. Note that for construction, the adoption of existing good practice is likely to minimise dust levels, and additional control may not be possible. Effects will of course be extremely site specific.

4.2 COMMONLY DEPLOYED ABATEMENT OPTIONS

This Section describes abatement techniques commonly deployed across a number of sectors for control of particles [based largely on submissions to UNECE/TFEIP, 2001]. Fuel switching could be added to the list, as it is also, quite clearly, an option that could be applied across a range of sectors (any that burn coal or oil). The Chapter also identifies the applicability of each abatement type to combustion or industrial process types and the efficiency of the abatement technique in removing pollutant species (normally particulate matter). The abatement techniques described are:

- Cyclones
- Electrostatic precipitators (ESP)
- Fabric filters
- Ceramic filters
- Wet Scrubbers

Discussion of cyclones is included for completeness in the context of this study. However, they are of limited interest in terms of future particle control as they are already very widely used, and additional uptake of the technology will be negligible.

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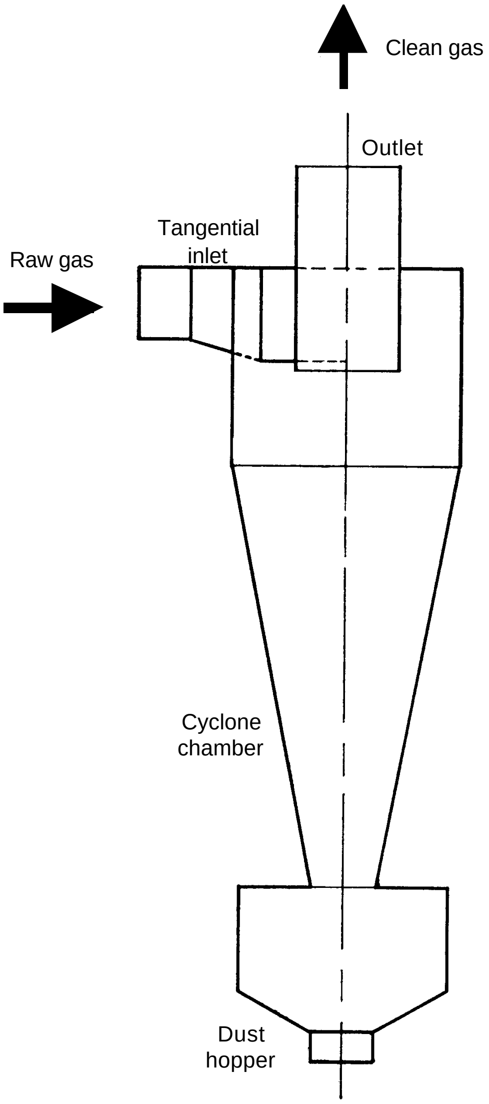
[1] Particle emissions from construction are generally greater than 2.5µm.

4.2.1 Cyclones

The cyclone is an inertial gas-cleaning device that increases the normal gravitational forces on particles entering the device, by causing them to spin or rotate and then to separate from the gas stream. The most common cyclone type is the tangential cyclone (Figure 8).



Dust laden air enters the upper, cylindrical portion of the cyclone through a tangential inlet duct. The flow spirals downwards into a lower conical section and inwards towards the axis with increasing spin velocity and is discharged through the axial outlet duct. Suspended dust particles are thrown outwards by centrifugal force arising from the rotation and find their way down into the dust hopper at the lower end of the cone.

Figure 8 - Schematic of a tangential flow cyclone

The cyclone is a cheap and compact particle collection device with low maintenance costs. It can be used at comparatively high temperatures, up to a typical maximum of 540°C. It is only suitable for use with dry dusts and is not suitable for use with sticky particles or fumes and dusts containing high proportions of fine particles. However the cyclone is widely employed across a variety of combustion and industrial processes and is particularly suitable for collecting particles >10μm in diameter. Cyclones are often placed preceding more expensive technologies (e.g. fabric filters) in order to remove coarse material from the gas stream and hence reduce the burden on the main abatement equipment.

The selection and design of a cyclone depends upon the efficiency of collection required, the properties of the gas stream to be cleaned and, the properties of the particles to be collected. The collection efficiency of cyclones is a function of the mass or particle size and temperature. In general, the efficiency of particle collection increases with corresponding increases in:

- density of particulate material,
- inlet velocity,
- cyclone length,
- number of gas revolutions,
- ratio of body diameter:outlet diameter,
- particle diameter
- amount of dust,
- smoothness of cyclone wall.

The efficiency of particle collection however, decreases with temperature due to increased gas velocity. Cyclone efficiencies are classified as shown in Table 17.

Table 17 – Cyclone efficiencies

Type	Weight collection efficiency range (%)
Low	50-80
Medium	80-95
High	95-99

4.2.2 Electrostatic precipitators

Electrostatic precipitators use electric forces to extract solid or liquid particles carried in gas streams. Particle laden gases are passed through an intense electrical field set up between electrodes of opposite polarity. An electrostatic charge is imparted onto the particles as the gas steam passes between the electrodes. These charged particles are then attracted to collector electrodes. The dust particles build up in a layer on the collector electrodes until the electrodes are cleaned by a mechanical rapping or vibrating system (for dry ESPs) or by washing with water (wet ESPs). The resulting dust or sludge is collected in a hopper. Thus the separation process in an electrostatic precipitator can be described in three stages:

- particle charging,
- transport and deposition of the particles on the collecting electrode,
- cleaning of the collecting electrode.

Electrostatic precipitators consist of a precipitator casing, which houses the discharge electrodes (negative pole), and earthed collecting electrodes (positive pole) arranged opposite each other, and dust collection hoppers as depicted in Figure 9.

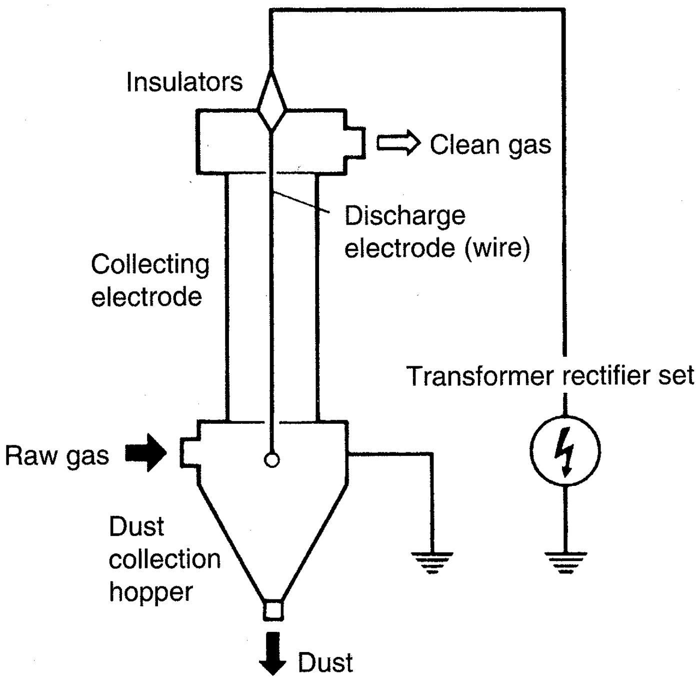


Figure 9 - Schematic of an electrostatic precipitator (Source: Lurgi AG)

The selection and design of an ESP is dependent upon the properties of:

- the gas stream to be cleaned; and
- the particles to be collected

The resistivity of the particles is an important parameter affecting the collection efficiency of the ESP. Temperature and humidity significantly affect the resistivity of particles. Particles of high resistivity can be treated by addition of sulphur trioxide, water or sodium carbon to reduce the resistivity and increase the conductivity of the particles. However, for particles with a high resistivity (e.g. char) ESP's are not a suitable technique. However, electrostatic precipitators are used to clean gas streams from a wide range of process effluent gas streams, including combustion and manufacturing processes. The technology is generally suitable for particle sizes >1 micron and overall removal efficiencies are around 99%. Apart from their application as dust arresters, dry electrostatic precipitators are also installed in semi-dry and dry sorption processes for particle collecting.

The collection efficiency of electrostatic precipitators, as previously discussed, is a function of the gas and dust conditions, design and layout of the ESP, and the operating conditions. Concerning the influence of particle size, the collection efficiency is often slightly lower for particle sizes from 0.2 to 2 µm.

High collection efficiencies for electrostatic precipitators are only achieved with dust resistances between $10^6\,\Omega\cdot\mathrm{cm}$ and $10^{11}\,\Omega\cdot\mathrm{cm}$. Problems with dust resistances, which are too high are often remedied through the injection of water or SO_3. Using a higher number of electric fields within the precipitator can also provide a higher collection efficiency. With pulsed energisation, clean gas dust emissions may be reduced by up to 25 - 50 %. An effective rapping and high voltage control system and an optimised gas flow in the precipitator also leads to higher collection efficiencies. Overall efficiencies in the region of 95% to >99% can be attained, depending on system design and the characteristics of the particles and flue gas flow.

There are a number of actions that can be taken to improve the efficiency of an electrostatic precipitator. These include, in order of increasing cost:

1. Eliminate leaks to reduce air ingress
2. For combustion processes - optimise combustion and eliminate excess air
3. Improve the voltage control system
4. Optimise the rapping sequence
5. Reduce the gas velocity through the device
6. Replace the unit with a newer more efficient design

The gas velocity through a precipitator can be reduced by increasing the cross sectional area so that the same volume flow rate results in a lower gas velocity. To increase the cross sectional area, an additional unit can be fitted in parallel. This results in a greater increase in efficiency than fitting an additional unit in series because reducing the velocity also reduces particle re-entrainment from the electrodes.

Measures 1 to 4 above would normally be applied first before any additional capacity is fitted. Measure 6 would typically only be applied in the case of an existing precipitator that was very old and incapable of meeting the required standard even at reduced gas velocities.

4.2.2.1 Dry electrostatic precipitators

Dry electrostatic precipitators are generally plate type ESP with horizontal gas flow. While the gas to be cleaned passes the electrostatic precipitator, the particles are charged through ions emitted from the discharge electrodes (corona discharge) to which a high DC voltage is fed. Under the action of the electric field between the discharge and collecting electrode the charged particles migrate to the earthed collecting electrode, where they are deposited. The layer of dust adhering to the collecting electrodes is periodically removed by means of a rapper system and falls into a collection hopper, from where it is removed with a screw conveyor. Some of the dust is re-suspended and entrained in the waste gas stream again. Today ESP are usually equipped with at least two electric fields arranged in series, each field with its own power supply. In technical applications up to five electric fields are common.

4.2.2.2 Wet electrostatic precipitators

Wet electrostatic precipitators are designed either for horizontal or for vertical flow. Generally the gases to be cleaned are cooled by the injection of water into the precipitator inlet until the saturation range is reached. The solid or liquid particles dispersed in the gas are deposited by the force of the electric field on the collecting electrodes covered with a film of liquid, and are thus washed away. The film of liquid is maintained by a sprinkling system. Condensing wet electrostatic precipitators are especially designed to remove aerosols and dusts from wet saturated gases. By condensing the wet gases, a film of liquid is formed, so that no continuous supply of spraying water is necessary.

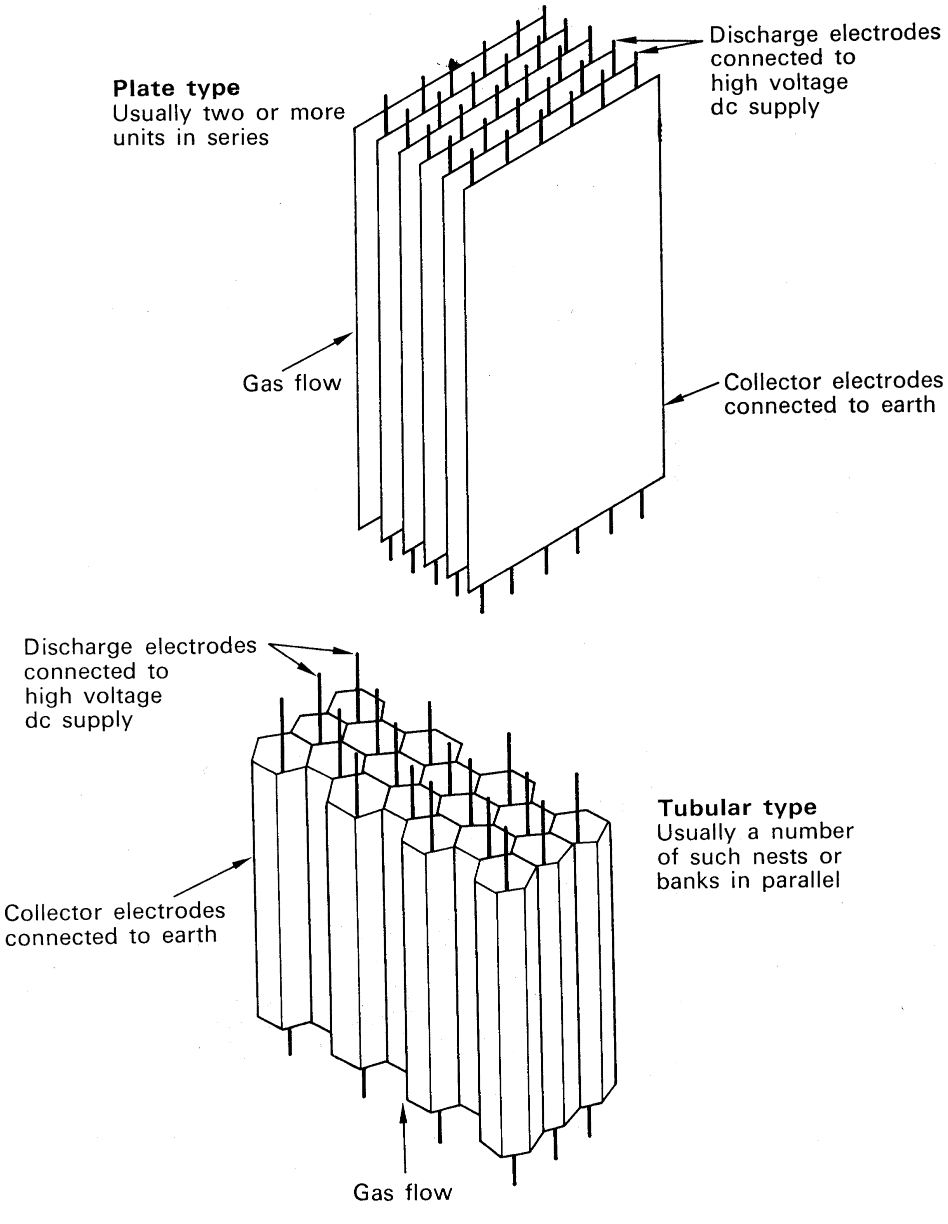


Figure 10 - Layout of a single stage precipitator unit [Source: Dorman].

Wet electrostatic precipitators are operated around the gas saturation temperature. The high voltage insulating system of dry electrostatic precipitators generally has to be provided with an electric heating system to prevent condensation during start-up.

4.2.3 Fabric filters

Fabric filters comprise a filter medium usually in the form of woven bags through which particulate material above a certain size cannot pass. In general the bags are supported on a frame and collection of particulate material can be on the inside or outside of the bags, depending on the type of fabric filter design.

The operation principle of a fabric filter is based on the separation of dust particles from a gas stream by retaining and collecting the particles on the surface and in the interior of the filter medium. In this way, heavy metals contained in the dust are arrested simultaneously. The growing market for fabric filters is due to their versatility with regard to a large number of dusts and their ability to capture all particles irrespective of their electrical characteristics. Restrictions concerning the application of fabric filters arise, where hot or wet waste gases have to be treated.

Fabric filters operate by passing the particle-laden gas through a dust cake that is constantly being built up with the support of the filter medium. In dry and semi-dry sorption processes this enables an improved removal of finest particles and also of gaseous pollutants, e.g. sulfur dioxide. However, the dust or filter cake eventually builds up to the extent that the gas flow is impaired and the dust cake requires removing.

There are 3 principal types of fabric filter: shaker, reverse flow, and pulse jet. These types relate to the mechanism by which the filters are cleaned during use.

The temperature and properties of the gas to be cleaned and the gas flow are the principal factors influencing filter design and selection. Table 18 provides a summary of typical filter materials and their properties.

Table 18 - Common filter media and their range of application

Filter media	**Abbreviation (trade mark)**	**Temperature resistance**		**Resistance to chemicals**			
		Service temp. (^{o}C)	**Peak temp. (^{o}C)**	**hydrolytic**	**acid**	**alkali**	**organic solvents**
Polypropylene	PP	90	100	xx	xx	xx	o
Polyester	PE	150	160	-	x	o	o
Polyacrylonitrile	PAN (Dralon T)	125	140	x	x	x	o
Aramides	AR (Nomex)	180	220	o	x	x	xx
Polyphenylenesulphide	PPS (Ryton)	190	200	xx	xx	x	x
Polyphenylenesulphide on PTFE fabric	PPS/PTFE	260	280	xx	xx	x	x
Polyimide	PI	250	270	o	x	-	xx
Polytetrafluorethylene	PTFE (Teflon)	250	280	xx	xx	xx	xx
Fibre glass		260	280	xx	x	x	xx
xx = very good o = moderately good	x = good - = unsuitable						

Fabric filters can be used to remove particles from a wide range of industrial effluent gas streams including combustion and manufacturing processes. Table 2 provides an indication of the range of application of these filters.

Typical abatement efficiencies are in excess of 99% for particles greater than 1micron.

4.2.4 Ceramic filters

Ceramic filters are similar in concept to fabric filters, but are capable of operating at higher temperatures. They are also relatively compact, making them suitable for use in smaller installations. The Environment Agency, however, reports that experience with ceramic filters in the UK has generally been poor, and regards fabric filters as the preferred technique for widespread use (C. Powlesland, personal communication, 2001).

4.2.5 Wet scrubbers

Wet scrubbers are commonly used to remove acid gases such as sulfur dioxide from gas streams and in addition to removing trace gases these scrubbers also simultaneously remove particles. Particle collection by liquid scrubbing occurs by three principal mechanisms:

- Inertial impaction
- Interception
- Diffusion

Inertial impaction is predominant for particles >3 um diameter and diffusional collection is important for smaller particles. Efficiency of collection increases for inertial impaction as particle size increases and increases as particle size decreases for diffusional collection.

Particle scrubbers principally operate by inertial impaction. There are two types of collection process:

- **Wetted surface dedusters**. Particles are collected on a solid surface which is then irrigated with a scrubbing liquid.
- **Distributed liquid dedusters.** Particles are collected directly by impaction with the scrubbing liquid, usually in the form of drops.

In both collection processes the particles are retained by the scrubbing liquid and are subsequently removed from the gas stream using either gravitational forces, inertial forces, filtering etc.

The principal scrubbers employed in industrial and combustion processes are described below

4.2.5.1 Spray scrubbers and packed towers

In spray scrubbers, the spray generated from the scrubbing liquor by nozzles is introduced axially or around the circumference at the top of the tower and at various lower levels, meeting the rinsing stream of dust laden gas, which usually enters from the bottom. In addition to scrubbers without inserts, variants with plates, baffles, grids, or packing materials are also possible. Spray scrubbers filled with a packing material are described as packed towers.

4.2.5.2 Rotor scrubbers

In rotor scrubbers a liquid is dispersed on a rotating disk by centrifugal power. Often the casing is shaped like a cyclone so that the liquid droplets are arrested. Disintegrators are a special type of rotor scrubbers. The scrubbing liquid is sheared between static and high-velocity rotating blades, producing a finely atomised dispersion. The dust contained in the gas is fed from the side of the disintegrator and collected by impaction and centrifugal action.

