THE EFFECTS OF CHANGES IN THE UK ENERGY DEMAND AND ENVIRONMENTAL LEGISLATION ON ATMOSPHERIC POLLUTION AND FUTURE OPTIONS FOR FURTHER REDUCTIONS IN EMISSIONS

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Declaration

I hereby declare that this dissertation is the result of my independent investigation , and that reference is made where necessary to the work of other researchers and authors as indicated by the sources of reference .

I further declare that the work embodied in this dissertation has not already been accepted in substance for any degree and is not concurrently submitted in candidature for any other degree .

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Date 3rd July 1997

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DEDICATION

1 wish to dedicate this dissertation to my wife Mary, and my son Gareth Dafydd, in gratitude for the patience , understanding and support they have shown me during this research work.

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my Supervisors , Mr Brian Blakemore and Dr Clive Davies , for their guidance and assistance in the preparation of this dissertation .

SUMMARY

This thesis researches and analyses three aspects of UK atmospheric pollution:-

1.0 Evaluation of the annual atmospheric emissions arising from fossil fuels over the 1970 - 1994 period , and identification of the reasons for changing trends over this period of time.

2.0 Prediction of future emissions for the 1990 - 2020 period.

3.0 Evaluation of existing and new technology available for further reduction of emissions for the future.

Phase 1 establishes and analyses changing pattern of the UK air pollution emission over the period 1970-1994 .

Fossil fuels have been identified as the major source of man made air emissions and this thesis establishes the annual changing trends of carbon dioxide (as carbon) , sulphur dioxide , oxides of nitrogen (as nitrogen dioxide) and black smoke .

Estimations of the annual mass emission of the pollutants emitted from fossil fuels were based on the product of the emission factor coefficient for each of the pollutants and the annual consumption energy of the individual fossil fuels .

The analysis of these data have clearly shown that emissions of carbon dioxide , sulphur dioxide and black smoke over this period have declined , whereas the oxides of nitrogen have shown a less clear trend .

Further analysis of these data has identified and quantified three factors that have influence on the changing pattern of these emissions .

The changing pattern of energy consumption
The changing pattern of fossil fuel mix .
UK and EEC Environmental legislation.

Phase 2 considers future emission levels up to the year 2020 .

Using the calculated and empirically developed emission factors established in this thesis and a predictive energy consumption and energy mix energy model future forecasts of mass emissions from fossil fuels were established for the period 1990 - 2020 .

An analysis of this data indicates : -
A decline in carbon dioxide emissions up to the year 2000 , and thereafter a significant increase in the level of emissions .
A steady but significant decline in the emissions of sulphur dioxide over the whole of the 1990-2010 period , due mainly to environmental legislation and changes in energy mix .
With the predicted increase in demand for travel in the UK, the major source of emissions of oxides of nitrogen during the 2000 -2020 is expected to continue to be the road traffic sector .
The road traffic sector is currently by far the major source of black smoke . The implementation of legislative contol will determine future levels of emissions.

Phase 3 considers the potential for reductions in emissions from the power generating sector by the adoption improved existing technology and also advances technology.

The power generating sector has been shown to be the major emitter of carbon dioxide , and sulphur dioxide and also significant generators of oxides of nitrogen. Technology options for reducing emissions have been identified and evaluated .

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1.0 INTRODUCTION

1.1 General Background

Care for the environment is one of the most important issues facing the UK and public demand and expectation for an improved environment rises continuously year by year . It is achnowledged that good air quality is essential for human health and the well - being of the environmental as a whole .The impact of improved living standards , increased industrialization and the expansion of the road transport system in the 20 th century have contributed to a major increase in use of raw materials such as fuel , iron ore etc to satisfy the ever increasing demands of society with the inevitable consequence of higher pollution discharges to the air , waterways and land .

Atmospheric emissions comprise a wide range of gaseous products and particulate matter which can be generated from natural sources and from human activities principally from the domestic , transport , industrial and power generating sectors , but also from farming , landfill , animal digestion and waste , sewage sludge , off- shore gas flaring and fugitive emissions , and coal mining .The emissions may comprise carbon monoxide , heavy metals especially lead , industrial particulates , toxic organic compounds , Polychlorate biphenols, methane , benzene , nitrous oxide , sulphur dioxide and trioxide , carbon dioxide , oxides of nitrogen and black smoke. All pollutants have different impacts on the general environment i.e. Global warming and on the working environment i.e. toxicity .The scope of any thesis into this subject is largely dependent on the availability and soundness of well documented and accurate historical data , which is mainly generated by government sponsored research , by workshop test units particularly in the transport sector and well researched government annual pollution inventories .This thesis largely focuses on the mass of air pollutants with transboundary emissions characteristics arising from fossil fuel rather than the more localized emission of toxic material .
The major factors that are considered to influence the extent of atmospheric pollution can be summarized into the following categories -:
1.0 The consumption of fossil fuel - solid fuel , petroleum and natural gas.
2.0 The growth in the consumption of non- fossil fuel- nuclear and renewable energy.
3.0 The economic growth of the nation - The change in primary energy consumption per unit of Gross Domestic Product
4.0 The types of fossil fuel consumed - some fuels have a greater potential for generating pollutants per unit of energy.

5.0 Combustion efficiency of fossil fuels i.e. the effect on smoke and NOx generation.
6.0 The ever increasing demand for fuel by road transport especially for diesel fuel .
7.0 Environmental Legislation - UK , EU , and World Agreements on pollution control.
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The above list demonstrates the direct and indirect influence fossil fuel may have on the atmospheric pollution .The DTI Digest of UK Energy Statistics (1) has clearly demonstrated that over the past 25 years the combustion of fossil fuel in the UK is the major source of air pollution .Such emissions can give rise to a number of environmental problems such as acidic pollution , photochemical pollution , toxic pollutants and contribute to the green house effect which are discussed below .

The UK Government through the Department of the Environment produce statistical information on an annual basis on estimated emissions to the environment , energy consumption , industrial output and economic trends , which provide extensive background data relating on annual atmospheric emissions levels , energy demand , manufacturing output , and the Gross Domestic Product which contribute to the understanding of the changing environment in the UK.

In addition there are a wide range of technical journals national and international conferences devoted to environment matters which also provide a useful fund of information on the environment and energy consumption.

This type of published data forms the major source of background information for the research work involved in the environmental analysis undertaken in this thesis .

This thesis assesses the changing trends of atmospheric pollutants including carbon dioxide (as carbon) , sulphur dioxide , oxides of nitrogen ,(as nitrogen dioxide) and black smoke and their relationship to changing energy consumption , changing mix of energy consumption , economic trends and UK and EU environmental legislation .

1.2.Atmospheric Problems arising from the combustion of fossil fuels

The potential atmospheric pollution problems arising from the combustion of fuels are defined and summarized in the AEA Emission Inventory **(2)** and categorized below under the five major . Several studies have been published which have sought to quantify the damage caused by a range of atmospheric pollutants . However there are

many uncertainties involved in such an evaluation and additional work is still required to improve the level of confidence .However the National Air Quality Strategy Consultation Report **(3)** does contains some broad estimates of these possible costs :-

Sulphur dioxide incremental damage is given as in the range of £ 1,329 - £ 2.372 per tonne of SO2 emitted .

For particulates the estimated incremental cost of total damage is £ 3,680 per tonne emitted.

The incremental cost of oxides of nitrogen is estimated to be between £ 720 - 805 per tonne emitted .

Acidic pollution

Sulphur and nitrogen oxides from **fossil fuel combustion** are the major contributors to acidification ; they can be deposited both by precipitation and directly by dry deposition . The combustion of fuel accounts for 99.5% of the U.K. SO_2 emissions and 97% of the NO_x generated At the request of the DoE the Review Group on Acid Rain (4) undertook a detailed model study of acidic deposition over the U K during the period 1986 - 1988 .The study provided a major contribution to the knowledge on wet and dry deposition of acid rain confirmed that SO_2 and NOx were the main precusors to acid rain formation . More recent estimates for 1993 suggest that more than 75% of the UK's $SO_2$and as much as 90% of NO_x emissions are transboundary , leading to deposition either in other countries or in the sea **(3).** These pollutants are often converted through atmospheric chemical reactions into secondary pollutants , such as sulphates and nitrates which are the primary cause of acidification of the land, lakes and forests.

Photochemical Pollution

Nitrogen oxides in the form of NO and NO_x are emitted from **combustion sources** i.e fuel conversion industries and road vehicles and are of great concern because of their role as precursors to ozone production in the presence of sunlight, and Peroxyacetyl Nitrate the main irritant of photo chemical smog .

Toxic Pollutants

Nitrogen dioxide (NO_2) is also a toxic gas and can be a significant contributor to poor urban air quality.

Green house Effect

Carbon dioxide is considered to be involved in global warming and the **combustion of fossil fuel** is the major sources of carbon dioxide in the U.K.

Smoke Pollutant

Black smoke is generated from the incomplete combustion of solid fuels and petroleum products . The domestic , power generating manufacturing and transport sectors can give rise to black smoke emissions

2 AIMS OF THIS STUDY

1 To identify the changing pattern of the overall energy demand in the UK during 1979 - 1994 period.

2 To identify the changing trends of energy demand in the four major energy consuming sectors ; domestic/service , transport , power generation and industry.

3 To establish by calculation or from existing empirical data pollution emission factors for each of the main atmospheric pollutants - carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke in the form of grams of pollutant per unit of energy , grams per tonne of energy and in the case of transport grams per km traveled , for each of the major fossil fuels consumed ; coal , petroleum and natural gas .

4 To apply the calculated / empirically derived emission factors to the individual fossil primary energies consumed over the period 1970-1994 and estimate and analyze :-
4.1 The total overall annual mass emission of each of the pollutants - carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke.
4.2 The annual mass emission of each of the pollutants - carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke arising from the major energy consuming sectors ; the industrial , domestic , power generating , transport and service sectors .

5.0 To establish the relationship between energy consumption , Gross Domestic Product , mass emission , and the calculated or derived emission factor for each of the pollutants.

6 To establish the impact of UK and EU Legislation and World Agreements on atmospheric emission levels .

7 Utilizing published projected energy data to establish future energy demand and mix up to the year 2020 and applying the calculated / empirically derived emission factors to the annual energy consumption values to predict future mass emission levels up to the year 2020 and assess the overall impact of these emissions for the future

8 To examine the potential for further reducing atmospheric emissions through increased use of Combined Cycle natural gas turbines and the adoption of clean coal technology.

3 THE PLAN OF THE STUDY

Chapter 1 outlines general background on atmospheric pollution and problems that arise from theses pollutants.

Chapter 2 sets out the aim of the study , and the research plan .

Chapter 3 outlines the plan of study adopted .