4.2.5.3 Venturi scrubbers

Venturi scrubbers consist essentially of a narrow throat in a duct, through which very high dust and gas velocities are maintained. Water is introduced into the throat through atomising nozzles or perforated tubes, the liquid is then atomised by the high velocity gas stream. A wet cyclone is provided for droplet collection or, where very low clean gas dust concentrations are required, a mist eliminator. A typical Venturi scrubber is shown in Figure 11.

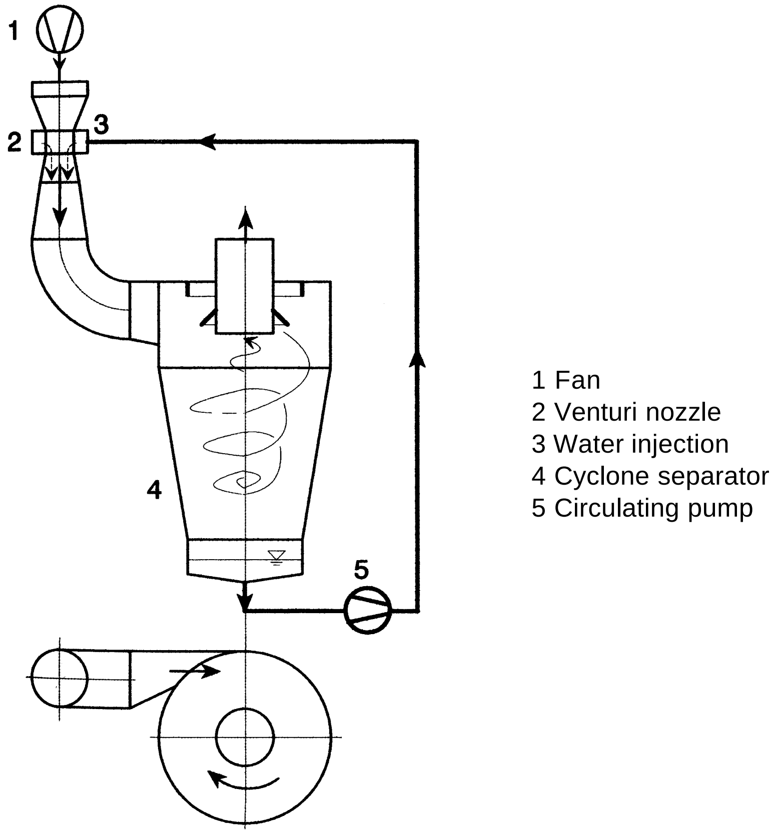


Figure 11 - Venturi Scrubber (Source: Muschelknautz et al)

Wet scrubbers are widely employed over a wide range of combustion and industrial sectors. In addition to removal of particulate matter particular pollutants can be targeted through the selection of the scrubbing liquid e.g. use of alkalis to remove acid gases, acids to remove metallic species.

The collection efficiency of spray towers depends strongly on the dust conditions, the particle size, the dust specific weight, and the operating conditions of the scrubber. Even with long retention times only efficiencies of 50 % to 80 % can be obtained.

Collection efficiencies above 95 % are possible with Venturi scrubbers and rotor washers, which generally results in dust concentrations in industrial applications below 50 mg/m^3 (STP). With correspondingly higher energy consumption it is possible to obtain dust concentrations far below this value. Irrespective of the type of wet scrubber the collection efficiency decreases with a decreasing particle size. A higher energy input to improve the collection efficiency leads to a shifting of this decrease to smaller particle sizes.

4.3 POWER STATIONS

4.3.1 Emissions

The combustion of fossil fuels in power stations is currently one of the largest sources of PM_{10} emissions in the UK. Emissions from this sector amounted to around 10% of the total in 1999; by 2010 their share of total emissions is expected to fall to 7.3%. However, power stations are projected to contribute only minimally to population-weighted particle concentration levels (see Table 16).

Coal-fired power stations in the UK are fitted with ESPs and three of them are also fitted with flue gas desulphurisation (FGD). They account for a significant share of PM_{10} emissions from the power station sector. No oil fired power stations are forecast to be operational in the UK by 2010. The amount of particulate emitted from gas-fired stations, is very small compared with both coal and oil fired stations in terms of mass emitted per kWh of electricity generated[1].

4.3.2 Options for PM_{10} abatement

For the purpose of the cost analysis, only coal-fired plants were considered as potentially offering the opportunity for additional abatement. In principle, available options for coal power stations include:

- Upgrading existing ESPs;
- Fitting FGD;
- Fuel switching.

Upgrading of existing ESPs is the easiest emission abatement option, and is an ongoing process under current IPC authorisations. FGD, although very effective, is also very costly[2] and would not be implemented for purposes of particulate reduction alone. However, market structures in the electricity supply industry (ESI) are changing irrespective of any measures to reduce PM_{10} emissions, with generating capacity from coal-fired plants having been progressively substituted by gas-fired plants, particularly by combined cycle gas turbine (CCGT) plants. The UK Electricity Supply Industry (ESI) is projected to consist of CCGT stations, coal-fired stations with upgraded ESPs or FGD, remaining nuclear stations and various renewable sources by 2010. Consequently, for the purposes of this analysis it was assumed that no emissions abatement above the baseline scenario is feasible in the case of coal-fired power stations. The very small contribution to population-weighted concentration levels (Table 16) also suggests that abatement options in this sector will achieve very little.

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[1] Gas-fired stations currently all report either zero particulate emissions or “below reporting threshold” in the Environment Agency’s Pollution Inventory. However, a further assessment is needed given their increasing share of electricity generation.

[2] FGD typically requires a capital cost in the region of £100M for a typical coal fired power station, and operating costs of several million pounds per year.

4.4 RESIDENTIAL COMBUSTION

4.4.1 Emissions

Residential combustion is forecast to be one of the major contributors to population-weighted concentration levels of primary particles in 2010 (see Table 16). Table 19 lists the breakdown for the sector of fuel and end use in 1996 [BRE, 1998]. Table 20 presents PM_{10} emissions derived from these numbers.

Table 19 - Total household energy use (GB) 1996 by end use and fuel (PJ) [1]

	Solid Fuel	Electricity	Gas	Oil
Space heating	72	156	925	48
Water heating	25	25	346	78
Lights & appliances	0	225	0	0
Cooking	0	9.1	82	0

Table 20 - PM_{10} emissions (kt) derived from energy use data in Table 19

	Solid Fuel	Electricity	Gas	Oil
Space heating	21	0	4.2	0.27
Water heating	7.1	0	1.6	0.43
Lights & appliances	0	0	0	0
Cooking	0	0	0.37	0

It should be noted that the emission factor for residential gas burning that is currently assumed in the NAEI inventory is subject to considerable uncertainty through a lack of case-specific measurement data. Further investigation is required. The authors and other informed commentators consider it likely that the emission factor used significantly overestimates the true emission level.

The Tables demonstrate that PM_{10} emissions from the use of solid fuel for space heating represent approximately 60% of the total emission from residential combustion. Continuing from this, BRE [1998] provide additional information on residential solid fuel use (Table 21).

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[1] BRE [1998] does not include a breakdown such as that presented in Table 19. The data were estimated from a) a breakdown of delivered energy by end use (Table 4.v in BRE 1998), b) a breakdown of delivered energy by fuel (Table 6.i) and c) a breakdown of numbers of households using different fuels for space heating (Tables 4.iv.a & 4.iv.b). In addition to this it was assumed; 1) space heating energy use is split in proportion to the number of households, 2) “Lights & Appliances” is 100% electricity, 3) solid fuel and oil are not used for cooking, 4) energy used in cooking is 10% electricity and 90% gas and 5) the amount of electricity used for water heating is the same as the amount of solid fuel used for water heating. Unfortunately, using these assumptions it is impossible to make the total electricity consumption equal that reported in BRE, [1998] (414.9 PJ as opposed to 377 PJ). However, this is not a large difference and is not used in this report, as electricity consumption does not lead to emissions at the point of use.

Table 21 - Distribution of different types of solid fuel burning

Type of heating	1000s of households	%
Central heating	840	61.8%
Non-central heating - fire	338	24.9%
Non-central heating - stove	182	13.4%

We interpret “fire” to mean an open fire, “stove” to mean an enclosed appliance and “central heating” to mean either an enclosed appliance with a back boiler or a stand-alone central heating boiler. Thus, of the 60% of the emission accounted for by the use of solid fuel for space heating, roughly 25% is burned in open fires.

Table 22 provides a breakdown of emissions in terms of the specific fuels used. As before, the Table indicates that residential combustion of natural gas contributes significantly to PM_{10} emissions, though emissions in this case seem likely to be overestimated (see text below Table 20).

Table 22 - PM_{10} emissions from residential combustion for 1998

Fuel	Emission (kt)
Coal	13.92
Wood *	7.1
Natural Gas	5.86
Smokeless Solid Fuel	3.38
Anthracite	3.04
LPG	0.056
Coke	0.050
Gas Oil	0.048
Burning Oil	0.037
Fuel Oil	0.001
Total	**34.5**

* Provisional estimate

4.4.2 Options for PM_{10} abatement

Emissions from the burning of coal and anthracite can be reduced by:
- Replacing open grates with enclosed appliances.
- Switching to smokeless solid fuel (SSF)
- Switching to gas

In addition to this, emissions from the burning of all fuels can be reduced by the use of energy saving measures such as insulation and double-glazing. These techniques already have significant uptakes in the UK housing stock. However, energy-saving measures are usually undertaken or promoted for other reasons – cost savings, CO_2 control or energy security. They are not considered further here because of uncertainty in their further applicability, given the existence of market barriers.

Residential fuel burning appliances are available in a very wide variety of designs, and the price variation can be quite wide. The approximate cost of buying and installing an enclosed solid fuel appliance is £350. In theory, enclosed appliances are also more fuel-efficient and could therefore lead to a reduction in fuel use. However, in practice the increased thermal efficiency is likely to increase the level of heating rather than to decrease the rate of fuel consumption. Applicability of the measure for switching to solid smokeless fuel (SSF) is an option only available additionally outside Smoke Control Areas. In the cost analysis, the restrictions on the use of SSF are reflected through both the total emission (and emission breakdown) considered and the applicability of the measure. The approximate cost of buying and installing a gas appliance is of the order of £350 per household (accepting variation around this figure for appliances with additional features and so on).

Table 23 shows that the cost per tonne PM_{10} abated ranges from around £5,500 and £8,958 for adopting enclosed appliances and switching to smokeless fuels but more than £22,000 for fuel switch to gas. Therefore, two of the main abatement measures available in this sector appear potentially cost-effective in terms of emission reductions; the latter option switching to gas possibly less so. All of these measures look rather less cost-effective in terms of reductions in population-weighted concentrations, given that solid fuels tend to be used outside the main centres of population.

Table 23 - Costs of emission reduction measures in the residential combustion sector

Fuel: Coal and anthracite			
Measure:	Replacing open grates with enclosed appliances.	Switching to smokeless solid fuel (SSF)	Switching to gas
Approximate capital cost	350	na	350
Lifetime of the plant (years)	15	na	15
Annualised capital cost	36	na	36
Annual operating costs	-	na	100
Total annualised cost	36	-	136
Annualised cost per tonne abated, 2010	£5,508	£8,958	£22,725

4.5 QUARRYING

4.5.1 Emissions

Quarrying is a major source of primary PM_{10} emissions in the UK, projected to generate just over 12% of total emissions in 2010. However, the derivation of the emissions is subject to considerable uncertainty. In particular, there are no emission factors for different types of quarries (described below) and for the different operations carried on in a quarry; also little information is available about the size distribution of emissions from quarries. The effects of the Arup report on best practice in the industry, written in 1995, are also presently unclear. Since quarries are usually located outside densely populated areas, additional abatement effort in this sector is likely to have a minor impact on the reduction of (population-weighted) PM_{10} concentration. Particulate emissions from quarries are likely to be dominated by larger size particles, which can induce acute health effects at a local level but whose link to chronic health effects is less certain. Given these uncertainties, any potential abatement measures from the quarrying sector are provided for information but are not considered in the illustrative package of measures considered in the IGCB report [IGCB, 2001].

4.5.2 Major types of quarry in the UK

4.5.2.1 Chalk

A chalk quarry has a lifetime more than a decade. The mineral is relatively soft and may be used as a soil-improving agent in which case its quarrying is exempted from regulatory control under the Environmental Protection Act 1990. On the other hand, chalk may be processed with blasting materials for industrial (e.g. cement) purposes that may require further special re-processing treatment. In this case, quarrying is subject to environmental legislation under EPA.

4.5.2.2 Clay

Clay is used extensively in brick and tile making. Initially, top-soils and overburden materials of the quarry site are removed to prepare for clay quarrying. During this ongoing and intensive process, dust emission can be high regardless of the scale of operation, however, this is only done for a relatively short time at the beginning of the process. Clay is extracted from the site using hydraulic excavators and loaders, crushed and screened to the conveyors. Because of its nature, dust emission during clay extraction is relatively low.

4.5.2.3 Hard rock

The category of ‘hard rock’ includes granite (and other types of igneous and metamorphic rocks), as well as sandstones and grit stones. Hard rock that has been extracted, crushed and sized is used primarily as construction aggregate, a small proportion of which is used as stone for building.

Drilling of the blast holes by drill rigs during hard rock quarrying creates a significant dust emission and hence venting of air using filters is required. At the primary crusher, the extracted material may be tipped directly from the truck into the crusher, or into a storage pile for gradual loading into the crusher. At this stage, materials of size between 300 and 400 mm are produced. The screening process removes any undersized material and rejects oversize materials. The primary products then enter a secondary, tertiary or even quaternary crushing and grading process, until aggregate materials of a range of sizes and shapes are produced. The crushing and screening process generates a significant amount of dust.

The aggregates may undergo a further process, by either coating with molten bitumen to form coated roadstone, or batching with cement to form concrete. Prior to coating, aggregates are dried in a rotary drier with hot air, which picks up particulate matter.

4.5.2.4 Limestone & dolomite

Limestone and dolomite are two types of calcium carbonate, differing in their magnesium contents. Extraction and handling of limestone and dolomite are similar to those of ‘hard rock’. The final processed minerals are used primarily in the cement and lime manufacturing industries.

4.5.2.5 Sand, industrial sand & gravel

‘Sand’ and ‘gravel’ are used as a construction aggregate, whilst ‘industrial sand’ is a silica sand, high in quality and purity, that is used extensively in glass making, foundry and chemical industries. Although the end uses of the two mineral types differ, their extraction processes are similar.

Raw sand and gravel are washed to remove impurities, such as silts. The waste slurry is treated to remove silt prior to discharge or to be re-used. The material is screened and graded, from which the oversized materials are crushed and re-graded. Where wet product is involved, and undergoes wet processing, dust emissions are very small and regulatory authorisation is not currently required in the UK.

Similarly, raw industrial sand must also be washed to remove impurities. However, it often undergoes further treatment to remove contaminants such as clay, iron, mica and other minerals; the requirements of treatments depend on end uses of the material, for instance, intensive treatments of industrial sand are necessary to attain the purity required for glass making.

4.5.3 Mitigation options

The following list of particle emission mitigation options for quarrying is taken from the Arup report on best practice by the industry [Arup, 1995].

Overburden Removal

1. Locate activity away from sensitive land areas
2. Use water sprays to maintain damp surfaces in dry weather
3. Minimise unnecessary handling of material
4. Use of chemical additives in sprayed water
5. Seeding surfaces of completed mounds
6. Use of wind fences at perimeter or around dust sources
7. Regulate activities in relation to weather

Soil Stripping

1. Locate activity away from sensitive land areas
2. Chemical additives in water to stabilise surfaces of incomplete or un -vegetated storage mounds (unnecessary in the majority of cases).
3. Seeding surfaces of storage mounds
4. Wind fences
5. Monitor weather and modify or stop working during windy weather
6. Profiling of exposed surfaces of soil mounds. Locating further stockpiles downwind of existing stockpiles
7. Use of equipment to collect & contain soil and protecting from the wind.
8. Control of Stockpile size

Mineral extraction

1. Locate away from sensitive land areas
2. Water sprays to maintain dampness of material during dry weather
3. Reduce drop heights when loading material into trucks or onto conveyors
4. Minimise unnecessary handling of material
5. Protect from wind

Site haulage

1. Hard surface permanent site roads
2. Temporary surface site roads, for example with geo-textiles
3. Improve surface of unpaved site roads by regular grading
4. Restrict vehicle access to treated road surfaces
5. Restrict vehicle speeds
6. Design site roads to remove sharp corners and other features that cause intense vehicle braking.
7. Design roads to take advantage of natural screening afforded by other site features
8. Water road surfaces in dry weather to maintain dampness
9. Use dust suppressant chemicals on road surfaces
10. Planting between roads and off site sensitive land uses to provide shelter
11. Install wind fences
12. Vehicle exhausts to be directed upwards
13. Locate new routes away from sensitive land uses and avoid ad-hoc routes

Crushing & Screening

1. Use of fixed water sprays on material to be crushed
2. Enclosure of plant and use of dust filtration system for dust laden air to be vented from inside the enclosed plant
3. Provide protection from wind for stockpiles
4. locate activities within site away from sensitive land uses
5. Locate activities to take advantage of natural protection from the wind
6. Minimise drop heights of material falling from conveyors
7. Cover conveyors to protect material from wind

Materials handling by conveyor

1. Use of fixed water sprays on material on conveyor
2. Enclosure of conveyor to provide protection from wind and/or contain airborne dust (eg cover conveyors and enclose transfer points)
3. Provide protection from wind for stockpiles
4. Locate activities within site away from sensitive land uses
5. Locate activities to take advantage of natural protection from wind
6. Minimise drop heights of material falling from conveyors
7. Clean conveyors with belt scrapers and collect scrapings for disposal
8. Minimise unnecessary handling of material

Blasting

Filtration of drilling waste air

4.5.4 Summary and cost data

For the purposes of this study and in the absence of other data, we have assumed that all types of quarry are the same and that the main sources of particle generation are:

1. Mineral extraction
2. Crushing & Screening
3. Haulage
4. Conveyors

Other stages, such as overburden removal and soil stripping, have been ignored, as associated emissions are likely to be both minor and intermittent. In the absence of more detailed information, it is assumed that the total emission from a quarry is divided equally among these operations. To simplify the calculations even further, the number of emission reduction measures for each operation has been rationalised (Table 24). The Arup report investigated the effectiveness and cost of the measures and assigned them to one of three categories, "high", "moderate" and "low". Table 24 also lists these categories.

Assumptions on the costs and efficiencies linked to the measures are shown in Table 25. Values were chosen on the basis of the range of costs per tonne in the cost-curve as a whole. That is, the “low” cost measures have been chosen so that the appear near the bottom of the cost-curve, the “moderate” ones so that they appear somewhere in the middle and the “high” cost one so that they appear near the top. This is clearly not an ideal approach to assessment of the quarrying measures. However, in this national-scale assessment to support the development of the NAQS, it is an acceptable approach for the quarrying sector because:

1. Emissions from this sector have a minimal effect on the national population-weighted exposure to PM, and
2. These emissions and abatement options are not considered in the work undertaken by the IGCB.

For cost-effective control of particles at locations where significant effects arise from quarrying it will be necessary to undertake a site-specific review of the feasibility and cost-effectiveness of the various control options listed.

Table 24 - Process operations and emission reduction measures in the quarrying industry

Source	Measure	Cost	Effectiveness
Mineral extraction	1 Water sprays (to maintain dampness during dry weather) 2 Reduce drop heights when loading material onto trucks or conveyors. 3 Minimise unnecessary handling of raw material 4 Protect from wind	1 Moderate (if equipment is available) to High (if not) 2 Low 3 Low 4 High (if trees have to be planted & maintained. Moderate to Low if natural features can be exploited.	1 Moderate to High 2 Moderate 3 Moderate 4 Moderate
Crushing & screening	1 water sprays 2 enclosure + extraction & filtration systems	1 Moderate 2 High	1 High 2 High
Haulage	1 Restrict vehicle speeds. 2 Improve road surfaces. 3 Improve road design (to avoid sharp corners). 4 Shield roads from wind (with trees and wind fences). 5 Water road surfaces in dry weather. 6 Use dust suppressant chemicals on roads.	1 Moderate 2 High 3 Moderate 4 Moderate to High 5 High to Moderate 6 High	1 Moderate 2 High 3 Moderate 4 High 5 High 6 Moderate
Conveyors	1 water sprays 2 enclosure 3 minimise drop heights 4 clean with belt scrapers	1 Moderate 2 Moderate 3 Low 4 Moderate	1 High 2 High 3 Moderate 4 Moderate
Mounds & stockpiles	1 water spray 2 chemical dust suppressants 3 shield from wind	1 Moderate 2 High 3 High	1 High 2 Moderate 3 Moderate

Table 25 - Cost assumptions for quarrying measures

	Cost-effectiveness	Efficiency
Low	£200/tonne	50%
Moderate	£10,000/tonne	75%
High	£100,000/tonne	99%

4.6 INDUSTRIAL COMBUSTION

4.6.1 Emissions

This sector consists of combustion processes mainly used for space and process heating in a diverse set of industries. It includes:

- Other Industry (Combustion)
- Other Industry (Large Processes)
- Other Industry (Small Processes)

Other industry (large processes) are point sources from the pollution inventory for industries categorised as “other” (i.e. excluding iron and steel, cement, lime, refineries etc). Other industry (small processes) includes an extremely diverse range of sources such as respraying of vehicles, manufacture of timber and wood based products, coating of metals and plastics, crematoria, etc.

The NAEI estimate for the sector as a whole is 18.4 kt in 1999, contributing around 10% of overall PM_{10} emissions in the UK. This figure is expected to reach 11.4% by 2010. The contribution to population-weighted concentrations in 2010 for “other industry” is slightly higher than its contribution to emissions.

Process and space heating at industrial sites is usually generated in boilers of a wide range of sizes burning either natural gas, oil or coal. The combustion of solid and liquid fuels produces the largest emissions of particulates, although coal-fired boilers are becoming increasingly rare in industry. Current regulations specify an emission limit that is easily attainable with a well-maintained boiler. Therefore, it was assumed for the purpose of the cost analysis that emissions from this source are currently unabated.

4.6.2 Options for PM_{10} abatement

The abatement options that are in principle available in this sector include:

- Fuel switching from coal and oil to gas
- Use of ceramic filters
- Use of fabric filters

There is already widespread ‘natural’ replacement of coal-fired boilers by gas-fired boiler as existing facilities reach the end of their working lives. Oil fired boilers can be converted to gas simply by replacing burners. In itself, this operation is relatively cheap, but it is particularly difficult to estimate the cost of establishing a new gas supply, which is very site specific and can vary from zero up to a very large amount.

In practice, ceramic filters or fabric filters are likely to be the technology of choice if this sector is required to implement additional emission reduction measures. The choice between these two technologies is likely to be based on the assessment of variation in cost-effectiveness according to differences in flow rate, particle load, filter specification (e.g. with respect to the fabric used), flue gas temperature, etc. between plant.

A detailed assessment of the rate of adoption of ceramic vs. fabric filters has not been attempted in this study. The Environment Agency [C. Powlesland, personal communication 2001] reports that experience with ceramic filters is “poor” in many industries. This does not rule out their use altogether, but suggests a strong preference for fabric filters where the choice exists.

4.6.3 Costs

4.6.3.1 Conversion to gas

Coal fired boilers are being replaced with units running on natural gas as they reach the end of their economic life.

Costs for converting an oil-fired boiler (without dual fuel firing) to run on natural gas are shown in Table 26. Above 2MW a gas booster pump would be required. Very often, the biggest cost is getting the gas to the site. These vary considerably from one site to another depending on location and other site-specific factors.

Table 26 - Approximate costs of boiler conversions

Size of burner	Approximate cost
0.5 MW or less	£5k
0.5 to 1 MW	£6 to 7k
2MW	£10k
3MW	£12k

Because of the large uncertainties involved, and because only a small proportion of the emission from these sources is likely to be from coal or oil fired boilers anyway, we have omitted the fuel switching option from the cost-curve.

4.6.3.2 Ceramic Filters

Table 27 reproduces data obtained from an equipment supplier regarding ceramic filters for application to oil fired boilers [Equipment Supplier 1, 2000].

Table 27 - Costs of ceramic filters

Thermal Input kW	Flue Gas Flow Rate (m^3/hour)	Total Particulate Loading (mg/m^3)	PM_{10} Loading (mg/m^3)	Efficiency	Initial emission rate (te/h)	final emission rate (te/h)	Operating hours per year	Annual tonnes abated	Price £$_{2000}$	£/te
200	700	150	112	99.95%	0.0000784	3.92E-08	4,000	0.31344	7,500	23,928
500	1,700	150	112	99.95%	0.0001904	9.52E-08	4,000	0.76122	9,500	12,480
1000	3,500	150	112	99.95%	0.000392	1.96E-07	4,000	1.56722	19,000	12,123
								Average		**16,177**

4.6.3.3 Summary position on cost data for the 'other industry' sector

Further research would be needed to properly characterise this sector, relating to the suitability of different abatement options, size of boilers and so on. To account for the uncertainty in the assessment, the range shown in Table 27 has been applied to the sector as follows:

- a lower cost option (£12,000 per ton abated) for 30% of plant
- a higher cost option (£25,000 per ton abated) for 30% of plant

For the other 40% it is assumed that measures are already in place or impractical.

4.7 PUBLIC AND COMMERCIAL BUILDINGS

4.7.1 Emissions

This sector consists mainly of office buildings, shopping malls, schools and leisure facilities such as sports centres and swimming pools (contained with the broader sector commercial, public and agricultural combustion). Overall, emissions of PM_{10} from public and commercial buildings are relatively small, projected to be less than 2% in 2010. The boilers that typically provide space heating and hot water for these buildings are not usually subject to specific abatement measures.

These buildings are often heated by oil, coal or gas fired boilers. Typical energy consumption for heating and hot water is in the range 100 to 200 kWh/m^2 of treated floor area per year [EEO, 1998]. Most office buildings are in the range 2,500 to 12,000 m^2 of net floor area and would require a boiler in the range 200 kW to 1 MW (assuming 2,000 hours per year operation). Sites such as shopping malls or business parks may have a larger boiler supplying several buildings.

4.7.2 Options for PM_{10} abatement

The emission data show that in the public sector there is very little oil burned but a significant amount of coal, particularly in schools. This situation is likely to be different in the private sector, although no data are available to confirm this.

The abatement options that are in principle available in this sector include:

- Fuel switching from coal and oil to gas

- Use of ceramic filters

Fuel switching is happening naturally as old coal fired plants are replaced with gas or dual-fuel equipment. Accelerating this process would have high costs but would make a negligible contribution to PM_{10} abatement. Ceramic filters were therefore identified as the preferred option for abatement of PM_{10} emissions in this sector. An applicability of 75% was assumed as emissions from some plants would be too low to warrant abatement or the plants would have too limited a remaining life to warrant the expense. Also, it was acknowledged that for some plant it would not be physically possible to install abatement devices. Based on the information given in Table 27 an average cost of just over £16,000/tonne PM_{10} abated is taken for this sector.

4.8 PETROLEUM REFINERIES

4.8.1 Emissions

There are 9 major oil refineries in the UK (Table 28) and three smaller specialist refineries producing specific products at Eastham near Ellesmere Port, Harwich and Dundee. Both Dundee refinery, which is owned by AB Nynas Petroleum Group and Eastham Refinery, which is jointly owned by Shell UK and AB Nynas, produce mainly bitumen. Carless's Harwich refinery produces a wide range of oils, fuels and solvents. NAEI estimated the contribution of this sector to PM_{10} emissions in 1999 at less than 2% of the overall particle emissions in the UK; under the baseline scenario the contribution could increase towards 4% by 2010.

Table 28 - Emissions from major oil refineries in the UK (tonnes)

Operator	**Site**	**1998 Crude throughput (Mte)**	**TP 1998 (te)**	**PM_{10} 1998 (te)**	**TP 1999 (te)**	**PM_{10} 1999 (te)**
Esso Petroleum Co. Ltd	Fawley	15.6	248	248	301	301
Shell UK Ltd	Stanlow	12.5	750	150	660	160
BP Amoco. Ltd	Grangemouth	10.2	not available	not available	not available	not available
BP Amoco. Ltd	Coryton	9.6	160	152	81	77
Lindsey Oil Refinery Ltd	South Killingholme	9.4	120	110	310	220
Texaco Refining Co. Ltd	Pembroke	9.1	480	420	398	349
Conoco Ltd	Killingholme	8.7	380	380	510	400
Total Fina Elf	Milford Haven	5.3	383	244	247	115.3
Phillips-Imperial Petroleum Ltd	NorthTees	5.0	24.81	not reported	46.09	not reported

4.8.2 Process description

Petroleum refineries convert crude oil into a large number of different products, including:

- LPG
- Gasoline
- Solvents
- Kerosene
- Fuel Oil
- Lubricating oil
- Wax
- Bitumen
- Coke
- Petrochemical feedstocks

Of these, gasoline is the most important in terms of volume.

The main process operations in a refinery are distillation, cracking and reforming.

4.8.2.1 Distillation

Crude oil is first distilled at atmospheric pressure separating it into a number of different fractions. Some of these are sold directly but most are converted to other products via downstream operations. The oil fed to the column is heated in a process heater fired by heavy fuel oil. The bottom residue from the atmospheric distillation column is fed to a vacuum distillation column where it is further separated.

Crude oil is a complex mixture of hydrocarbons containing several thousand distinct substances. It also contains small amounts of organic sulphur, oxygen and nitrogen compounds and trace amounts of nickel and vanadium. Crude oils vary in their characteristics according to source and refineries have to be flexible in their ability to convert different crude oils into different products in different quantities according to demand.

A typical refinery has several hundred distillation columns of various shapes and sizes. Many of these are heated using steam and some are heated using fired heaters. To supply steam to these and other process operations, a typical refinery has a large central boiler house. This is usually fired with heavy fuel oil.

4.8.2.2 Cracking

The fractions from the crude columns undergo a number of downstream operations to produce final products for sale. The most important of these operations are cracking and reforming. Straight distillation of crude oil does not produce enough gasoline to meet demand and at the same time produces too much of the heavier and lighter products. To enable more gasoline to be produced, heavier fractions are converted into gasoline in a catalytic cracker and lighter fractions are converted to gasoline in a reformer.

In a fluid catalytic cracking unit (FCCU) the feedstock gas is mixed with catalyst particles in a rising pipe leading into the reaction vessel. During the cracking reactions, a layer of coke builds up on the catalyst particles and this renders them unreactive. To remove this coke deposit they are then fed to a regenerator unit where the coke is burned off in a stream of air. The exhaust gas from the regenerator contains entrained fine catalyst particles and most of these are removed from the gas stream by passing through a pair of cyclones in series. This does not, however, remove all of the particles, especially the smaller ones.

4.8.2.3 Reforming

Reforming is the opposite of cracking in that it takes lower molecular weight fractions that are too light to be used in gasoline, and converts them into higher molecular weight fractions that can be blended into gasoline. The process does not emit particles in significant amounts.

4.8.3 Particulate Emission Sources

Based on the above descriptions it can be seen that the largest single source of particulate emissions on oil refinery is the fluid catalytic cracking unit (FCCU). Additional emissions come from the many combustion facilities at a refinery including the central boiler and fired process heaters.

As already noted, FCCUs are typically fitted with two cyclones in series to remove particles. Currently only one FCCU in the UK is fitted with an electrostatic precipitator. The boiler house and some of the larger fired process heaters are sometimes fitted with electrostatic precipitators.

4.8.4 Options for PM_{10} abatement

For every process, further emission abatement could be achieved through the following options:

- Adopting wet flue gas scrubbing;
- Fitting additional electrostatic precipitators;
- Switching to gas in combustion processes.

As far as PM_{10} control is concerned, the first two measures have to be considered as alternatives. Indeed, it would not be reasonable to add wet scrubbing to control particles on top of an ESP (there are plants with both but for purposes of multi- pollutant controls). By contrast, switching to gas in combustion processes could potentially be implemented in addition to one of the other measures. However, gas supply at certain UK refinery sites is likely to be insufficient to allow fuel switching. The applicability of this measure assumed in the cost-curve has been adjusted down to reflect this.

4.8.5 Costs

It can be seen from Table 29 that ESPs would be a potentially cost-effective measure in terms of abating PM_{10} emissions in the refinery sector, the cost for a large plant being around £384 per tonne abated. Indeed, considering all sources of PM_{10} emissions, fitting additional ESPs in the oil refinery sector would be among the more cost-effective abatement options. Switching to gas for refinery combustion processes would imply a cost per tonne of £833. When viewed in terms of cost-effectiveness in reducing population-weighted concentration levels, these measures look less effective.

Table 29 – Costs of emission reduction measures in oil refineries

Plant size range	Flue gas flows 650 000 Nm^3/hr
Measure	Electrostatic precipitator
Approximate capital cost	£ 3 M
Lifetime of the plant (years)	30
Annualised capital cost	£ 217,947
Approximate Annual Operating Costs	£ 120,000
Total annualised cost	£ 337,947
Annualised cost per ton abated	£ 384

4.9 IRON AND STEEL INDUSTRY

4.9.1 Main emission sources

In 2010 the iron and steel industry is projected to account for approximately 7.6% of total UK emissions of particles. In terms of contribution to population-weighted concentration levels in the UK, the iron and steel industry contributes considerably less compared to emissions. This is likely to be a factor of being located away from population centres. The different industrial process/installations include:

- Coke production
- Sinter production
- Blast Furnaces for the production of pig iron
- Basic oxygen furnaces for the production of steel
- Electric arc furnaces for the production of carbon and alloy steels.

4.9.2 Coke Ovens

4.9.2.1 Process description

Coke is produced in ovens by the pyrolysis of coal in the following stages:

1. Crushing, screening and blending
2. Preheating
3. Charging
4. Coking

After coking is complete the doors on both sides of the oven are removed and the coke is pushed out of the oven through a coke guide into a collecting (quench) car. The quench car moves along the battery to a quench tower where water is sprayed on to the hot coke to prevent ignition. Approximately 1.6 tonnes of coal are used to produce 1 tonne of coke (depending on fuel quality and process control).

4.9.2.2 Particulate emission sources

The potential sources of particulate release to atmosphere in the coke production process are:

- Coal crushing operations
- Preheating (if this is carried out)
- Oven charging
- Oven door leaks
- Oven pushing operations
- Coke quenching
- Combustion
- Coke handling

4.9.2.3 Current and future abatement techniques

Coke production is potentially a highly polluting activity, and hence is subject to major controls already, for example through the use of emission minimised wet quenching, and maintenance of oven doors. Much concern has focused on PAH releases associated with particles. The Environment Agency considers that future improvements can be made in operational control and through the use of bag filters, though data are unavailable on the costs and effectiveness of controlling these largely fugitive emission sources. Redevelopment of some older plant would undoubtedly help, but is typically not considered to be economically viable.

4.9.2.4 Costs

No options for abatement at cokeries are included in the cost-curves.

4.9.3 Sinter Production

4.9.3.1 Process Description

In the sintering process iron ore, coke & limestone, together with small amounts of fluxes and recycled materials from the sinter plant and other parts of the steelworks, are crushed, sieved, mixed and placed on a continuous, travelling grate called a sinter strand. A burner at the beginning of the strand ignites the coke in the mixture after which the combustion is self-supporting. Windboxes beneath the sinter strand draw air and combustion gases down through the bed into a duct.

Fused sinter from the end of the strand is crushed and screened. Undersize material is recycled to the mixing mill and back to the strand. The remaining sinter product is cooled in the open air or in a cooler with water sprays or mechanical fans. The most common types of sinter coolers are circular or straight line moving beds, quiescent beds, or shafts. Air or water is used as the cooling medium in these coolers, with air being prevalent in newer plants and water being dominant in older plants [EIPPCB, 1999,1].

The cooled sinter is crushed and screened for a final time, then the fines are recycled, and the product is sent to the blast furnaces.

An alternative process is pelletisation, where no combustion is necessary. By 2010 a new technology called "converted blast furnace" or "melting-reduction technology" is expected to be operational. For this process sintering, pelletisation, and coke input is no longer necessary [EIPPCB, 1999,1].

4.9.3.2 Particulate emission sources

The main emission sources in a sinter plant are:

- Gases from the windboxes - these contain considerable amounts of entrained particulate
- Crushing,
- Raw material handling,
- Belt charging and discharging from the breaker and hot screens,

4.9.3.3 Current and future abatement techniques

There are four iron and steel plants in the UK: Llanwern, Port Talbot, Scunthorpe and Redcar. Table 30 lists these together with the number and size of the strands in use.

Table 30 - Sinter plant in the UK at the end of 1997

Company	Site	No of strands	Strand width (m)	Total useful grate area(m^2)
British Steel	Redcar	1	4.0	336.0
British Steel	Scunthorpe	2	4.0	582.0
British Steel	Llanwern	1	2.9	180.0
British Steel	Llanwern	1	2.5	120.0
British Steel	Port Talbot	1	4.0	336.0

These plant all employ modern dry electrostatic precipitators (ESP) to control the air releases of particulate matter. The strand windbox emissions are passed through an EP to vent at the main stack, whilst the other emissions, (e.g. from the crusher) are gathered together and passed through a separate ESP and are normally discharged from a separate stack.

In the UK, therefore, the main scope for further reducing particulate emissions from sinter plant would come from either upgrading existing ESPs or from the use of fabric filters downstream of the existing ESPs.

4.9.3.4 Costs

EIPPCB [1999, 1] quotes the following examples of emission reduction technology applied at European sinter plant.

Table 31 - Costs of emission reduction measures for sinter plant

Measure	ESP	Bag Filter - after ESP	cyclone
Capital cost	6,000,000	5,000,000	500,000
Lifetime of the plant	20	20	20
Annualised capital cost	523,107	435,923	43,592
Total Annual Operating Costs	73,478	160,618	82,550
Total annualised cost	596,586	596,540	126,142
activity statistic (tonnes of sinter/ y)	8,640,000	2,246,400	3,175,000
Volume flow rate (Nm^3/hour)	2,000,000	500,000	1,000,000
Volume flow rate (Nm^3/year)	17,280,000,000	4,320,000,000	8,640,000,000
Upstream particulate concentration	1,000	300	1,500
Downstream particulate concentration	50	0.30	300
Removal Efficiency	0.950	0.999	0.800
Tonnes abated	16,416	1,295	10,368
Annualised cost per tonne abated	36	461	12

Of these options it is the central one (bag filters fitted after an ESP) that is of interest in the context of the cost-curve developed here.