Chapter 4 identifies the sources of the information used in the thesis ; fossil fuel technical data , National statistics on annual GDP values , energy demand , transport activity, and estimated and empirically derived data on emission of pollutants. This chapter also considers the accuracy of estimated emissions by calculation involving the product of energy composition and consumption and empirical data on emissions established mainly by government research establishments .

Chapter 5 identifies the overall changing pattern in the UK primary energy consumption solid fuel , petroleum, natural gas and primary electricity over the 1970-1994 period . It also considers the changing pattern of fossil fuel demand by the four final users sectors defined as the domestic , industrial , transport and service sectors and also the power generating sector which supplies electricity to the final user sectors.

Chapter 6 deals with the estimated contribution of combustion products from fossil fuel to carbon dioxide, sulphur dioxide , oxides of nitrogen and black smoke emissions. The annual mass emission of these pollutants arising from the combustion of fossil fuels during 1970 and 1994 is analyzed.

Chapter 7 considers the fuel technical data required to calculate atmospheric emission factors for carbon dioxide and sulphur dioxide .This technical data is outlined for each of the fossil fuels ; solid fuel , petroleum and natural gas.

Chapter 8 outlines the calculated emission factor values in grams per unit of energy and per tonnes of energy for carbon dioxide and sulphur dioxide generated from coal , petroleum and natural gas from energy consumption statistics and fuel technical data. This chapter also compares the emission factors for each fossil fuel and pollutant.

Chapter 9 outlines the estimation of emission factors for NO_X and smoke derived empirically by government research establishments for the road , industrial , power and domestic sectors

Chapter 10 summarizes the average emission factors for carbon dioxide , sulphur dioxide oxides of nitrogen and smoke generated by the four fossil fuels .

Chapter 11 Analyses the overall changing pattern of carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke The chapter also examines the relationship between the changing trends in fossil energy consumption , Gross Domestic Product , and the mass emission and the emission factor for each of the four pollutants.

Chapter 12 considers the changing pattern of emissions arising from each of the major energy consuming sectors . An analysis of the trend for carbon dioxide , sulphur dioxide, oxides of nitrogen and black smoke in each of the industrial , transport , domestic, power and service sectors is undertaken.

Chapter 13 deals with the implications of a wide range of UK and EEC Environmental Legislation and World Agreements on Environmental Control
The following major enacted legislation and agreements were considered in this chapter .

The effect of the UK Climate Change Programme and UK carbon / energy tax proposed by the EC on carbon dioxide emissions.
The EEC Legislation enacted in 1988 and brought into force in 1990 to reduce emission of sulphur dioxide and oxides of nitrogen arising from Large Combustion Plant.
The EEC emission standards relating to particulates and oxides of nitrogen from the transport sector.

Chapter 14 deals with future projections for fossil fuel demand and mix up to the year 2020 .This chapter also projects the overall changes in patterns of carbon dioxide and sulphur dioxide emissions and the changes in the emission of oxides of nitrogen and black smoke in the transport sector.

Chapter 15 considers the possible future reductions in carbon dioxide , sulphur dioxide oxides of nitrogen and black smoke that may be achieved by the increased use of natural gas turbines and advanced clean coal technology in the form of supercritical coal and integrated cycle gas turbine by the power generating industry .

4.0 Identification of the Sources of Information Used in the Study and an Assessment of the Accuracy of Estimating Atmospheric Pollutants

This thesis utilizes the annual background data outlined in Government publications including the Digest of Energy Statistics (1) , AEA National Atmospheric Emission Inventory (2),the UK National Air Quality Strategy (3) DoE acid rain reports (4) the Digest of Environmental Statistics (5), Economic Trends National Statistics (6) , Transport Statistics (7) ,and DOE Digest of Environmental Protection and Water Statistics (8) and a wide range of published literature and periodicals on the environment for analyzing the changing trends of the mass emission of pollutants to atmosphere over the 25 year period .

The research study has shown that there is very little continuous monitoring of atmospheric emissions in the U.K , hence information is rarely available on actual emissions over a specific period of time from an individual emission source with the exception of large power generating plants operating in the power plant , the industrial and refineries sectors , which are required under recent legislation to monitor emissions of SO_2 and NO_x. . Clearly it would be impossible to measure every emission source in the UK ; therefore the majority of emissions are estimates based on the product of fuel consumption , distance traveled or other statistical data related to the emissions and the calculated / empirically derived emission factors for each fuel for mobile and stationary emission sources.

The emission factors have therefore been derived by direct calculation involving fuel usage and composition in the case of $CO_2$and SO_2 and on part calculation and part empirical data from a limited number of measurements on a number of typical sources in the case of NO_x and black smoke emissions .

Due to the complex nature and uncertainties in estimating emissions the absolute precision of the emissions can vary over a wide band. The AEA Atmospheric Emission Inventory annual report (2) provides an 'estimated precision' for each of the four pollutants considered in this thesis.

Pollutant	Estimated Precision %	
Carbon Dioxide	+/ - 5%	dependent largely on the accuracy of the monitored consumption and fuel analysis.
Sulphur dioxide	+/- 10-15%	dependent largely on the accuracy of the monitored consumption , fuel analysis and estimations of the sulphur retained in the ash. Since the introduction of the Large Combustion Plant Directive in 1990 power plants monitor SO_2 and provide more accurate data
Oxides of Nitrogen	+/- 30 %	the estimation of NO_x emission is based on relatively few measurements .However since the enactment of L.C.P Directive in 1990 power plants monitor NO_x on a regular basis and report the results to the HMIP.
Black Smoke	+/- 20-25 %	the method of measurement involves a non - gravimetic technique .

In the case of nitrogen oxides and black smoke the emissions are estimated on the basis of empirical data coupled with distance traveled or some other appropriate statistical data .The empirical data available as already stated are limited and hence the estimated precision of emission estimation are lower for NO_x and smoke than for the calculated values for SO_2 and CO_2 .However the Government sponsored research establishments and Universities are the sole source of this type of environmental data and it is the best information available on this subject . Despite the apparent lack of absolute accuracy of estimated emissions it is considered that trends over time are likely to be more reliable .The analysis in this study is based on changing trends of consumption and associated atmospheric emissions .

5.0 The Changing Pattern of Energy Utilization in the UK

5.1 The Changing Demand for UK Primary Energies 1970-1994

Historical records compiled by the DTI **(1)** shown in **Figure 1** demonstrates the changing market for primary energy over the 1970-1994 period .These primary energies comprise solid fuel , petroleum , natural gas and primary electricity produced by hydro , nuclear and renewable energy.

The overall demand for primary energy has remained relatively stable, increasing marginally by only 7 million tonnes of oil equivalent (3.1 %) over the 1970-1994 period , where as the demand for fossil fuel declined 4.9 %. However the composition of the mix of primary fossil fuel consumed had changed very dramatically as shown on an annual time trend basis as shown in **Figure 1** and **Table 1** for years 1970 and 1994.

TABLE 1

UK Primary Energy Consumption 1970-1994

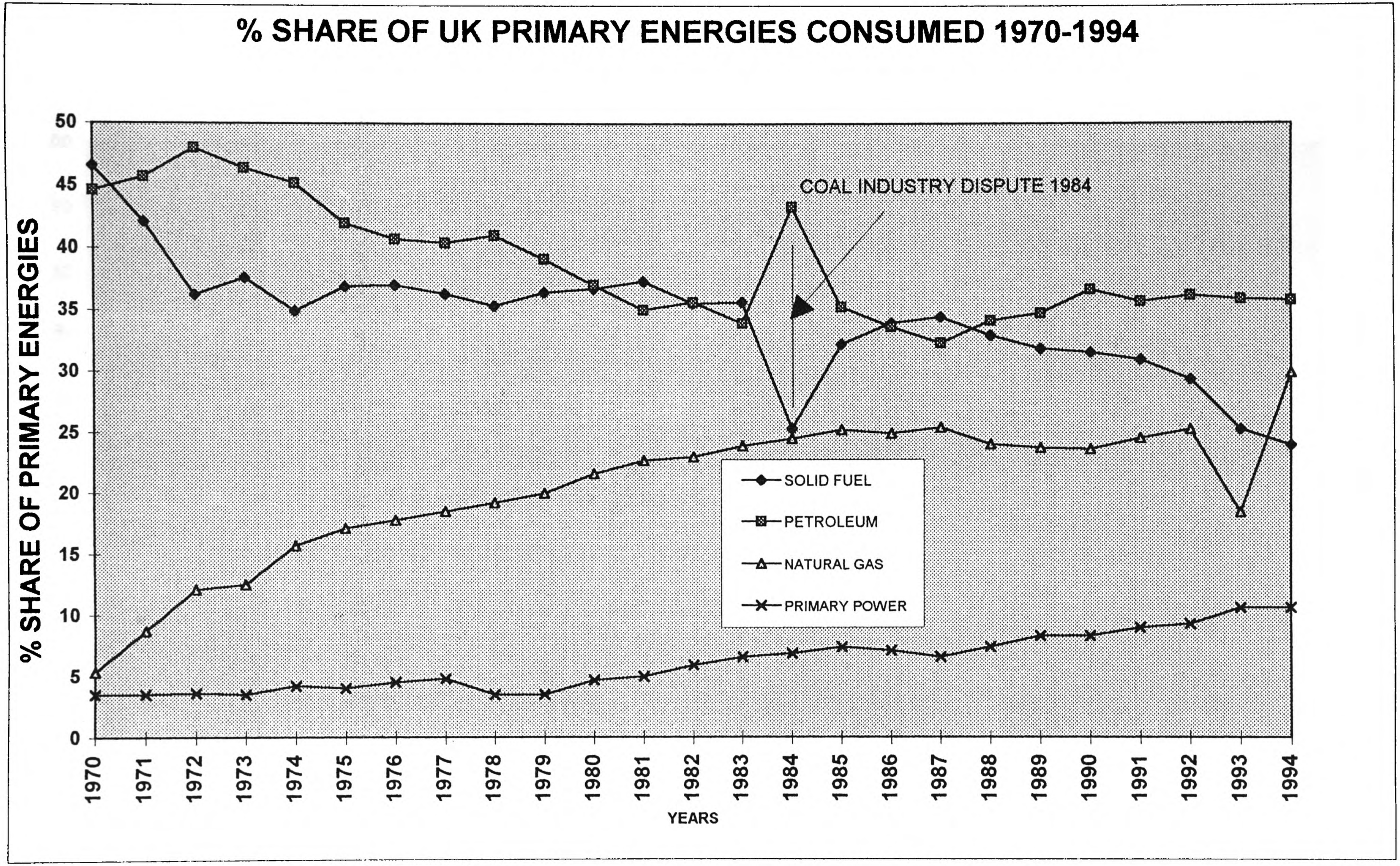
Million Tonnes of Oil Equivalent

	1970	1994	% Change
Solid fuel	98.8	52.2	- 47.1
Petroleum	94.5	77.9	-17 .6
Natural gas	11.2	65.2	+ 481
Primary Electricity	7.4	23.2	+ 211.
Overall	**211.9** (204.5)*	**218.5** (195.3)*	**+ 3.1** (- 4.9)*

(*) fossil fuel

The demand for coal and petroleum have declined whereas the growth for natural gas and primary electricity have increased to fill the primary energy gap The effect of this change in mix on the environment is best shown shown in **Figure 2** , by combining the declining annual energy demand for solid fuel and petroleum which are regarded as the high polluting energies and comparing this with the increasing demand for the low and non- polluting energies natural gas and primary electricity .