4.9.4 Blast Furnaces

4.9.4.1 Process Description

Blast furnaces are large vertical cylindrical refractory lined vessels used for the production of pig iron.

4.9.4.2 Particulate Emission Sources

Particulate emissions arise from blast furnaces through:

- Raw material handling
- Charging
- Casting
- Desulphurisation

Raw material handling areas, especially the returned fines section, are a major source of dust. However, the particle size tends to be quite large.

The top gas leaving the furnace contains up to 15 g/Nm^3 of dust [WS Atkins, 1993], but is not vented to atmosphere, instead being used as a fuel in the sinter strand and in boilers. Wet scrubbers or fabric filters normally remove any entrained particulate matter before being used for fuel purposes.

During the casting operation, particles rich in iron oxides, magnesium oxide and carbonaceous compounds are generated. Particulate emissions also occur during the hot metal desulphurisation stage when sulphur reacts with reagents and is skimmed off. This dust contains mainly iron and calcium oxides.

4.9.4.3 Current and future abatement techniques

Air releases occurring during charging are generally not abated. However, particulate emissions occurring during casting operations are controlled by a number of techniques. Some facilities are uncontrolled with roof discharges. More commonly, existing facilities are controlled by evacuation through retrofitted capture hoods to a gas cleaner, or by suppression techniques. Emissions controlled by hoods and an evacuation system are usually vented to a bag-house.

The basic concept of suppression techniques is to prevent the formation of pollutants by excluding ambient air contact with the molten surfaces. New facilities have been constructed with evacuated runner cover systems and local hooding ducted to a bag- house. Such techniques are already in place at all UK blast furnaces except Port Talbot, where it will be installed by 2004.

Particulate emissions generated during desulphurisation are normally collected by a hood positioned over the ladle, and vented to a bag-house.

Additional measures beyond those in existence or already in the pipeline are not envisaged.

4.9.5 Basic Oxygen Furnaces

4.9.5.1 Process description

The basic oxygen process reduces the carbon content of pig iron by injecting pure oxygen into it while molten. The reactions take place in a large refractory lined pear-shaped vessel called a converter. These are typically up to 400 tonnes in capacity.

A typical basic oxygen cycle consists of the scrap charge, hot metal charge, oxygen blow (refining) period, testing for temperature and chemical composition of the steel, alloy additions and reblows (if necessary), tapping, and slagging. The full furnace cycle typically ranges from 25 to 45 minutes. In a modern steelworks, 300 tonnes of steel are produced in a 30 minute cycle.

4.9.5.2 Particulate emission sources

The most significant particulate emissions from Basic Oxygen Furnaces (BOFs) occur during:

1. Oxygen blowing.
2. Charging
3. Tapping
4. Hot metal transfer

4.9.5.3 Current and future abatement techniques

BOFs are equipped with a primary hood capture system located directly over the open mouth of the furnaces to control emissions during oxygen blow periods. BOF gas is collected for re-use – with the existing recommendation being to use ESPs to clean gas beforehand. EIPPCB [1999, 1] also discusses the use of fabric filters.

4.9.5.4 Costs

EIPPCB [1999, 1] gives the following costs for fabric filters for particulate matter abatement (Table 32).

Table 32 - Costs for fabric filters on basic oxygen furnaces

Item	**Cost (£)**
Capital cost	6,500,000
Lifetime of the plant	20
Annualised capital cost	566,700
Total Annual Operating Costs	845,000
Total annualised cost	1,411,700
Volume flow rate (Nm^3/hour)	40,000
Volume flow rate (Nm^3/year)	333,600,000
Upstream particulate concentration	10,000
Downstream particulate concentration	10
Tonnes abated	3,333
Annualised cost per tonne abated	424

4.9.6 Electric Arc Furnaces

4.9.6.1 Process description

Electric arc furnaces (EAFs) are used to produce carbon and alloy steels. They are cylindrical refractory lined vessels with three carbon electrodes that can be raised or lowered through a removable roof. Furnace capacities range from 5 to 350 tonnes. The feedstock is mainly scrap steel and waste pig iron from steel works. The scrap is often heavily contaminated with paint, oil or grease. Other raw materials can include flux, coke or coal and alloying agents. These materials can be introduced through doors on the side of the furnace.

4.9.6.2 Particulate emission sources

The operations that generate emissions are:

- Charging the scrap,
- Melting and refining,
- Tapping steel and
- Dumping slag.

The particulate matter emitted is predominantly iron oxide for most stages of the process but calcium oxide emissions predominate during the refining period.

4.9.6.3 Current and future abatement techniques

All furnaces have primary emission control whereby fumes are extracted directly from the furnaces and fabric filtration is used to abate the particulate discharges. All facilities also employ secondary emission control systems, whereby extraction hoods or canopies are used to collect fugitive particulate emissions associated with charging, tapping and slagging. These secondary collection systems are normally connected to a separate fabric filter bag house. Some plants also have a tertiary collection / control system whereby the furnace is totally enclosed in a "dog-house". Any fugitive emissions released during the melting and pouring periods are collected from the top of the dog-house and passed to a fabric filter.

Some emissions escape unabated as fugitive releases through roof vents. Further controls on these releases may be considered, though costs and effectiveness will be highly site-specific. Overall it is considered that there is little scope for additional abatement from these furnaces.

4.10 CEMENT PRODUCTION

4.10.1 Process description

Most cement produced is Portland cement but small amounts of other types, including blast furnace cement, are produced for specialised applications.

Portland cement manufacturing can be divided into the following primary process stages:

- Raw material acquisition and handling
- Fuel grinding if solid fuel is used
- Kiln feed preparation
- Pyroprocessing in a rotary kiln to form clinker
- Finished cement grinding and blending

The raw materials (limestone, sand, shale, clay and iron oxide) are mixed, crushed and then transferred into large rotary kilns where they are converted to cement clinker.

Most cement kilns now use the dry process, in which raw mill material is fed into the rotary kiln dry. The use of the wet process, where the ground meal is mixed with water and fed into the kiln as a slurry, is now less common. The wet process uses about 40% more energy than the dry process.

Cement kilns are highly energy intensive and use large quantities of fuel. The fuel price has a critical effect on profitability and this has led to a drive to find cheaper fuels. In the past coal, oil and natural gas were used but since the late eighties most plants have switched first to coal. In addition, many plants are now using a mixture of coal and waste fuels, such as tyres and secondary liquid fuels (mainly waste solvents and other chemicals which would otherwise be sent to specialist chemical incinerators for disposal). This practice has led to concerns about emissions of air toxics.

Irrespective of the type of pyro-process used, the last stage of the pyro-process involves cooling the clinker. As the hot clinker comes off the end of the lower end of the kiln it is rapidly cooled by ambient air in a clinker cooler. There are many different designs of cooler, the most common of which is a travelling grate with under-grate fans that blow cool air through the clinker. Some of this air can be used for combustion, but some is vented to atmosphere or used for drying solid fuels and raw materials.

Finally, the cooled clinker is mixed with 4 - 6% gypsum and ground to a fine homogeneous powder, which is then stored in silos prior to bulk transportation or bagging.

4.10.2 Emissions

The potential sources of particulate matter emissions at cement plants include the following process stages:

- Grinding and blending of dry raw materials
- Preheating and precalcining of raw materials and
- Clinker production (rotary kiln)
- Clinker cooling
- Clinker grinding and blending
- Storage, bulk loading, packaging of final product

The main source of particulate matter is from the kiln and clinker cooler exhaust stacks. Often, some of the cement kiln dust (CKD) is recycled into the process to produce more clinker but this is limited by the alkali content of the product. Consequently, CKD is the cement industry's largest volume waste product. Some CKD is fed back into the kiln, some is sent to landfill and some is used in building materials.

Fugitive emissions of particulate matter can arise from materials handling and transfer operations, as well as from raw milling dry process facilities, and finish milling operations.

According to the NAEI, in 2010 cement production is projected to contribute almost 3% to overall PM_{10} emissions in the UK. However, most of the UK cement works are located outside densely populated areas and therefore their contribution to population-weighted PM_{10} is relatively less important.

PM_{10} is emitted at several stages of the cement manufacturing process[1], the main source of particulate matter being from the kiln and clinker cooler exhaust stacks. Also, fugitive emissions of particulate matter can arise from materials handling and transfer operations, as well as from raw milling dry process facilities, and finish milling operations.

4.10.3 Current and future abatement techniques

Particulate matter emissions from rotary cement kilns are normally controlled by electrostatic precipitators (ESP) and one works has fitted fabric filters. Electrostatic precipitators in this sector can achieve dust concentrations of 30 - 40 mg/m^3. Fabric filters in this sector are commonly delivering values between 20 and 50 mg/m^3. A mixture of fabric filters and electrostatic precipitators are used to control the particulate emissions associated with coal, cement and raw meal crushing.

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[1] Cement manufacturing involves mixing and crushing raw materials (limestone, sand, shale, clay and iron oxide) which are then transferred into large rotary kilns where they are converted to cement clinker.

4.10.4 Costs

ESPs are currently already fitted to all but one cement works, the exception having bag filters fitted already as part of a major plant upgrade. The costs for these measures, reported in Table 33, are all taken from the European IPPC Bureau Best Available Techniques Reference Document in the Cement and Lime industries [1999, 2] and therefore the figures refer to representative European plants. In the UK, in order to achieve further abatement of particle emissions from cement kilns it would be necessary to introduce bag filters in addition to ESPs. This would imply a cost per tonne abated of around £1,149. Therefore, in spite of being an incremental measure, fitting bag filters at cement kilns emerges as a potentially cost-effective measure to reduce PM_{10} emissions in comparison with many others considered in this report.

Table 33 – Costs of emission abatement in the cement industry

Measure	**ESP**	**Bag Filter after ESP**
Capital cost	£ 3,250,000	£ 3,120,000
Lifetime of the plant	20	20
Annualised capital cost	£ 283,350	£ 272,016
Total Annual Operating Costs	£ 286,650	£ 464,100
Total annualised cost	£ 570,000	£ 736,116
Annualised cost per tonne abated	£ 71	£ 1,149

4.11 LIME PRODUCTION

4.11.1 Process Description

The lime making process involves heating limestone (calcium carbonate, $CaCO_3$) to temperatures between 900 and 1200°C. Carbon dioxide is driven off leaving calcium oxide:

$$CaCO_3 \rightarrow CaO + CO_2$$

Lime works are usually located adjacent to, or sometimes within, limestone quarries to minimise transportation costs. The rock is crushed in the quarry and delivered to the lime burning plant in the form of aggregate sized in the range 10mm to 50mm for rotary kilns or 50mm to 300mm for vertical kilns. Emissions from the blasting and crushing are part of quarry operations and not classified as lime making emissions.

4.11.2 Particulate Emission Sources

The kiln is the most important source of particle emissions, followed by the hydrator. Fugitive emissions can occur from almost any part of the process.

4.11.3 Current and future abatement techniques

Modern lime works are equipped with electrostatic precipitators that remove at least 98 % of the particulate matter from exhaust gases. Other control devices are also used including multiple cyclones, wet scrubbers, and baghouses. Improvements could be made by switching to bag filters on kilns and the use of wet scrubbers with lime hydrators, as shown below drawing on data from the IPPC Bureau.

4.11.4 Costs

EIPPCB [1999, 2] gives the following costs for emission reduction measures in the lime industry. Data are from individual plant in Europe, and hence not specific to UK conditions.

Table 34 - Emission reduction measures in the lime industry (EIPPCB, 1999, 2)

Source	**Rotary kiln**	**Other kilns (e.g. shaft kiln)**	**Lime hydrator**
Measure	**ESP / fabric filter**	**Fabric Filter**	**Wet scrubber**
Capital cost	1,950,000	650,000	117,000
Lifetime of the plant	20	20	20
Annualised capital cost	170,010	56,670	10,201
Total Annual Operating Costs	215,800	85,800	16,250
Total annualised cost	385,810	142,470	26,451
Activity statistic (tonnes of sinter/ y)	150,000	100,000	50,000
Volume flow rate (Nm^3/year)	600,000,000	400,000,000	40,000,000
Upstream particulate concentration	500	500	500
Downstream particulate concentration	50	50	50
Tonnes abated	270	180	18
Annualised cost per tonne abated	1,429	791	1,469

4.12 NON-FERROUS METALS

4.12.1 Emissions

The non-ferrous metals industry (which includes aluminium, lead and zinc and copper refining) is projected to account for 1.2% of overall UK emissions in 2010. The assessment here concentrates on the aluminium industry as production of the other non-ferrous metals in the UK is limited (there are, for example, no copper smelters currently operating in the UK).

4.12.2 Options for PM_{10} abatement

The main abatement options in this sector include:

- Electrostatic precipitators
- Fabric filters

As can be seen from Table 35, with a cost per tonne PM_{10} abated ranging from £1,200 to £1,300 approximately, this sector offers the opportunity for achieving moderately cost-effective emission abatement, relative to other potential measures. For the purpose of the cost analysis, it was assumed that the technology of choice in this sector in the UK would be fabric filters, which would imply a cost of £1,191 per tonne PM_{10} abated.

Table 35 – Costs of abatement measures in the aluminium industry

Measure	**Fabric filter with simple injection**	**Spray absorber, fabric filter and absorbent re-circulation**	**Spray absorber, fabric filter and absorbent re-circulation with SO_2 free gas**	**Wet ESP and scrubber**
Capital cost	£652,174	£869,565	£608,696	£739,130
Lifetime of the plant	15	15	15	15
Annualised capital cost	£67,150	£89,533	£62,673	£76,103
Total Annual Operating Costs	£88,748	£105,443	£113,270	£78,487
Total annualised cost	£155,897	£194,976	£175,943	£154,590
Annualised cost per ton abated	£1,191	£1,490	£1,344	£1,181

5 Abatement Options for Transport

5.1 INTRODUCTION

Road transport is a major source of PM_{10} emissions, particularly in urban areas. It is estimated that, in 1999, urban road traffic emissions of PM_{10} were around 14.1 ktonnes. By 2010, these emissions are projected to fall to around 6.4 kt, primarily as a result of more stringent EU vehicle emission standards but also because older, more polluting vehicles will gradually drop out of the vehicle fleet. This reduction in emissions is set to occur despite a projected increase in traffic of around 17% over the next decade.

In July 2000, the Government published its 10 Year Plan for transport[1]. The Plan sets out a long term strategy for delivering a quicker, safer, more reliable transport system that has less of an impact on the environment. It aims to provide:

- A step change in investment through new public and private partnerships;
- The resources to implement the vision of an integrated transport system that was set out in the Integrated Transport White Paper[2], improving transport for all; and,
- A multi-modal response to the problems of congestion and pollution that threaten our quality of life and our future economic well being.

Key outputs and targets for 2010 include reducing traffic congestion below current levels on the inter-urban network and in large urban areas, a 50% increase in passenger rail use, a 10% increase in bus use, a doubling of light rail use, and a trebling of cycling trips. The background analysis for the Plan indicated that its implementation should reduce national traffic growth between 2000 and 2010 from 22% to 17%. This will make a relatively small but helpful contribution to reductions in air pollution, especially in areas of major cities where air pollution remains a problem. For the purposes of the current analysis, the impact of the 10 Year Plan on traffic growth and emissions is included in the baseline for 2010.

A number of additional transport scenarios have been modelled to illustrate the cost-effectiveness of a range of potential technological measures. The scenarios are primarily aimed at reducing PM_{10} emissions from diesel vehicles – the dominant source of PM_{10} emissions from road transport. A number of them will, however, also impact on other pollutants such as NOx and CO_2.

The additional transport scenarios are mainly focused on measures at a national level. However, Local Authorities are required to work towards air quality objectives and as such will implement measures at a local level, for example, changes to planning decisions or measures related to the air quality part of local transport plans. Because of the targeted nature of such measures, they may well be more cost-effective than some of the national measures examined here.

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[1] Transport 2010: The 10 Year Plan, July 2000, DETR. The Plan's focus is on surface transport and access to ports and airports in England, with the exception of railways where the scope extends to Great Britain.

[2] A New Deal for Transport: Better for Everyone, July 1998, Cm 3950, The Stationary Office. A white paper for Scotland, Travel Choices for Scotland, a statement for Wales, Transporting Wales into the Future, and a statement for Northern Ireland, Moving Forward, were also published alongside the UK white paper.

5.2 ABATEMENT OPTIONS

5.2.1 Mandatory particulate traps for new light and heavy duty diesel vehicles

5.2.1.1 Light duty diesel vehicles

This hypothetical scenario assumes all new light duty vehicles are fitted with particulate filters, which some manufacturers are already introducing to selected diesel car models. This could be achieved through the development of tighter European emission standards (beyond Euro IV standards) which set an emission performance which will effectively mandate particulate filters (or equivalent emission abatement technology). For the purposes of the analysis, it has been assumed that the standard will be introduced early, using fiscal or other measures, from 2006.

The analysis has assumed that traps reduce PM_{10} emissions by 90% relative to Euro II standards. The estimates of the costs to manufacturers of meeting this standard for light duty vehicles are highly uncertain. Although two models of light duty vehicles with traps have recently been introduced onto the market, the technology is still in its infancy and there is therefore little information on the likely lifetime costs. To take into account both the uncertainty over the cost and the likely variation between cars and vans of different sizes, a range of £300-£750 per vehicle has been assumed. In line with the industrial scenarios, emission savings have been estimated over the lifetime of the abatement technology – which is assumed to be 6 years for a light duty trap.

If light duty traps have an impact similar to HGV traps, we would expect them to lead to a small increase in fuel consumption. An increase of 1% has been assumed and the additional resource cost included in the cost estimates. Table 36 shows the results of the cost analysis for light duty vehicles in 2010.

Table 36 – Particle traps and light duty vehicles

Particulate traps, £	Diesel cars Low cost	Diesel cars High cost	Light vans Low cost	Light vans High cost
Trap cost	300	750	300	750
Lifetime (years)	6	6	6	6
Discount rate	6%	6%	6%	6%
Annualised capital cost	61	153	61	153
Annual fuel cost	7	7	11	11
Total annual cost per vehicle	68	159	72	163
Total annual cost	166 million	390 million	83 million	190 million
Total emission savings (kt)	0.37	0.37	0.88	0.88
Cost per tonne	446,119	1,047,314	95,203	216,275

Source: DTLR

The cost per tonne of PM_{10} reduced is estimated to be between £450k and £1 million for diesel cars and between £95k and £220k for diesel light vans. The difference in the cost-effectiveness between cars and vans largely reflects the higher initial emissions of PM_{10} from light vans and therefore the greater emission savings from fitting a trap. This works out as an overall average for the low cost scenario of £200k per tonne and for the high cost scenario £460k.

Fitting particulate traps to light duty vehicles is a less cost-effective means of reducing PM_{10} emissions than many of the potential measures in the industrial and residential sectors, but it is a relatively cost-effective way of tackling PM_{10} emissions in the transport sector. There are also potentially wider benefits from such a measure, for example, the reduction in emissions of ultra fine particles that traps would entail.

5.2.1.2 Heavy duty diesel vehicles

Although some heavy duty vehicles have already been fitted with particulate traps, their widespread application to new vehicles will almost certainly require the development of tighter European vehicle emission standards (beyond the existing Euro IV standards) for new heavy duty diesel vehicles which set a particle emission performance which will effectively mandate particulate traps (or equivalent emission abatement technology). Although Euro IV standards set a very stringent mass based PM_{10} emissions limit, vehicle manufacturers are able to meet this limit through improvements in engine technology and will not necessarily use particulate filters. Whilst this will result in significant PM_{10} reductions in terms of mass, heavy duty vehicles are still likely to produce significant quantities of ultra fine particles (PM_1 or less) which are likely to require particulate traps. Potential fiscal or other measures could be used to encourage their early introduction from 2006.

As a result of the stringent mass based Euro IV standards being in the baseline, the benefit for PM_{10} of mandating particulate traps for heavy duty vehicles is likely to be relatively small. Given the widespread availability of heavy duty vehicle particulate traps for retrofitting purposes, there is less uncertainty over the estimated costs than for light duty vehicles, although it is possible that the fitting of traps during manufacture will have a slightly different cost to retrofitting. The analysis has assumed the cost of the trap will range between £2,000 and £3,000, to allow for potential economies of scale in production. An annual maintenance cost of £288 has also been assumed, in line with experience from retrofitted vehicles.

Table 37 shows the relative cost-effectiveness for rigid and articulated HDVs and buses for the high and low trap cost scenarios.

Table 37 – Particle traps and heavy duty vehicles

Particulate traps, £	Rigid HGV Low cost	Rigid HGV High cost	Artic HGV Low cost	Artic HGV High cost	Buses
Trap cost	2,000	3,000	2,000	3,000	3,000
Lifetime (years)	7	7	7	7	7
Discount rate	6%	6%	6%	6%	6%
Annualised capital cost	358	537	358	537	537
Annual fuel cost	22	22	64	64	21
Annual maintenance cost	288	288	288	288	288
Annual cost per vehicle	668	847	710	889	845
Total annual cost	104,007,837	131,896,509	66,254,027	82,973,898	36,871,496
Total emission savings (kt)	0.14	0.14	0.16	0.16	0.07
Cost per tonne	746,201	946,287	414,322	518,881	515,250

Source: DTLR

The average cost per tonne for all HDVs works out at around £620k. As with light duty vehicles, this is a less cost-effective means of reducing PM_{10} emissions than many of the potential measures considered for other sectors. However, as with the light duty vehicles there are potential wider benefits, including the reduction in emissions of ultra fine particles.

5.2.2 Introduction of 10ppm sulphur in diesel

This scenario has modelled the impact of the widespread introduction of ‘sulphur free’ (10ppm) diesel. It has been assumed that a combination of European wide regulatory standards and fiscal measures will encourage its early introduction from 2005. The European Commission has recently published a draft proposal for sulphur free fuel recommending mandatory introduction by 2011 with widespread availability from 2005.

In line with European Commission work, it has been assumed that sulphur free diesel will reduce PM_{10} emissions from Euro I/II/III light and heavy duty diesel vehicles by 5%. It is not expected to have an additional impact on top of Euro IV standards (all new cars coming onto the market from 1st January 2006). It is also unlikely to have an additional impact on top of particulate traps, although for the purposes of the cost analysis the two measures have been estimated in isolation. The estimated cost to refineries from producing 10ppm diesel has been assumed to be between 0.2 – 1 pence per litre, with a central estimate of 0.4p.

The cost per tonne of PM_{10} abated in 2010 for the central scenario is estimated to be £310k. This falls above the estimated costs of fitting traps to new diesel vans but below those for new diesel cars and new heavy duty vehicles. Nevertheless, sulphur free diesel does not appear to be a particularly cost-effective measure for reducing PM_{10} relative to the industrial sector. The introduction of sulphur free diesel, however, needs to be considered in a much broader environmental context. Its introduction is expected to improve the fuel efficiency of Euro IV cars, vans and heavy duty vehicles by around 2% (range 1-3%), helping to reduce CO_2 emissions from transport. It is not expected to have any beneficial effect on the fuel efficiency of older vehicles. Perhaps more importantly though, it would facilitate the introduction of advanced emissions reduction technologies such as de-NOx catalysts.

5.2.3 Retrofitting existing vehicles with pollution abatement technology

A number of pollution abatement technologies can be retrofitted to existing vehicles, including oxidation catalysts, particulate traps, re-engining and conversion to compressed natural gas (CNG) or liquefied petroleum gas (LPG). The Department of Transport, Local Government and the Regions already has two retrofitting programmes to reduce emissions from existing vehicles over the period 2001-2004: the "Clean Up" programme[1] and a dedicated HGV retrofitting programme (from the £100m haulage modernisation package announced in the 2001 Budget). However, as the details of these retrofitting programmes were not finalised until recently, they were not included in the baseline. The components of the scenario include:

- The existing £30 million Clean Up programme;
- The £30 million dedicated HGV retrofitting programme financed from the £100 million Haulage Modernisation Fund;
- A further (hypothetical) £30mn funding for the Clean Up programme.

Stedman et al [2001] provides further details of the scenario modelled.

Given that these retrofitting programmes are focused on the short term, with many of the retrofitted vehicles having left the fleet by 2010, they have not been included in the cost analysis for 2010. However, by virtue of their targeted nature and ability to focus on areas of poor air quality, benefits will be delivered where they are needed most. In addition, some of the retrofitting technologies such as re-engining, LPG and CNG, will also reduce NOx and other pollutants.

5.2.4 Promotion of CNG for new Heavy Goods Vehicles

This scenario has assumed the further encouragement of CNG in the HGV sector through a combination of fiscal measures such as the low fuel duty rate and capital grants (for example through the Powershift programme[2]). The additional cost per new CNG vehicle is estimated to be between £20,000 to £30,000. The modelling has assumed the following number of CNG vehicles are introduced each year, as shown in Table 38.

Table 38 – Assumed numbers of introduced CNG vehicles

Year	2001	2002	2003	2004	2005+
Number of new CNG HGVs	**100**	**200**	**300**	**500**	**500**

Source: DTLR

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[1] The "CleanUp" programme is sponsored by DETR but administered by the Energy Saving Trust (EST). It provides grants to support the fitment of pollution abatement technology such catalytic converters and particulate traps to existing vehicles. In November 2000, the Deputy Prime Minister announced a budget of £30m over the next 3 financial years, 2001/02 - 2003/04.

[2] The PowerShift programme provides grants towards the additional cost of buying cleaner vehicles running on LPG, natural gas and electricity. For more information on this and CleanUp see the website at www.transportaction.org.uk.

It is unlikely that a new CNG vehicle would have any additional PM_{10} benefits on top of a heavy duty vehicle with a particulate filter (i.e. a 90% reduction in PM_{10} relative to Euro II). However, as with sulphur free diesel, for the purposes of the cost analysis the measures have been modelled independently. Table 39 shows the estimated cost-effectiveness in 2010 for a range of estimates of the additional costs of new CNG vehicles.

Table 39 – Estimated cost-effectiveness for a range of cost estimates for new CNG vehicles

New CNG HGVs, £	**Rigid HGV Low cost**	**Rigid HGV High cost**	**Artic HGV Low cost**	**Artic HGV High cost**
Additional CNG cost	20,000	30,000	20,000	30,000
Lifetime (years)	10	10	10	10
Discount rate	6%	6%	6%	6%
Annualised capital cost	2,717	4,076	2,717	4,076
Annual fuel cost	3,760	3,760	7,359	7,359
Total annual cost per vehicle	6,477	7,836	10,077	11,435
Total annual cost	13,277,651	16,062,944	20,657,330	23,442,623
Total emission savings (k tonnes)	0.003	0.003	0.003	0.003
Cost per tonne	4,141,298	5,010,031	7,035,048	7,983,606

Source: DTLR

The average cost per tonne of PM_{10} reduced is £6 million. Part of the reason this measure is so expensive is because the additional fuel costs, in terms of the resource cost of CNG relative to diesel, are included. The resource cost of CNG is currently around double that of diesel, largely due to additional storage and distribution costs. Another reason this option looks expensive is because it has been assumed that the entire costs of the new CNG vehicle are attributable to PM_{10} abatement, ignoring the significant impact on NOx and noise. However, assuming only half of the costs are attributable to PM_{10} abatement – thereby halving the cost per tonne – still makes it a very cost ineffective transport measure compared with the fitting of particulate traps.

5.2.5 Zero emission buses

Another potential transport measure is to accelerate the introduction of zero emission buses – fuel cell or battery electric – in urban areas. The forthcoming AEA Technology report: “Projections of PM_{10} and NO_x concentrations in 2010 for additional measures scenarios” illustrates the impact of introducing 1,750 such buses by 2010. However, because of the large uncertainties surrounding the likely cost of these vehicles and their high initial cost, this scenario has not been included in the cost-curve analysis. Nevertheless, such demonstration vehicles will play an important part in establishing the new technology in niche markets, where it is possible to introduce targeted subsidies and a limited refuelling infrastructure is required. The urban bus market is potentially ideal as buses receive public subsidy, undertake limited mileage on pre-determined routes and are depot based. There are already some demonstration fuel cell bus projects being conducted world-wide and it is feasible that commercially viable fuel cell buses will be available after 2005, albeit probably requiring some additional subsidy.

6 Cost-curves

6.1 INTRODUCTION

Drawing on data from the analysis described above, a range of variables are accounted for in the cost-curves presented in this chapter:

- Geographical area – whole and 6 densely populated regions (Glasgow, Greater London, Greater Manchester, Neath-Port Talbot, West Midlands, West Yorkshire)
- Particle fraction - PM_{10} and $PM_{2.5}$
- Time (1998, 2000, 2005, 2010, 2015)
- Cost-effectiveness expressed as £/tonne abated and £/[µg.m^{-3} population-weighted exposure reduced].

The Chapter starts with a review of results for PM_{10} control in 2010 at the national level as this provides data of most relevance to the current policy debate. It includes assessment of the uncertainties in the cost-curve for that year.

6.2 RESULTS FOR 2010

6.2.1 National cost-curve for PM_{10} emission abatement

Table 40 presents the results of the national cost-curve analysis for 2010, assessed in terms of mass reduction of PM_{10}. For each measure, the table describes the abatement technique applied and its efficiency (% reduction in emissions at a source fitted with the abatement technique) and applicability (% of sources to which each technique can be applied, recognising technical and other limitations), together with information on the (marginal[1]) cost per tonne. The marginal cost-curve is shown in Figure 12. The starting point is the total emissions estimated for the business as usual position in 2010.

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[1] Both average and marginal costs are presented in the table. In some cases, there will be several applicable measures which could potentially reduce emissions. If the first, most cost effective measure is applied, this will change the emission reduction potential for the second measure and therefore the cost per tonne. This is reflected in the marginal cost estimates.

Table 40 - Summary of emission cost-curve data for 2010

Source	Sub-source	Emission (kt/y)	Technique	Efficiency	Applic-ability	Marginal emission abated (kt)	Marginal cost (£/t)	Emission remaining (kt)	Total cost (£k)
								101	**0**
Quarrying	Mineral Extraction	2.42	minimise unnecessary handling	40%	50%	0.48	200	101.01	97
Quarrying	Conveyors	2.42	minimise drop heights	50%	50%	0.61	200	100.40	218
Quarrying	Mineral Extraction	1.94	reduce drop heights	75%	50%	0.73	200	99.67	364
Refineries (Combustion)		3.84	ESP	92%	92%	3.24	384	96.43	1,609
Iron & Steel	Basic oxygen Furnaces	0.41	fabric filter	100%	100%	0.41	424	96.02	1,782
Iron & Steel	Sinter Plant	2.27	fabric filter	100%	75%	1.70	461	94.32	2,566
Iron & Steel	Combustion	1.84	fabric filter	100%	100%	1.84	461	92.48	3,415
Lime Production	other kilns (e.g. shaft kiln)	0.20	Fabric Filter	100%	100%	0.20	791	92.28	3,573
Cement		2.86	fabric filter	92%	90%	2.37	1,149	89.91	6,294
Non-ferrous Metals	Aluminium Production	0.76	fabric filter	99%	100%	0.75	1,191	89.16	7,189
Lime Production	Rotary kiln	0.35	ESP/fabric filter	100%	100%	0.35	1,429	88.81	7,688
Lime Production	lime hydrator	0.35	wet scrubber	75%	100%	0.26	1,469	88.55	8,074
Refineries (Combustion)		3.84	fuel switch	100%	62%	0.37	1,985	88.18	8,815
Residential combustion	All solid fuels	5.16	improved appliance design	50%	15%	0.39	5,508	87.79	10,948
Residential combustion	All solid fuels	5.16	switch to SSF	46%	83%	1.83	8,958	85.96	27,317
Quarrying	Mineral Extraction	1.21	water sprays	50%	50%	0.30	10,000	85.66	30,347
Quarrying	Conveyors	1.82	clean with belt scrapers	50%	50%	0.45	10,000	85.20	34,892
Quarrying	Haulage	2.42	speed restrictions	30%	50%	0.36	10,000	84.84	38,528
Quarrying	Conveyors	1.36	enclosure	50%	50%	0.34	10,000	84.50	41,936
Quarrying	Conveyors	1.02	water sprays	90%	50%	0.46	10,000	84.04	46,538
Quarrying	Haulage	2.06	improve road design	50%	50%	0.52	10,000	83.52	51,689
Quarrying	Crushing & Screening	2.42	water sprays	90%	50%	1.09	10,000	82.43	62,596
Quarrying	Mounds & Stockpiles	2.42	water sprays	90%	50%	1.09	10,000	81.34	73,504
Quarrying	Haulage	1.55	water road surfaces	90%	50%	0.70	10,000	80.65	80,457
Quarrying	Mounds & Stockpiles	1.33	chemical dust suppressants	50%	50%	0.33	10,000	80.31	83,790
Quarrying	Haulage	0.85	use dust suppressant	50%	50%	0.21	10,000	80.10	85,915

Source	**Sub-source**	**Emission (kt/y)**	**Technique**	**Efficiency**	**Applic-ability**	**Marginal emission abated (kt)**	**Marginal cost (£/t)**	**Emission remaining (kt)**	**Total cost (£k)**
			chemicals						

Table 40- Summary of emission cost-curve data for 2010 (continued)

Source	**Sub-source**	**Emission (kt/y)**	**Technique**	**Efficiency**	**Applic-ability**	**Marginal emission abated (kt)**	**Marginal cost (£/t)**	**Emission remaining (kt)**	**Total cost (£k)**
Quarrying	Haulage	0.64	shield roads from wind	80%	50%	0.25	10,000	79.85	88,464
Quarrying	Mounds & Stockpiles	1.00	shield from wind	50%	50%	0.25	10,000	79.60	90,964
Other Industry (Large Processes)		1.726	low cost filter	99%	60%	1.03	12,000	78.57	103,317
Other industry (Combustion)		3.86	low cost filter	99%	30%	1.15	12,000	77.42	117,129
Other Industry (Small Processes)		4.38	low cost filter	99%	30%	1.31	12,000	76.11	132,814
Public Services	Building Services	1.72	ceramic filters	99%	75%	1.28	16,000	74.83	153,219
Other industry (Combustion)		3.86	high cost filter	99%	30%	1.15	25,000	73.68	181,993
Other Industry (Small Processes)		4.38	high cost filter	99%	30%	1.31	25,000	72.38	214,669
Quarrying	Haulage	0.38	pave road surfaces	90%	50%	0.17	100,000	72.20	231,879
Quarrying	Mineral Extraction	0.91	shield from wind	50%	50%	0.23	100,000	71.98	254,603
Quarrying	Mounds & Stockpiles	0.75	enclose	95%	50%	0.36	100,000	71.62	290,223
Quarrying	Crushing & Screening	1.33	enclosure, extraction & treatment	99%	50%	0.66	100,000	70.96	356,214
Residential combustion	All solid fuels	5.16	fuel switch	98%	45%	0.45	152,875	70.52	424,309
Road Transport*	LDVs (cars and vans)*	10.87	Particulate trap*			1.25	199,734	69.27	673,679
Road Transport	Entire fleet	13.29	10ppm sulphur fuel			0.28	308,886	68.98	760,961
Road Transport	HDVs	2.42	Particulate trap			0.37	618,676	68.61	990,399
Road Transport	HDVs	2.4	CNG			0.01	5,978,065	68.61	1,027,119

* Road transport, particulate trap for LDV measure – cost-curve shows “low” cost scenario only. “High” cost scenario has marginal cost of £463,827.

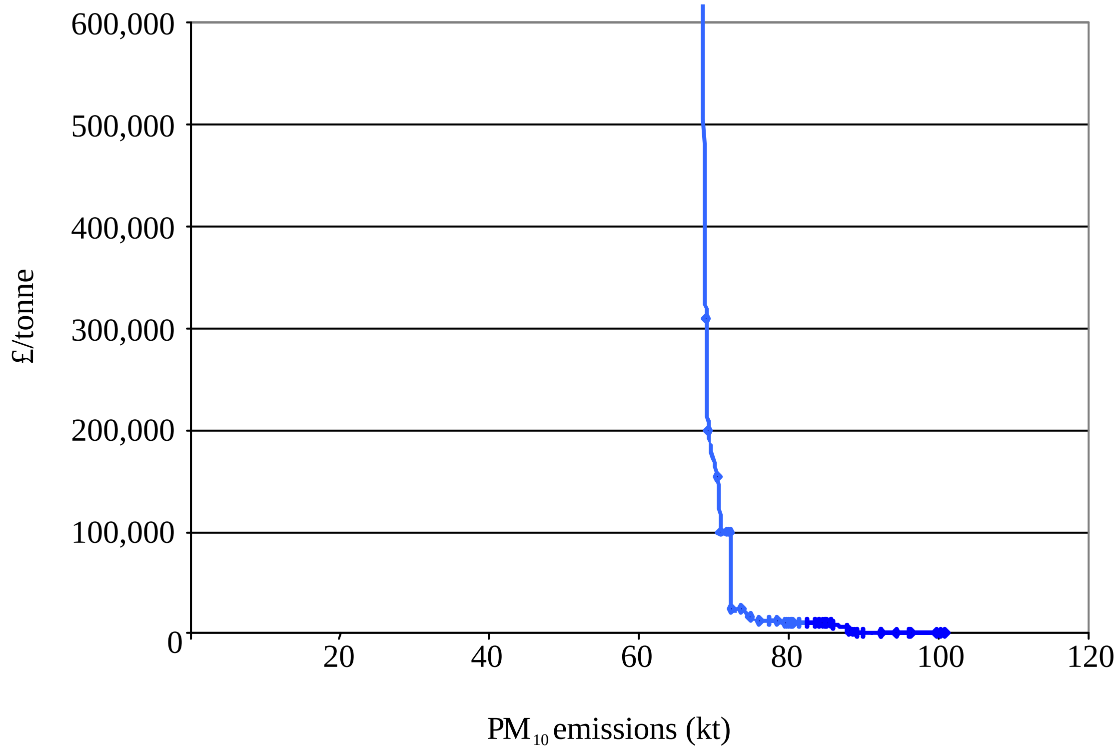

Figure 12 - Marginal cost-curve for emission reductions, 2010

The cost-curve presented in this section shows a wide range of cost-effectiveness of measures. The most cost-effective measures (in terms of unit reductions in emissions) are from stationary sectors such as cement, quarrying, iron & steel, non-ferrous metals, refineries, lime production and residential combustion. There are no proposed additional measures from the power sector compared with what is already assumed within the baseline. The key road transport measures which appear on the cost-curve are the fitting of particulate traps for HDVs and LDVs (with a high and low cost scenario for LDVs because of the uncertainty over cost), the introduction of 10ppm sulphur fuel, and promoting CNG for new heavy goods vehicles (see Chapter 5). The retrofitting measures are not included since these are primarily focused on achieving improvements in air quality in earlier years. None of the transport measures are among the most cost-effective options in 2010 in terms of particle emission reductions but have wider environmental benefits.