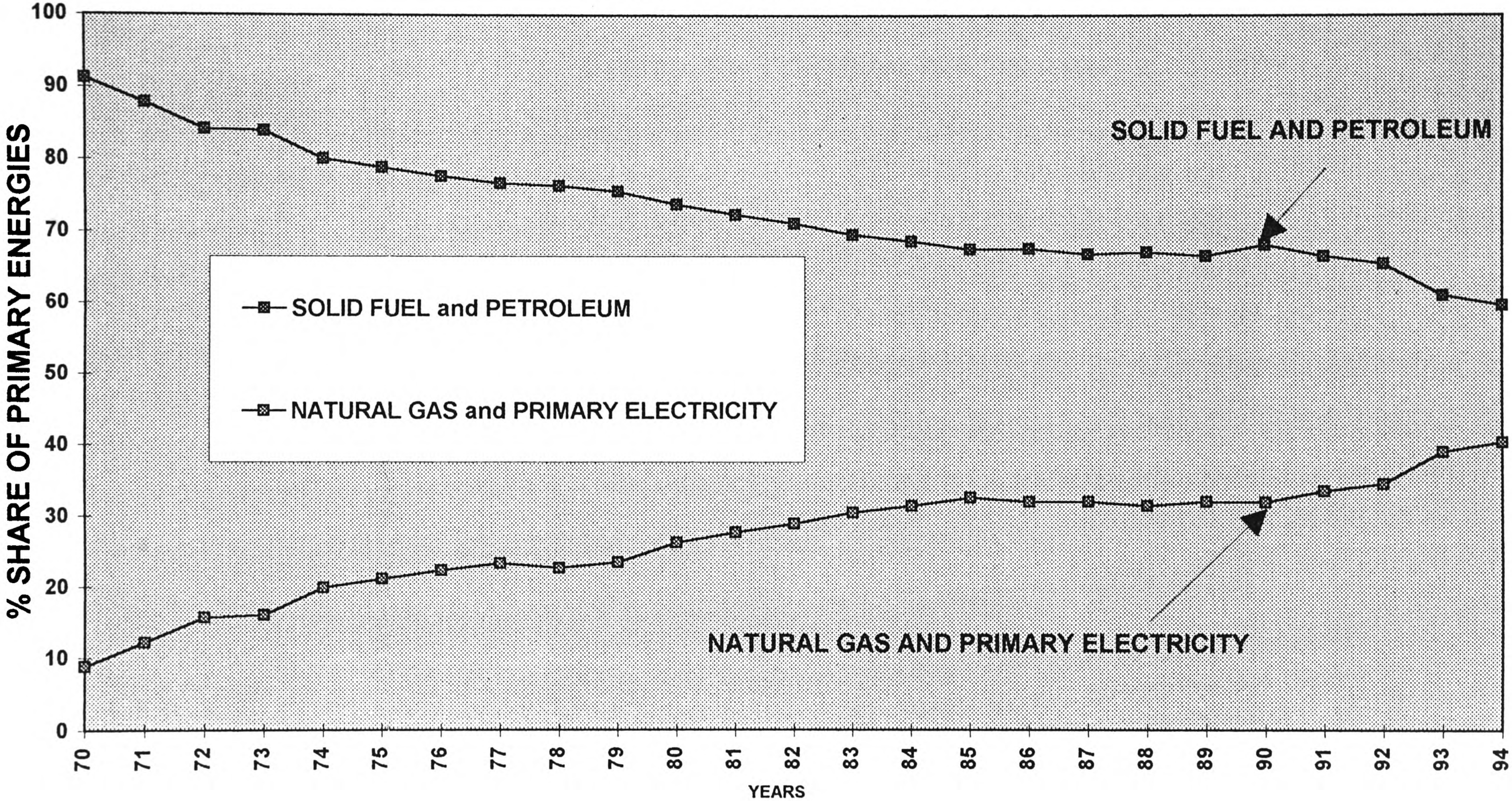
Figure 3 shows the changes in the percentage share of primary energy demand over the three decades and especially natural gas where the percentage share has increased from 5.3 % in 1970 to 21.6 % in 1980 to nearly 30 % in 1994 due largely to the price competitiveness and availability of natural gas in commercial quantities in the 1970's



SOURCE : DIGEST of UK ENERGY STATISTICS

FIGURE 1

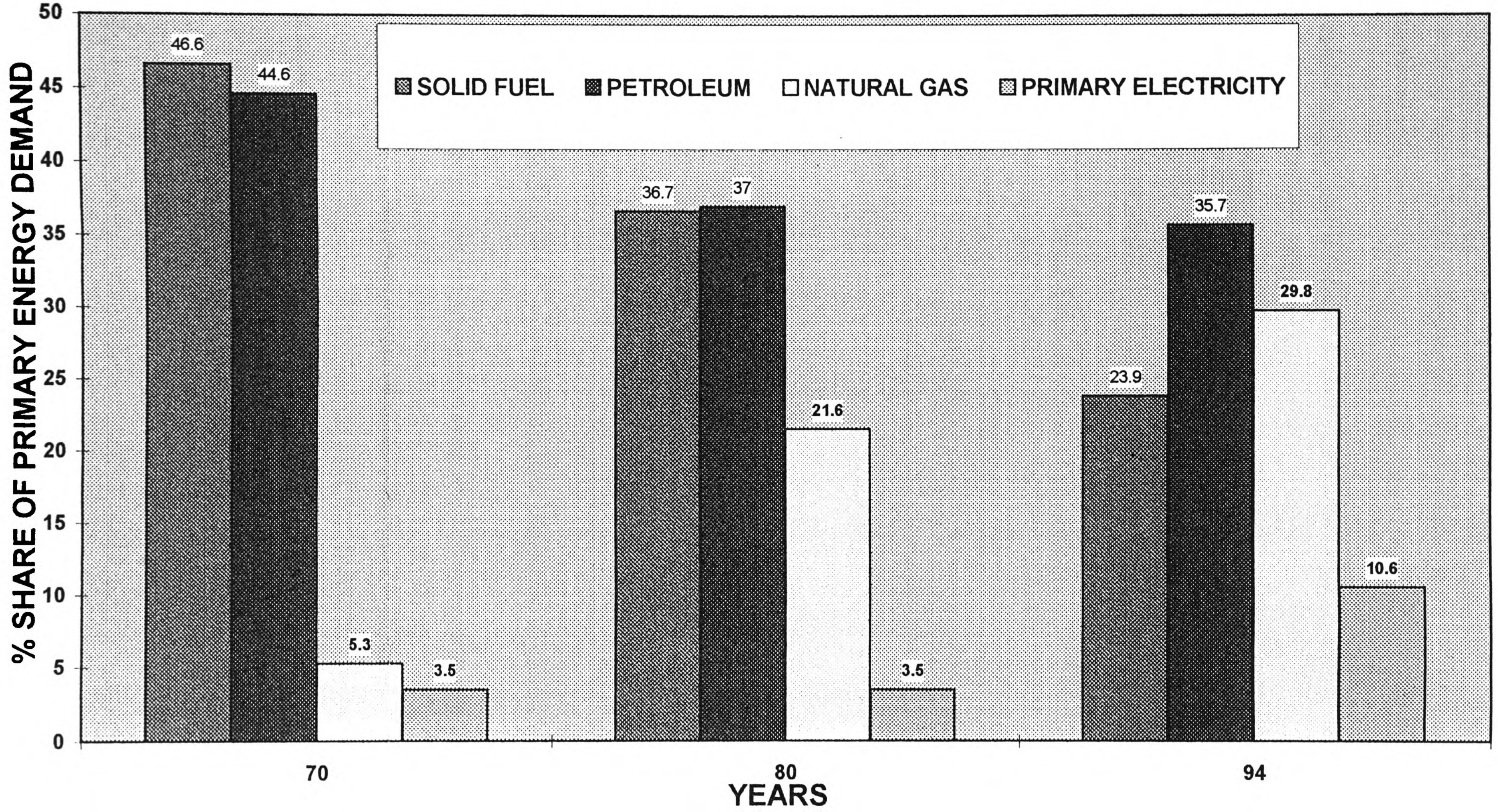
THE DECLINE IN THE TOTAL DEMAND FOR SOLID FUEL and PETROLEUM COMPARED WITH THE INCREASE FOR NATURAL GAS and PRIMARY ELECTRICITY



SOURCE : DIGEST of ENERGY STATISTICS

FIGURE 2

PRIMARY ENERGY MARKET DEMAND OVER THREE DECADES



SOURCE : DIGEST of ENERGY STATISTICS 1975 AND 1996

FIGURE 3

consequently making major inroads in the energy market in the domestic , industrial and power generating sectors .

The progressive increasing annual demand for this clean fossil fuel is clearly demonstrated in **Figure 1** which increased by six fold between 1970 and 1994 . This was accompanied by a significant increase in demand for primary electricity part of which was purchased from the French nuclear industry.
The thesis plans to establish the effect of these changes in energy mix on atmospheric emissions associated with fossil fuel .

5.2 The Changing Pattern of Fossil Fuel Mix and Consumption by the User Sectors

The combustion of fossil fuel is demonstrated in **Chapter 6** to be the major source of atmospheric pollution regarding carbon dioxide , sulphur dioxide oxides of nitrogen and smoke.

This chapter considers the changing pattern of fossil fuel mix and consumption over the 1970-1994 period and the resulting implications for the atmospheric environment.