6.2.2 National cost-curve for PM_{10} population-exposure control

Table 41 presents the national PM_{10} cost-curve for 2010 in terms of population-weighted concentrations. These data, unlike those given in Table 40, bear a direct relationship with effects on health, assuming linearity in the exposure-response function. Table 41 shows a somewhat different ordering of measures than that presented in the emission cost-curve. The most important sector in terms of contribution to population-weighted concentrations is road transport. However, the concentration cost-curves show that the road transport measures still remain largely at the bottom of the cost-curve: in other words, their proportionately higher contribution to exposure is not sufficient to overcome their higher costs.

Table 41 – Summary of population-weighted concentration cost-curve data for 2010

Source	Sub-source	Emission (kt/y)	Concentration ($\mu g/m^3$) TEOM basis	Technique	Efficiency	Applic-ability	Average cost (£/t)	Marginal concentration reduction ($\mu g/m^3$)	Marginal cost, £/($\mu g/m^3$)	Concentration remaining ($\mu g/m^3$) TEOM basis
										1.504
Quarrying	Mineral Extraction	2.42	0.02073	minimise unnecessary handling	40%	50%	200	0.00	23,390	1.50
Quarrying	Conveyors	2.42	0.02073	minimise drop heights	50%	50%	200	0.01	23,390	1.50
Quarrying	Mineral Extraction	2.42	0.01658	reduce drop heights	75%	50%	200	0.01	23,390	1.49
Cement		2.86	0.01855	fabric filter	99.8%	60%	177	0.01	27,294	1.48
Lime Production	other kilns (e.g. shaft kiln)	0.20	0.00441	Fabric Filter	99.9%	100%	791	0.00	35,885	1.47
Iron & Steel	Basic oxygen Furnaces	0.41	0.00476	fabric filter	99.9%	100%	424	0.00	36,320	1.47
Iron & Steel	Sinter Plant	2.27	0.02238	fabric filter	99.9%	75%	461	0.02	46,806	1.45
Lime Production	Rotary kiln	0.35	0.00783	ESP/fabric filter	99.9%	100%	1,429	0.01	63,816	1.44
Lime Production	lime hydrator	0.35	0.00783	wet scrubber	75%	100%	1,469	0.01	65,602	1.44
Refineries (Combustion)		3.84	0.00566	ESP	92%	92%	384	0.00	260,682	1.43
Other Industry (Large Processes)		1.73	0.05466	low cost filter	99.40%	60%	12,000	0.03	378,922	1.40
Other Industry (Small Processes)		4.38	0.13851	low cost filter	99.40%	30%	12,000	0.04	379,727	1.36
Other industry (Combustion)		3.86	0.08278	low cost filter	99.40%	30%	12,000	0.02	559,493	1.33
Other Industry (Small Processes)		4.38	0.13851	high cost filter	99.40%	30%	25,000	0.04	791,097	1.29
Other industry (Combustion)		3.86	0.08278	high cost filter	99.40%	30%	25,000	0.02	1,165,611	1.27
Quarrying	Mineral Extraction	0.01	0.00009	water sprays	50%	50%	10,000	0.00	1,169,479	1.27
Quarrying	Conveyors	0.02	0.00013	clean with belt scrapers	50%	50%	10,000	0.00	1,169,479	1.27
Quarrying	Haulage	2.42	0.02073	speed restrictions	30%	50%	10,000	0.00	1,169,479	1.27

Table 41 – Summary of population-weighted concentration cost-curve data for 2010 (continued)

Source	Sub-source	Emission (kt/y)	Concentration (μg/m^3) TEOM basis	Technique	Efficiency	Applic-ability	Average cost (£/t)	Marginal concentration reduction (μg/m^3)	Marginal cost, £/(μg/m^3)	Concentration remaining (μg/m^3) TEOM basis
Quarrying	Haulage	0.02	0.00015	improve road design	50%	50%	10,000	0.00	1,169,479	1.27
Quarrying	Crushing & Screening	2.42	0.02073	water sprays	90%	50%	10,000	0.01	1,169,479	1.26
Quarrying	Mounds & Stockpiles	2.42	0.02073	water sprays	90%	50%	10,000	0.01	1,169,479	1.25
Quarrying	Mounds & Stockpiles	0.01	0.00010	chemical dust suppressants	50%	50%	10,000	0.00	1,169,479	1.25
Residential combustion	All solid fuels	5.16	0.02397	improved appliance design	50%	15%	5,508	0.00	1,186,667	1.25
Refineries (Combustion)		3.84	0.00566	fuel switch	100%	62%	833	0.00	1,347,370	1.24
Residential combustion	All solid fuels	5.16	0.02397	switch to SSF	46%	83%	8,958	0.0092	1,930,050	1.24
Road Transport	LDVs (cars and vans)	10.87	0.27582	Particulate trap			199,734	0.03	7,871,409	1.20
Quarrying	Crushing & Screening	0.01	0.00010	enclosure, extraction & treatment	99%	50%	100,000	0.00	11,694,793	1.20
Road Transport		13.29	0.33723	10ppm sulphur fuel			308886	0.01	12,173,021	1.20
Road Transport	HDVs	2.42	0.06141	Particulate trap			618,676	0.01	24,381,664	1.19
Residential combustion	All solid fuels	5.16	0.02397	fuel switch	97.8%	45%	37,164	0.00	61,218,177	1.19
Road Transport	HDVs	2.42	0.06141	CNG			5,978,065	0.00	235,591,998	1.19

* Road transport, particulate trap for LDV measure – cost-curve shows “low” cost scenario only. “High” cost scenario has marginal cost of 18,279,135 per ug/m^3.

6.2.3 Uncertainty analysis on the 2010 PM_{10} cost-curve

Uncertainty arises at many points in the development of a cost-curve. It is clearly important to gain an understanding of the extent of these uncertainties and which are likely to be the most important.

The key uncertainties in costs are:

- Identification of abatement options
  Ideally the cost-curve would include all potential abatement options for reducing the pollutant in question. Unfortunately this is extremely difficult. In this study, for example, two types of option have certainly been omitted:
    - Energy efficiency options, on the grounds that further implementation of energy efficiency measures would need to deal with the market barriers that currently exist.
    - Local transport related options (e.g. traffic management measures), as cost-effectiveness for these measures will be extremely site specific, and they need to be considered in the context of other local plans.

  Others may also have been omitted. The work carried out here has largely been undertaken from a technology perspective. Legislation to reduce emissions may lead industry to adopt the measure identified here, or they may prefer to take an alternative route. Early assessments of the costs of reducing UK sulphur emissions, for example, did not consider that there would be a widespread switch from coal to gas in power generation and other industries.

  Any omission is likely to have two effects on the cost-curve. First, the maximum feasible reduction in emissions will be reduced. Second, the costs of reaching any given level of emissions control may increase. Clearly, therefore, this source of error will bias towards overestimation of costs and future emissions.

- Applicability of abatement techniques.
  Uncertainties in applicability vary according to the source and technique. For sectors that cover large industrial installations (e.g. iron and steel, power generation, refineries) the existing state of technology is well characterised and the potential for further refinement reasonably well understood. Problems increase as one starts to consider technologies deployed in smaller installations (e.g. small industrial processes or the residential sector), and cases where technologies have a very long life expectancy (this would include residential, but exclude transport). Overall it has been concluded for this study that uncertainty on applicability is essentially symmetric in that the cost-curve is not likely to systematically under-estimate nor to over-estimate the applicability of abatement techniques.

- Efficiency of abatement techniques
  In general, the efficiencies of techniques applied to the major sources (stationary combustion; transport) are relatively well known for PM_{10}. However, for some other sources (notably quarrying, construction and residential), efficiencies are poorly understood. On the transport side, there is some uncertainty over the long-term

durability of technologies such as particulate traps and CNG, as well as variations in emissions performance over different driving conditions. Overall, however, as far as the cost-curve is concerned (and particularly when excluding quarrying), the uncertainty on efficiency is likely to be small and symmetric for most sources.

- Technology unit costs
  The costs of abatement measures for PM_{10} are the individual area where uncertainties seem likely to be the most significant. For stationary sources, many of the measures are derived from UK BAT or the BREF notes which means that the costs have been subject to careful industry assessment. However, the costs are for representative firms and are therefore likely to vary according to the size of industry and plant. For the transport measures, costs are particularly uncertain where they concern developing technologies such as particulate traps for light duty vehicles. There are a number of uncertainties here such as durability, impact on fuel consumption and maintenance costs.

  It is possible that some cost components for the measures identified have not been identified, leading to a potential bias towards underestimation. The costs of the transport measures are calculated on a social cost basis whereas the industry measures estimate direct costs. However, the difference in the direct and social costs for industry is not expected to be significant. Conversely, there is evidence that estimated abatement costs tend to fall over time - for example as more suppliers enter the market creating competition and development costs are recouped. Furthermore the actual costs may decrease with time as the market for a given technique matures. Finally, it may be difficult to know how to attribute the cost of an abatement technique if it reduces emissions of other pollutants concurrently (particularly the transport measures) or if these measures could potentially be undertaken in any case through IPPC.

Monte-Carlo analyses were carried out on the national cost-curve for reductions in PM_{10} emissions in 2010 to take into account uncertainty in the following factors:
- baseline emissions;
- efficiency of abatement technologies;
- applicability of abatement technologies;
- average costs (£ per tonne) of abatement technologies.

The analysis was carried out in two parts. First, the effects of the combined uncertainties of the costs of abatement was assessed (Figure 13). The second analysis looked at the other three factors listed (Figure 14). In both cases the analysis was based on a ‘high’ cost scenario for transport options. The figures describe the 90% confidence interval around the best estimate. Simultaneous analysis of all sources of uncertainty was not carried out.

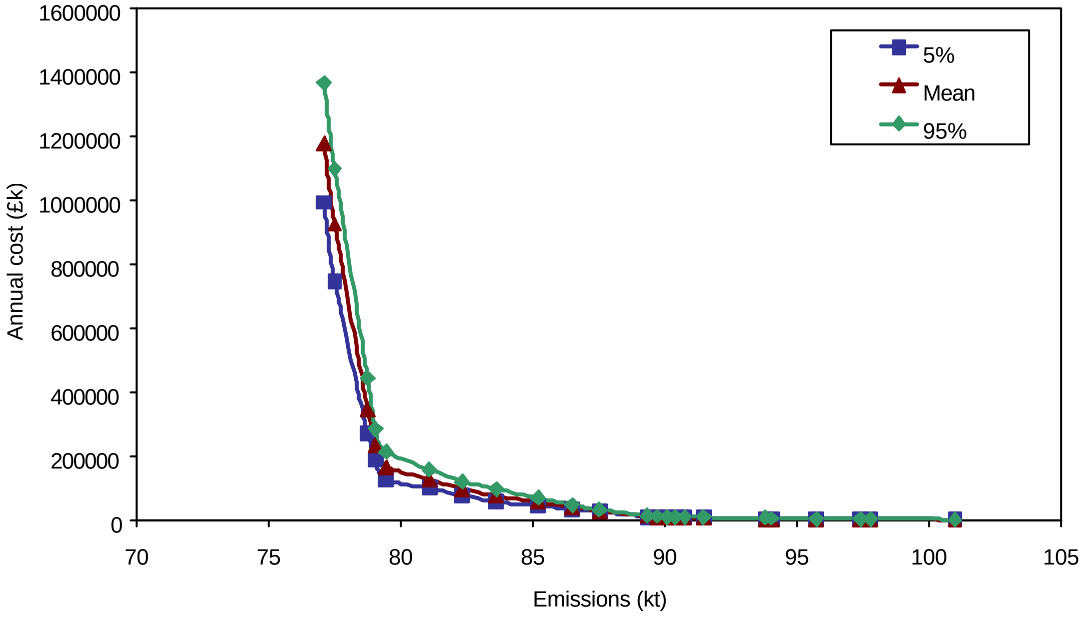

Figure 13 – The impact of uncertainty in costs of abatement measures on the total annual costs of the measures contained in the cost-curve

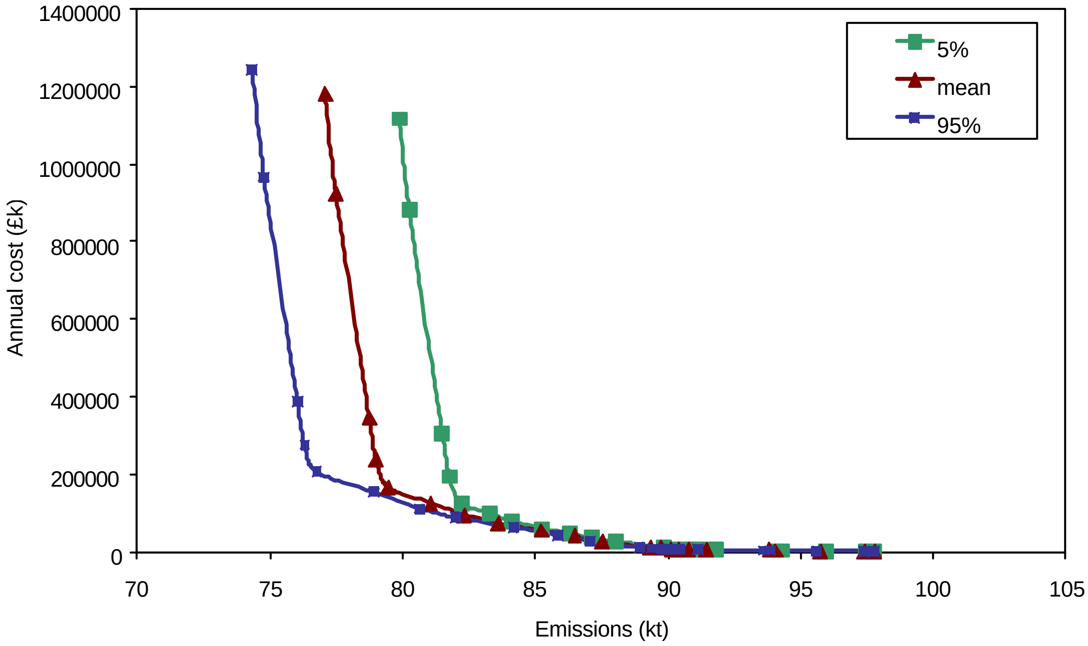

Figure 14 – The impact of uncertainty in abatement levels on the total annual costs of the measures contained in the cost-curve

Figure 13 demonstrates that there is a maximum uncertainty in the costings of +30%, -24% around the mean. Annual costs for the complete set of measures vary between £993 million and £1,370 million. Figure 14 shows that the 90% confidence interval for the emission reduction through full implementation of the measures contained in the cost-curve is roughly ±4 kt/year. The costs of the overall set of measures varies less in this case than in Figure 13, a range of £1,117 to 1,243 million/year, though these figures of course relate to differing levels of abatement. The costs of attaining particular emission levels varies little down to about 83 kt/year. Thereafter, highly significant variation is seen because of differences in the total emission at which the most expensive set of measures (mainly those relating to transport, that are significantly more expensive than others shown in the cost-curve) are introduced.

The analysis presented thus far did not include variation in the discount rate within the uncertainties associated with the costs of abatement. The analysis has used a 6% discount rate, which is consistent with current Treasury guidance. Sensitivity to the use of a 3 % discount rate has also been explored. The measures most sensitive to discount rate are those with high initial costs and low operating and maintenance costs. Analysis found a reduction of around 20% in costs when applying the lower discount rate for these measures. For some other measures, in which initial costs are low, there was not surprisingly little difference in costs between the two discount rates. Further information is provided in the IGCB [2001] report.

6.3 NATIONAL COST-CURVES

6.3.1 PM_{10}

Cost curves based on reductions in terms of mass emissions and population-weighted concentrations (expressed on a TEOM basis) are shown in Figure 15 and Figure 16 respectively. A summary of key data extracted from these curves is presented in Table 42.

Table 42 – Summary of key data for national PM_{10} cost curves

	Emission, kt			Concentration, µg.m^{-3}			
Year	**Start**	**End**	**Reduction**	**Start**	**End**	**Reduction**	**Cost, £M***
1998	167	120	47	2.1	1.8	0.34	870
2000	126	88	38	1.9	1.6	0.29	630
2005	115	81	34	1.7	1.4	0.29	600
2010	102	69	33	1.5	1.2	0.32**	1000 - 1400*
2015	96	63	33	1.4	1.1	0.35	1700 - 2400*

* The range shown arises through the use of high and low estimates of the costs of particle traps used on cars and vans in 2010 and 2015 (1250 tonnes PM_{10} abated at marginal costs from £0.2 million/tonne to £0.46 million/tonne.

** The IGCB report cites a population-weighted concentration of 0.75 µg.m^{-3} in 2010 compared to the 0.32 µg.m^{-3} estimated here. There are two reasons for this disparity. First, our results are expressed on a TEOM basis, whereas those given by the IGCB are expressed gravimetrically and hence a factor 1.3 higher. Second, the reduction in particle concentrations considered here is restricted to impacts of measures on primary particles only: the analysis for the IGCB report, in contrast, included account of secondary particles also.

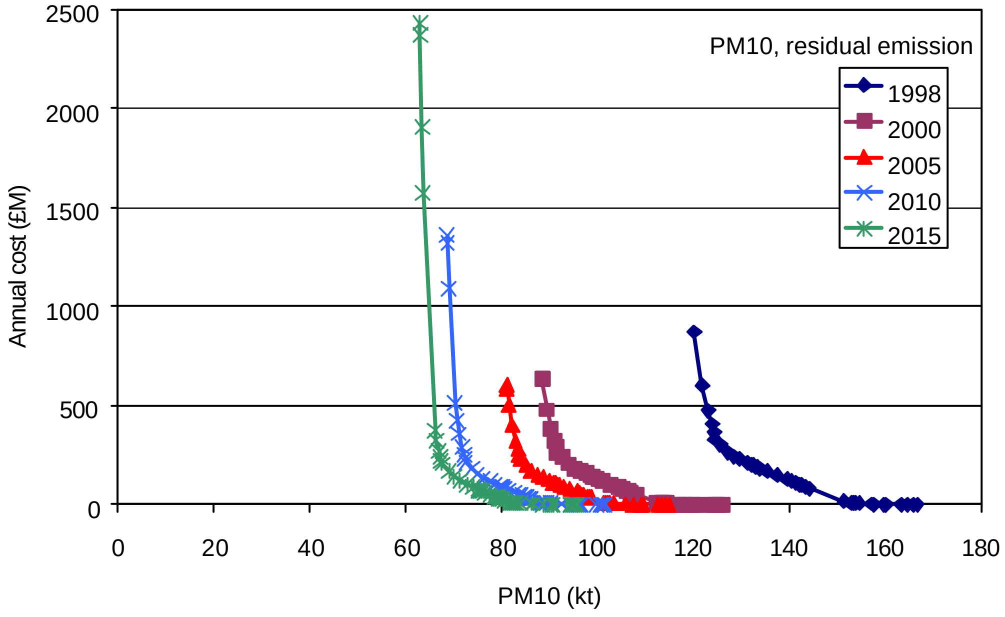

Figure 15 – National cost-curve for PM_{10} control, 1998 to 2015, £/[tonne emission abated]

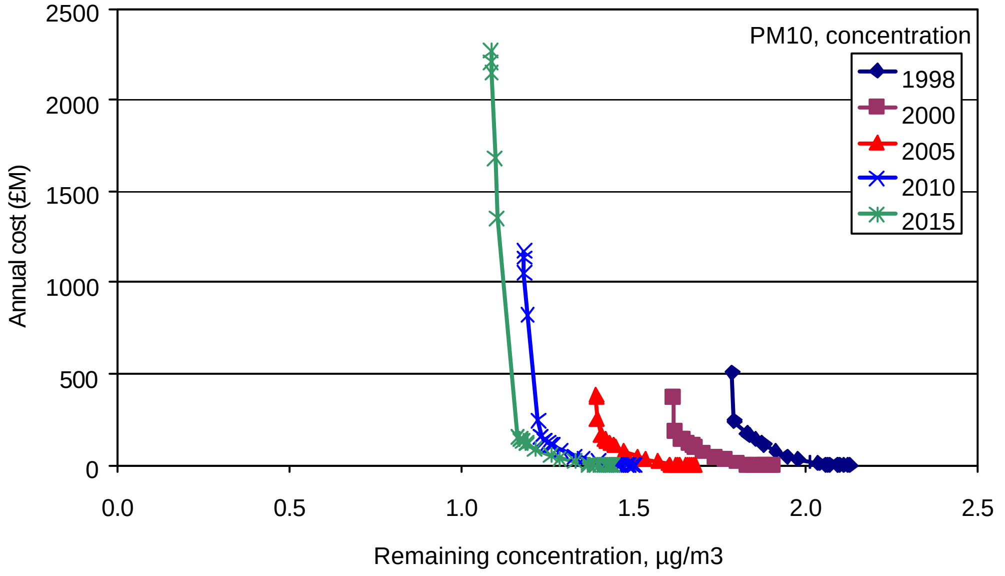

Figure 16 – National cost-curve for PM_{10} control, 1998 to 2015, £/[µg.m^{-3} population-weighted concentration reduction]

6.3.2 $PM_{2.5}$

Cost curves based on reductions in terms of mass emissions and population-weighted concentrations (again expressed on a TEOM basis) are shown in Figure 17 and Figure 18respectively. A summary of key data extracted from these curves is presented in Table 43.

Table 43 – Summary of key data for national $PM_{2.5}$ cost curves

	Emission, kt			Concentration, $\mu g.m^{-3}$			
Year	**Start**	**End**	**Change**	**Start**	**End**	**Change**	**Cost, £M***
1998	85	64	21	2.1	1.9	0.19	870
2000	66	48	18	1.6	1.5	0.16	630
2005	59	42	17	1.4	1.2	0.17	600
2010	52	33	18	1.0	0.9	0.20	1000-1400
2015	48	29	19	0.9	0.7	0.22	1700-2400

* The range shown arises through the use of a range of costs for the transport measures applicable in 2010 and 2015.

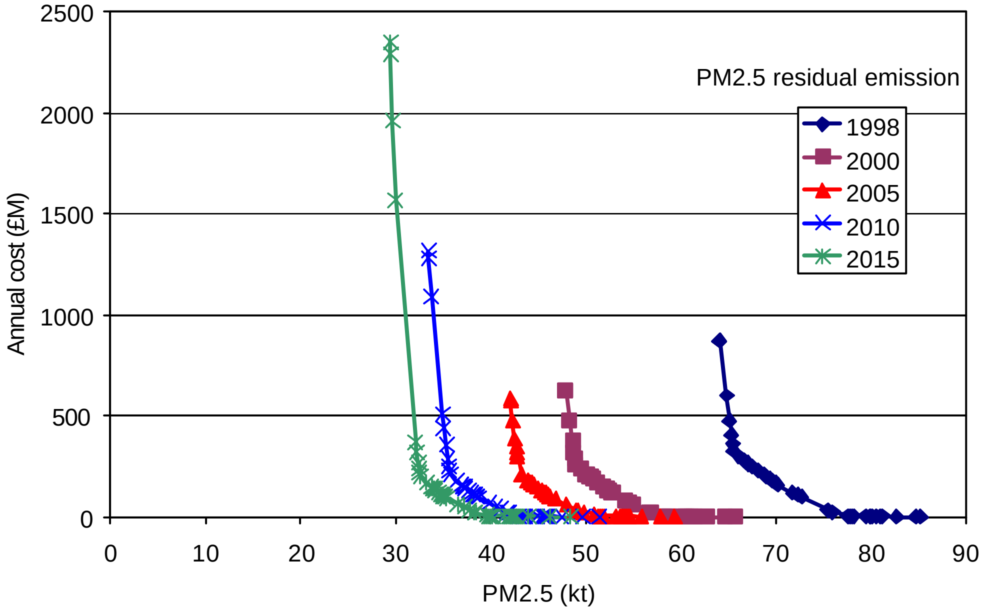

Figure 17 – National cost-curve for $PM_{2.5}$ control, 1998 to 2015, £/tonne emission abated

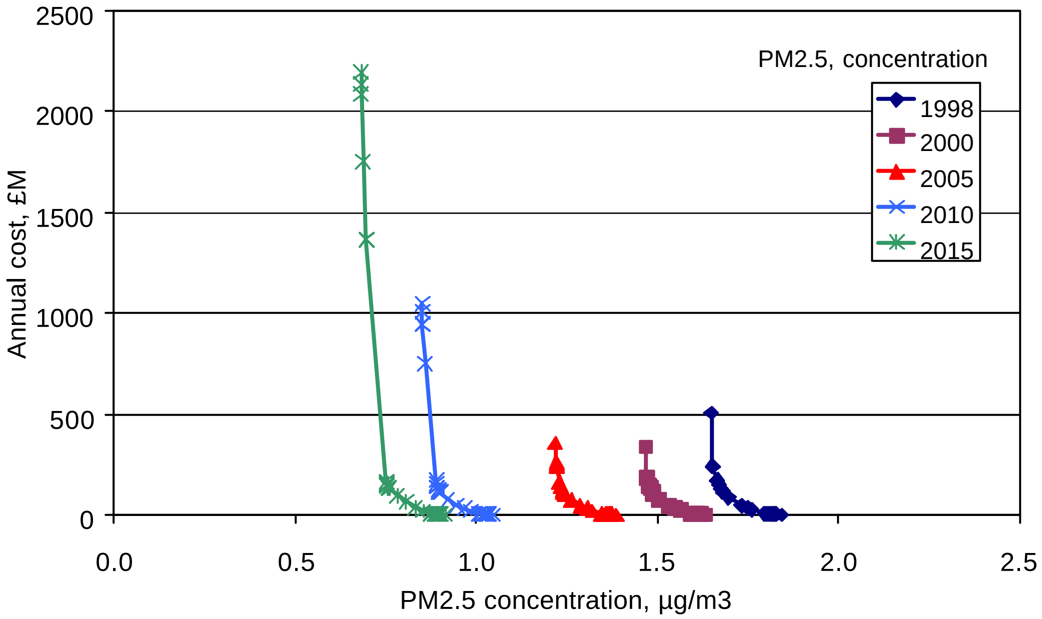

Figure 18 – National cost-curve for $PM_{2.5}$ control, 1998 to 2015, £/[µg.m^{-3} population-weighted concentration reduction]

6.3.3 Commentary on the national cost-curves for PM_{10} and $PM_{2.5}$

The following trends are observed from these data:

1. Baseline emissions/concentrations (the starting point for each of the curves) decrease over time, as noted already in Chapter 3.

2. The total emission reduction across each cost-curve (i.e. between the baseline emission and the maximum feasible reduction) in Figure 15 and Figure 17 falls over time as opportunities for abatement decline. Reasons include trends away from coal or oil, and new legislation coming in that requires the use of particular abatement options.

3. The total reduction in population-weighted concentration across each set of cost-curves falls from 1998 to 2005, but then increases. The increase is a consequence of the introduction of additional transport options after 2005, and reflects the fact that population exposure to transport emissions tends to be higher than to emissions from most stationary sources.

4. Following from [2], the total cost of all available measures in the cost-curve (excluding some of the transport options which only become available later) falls from 1998 to 2005 as opportunities for abatement decline.

5. The total costs of the measures considered for 1998 to 2005 continues to decline in 2010 and 2015. However, total costs of all measures increase substantially in these years as additional transport options are introduced. As noted in Chapter 5, these measures tend to have substantial benefits in terms of control of other pollutants (which

are not reflected in the cost-curve). It is possible that they would not be seriously considered for their effect on PM_{10} levels alone.

6. The cost-effectiveness of the transport measures compared to other measures improves when investigating abatement of the finer $PM_{2.5}$ fraction compared to PM_{10}. However, this is not reflected by a significant change in the ranking of the transport measures relative to the others, because the marginal abatement costs for transport are so much higher than for the other sectors (with the partial exception of the residential sector).

6.4 REGIONAL COST CURVES

This section starts with presentation of the regional cost curves for PM_{10} and then $PM_{2.5}$, before a short discussion of the observed trends. Results are restricted to 1998 as that is the year for which data are most complete. The purpose of this part of the analysis is to demonstrate similarities and differences between the regions with respect to opportunities for, and the costs of, abatement.

6.4.1 PM_{10}

Cost-effectiveness of PM_{10} abatement in terms of reducing mass emissions and population-weighted concentration in the six regions considered is shown in Figure 19 and Figure 20, respectively. It is immediately apparent that there are substantial differences in the opportunity for abatement between regions, taking into account the measures explored in this report and applicable in 1998.

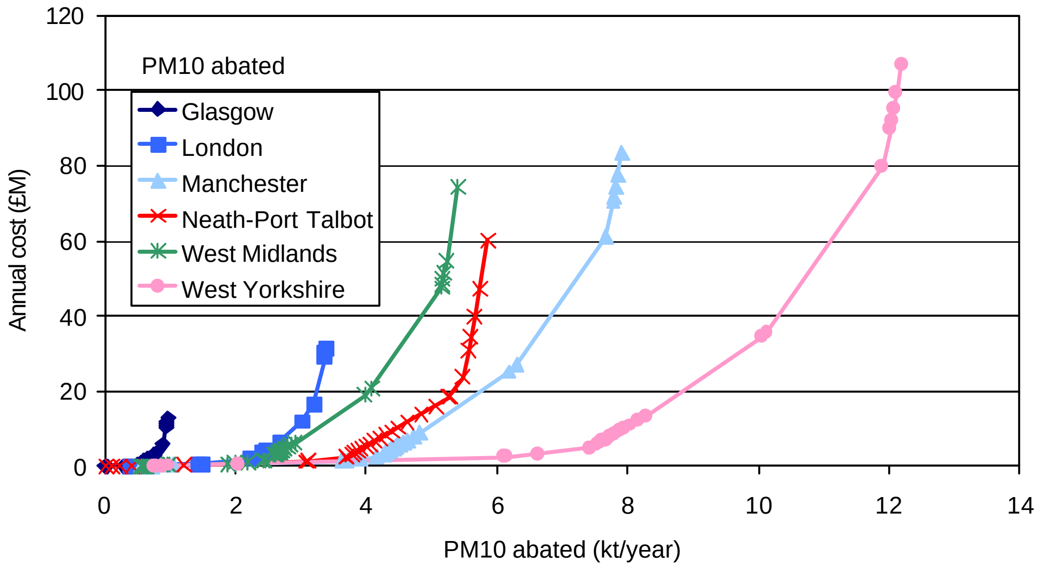

Figure 19 – Regional cost-curves for PM_{10} control, 1998, in terms of mass emission avoided

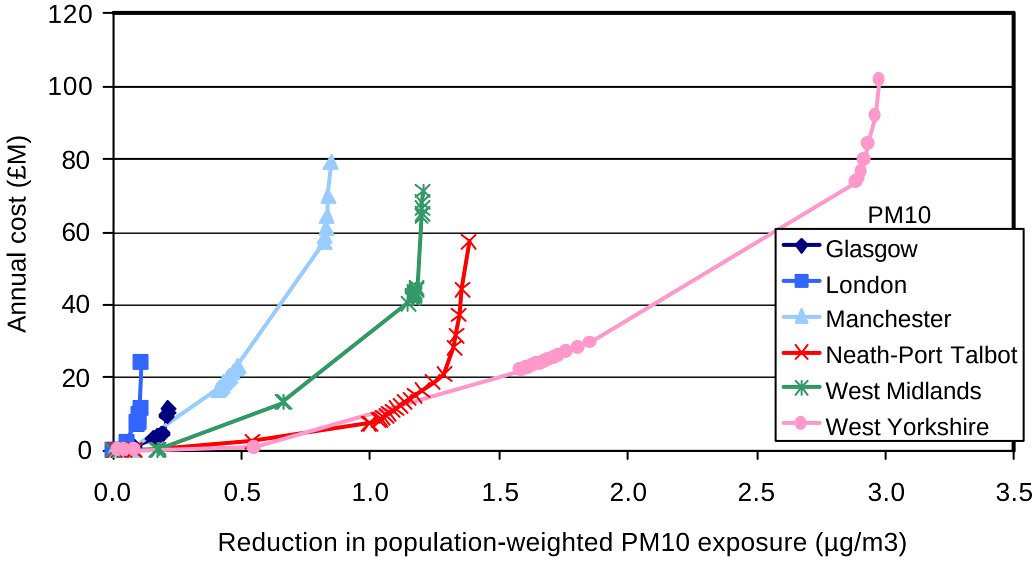

Figure 20 – Regional cost-curves for PM_{10} control, 1998, in terms of reduction in population-weighted concentration (TEOM basis)

6.4.2 $PM_{2.5}$

Cost-effectiveness of PM_{10} abatement in terms of reducing mass emissions and population exposure in the six regions considered is shown in Figure 21 and Figure 22, respectively. It is again apparent that there are substantial differences in the opportunity for abatement between regions, taking into account the measures explored in this report and applicable in 1998.

6.4.3 Commentary on the regional cost-curves for PM_{10} and $PM_{2.5}$

The following trends are observed from these data:

1. There is a very large range in the potential of the measures identified in this report to abate emissions and reduce concentrations in different parts of the UK. The greatest potential arises in areas where there is significant heavy industrial activity, the least in areas such as London where the local economy is more dependent on the service sector.

2. The abatement potential in London and Glasgow, particularly when considering the reduction in exposure to particles, appears to be trivial. Importantly, however, there were no measures included in this part of the assessment for abatement of particles from vehicles, which are the dominant source in both areas.

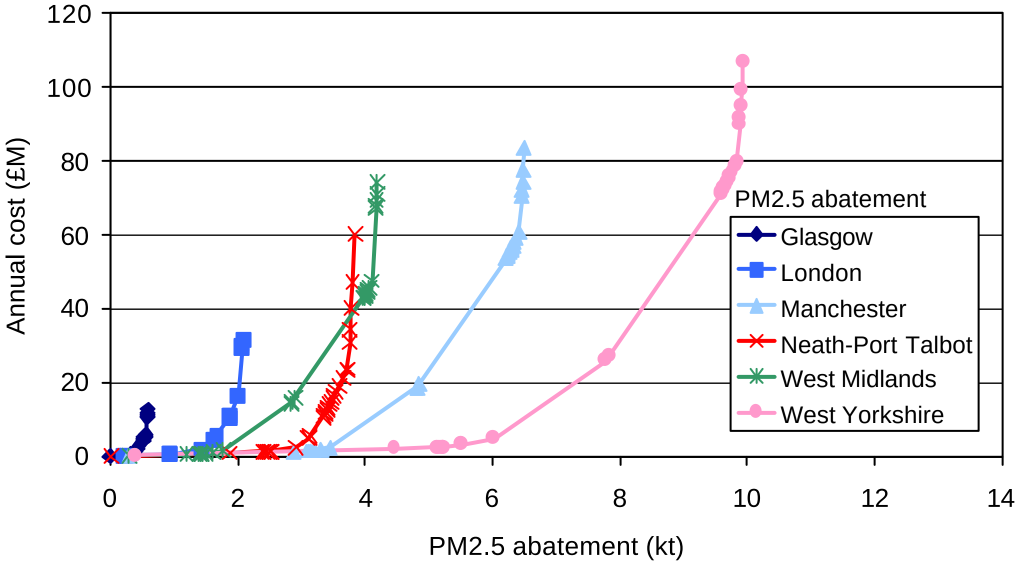

Figure 21 – Regional cost-curve for $PM_{2.5}$ control, 1998, in terms of tonne abatement

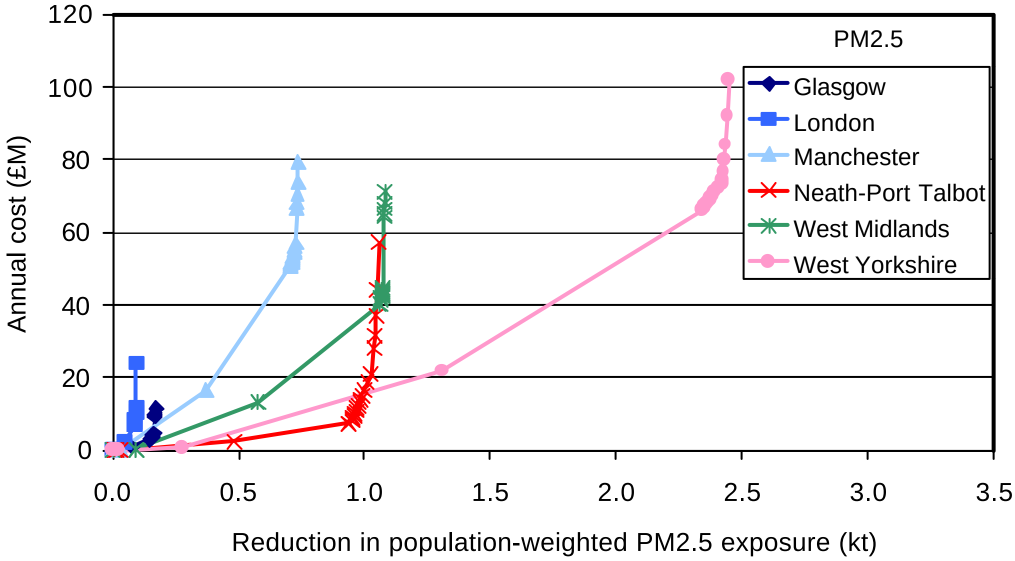

Figure 22 – Regional cost curve for $PM_{2.5}$ control, 1998, in terms of reduction in population-weighted concentration (TEOM basis)

3. The order of regions in terms of maximum feasible reduction (with respect to the package of measures considered) changes between the figures for PM_{10} mass abatement and $PM_{2.5}$ mass abatement. This results from differences in the fraction of PM_{10} present as fine particles from different sources.

4. There are also differences between the order of regions with respect to possible control of emissions (of both $PM_{2.5}$ and PM_{10}) compared to possible control of exposure. The main factor here is the difference in population in different regions. For example, although the potential for abatement in tonnes of PM in London is greater than in Glasgow, benefits are spread across a much larger number of people (6.8 compared to 0.58 million). This issue is explored further in Figure 23.