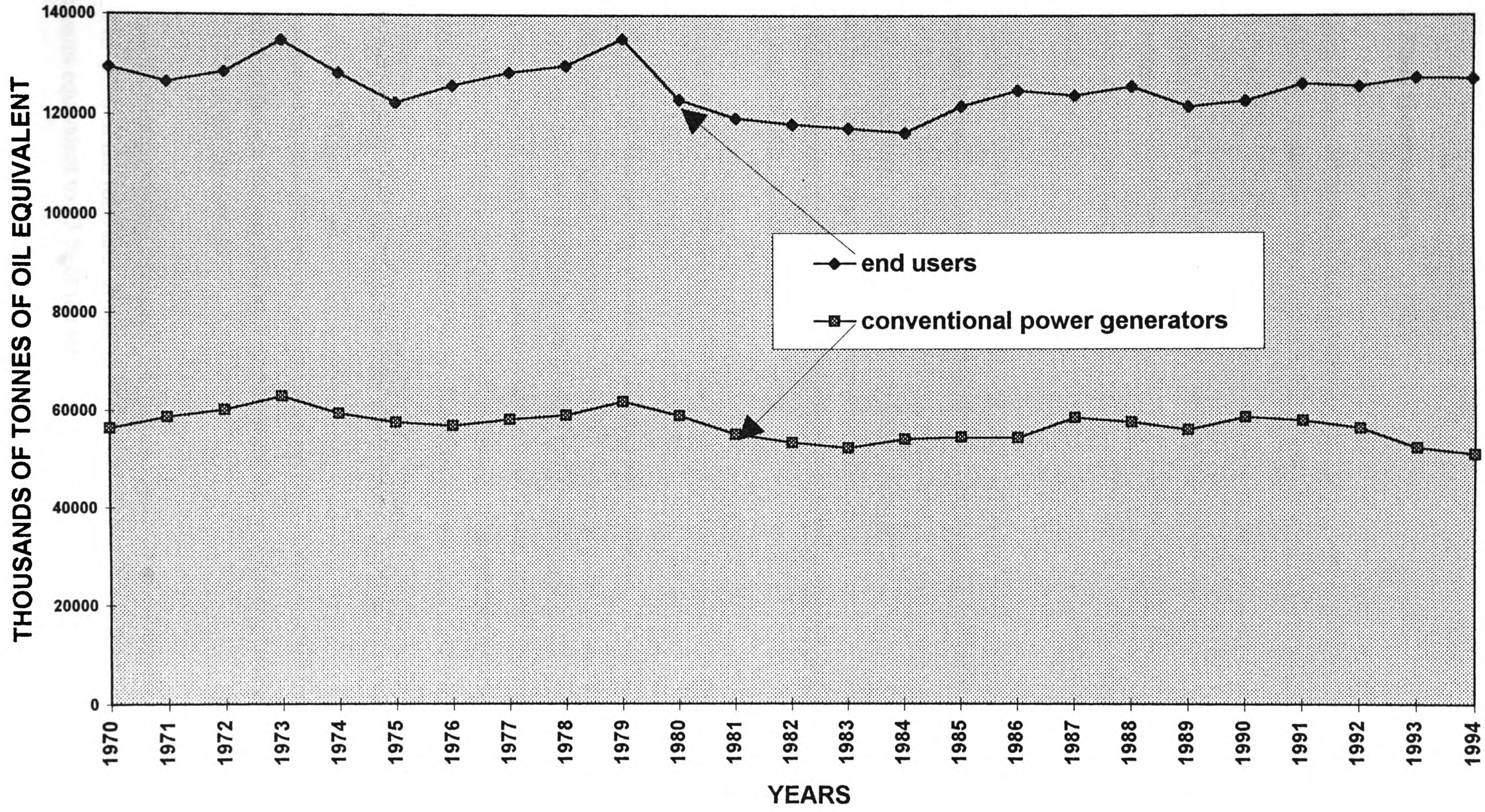
The two major fossil fuel consuming sectors comprise :-

The Final Users Sectors

The Power Generating Sector- which supplies electricity to the final users sector

Figure 4 shows the changing fossil fuel demand pattern in these two sectors over the 1970-1994 period . It can be seen that there has been a slight overall decline in demand for energy in both sectors , but a major changes in the mix of energy in these sectors has taken place which is shown in the thesis to have had significant effects on the overall emissions

FOSSIL FUEL CONSUMPTION BY END USERS AND CONVENTIONAL POWER GENERATORS SECTORS



SOURCE ; DIGEST of ENERGY STATISTICS

FIGURE 4

5.2.1 The Final Users Sectors

The changing pattern of the four final end users with regard to fossil fuel mix are considered below , together with potential implications for environmental emissions from each of the four following sector :-

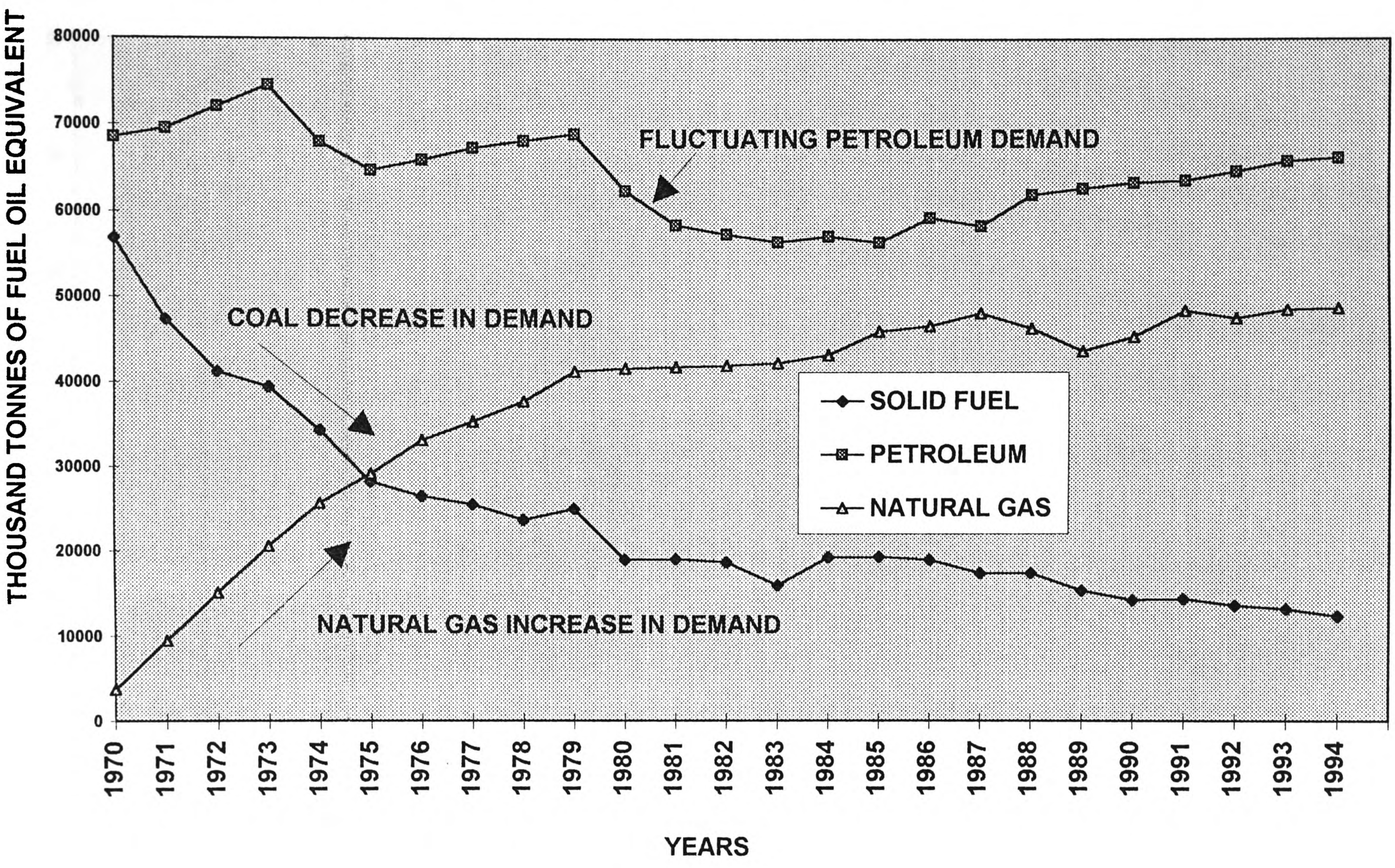
Industrial sector
Transport sector
Domestic sector
Service sector

Figure 5 shows the overall changing mix of the fossil fuel ie solid fuel , petroleum and natural gas demand in these individual end user sectors over the 1970-1994 period. Fossil fuels consumption in the production of electricity by the major power generating stations will be considered separately in this chapter in section 5.2.2.
The overall fossil fuel demand by the end user sectors has fallen slightly by 1.6 % however this fall was not experienced by all the final user sectors which is discussed below and demonstrated in **Figure 6**.

The industrial sector has experienced only marginal fluxuating trends in output over this period , but it has suffered an overall reduction of 44 % in the demand for fossil fuel , whereas in the other sectors the energy demand had increased .In particular the manufacturing sector within the industrial sector had experienced a very significant reduction in the demand for fossil fuel which may be accounted for by the follows changes -: improved energy performance giving rise to reduced specific energy consumption especially in the energy intensive industries , rationalization of the manufacturing industry involving the closure of inefficient plant , and the introduction of new process technology .The decline in the energy demand / manufacturing output ratio defined as energy intensity over the 1970-1990 period and indexed to 100 = 1990 is outlined in **Figure** 7 which clearly shows that the demand for energy declined very sharply by 49 % over this period , while manufacturing output was relatively stable gaining only by 6 % , resulting in a decline in the energy intensity ratio similar to the fall of 44% in energy demand .

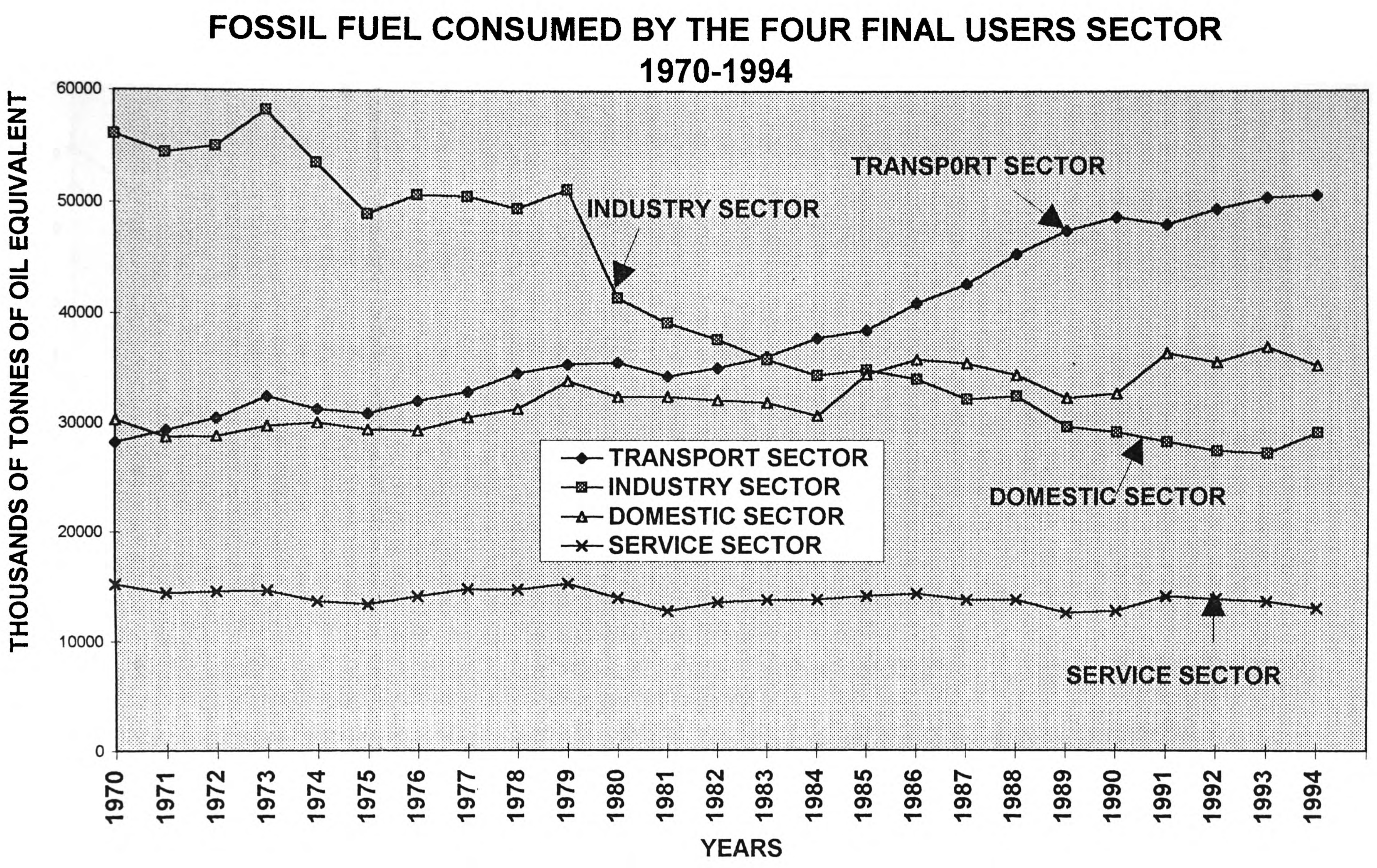
In 1970 manufacturing industry consumed 56 million tonnes of oil equivalent as fossil fuel equal to 43% of the total user energy demand and by 1994 this had fallen to 29 million tonnes equivalent to 23 % of the total user energy demand , an overall

FOSSIL FUEL DEMAND BY THE FINAL USER SECTOR 1970-1994



SOURCE : DIGEST of ENERGY STATISTICS

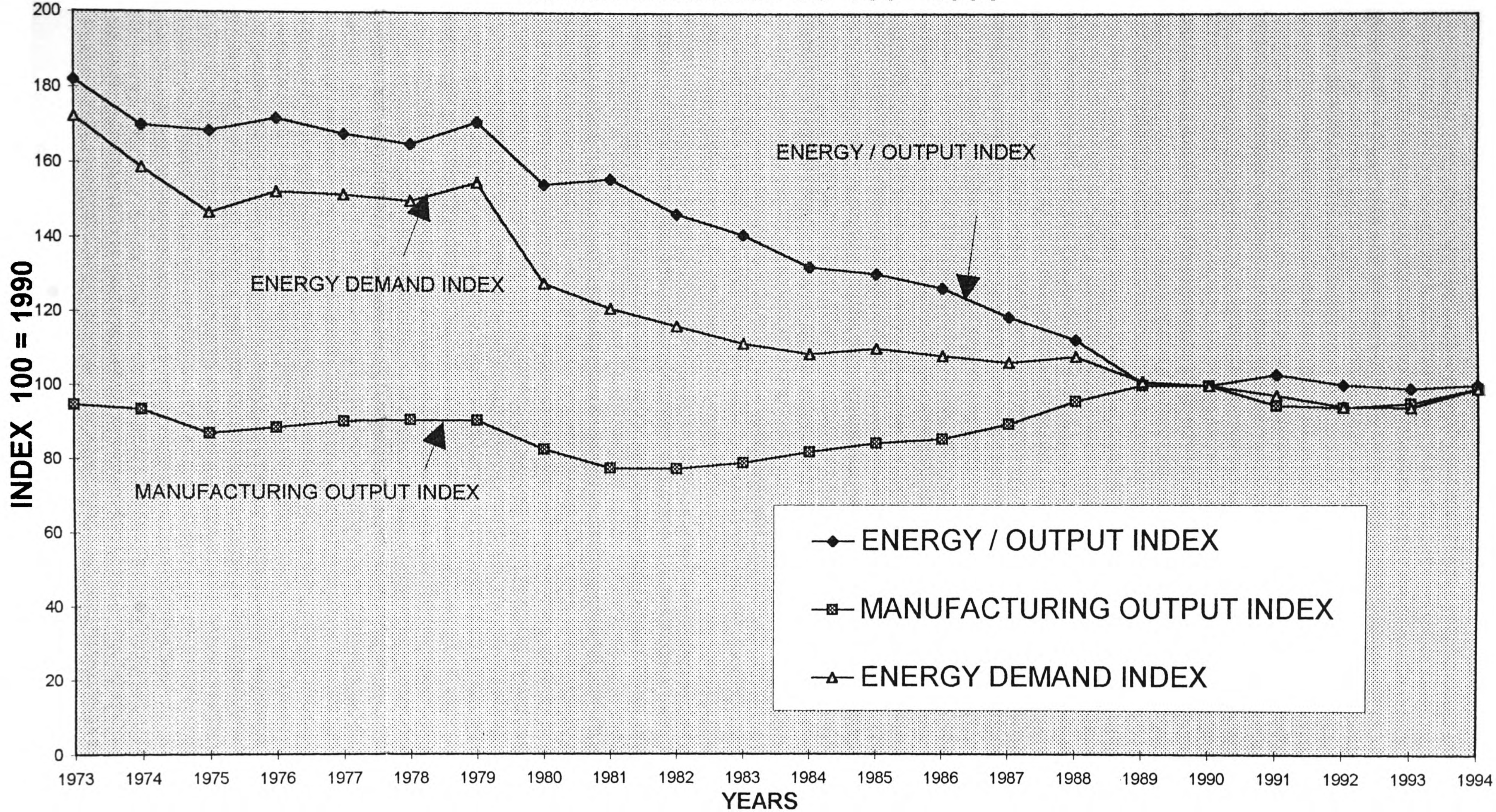
FIGURE 5



SOURCE: DIGEST of ENERGY STATISTICS

FIGURE 6

MANUFACTURING ENERGY DEMAND , OUTPUT AND ENERGY / OUTPUT RATIO INDEXED TO 100 =1990



SOURCE : NATIONAL ACCOUNTS CSO 1995

FIGURE 7

reduction of 20 % and this will be shown to have had major impact on the UK overall generation of atmospheric pollutants.

In contrast the energy consumption for **the transport sector** as shown in **Table 2** escalated by 79 % , mainly due to the expansion of road transport and the increase in petroleum and diesel fuels .This dramatic increase in demand will be shown to have had a major effect on the environment.

The domestic sector decreased its overall energy demand by a modest 16 % , however there was a major switch from coal to smokeless fuel and natural gas again this change in fuel mix as expected has had a significant change in emissions from this sector.

The service sector energy demand remained relatively static over this period .The change in energy mix is similar to the domestic sector i.e replacement of coal with natural gas and electricity.

Table 2 shows the overall change in fossil fuel consumption for the end user sectors. Solid fuel experienced a decline of 30 million toe equivalent to 71% fall over the 24 year period . Petroleum demand was unchanged but there was a change in the mix a switch from fuel oil to road transport fuel . Natural gas demand increased by nearly 300% equivalent to 38% of the total final user demand compared with 10 % in 1970.