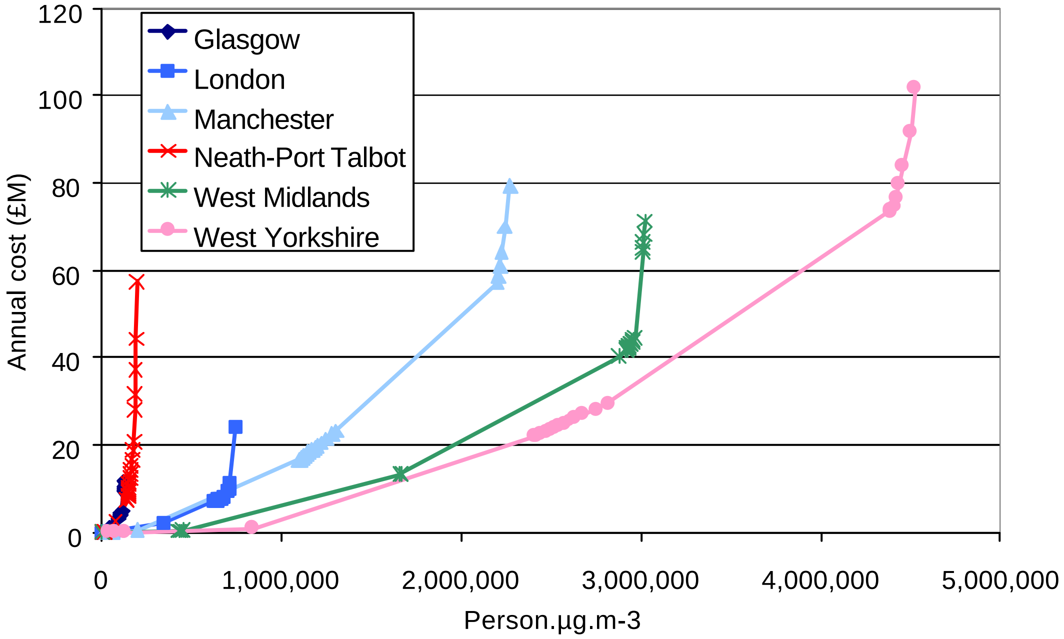

Figure 23 - Regional cost-curves for PM_{10} control, 1998, in terms of reduction in exposure (TEOM basis)

Figure 23 should be compared against Figure 20. A comparison of the order of regions in terms of abatement potential is shown in Table 44. This shows that there are, not surprisingly, differences in the order of regions when population is factored into the equation.

Table 44 – Rank order of potential for reducing exposure to PM_{10} considering the regions and package of measures adopted in this study

Rank	Population-weighted PM_{10} concentration, µg.m^{-3}	Exposure, person.µg.m^{-3}
1 (most potential)	West Yorkshire	West Yorkshire
2	Neath-Port Talbot	West Midlands
3	West Midlands	Manchester
4	Manchester	London
5	Glasgow	Neath-Port Talbot
6 (least potential)	London	Glasgow

5. Presentation of data in the format used in Figure 23 takes the assessment closer to a full cost-benefit analysis. Assuming that there is no threshold for the action of particles on health, health impacts and their monetised equivalents would scale directly against the exposures given in the figure.

   There would of course be other factors to consider when carrying out a full CBA for this case, for example:
   a) Impacts on non-health receptors (buildings, ecosystems, etc.)
   b) Impacts of the abatement options through changes in emissions of other pollutants (as highlighted in the following section)
   c) Impacts on people outside the regions considered (given the potential for long-distance transport of fine particles).

   The important factor shown by this part of the discussion is that different ways for expressing 'cost-effectiveness' can have a profound influence on the way that money could be allocated to abatement projects.

7 Effects of PM_{10} Control on Emissions of Other Pollutants

Most options for control of primary PM_{10} emissions have consequences for other pollutants[1]. With respect to air pollutants these effects may be:

- Direct, for example as a result of switching from coal to natural gas, which reduces SO_2, NO_x, CO_2, and other pollutants, as well particles, or;
- Indirect, for example through increased emissions of other pollutants as a result of increased demand for electricity to run the fans for forcing flue gases through fabric filters.

Marked reductions in emissions of some important trace pollutants are possible through particle abatement. These include dioxins and furans, many heavy metals (with the exception of mercury, because of its high volatility), and many PAHs. These pollutants are abated by many of the options described in this report because they share a common source (e.g. coal combustion), and rapidly condense onto particles in the flue gas stream. Abatement of these pollutants is considered here only briefly, as they are being covered specifically under another consultancy contract relating to the abatement of all of the above emissions [AEATechnology, forthcoming].

Many of the abatement options included in the cost-curve, such as the use of fabric filters, simply transfer pollutants across media, from air to land. It is clearly necessary to ensure that this leads, overall, to a reduction in the risks to environment and health (this of course being the driver for IPC/IPPC legislation). In contrast, some of the options identified lead to a reduction in air emissions generally and no cross-media transfers. These include options such as fuel switching and various of the quarrying options, such as reducing drop heights. Energy (and other) efficiency options also fall into this category, though for reasons given elsewhere in this report have not been included in the study.

These factors highlight a deficiency in the overall approach of developing cost-curves against a single pollutant: that it does not credit those options that assist in the control of a number of pollutants with any advantage over those that are specific to PM_{10}. This is one reason why the transport options identified here are likely to be introduced, despite their apparently poor cost-effectiveness for PM_{10} control.

7.1 EFFECTS ON CO_2 EMISSIONS

In the context of this report, changes in emissions of CO_2 will arise principally through fuel switching, changes in power demand to run abatement equipment, and (though not covered

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[1] Exceptions being limited to some of the quarrying measures.

in this report) reductions in energy consumption through energy efficiency. Results are summarised in Table 45, and discussed further below.

Table 45 - Impact on CO_2 emissions of industrial and transport measures for PM_{10} abatement in 2010

	Additional CO_2 emissions		
Source	**tonnes CO_2/year**	**% overall UK emissions in 1998***	**Quality of estimates**
Cement	30,000	0.005%	medium
Refineries	-1,900,000	-0.34%	medium/good
Iron and steel	44,000	0.008%	medium/high
Non-ferrous metals	5,800	0.001%	medium
Lime production	4,600	0.001%	high
Residential combust.	reduced		-
Public services	17,000	0.003%	low
Other industry	97,000	0.018%	low
Road transport	570,000	0.100%	medium
SUBTOTAL	**-1,100,000**	**-0.21%**	

Additional source: DTLR (personal communication, 2001).
(*) = 550 million tonnes CO_2

The most significant effect on CO_2 emissions from measures applied to stationary sources is calculated to relate to the savings made at refineries from a switch to natural gas. This could save nearly 2 million tonnes of CO_2 each year. Some (albeit less significant) savings may also be possible from the residential sector.

As already noted, increased emissions of CO_2 arise from the increase in energy consumption associated with end-of-pipe abatement techniques. Electricity demand for ESPs, fabric filters and wet scrubbers was calculated using data from the BREF notes produced by the European IPPC Bureau. Associated CO_2 emissions were then calculated on the basis of the average emission coefficient (tonne CO_2/kWh) for electricity production for the fuel mix given by DTI projections for the Central High energy scenario for 2010 [DTI, 2000]. Emission factors were taken from AEA Technology [1998] and reflect emissions across the full fuel chain (e.g., for coal, covering mining, transport of fuels and other materials, power generation and waste disposal) for each power generation technology. They also take into account technical parameters of power plants likely to influence emissions in 2010.[1]

Most of these estimates are based on limited information from the BREF notes for electricity consumption by different types of equipment per unit of gas shifted. Moreover, some data

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[1] Whilst we have here applied emission factors that average across the generating mix forecast for 2010, it may be appropriate to adopt emission factors for whatever may be considered to be the ‘marginal technology’ for 2010. Associated emission changes would fall to around zero were nuclear or renewable technologies assumed, remain about the same were natural gas CCGTs assumed, or increase to roughly double for coal fired plant.

extrapolation was necessary to extend estimates of additional CO_2 emissions to those sources or sub-sources (i.e., other industry, public services, cement, refinery combustion) for which there is less information available on the specific types of equipment that might be put in place. For this work the extrapolation was based on the amount of particles abated. Alternative bases for the extrapolation would doubtless provide different answers, though the method used here seems appropriate for an order-of-magnitude estimate.

The impact on CO_2 emissions of fitting particulate traps to light duty vehicles is highly uncertain, but, as the results in Table 45 show, could be significant. A few models have recently been launched with these traps, but the technology is still in its infancy and there is no clear evidence regarding its impact on fuel consumption and therefore on CO_2 emissions. However, if light duty traps have an impact similar to HGV traps, an increase in fuel consumption is to be expected. An increase of 1% has been assumed for both light and heavy duty diesel vehicles for the purposes of this analysis. This would lead to increased emissions in 2010 of around 570,000 tonnes CO_2 per annum.

The use of sulphur free diesel will increase emissions from refineries resulting from the additional energy used to produce very low sulphur fuel. However, this will be offset by improvements in the fuel efficiency of Euro IV diesel vehicles as a result of sulphur free diesel. It seems likely that, by 2010, the impact would be either broadly neutral or a small net reduction in CO_2 emissions.

The figures presented here show that:

- The CO_2 impacts of the PM_{10} abatement measures are likely to be relatively minor in terms of overall UK carbon emissions. Two notable exceptions are the refinery measures, which are expected to lead to a reduction in emissions and the transport measures, which, in contrast, imply an increase;
- Given the significant cut in CO_2 emissions from the refinery sector as a result of fuel switch, the overall impact of the package of industrial and transport measures is likely to be a decrease in carbon emissions of around 1.1 million tonnes CO_2 (around 0.3 million tonnes of carbon).

7.2 EFFECTS ON NOX EMISSIONS

In the residential sector, fuel switching measures have been assumed to have no significant effect on NOx although fuel switching in industry to reduce refinery emissions will create an approximate reduction of 16 kt. The transport measures are estimated to result in reductions of 22 kt. Overall, the majority of measures are not expected to have a significant impact on NOx emissions, although where quantification of these secondary reductions has been possible the health and non-health benefits resulting from these have also been quantified as a sensitivity analysis. Results are summarised in Table 46.

7.3 EFFECTS ON SO_2 EMISSIONS

Fuel switching measures to reduce residential PM_{10} emissions have been assumed to reduce SO_2 emissions by approximately 7 kt. In the refinery sector a 64 kt reduction is expected to result from fuel switching while the transport measures considered are not expected to give any significant effect on SO_2. As is the case for NOx, the impact from the majority of measures will not be significant but quantification has been attempted where feasible. Results are summarised in Table 47.

Table 46 - Impact on NO_2 emissions of industrial and transport measures for PM_{10} abatement in 2010

	Additional NO_2 emissions		
Source	**tonnes NO_2/year**	**% overall UK emissions in 2010***	**Quality of estimates**
Cement	60	0.005%	medium
Refineries	-16,000	-1.371%	medium/good
Iron and steel	88	0.008%	medium/high
Non-ferrous metals	12	0.001%	medium
Lime production	9	0.001%	high
Residential combust.	neutral		-
Public services	34	0.003%	low
Other industry	196	0.017%	low
Road transport	-22,000	-1.885%	medium
SUBTOTAL	**-37,602**	**-3.2%**	

Additional source: DTLR (personal communication, 2001).
(*) = 1,167,000 tonnes NO_2

Table 47 - Impact on SO_2 emissions of industrial and transport measures for PM_{10} abatement in 2010

	Additional SO_2 emissions		
Source	**tonnes SO_2/year**	**% overall UK emissions in 2010***	**Quality of estimates**
Cement	19	0.003%	medium
Refineries	-64,000	-10.940%	medium/good
Iron and steel	28	0.005%	medium/high
Non-ferrous metals	4	0.001%	medium
Lime production	3	0.001%	high
Residential combust.	saving >7,000		-
Public services	11	0.002%	low
Other industry	63	0.011%	low
Road transport	small		medium
SUBTOTAL	**-63,873**	**-11%**	

Additional source: DTLR (personal communication, 2001).
(*) = 585,000 tonnes SO_2

7.4 PAHS, DIOXINS, HEAVY METALS

Pollutants in these categories tend to attach themselves to the fine fraction of particulate. Therefore, measures that abate PM_{10} will automatically tend to reduce emissions of these pollutants. The package of stationary and transport measures is therefore likely to induce a significant reduction in the emissions of these pollutants.

7.5 CH_4

In the residential sector, the increased combustion control in enclosed appliances means that less methane will be emitted. Changing from coal to smokeless solid fuel gives reductions in methane emissions at or above 65%. On the other hand, fuel switching in the refinery sector may induce small increases in methane emissions. Overall, the whole package of stationary and transport measures is likely to reduce emissions of methane.

7.6 CO

In the residential sector, the increased combustion control in enclosed appliances means that less carbon monoxide will be emitted. Also, the switch to lighter fuels both in the residential sector and in the refinery sector will greatly abate emissions of carbon monoxide. Although these impacts might be partially offset to the extent that indirect effects imply an increase in combustion from electricity generation, the overall impact on carbon monoxide is likely to be a significant reduction.

7.7 N_2O

Switching to gas (and to a minor extent, to smokeless solid fuel) in the residential sector and switching to gas from heavy fuel oil in the refinery sector will reduce emissions of N_2O.

7.8 VOCS

In the residential sector, changing from coal to smokeless solid fuel gives emission reductions, at or above 65% for VOCs. Furthermore, switching to gas in the residential sector would almost completely abate emissions of VOCs from this source. On the other hand, fuel switching in the refinery sector is likely to induce small increases in VOCs emissions. Overall however, the impact of the measures on VOC emissions is likely to mean significant reductions in emissions.

7.9 NH_3

The measures for PM_{10} abatement in the residential sector (enclosed appliances, switching to smokeless solid fuel and, above all, switching to gas) would significantly abate emissions of this pollutant. Overall, the stationary and transport measures would decrease emissions of NH_3.

7.10 BENZENE

Again, introduction of enclosed appliances and switching to smokeless solid fuel in the residential sector and, above all, switching to gas in the residential sector and in the refinery sector would significantly abate emissions of benzene. The overall impact of the measures would be a significant reduction.

8 Conclusions

1. Particle concentrations in the UK atmosphere are comprised of:
   a) Primary particles emitted from transport, industry and homes in the UK;
   b) Secondary particles formed in the atmosphere from emissions of SO_2 and other pollutants in the UK;
   c) Natural particles, including sea salt spray, from the UK land mass and surrounding seas;
   d) Primary, secondary and natural particles originating in other countries.

2. These particles are widely regarded as being hazardous to human health, and hence are controlled under European legislation, enacted in the UK through the Air Quality Strategy for England, Scotland, Wales and Northern Ireland.

3. This report is focused on primary particle emissions, expressed as PM_{10}, in the UK. Other studies and activities have dealt with the costs of reducing emissions of the main pollutants responsible for the generation of secondary particles. The European Commission, UNECE, and various other European states are active in exploring the costs of emissions abatement elsewhere in Europe.

4. The report also considers abatement of the finer fraction of particles, $PM_{2.5}$. In addition to the national assessment cost-curves are also presented for a number of the most densely populated regions of the UK: Glasgow, Greater London, Greater Manchester, Neath-Port Talbot, the West Midlands and West Yorkshire.

5. Emissions of primary PM_{10} have fallen steadily over time, from an estimated 495 kt/year in 1970 to 186 kt/year in 1999 according to the latest NAEI data. It is further projected that emissions will fall to 98 kt/year by 2010 and 93 kt/year by 2020. These changes arise as a consequence of switching fuels from coal and oil to natural gas, improvements in energy and process efficiency, and the use of improved end-of-pipe abatement measures.

6. One consequence of these changes is that some previously insignificant sources are now much more prominent in the inventory than before, and vice-versa. In some such cases there is a strong need for additional work to refine the inventory – the most prominent case here relating to emissions of PM_{10} from residential gas combustion which currently seem to be significantly over-estimated. In many cases necessary refinements have already been initiated, for example, with respect to inclusion of emissions from residential wood burning.

7. The analysis presented in this report demonstrates that there are a variety of measures available for reducing concentrations of primary PM_{10} in the UK beyond activities that are already in the pipeline as a result of new legislation or existing trends.

8. Cost-curve analysis has previously focused on expressing the cost-effectiveness of control options in terms of the cost per tonne (£/tonne) of pollutant abated. Against a background of falling concentrations of particles, and rising costs for pollution control, however, it is appropriate to consider options that are best targeted to reduce human exposure, and hence health impacts. In this report therefore, options have been assessed not just in terms of £/tonne, but also as cost per unit population-weighted exposure (£/$\mu g.m^{-3}$).

9. Options for reducing emissions of particles from stationary sources (industry, houses, quarries) can be classified as follows:
    a) End-of-pipe abatement options (electro-static precipitators, fabric filters, etc.);
    b) Process modifications, such as flue gas recirculation;
    c) Switching from dirty fuels like coal or heavy fuel oil to smokeless solid fuels or natural gas;
    d) Improvements in the efficiency of energy use or process operation.

10. Similarly, options for controlling emissions from transport can be classified as follows:
    a) Technical improvements to engines;
    b) Improvements in fuel quality;
    c) Switching to less polluting fuels, such as compressed natural gas or, for the future, using fuel cells;
    d) End-of-pipe options such as particle traps;
    e) Reductions in fuel consumption by vehicles;
    f) Local measures, such as traffic management, congestion charging, use of light rail systems, park and ride schemes, and promotion of public transport, cycling and walking.

11. Some of these options have not been included in the cost-curves developed here. Whilst there is still undoubted potential for further energy efficiency options that save money whilst abating emissions, there are clearly market barriers to further penetration of such options. It was considered inappropriate to include these options given uncertainty regarding these market barriers. Local measures for reducing traffic emissions were also omitted from the analysis. The introduction of these measures needs to be based on localised assessment of need, potential costs and effectiveness: it would be inappropriate to assess the applicability and costs-effectiveness in a national scale assessment such as this.

12. Data for this study were collected from a variety of sources including government, industry, and regulators.

13. Measures have been identified for the following sectors:
    a) Transport
    b) Residential
    c) Quarrying
    d) Industrial combustion and processes
    e) Refineries

f) Iron and steel
g) Non-ferrous metals
h) Cement
i) Lime
j) Public and commercial buildings.

14. A few individual measures, spread across the refineries, residential, iron and steel and cement sectors each make contributions in excess of 1.5 kt/year to the total abatement of PM_{10} of around 30 kt/year in 2010. However, most measures make relatively modest contributions to the total abatement.

15. Expressing costs-effectiveness in terms of £/µg.m^{-3} leads to some changes in the order of measures in the cost-curve.

16. Development of regional cost-curves for Glasgow, London, Manchester, Neath-Port Talbot, West Midlands and West Yorkshire demonstrates that the package of measures assessed in this report will have varying effects in different parts of the country.

17. Abatement of particle emissions inevitably leads to changes in other emissions. Emissions of CO_2, NOx and SO_2 are forecast to fall, mainly through measures in the refineries sector. Important reductions are also forecast for trace pollutants across a variety of sectors such as PAHs, dioxins and heavy metals that are typically emitted to the air bound to particles.

18. There are, inevitably, uncertainties in the cost-curves. These arise through various factors including:
    a) Limited availability of data, for example with respect to the current emission factors for residential combustion of natural gas and quarrying;
    b) The aggregated nature of the data for many sectors, particularly where emission sources are small (e.g. heating facilities for public buildings such as schools);
    c) The omission of known measures from the cost-curve. As noted above, these include energy efficiency and traffic management measures.
    d) The potential for industry to adopt alternative abatement strategies.
    e) Uncertainty in prediction of future emissions.

    The work presented here will enable research to focus on a number of areas where uncertainties are most significant.

19. The methodological advances made in this report, and the data presented, will provide a better information base for future policy assessments of air quality strategies. Results have already been used in the second report of the Interdepartmental Group on Costs and Benefits (IGCB) regarding the review of the National Air Quality Strategy.