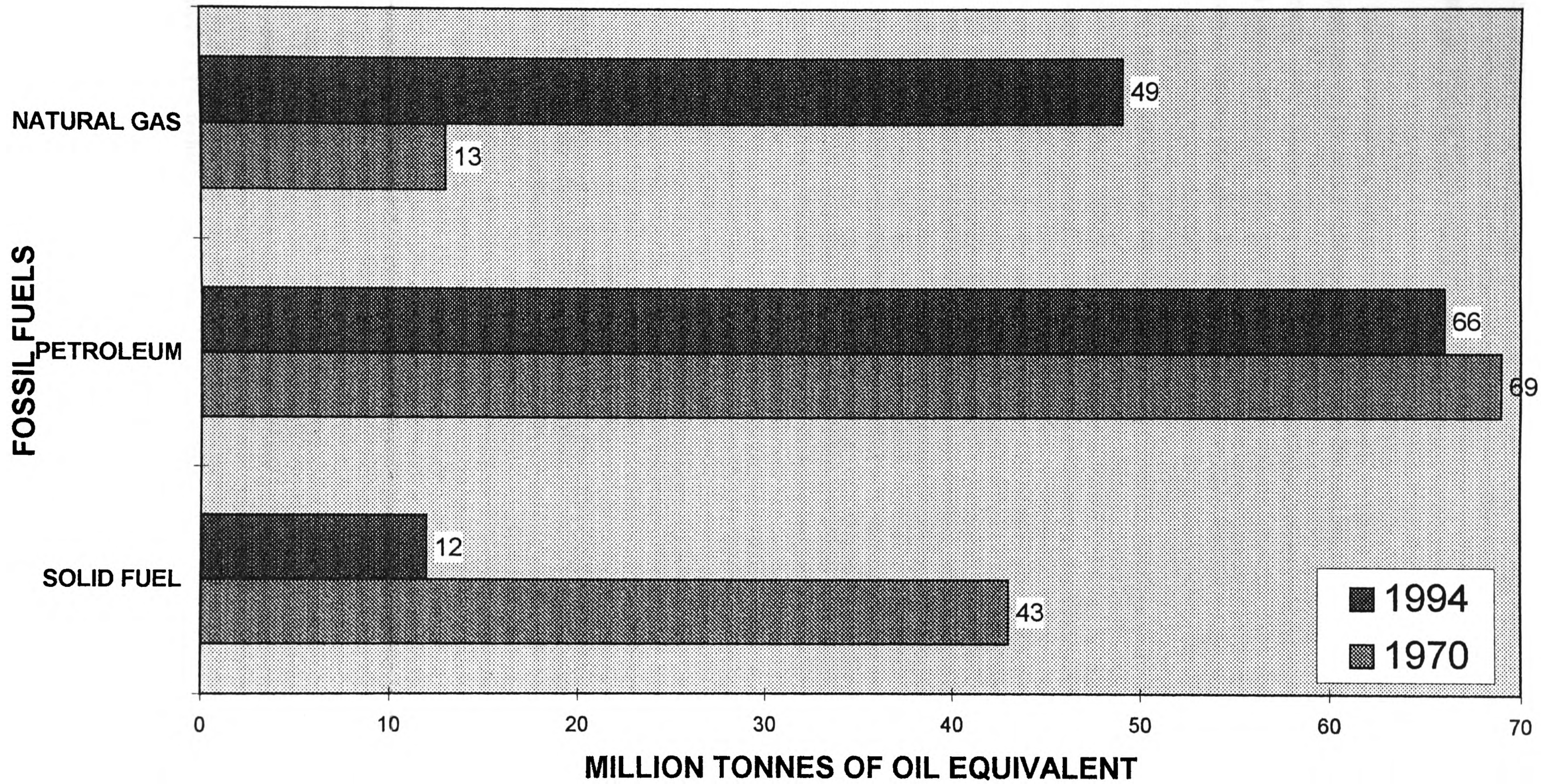
TABLE 2

Changing Trends in Fossil Fuel Demand in the Final Energy Users 1970-1994

Sector	Fossil fuel	% change 1970-1994 (thousand toe)
Industry	Solid fuel	-67 % (-15,809)
	Petroleum	-69 % (-19,470)
	Natural Gas	+585 % (+ 10,470)
	Total	**- 44 % (-24,809)**
Transport		
	Petroleum	+ 80 % (+ 22,273)
	Total	**+ 79% (+22,031)**
Domestic	Coal	- 79% (-14,170)
	Petroleum	-10% (-341)
	Natural Gas	a factor of 19 (+19,443)
	Total	**- 16% (- 4,942)**
Service	Coal	-87 % (-3,690)
	Petroleum	-53% (- 4,741)
	Natural Gas	+319% (+6,130)
	Total	**- 14 % (-2301)**

The major overall change in fossil fuel demand in the final user sector in years 1970 and 1994 can be seen in **Figure 8 .** There has been a dramatic fall in the demand for solid fuel , the market share has declined from 34 % to 10% . Petroleum usage has remained reasonably static , although the demand for fuel oil has weakened , this has been off set by the increased consumption for fuel in the transport sector. In 1970 transport accounted for 40 % of petroleum consumption , by 1994 this has increased to 75% .Natural gas has made major strides in the user sector and increased its share from a mere 10 % in 1970 to over 38% in 1994 equating to 49 million tonnes of oil equivalent .

SOLID FUEL , PETROLEUM , and NATURAL GAS CONSUMPTION BY THE FINAL USER SECTORS 1970 and 1994



SOURCE : DIGEST of ENERGY STATISTICS

FIGURE 8

5.2.2 The Major Power Generating Sector

The overall annual changing pattern of the total fossil fuel demand over the1970-1994 in the conventional major power generating industry shown in **Figure 9** . During the 1970's and early 1980's there was a clear pattern emerging regarding the replacement of solid fuel with petroleum . The coal industry dispute distorts the picture in the mid 1980's , however during the 1991/1994 period there was the fall off in usage of both coal and petroleum whereas the natural gas share of the market increased very dramatically by a factor of nearly 10 from 1.0 to 9.9 million tonnes of oil equivalent .**Figure 10** shows even more clearly the major advance that natural gas has made in this sector over the 25 year period and the demise of petroleum and to a lesser extent coal .

Power generated from nuclear stations had increased significantly which reduced the demand for electricity from fossil fired power stations . Nuclear power generation in 1994 was equivalent to the consumption of over 21 million tonnes of oil equivalent , and natural gas consumption was equivalent to 9.9 million tonnes of oil equivalent This overall change in strategy is shown to significantly reduce the level of atmospheric emissions .

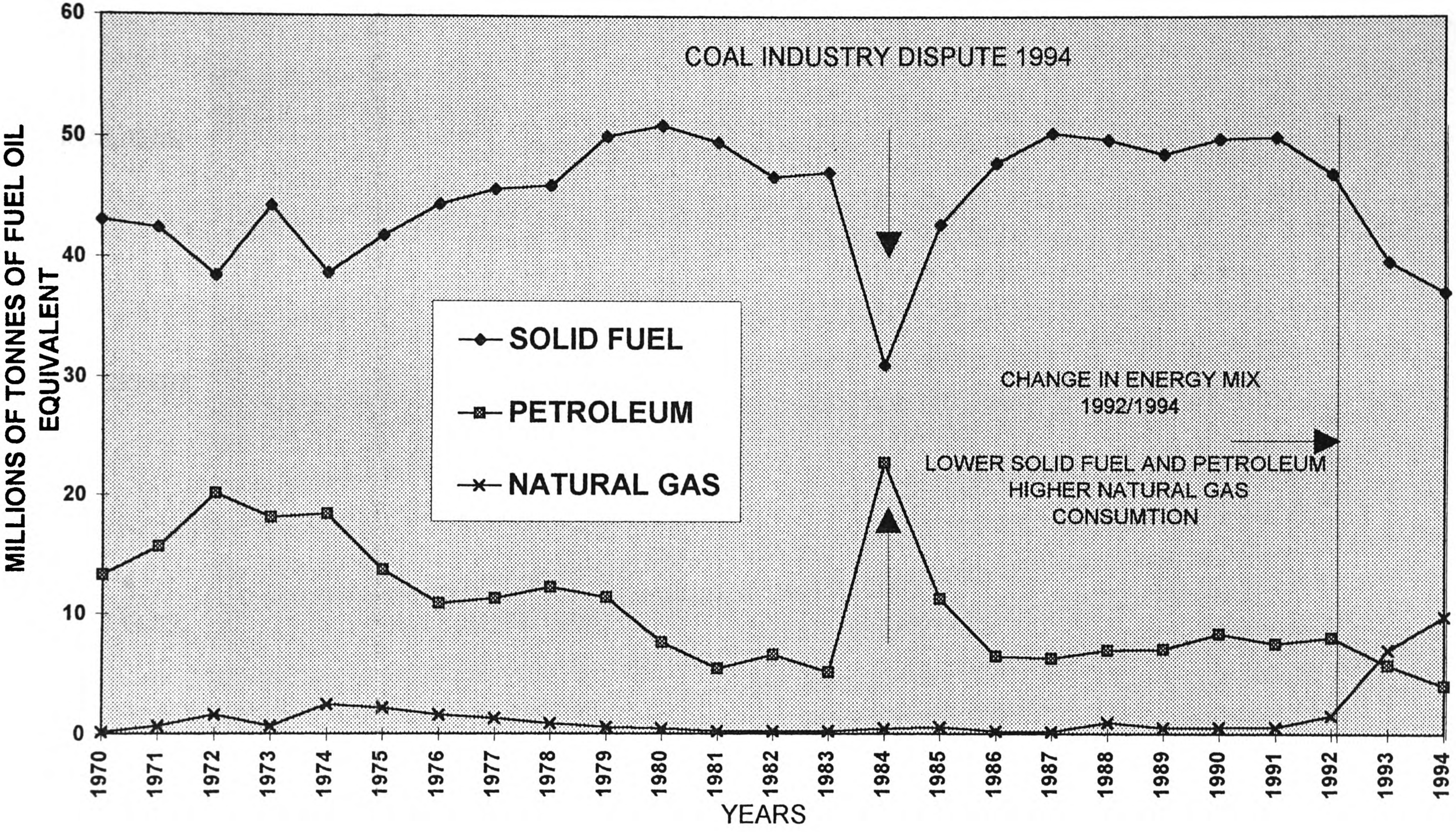
TABLE 3

The Changing Trend of Fossil Fuel Consumption in the Conventional Power Generating Sector 1970-1994

Fuel	% change 1970-1994 (thousands toe)
Coal	-13 % (- 5,960)
Petroleum	-70% (- 9,720)
Natural Gas	890 % (+ 9,740)

Table 3 shows a 13% reduction in demand for coal , and a 70% decline in demand for petroleum in the form of heavy fuel oil . This deficit in fuel is replaced by natural gas principally on combined cycle gas turbines which are up to more than 15% more thermally efficient than conventional coal fired steam boiler.

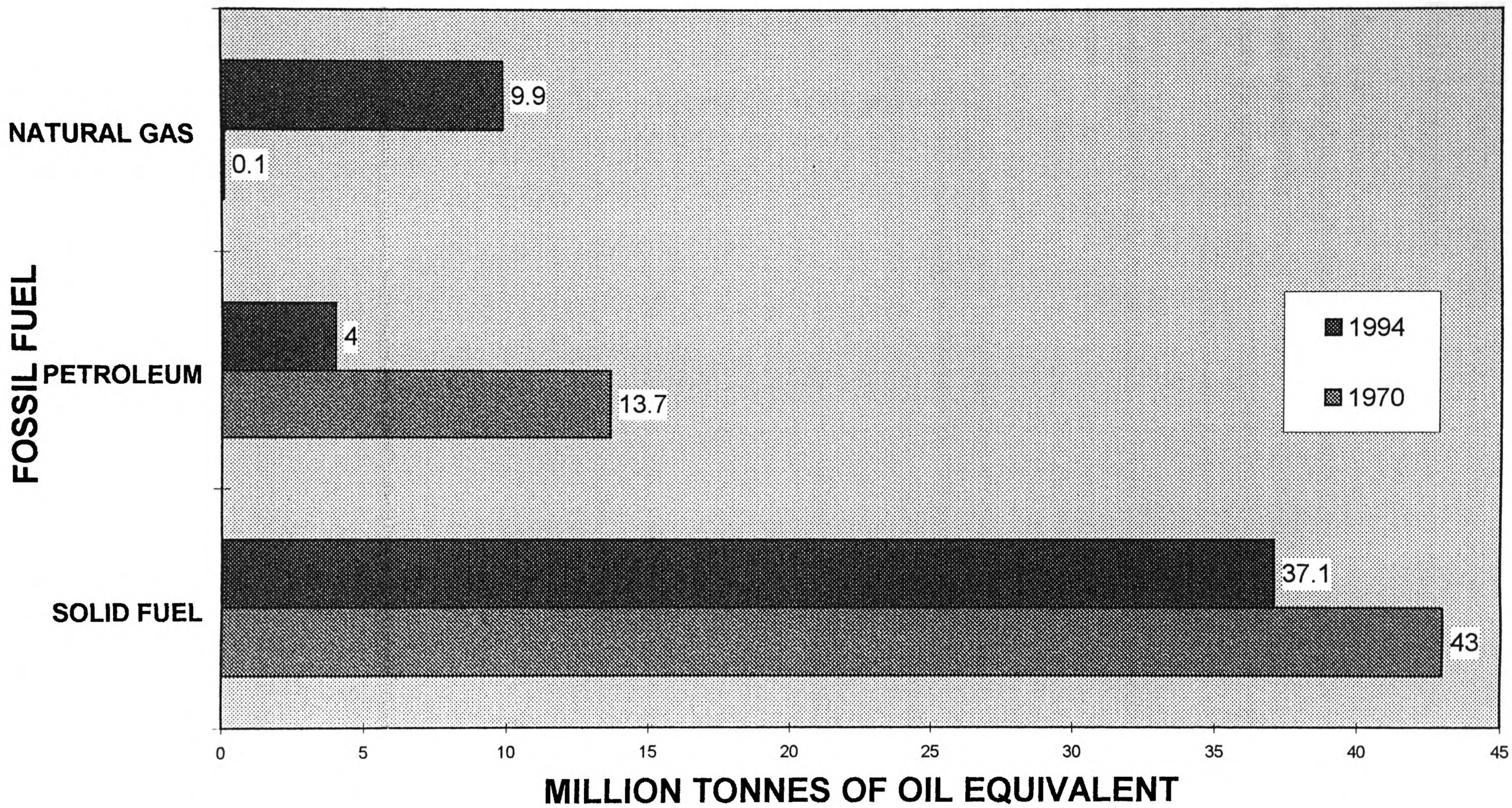
FOSSIL FUEL DEMAND BY THE MAJOR POWER GENERATING SECTOR 1970-1994



SOURCE : DIGEST of ENERGY STATISTICS

FIGURE 9

SOLID FUEL , PETROLEUM , AND NATURAL GAS CONSUMPTION BY THE POWER GENERATING SECTOR IN 1970 and 1994



SOURCE : DIGEST of ENERGY STATISTICS

FIGURE 10

In conclusion it can be seen that :-

1.0 In the final user sector natural gas has made major inroads into the domestic, industrial , and service sectors at the expense of solid fuel and petroleum which will be shown to result in a significant impact on the level of atmospheric emissions .By 1994 the market share for natural gas in these sectors represented 38% of the total fossil fuel consumed .

2.0 In the power sector fuel oil has been largely replaced by natural gas , which by 1994 accounted for 19 % of the total fossil fuel consumed in that sector .
Nuclear energy also increased its share of the energy market over the 1970-1994 period and by 1994 its usage equated to 29% of the total fuel consumed in this sector. Both these factors will be seen to have had a profound effect on reducting on emissions over this period , especially sulphur dioxide and oxides of nitrogen .

6.0 The Contribution of Fossil Fuels to Atmospheric Pollution

The importance of fossil fuels in the the generation of air pollutants during 1970 and 1994 can be seen in **Table 4** .This data clearly demonstrates the overwhelming dominance of the energy sector as the major source of atmospheric pollution which accounts for 99 % of sulphur dioxide , 97 % of carbon dioxide , 94 / 95 % of nitrogen dioxide and 90 / 91 % of black smoke generated .The table also shows the percentage contribution of the three fossil fuels , solid fuel , oil products and gas to the overall emission from the energy sector , natural gas clearly imposes the lowest impact to the environment of the three primary energies and in addition only gives rise to carbon dioxide and oxides of nitrogen .In contrast the combustion of solid fuel and oil products generate all four pollutants.

TABLE 4

The Contribution of Fossil Fuel Emissions to the Atmosphere 1970 and 1994

Pollutant	Fossil fuel emissions as a percentage of total man - made emissions		Contribution of different fossil fuels as a percentage of total fossil fuel emissions		
	1970	1994		1970	1994
Carbon dioxide	97%	97%	solid fuels	36%	34%
			oil products	37 %	37%
			gas	24%	26%
Sulphur dioxide	99%	99%	solid fuels	74%	74%
			oil products	25%	25%
Black smoke	91%	90%	solid fuel	35%	28%
			oil products	56%	62%
Oxides of nitrogen	95%	94%	solid fuels	25%	24%
			oil products	62%	64%
			gas	7%	6%

Table (5) outlines the estimated total mass emission in tonnes per year of the major atmospheric pollutants based on DTI Energy Statistical data on fuel consumption **(1)** in all sectors and vehicle distance travel **(7)** in the transport sector and emission factors employed in the AEA Atmospheric Emissions Inventory **(2)** . It demonstrates the changing pattern for years 1970 and 1994 and shows that carbon dioxide , sulphur dioxide and black smoke have reduced quite significantly over these years whereas nitrogen oxides have decreased marginally . However the total fossil fuel demand has been shown to decrease by only 4.9 % over the same period in **Table 1** , but the mix of fuel had changed very considerable which is shown to have a major bearing on the change in the annual mass emission of pollutants.

TABLE (5)

The Annual Mass Emission Of Pollutants Arising from Fossil Fuels in 1970 and 1994

Pollutant	M Tonnes 1970	M Tonnes 1994	% Change
Carbon dioxide (carbon)	177.60	144.0	- 19.0 %
Sulphur dioxide	6.39	2.7	- 57.8 %
Oxides of nitrogen (NO_2)	2.22	2.08	- 6.0 %
Black smoke	0.97	0.38	- 60.1 %

This chapter outlines the general background relating to the important part played by fossil fuels in the total discharge of emissions to the atmosphere , the changing pattern of total primary energy and of fossil fuel consumed by the five consuming sectors and the overall decline in the emissions from fossil fuel .

Chapter 7.0 Technical Data used to Estimate Atmospheric Emission Factors

The U.K. consumes four primary energies coal , petroleum , natural gas in gaseous or liquid form and electricity from nuclear and hydro sources . It has already been shown that the combustion of the three fossil fuels :- coal , petroleum and natural gas can give rise to a very major proportion of atmospheric emissions in the UK . **Table 4** has already demonstrated the very significant role that combustion of energy plays in the overall environmental scene with regard to sulphur dioxide carbon dioxide nitrogen oxides and black smoke emissions .

This chapter defines the physical properties of the fossil fuels consumed in the UK which are used to establish the emission factors for all pollutants arising from the three fossil fuels in terms of grams of pollutants per Gj of fuel heat content , or per unit of fuel weight consumed or km traveled .

mass emission	= emission factor	* consumption parameter
tonnes / year	grams / Gj	Gj of energy
	grams / kg	kg of energy by weight
	grams / km	km travelled

The three forms of emission factors are used in this thesis to establish past and future mass emissions of each pollutant .

This chapter describes the type of fossil fuels used in the UK and lists the technical data required to establish the emission factors for each of the pollutants generated by the combustion of the different types and grades of solid fuel , petroleum and natural gas .

7.1 Solid Fuel Technical Data

Solid Fuel types are broadly classified as anthracite (low volatile , high carbon) , semi / sub bituminous (medium volatile steam coals) , and bituminous (medium to high volatile medium carbon) and classification is based on :-

1 Heating Value (CV) Gj tonne

2 The composition by weight of fixed carbon , hydrogen , nitrogen , volatile matter , ash , sulphur and moisture.

Examples of typical properties of a range of coals used in the UK range from anthracite to general purpose coals are shown in **Table 6 (9 and 10)**

TABLE 6

The Properties of Solid Fuels used to Estimate Emission Factors

	constituents by weight and fuel properties				
Classification	carbon	nitrogen	sulphur	CV gross Gj /tonne	% volatile content
Anthracite	78.2	0.9	1.0	29.66	6.1 / 9.0
Sub bituminous					
Dry steam	77.2	1.2	1.0	30.59	9.1 / 13.5
Coking steam	77.1	1.2	1.2	30.70	13.5 / 19.5
Bituminous					
Medium volatile coking	75.8	1.3	1.2	30.82	19.6 / 32
Very strongly coking	71.6	1.6	1.7	29.19	32 / 36
General purpose					
Weakly coking	65.7	1.4	1.7	26.7	32 / 36

The major atmospheric pollutants generated by coal combustion comprise particulates, sulphur dioxide , carbon dioxide and nitrogen oxides , some unburned combustibles in the form of black smoke including carbon monoxide in small amounts.

It can be seen that the sulphur and nitrogen content increases as the volatile content increases and carbon content decreases.

7.2 Petroleum Fuel Technical Data

Fuel Oils are broadly classified into two major types distillates - light distillate, kerosene and gas oil and secondly residual oil - light , medium and heavy fuel oil and classification is based on :-

1 Heating Value (CV) Gj / tonne

2 The composition ; weight of fixed carbon , hydrogen and sulphur . Distillates are more volatile and have negligible ash and nitrogen content compared with residual oils. The properties of the fuel oils are shown in Table 7 (**9 and10**)

TABLE 7

The Properties of Petroleum used to Estimate Emission Factors

Fuel	constituents by percentage weight			
	carbon	sulphur	nitrogen and ash	CV gross Gj / tonne
Distillates				
Petrol	86.3	0.07	trace	44.8
Light distillate	84.1	0.05	trace	47.8
Kerosene	85.8	< 0.1	trace	46.5
Diesel road fuel	86.5	0.20	trace	45.7
Gas oil	86.1	<0.40	trace	45.6
Residuals				
Light fuel oil	85.6	2.5	0.2	43.5
Medium fuel oil	85.6	2.6	0.3	43.1
Heavy fuel oil	85.4	2.8	0.4	42.9

The prime atmospheric pollutants arising from petroleum products comprise the four pollutants researched in this thesis ; carbon dioxide , sulphur dioxide , nitrogen oxides , and particulate /smoke emissions. The residual fuels used primarily by industry and the power generating sector can be seen to contain high sulphur levels , whereas the road transport fuels and gas oils contain significantly lower levels .The consequences of the decline in the consumption of high sulphur petroleum in these industries and the marked increase in demand for low sulphur bearing fuel used in the transport sector .

7.3 Natural Gas Technical Data

The prime component of natural gas is methane , although varying amounts of ethane propane butane and carbon dioxide are also present as demonstrated in **Table 8** (9 and 10). The actual properties of the gas are very dependent on its source i.e. North sea gas has a high methane content and low nitrogen whereas the gas from the Groningen fields is the reverse .The major pollutants arising from natural gas from all sources are oxides of nitrogen , and carbon dioxide .

The properties of the gas are classified as follows :-

1 Heat Value (CV) Gj / m^3

2 Methane, ethane , propane , butane and carbon dioxide content
The properties of natural gas are outlined below:

TABLE 8

The Properties of Natural Gas used to Estimates Emission Factors

Gas	constituents by percentage volume						CV	
	CO_2	N_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	Gj / $m^3 10^3$ gross	Gj / kg
UK North sea	0.26	0.75	95.06	3.78	0.14	0.01	38.00	50.70
Groningen (Holland)	0.9	14.0	81.8	2.7	0.4	0.1	33.28	40.50

8 Estimation of Emission Factors for CO_2 and SO_2

To evaluate the influence of this changing energy scene on atmospheric emissions emission factors have been established by calculation using the technical data outlined in **chapter 7** and from government research establishments which derive emission factors on an empirical basis when the factors cannot be be based simply on mass balance calculation.
This chapter establishes by direct calculation in the case of CO_2 and $SO_2$and from empirical data derived mainly from government research establishments and industry in the case of NO_x and Black Smoke emission factors for each of the three fossil fuels.
In the future emission factors will need to be established for 'orimulsion' should the HMIP authorize this bitumen type fuel for use on Power Generating Plant .

The calculated SO_2 and CO_2 emission factors are based on a knowledge of the heat value , the carbon and sulphur content of the fuel and also the carbon and sulphur content remaining in the by- product and ash in the case of solid fuels . The accuracy of the emission factor estimates are largely determined by the precise knowledge of the calorific value and the fuel composition data .

With regard to NO_x the emission factor estimation is somewhat more complicated than for CO_2 and SO_2 since the gas is produced from two sources during the combustion process and the extent of the emission is greatly influenced by such factors as the percentage excess air , combustion temperatue , and the design of the combustion system .

Smoke emissions comprise solid carbon and liquid hydrocarbon particles which arise mainly from the inefficient combustion of fuel . The mass emission of smoke will vary from installation to installation depending on the combustion efficiency , and hence the emission factors must be based on actual measurement as opposed to a theoretically based calculation value .In common with NO_x the smoke emission factors used in this thesis are also be based on measured figures established by government research departments and industry .

8.1 Carbon Dioxide Emission Factors

8.1.1 Solid fuels - CO_2 emission Factors

The emission factors outlined in **Table 9 (9 and 10)** for carbon dioxide in gram of gas per Gj of solid fuel and kg / kg of solid fuel are based on the product of the carbon content in the coal , the CV of the fuel and the molecular weights of carbon and carbon dioxide The emission factors are calculated for the full range of coals used in the UK from anthracite , a high carbon low volatile coal to the bituminous / general purpose a low carbon high volatile coal

TABLE 9

Estimated Carbon Dioxide Emission Factors as Carbon for Solid Fuels

Coal type	Emission in grams / Gj of coal	Emissions in kg / kg of coal
Anthracite	26,390	0.782
Sub Bituminous		
Dry steam	25,320	0.772
Coking steam	25,140	0.771
Bituminous		
Medium volatile coking	24,600	0.748
Very strong coking	24,250	0.716
General purpose		
Weakly coking	24,580	0.657

The calculated emission factors outlined in the above table compare very favorably with published emission factors in the annual AEA environmental inventory (2) and are therefore used in this thesis to establish annual mass emissions of carbon dioxide .

8.1.2 Petroleum Fuel - CO_2 Emissions Factors

The emission factor for carbon dioxide in grams per Gj of liquid fuel and kgs / kg of liquid fuel is calculated on the same basis as that for solid fuel . i.e. the carbon content and CV of the fuel . Calculations of CO_2 emissions factors are based on the major range of petroleum products used within the U K from the light distillate to the heavy fuel oils .

TABLE 10

Estimated Carbon Dioxide Emission Factors(as Carbon) for Petroleum Fuels

Type of fuel	emissions in grams / Gj of liquid fuel	emissions in kg / kg of liquid
Distillates		
Light distillate	17.620	0.841
Kerosene	18,470	0.858
Gas oil	18,890	0.865
Petrol	19,270	0.865
Diesel engine road vehicle fuel	18,940	0.861
Residuals		
Light fuel oil	19,690	0.856
Medium fuel oil	19,870	0.856
Heavy fuel oil	19,920	0.854

8.1.3 Natural gas - CO_2 Emissions Factors

The carbon dioxide generated by the combustion of natural gas is calculated on the same basic data as the previous two fossil fuels

TABLE 11

Estimated Carbon Dioxide Emission Factors (as Carbon) for Natural Gas

	emission in gram / Gj of natural gas	emissions in kg / m^3 of natural gas
North sea gas	14,030	52.8 (1.4 kg / kg at NTP)

It can be clearly seen in the following table that when comparing the carbon dioxide emissions factor for the three fossil fuels in gram / Gj of fuel that the natural gas value is half of that for solid fuel and 75% of that for petroleum .

TABLE 12

8.1. 4 Comparison of CO_2 Emissions Factors from Fossil Fuels

FUEL	range of emissions factors in grams / Gj	ratio compared with natural gas
Natural gas	14,030	1.0
Liquid fuel	17,600- 19,920	1.26 - 1.42
Solid fuel	24,500 - 28,670	1.75 - 2.04

8 . 2 Sulphur Dioxide Emissions Factors

The calculated theoretical SO_2 emissions in grams of SO_2 / kg for each of the fuel typies outlined in the following table are based on the fuel consumption , heat content and on an assumed percentage retention of sulphur in coal ash , estimated to be 20 % in the domestic sector and 10 % in the industrial and commercial sectors.

8.2.1 Solid Fuel - SO_2 Emission factors

TABLE 13

Estimated Sulphur Dioxide Emission Factors for Solid Fuels

	sulphur content %	gram of SO_2/ Gj of coal	gram of SO_2 / kg of coal
Anthracite	1.0	674	20
Sub bituminous			
Dry steam	1.0	640	20
Coking steam	1.0	656	24
Bituminous			
Medium volatile coking	1.2	784	24
Very strong coking	1.7	1,152	34
General purpose			
Weakly coking	1.7	1,264	34
Non - coking	1.7	1,424	34

8.2.2 Petroleum Fuel - SO_2 Emissions Factors

TABLE 14

Estimated Sulphur Dioxide Emission Factors for Petroleum Fuels

	sulphur content %	grams of SO_2 / Gj of liquid fuel	grams of SO_2 / kg of liquid
Distillates			
Petrol	0.07	20	1.4
Light distillate	< 0.05	2	< 1.0
Kerosene	0.1	43	2.0
Gas oil	< 0.4	178	< 8.0
Residuals			
Light fuel oil	2.5	1,149	50
Medium fuel oil	2.6	1,206	52
Heavy fuel oil	2.8	1,305	56
Diesel			
Diesel engine road vehicle fuel	0.2	100	0.4

8.2.3 Natural Gas - SO_2 Emissions Factor

Natural gas consumed in the UK contains a very low sulphur content and in this analysis is regarded as having an emission factor of zero.

In conclusion it can be seen from the **Tables13 and 14** that the emission factors for coal are spread over a wide band 640 to 1424 grams / Gj corresponding to 1.0 to 1.7 % sulphur content , whereas the range of emission factors for fuel oils are much narrower at1149 to 1305 grams / Gj with sulphur contents of 2.5 to 2.8 % . The petroleum distillates are at the lower end of the emission factor spectrum of 2 to 178 grams / Gj with sulphur contents ranging from 0.05 to 0.40 %.

9.0 Empirically Based Estimations of NOx and Black Smoke Emission Factors.

9.1 NOx Emissions Factors

The formation of NO_x is much more complicated than that of CO_2 and SO_2 since during the combustion process NO_x is generated from two sources and hence the emission levels must be derived from empirical data and not by a simple mass balance using the composition of the fossil fuel .The two forms of oxides of nitrogen are classified as ' thermal NO_x 'and ' fuel derived ' .

Thermal NO_x is produced by the combustion of any fuel in air . The amount formed is dependent on fuel type , the fuel / air ratio and flame temperature .
The reactions which have been suggested **(11)** as the most significant contributors to NO formation in the combustion of nitrogen - free fuel in air are shown below

$$O + N_2 = NO + N$$
$$N + O_2 = O + NO$$

Fuel derived NO_x is defined as the production of NO from chemically bonded nitrogen contained with the fuel and its generation is dependent on the fuel nitrogen present .
An assessment of NO_x emission factors is considered separately for three sectors, road transport sector , industry and power sectors and the domestic sector since the research work on the emissions for these sectors was undertaken by different research organizations

9.1.1 Road Transport Sector Emissions Factors

The road transport sector in 1994 accounted for over 50 % of the total UK NO_x generated , compared with only 28 % in 1970. Most of this rise in the transport sector is due to the increase in petrol and diesel driven passenger vehicles.
A survey was undertaken to identify the research work that had been undertaken to establish by empirical means NO_x emission factors for this sector . Two sources were identified as -:
1.0 The Warren Spring Laboratory (WSL) at Stevenage **(12).**
2.0 The Department of Transport **(13).**

The NO_x emission factors established at WSL **(12)** for petrol and diesel road transport driven vehicles were based on empirical data derived from in - service measurements of vehicle emissions . These monitored vehicle exhaust emission factors outlined in **Tables15** and **16 (12)** were evaluated in the form of grams of pollutant / km and are based on speed - related factors and information relating to road usage and speed distributions in the UK and used in this thesis . The road users in this study were classified under four categories of types of roads and average values for three engine capacities .The mean speed , vehicle kilometers driven in each road class , proportion of petrol engines to DERV engined vehicles , engine size distribution , and vehicle age were all factors taken into account in establishing these overall NO_x emission factors .

TABLE 15

Measured Average NO_x Emission Factors during 1981-1985
For three sizes of passenger petrol- engined vehicles
1.4 , 1.4 -2.0 , and < 2.0 litres

Road type	**Mean Speed**	**NO_x Emission Factors**	**Road type**
	km p h	grams/ km	%
Urban	40	1.82	50
Rural single carriage	75	2.05	36
Rural dual carriage	95	2.42	4
Motorway	115	3.21	10

This table clearly shows that the emission factor value increases with increase in speed of vehicle and that the highest factor is produced on the motorways at a mean speed of 115 km per hour . The average weighted emission factor for petrol driven passenger cars has been calculated to be 2.01 grams / km.

TABLE 16

Measured NO_x Emission Factors for Diesel Engined Vehicles in grams / km

Vehicle type	Derv cars	Small HGV	Large HGV	Buses
Road type				
Urban	0.70	12.60	16.95	14.40
Rural single carriage	0.55	16.05	20.04	18.72
Rural dual carriage	0.55	16.50	20.04	18.72
Motorway	1.00	16.50	20.04	18.72

Tables 15 and **16** shows that the average NO_X emissions arising from petrol driven cars are higher than those for diesel driven cars and that petrol car emissions are significantly lower than the heavier diesel vehicles .
Despite the very high emission factors that apply to the diesel driven buses and heavy vehicles the road mileage undertaken by these vehicles is relatively low compared with passenger cars .

More recent work by Glover et al in 1994 **(13)** studied and analyzed energy and the emission effects of a switch to diesel fuel to establish emission factors for petrol and diesel fuel from 'real world measurements and traffic statistics '.
The emission factors derived from vehicle exhaust measurements agree well with the WSL **(12)** findings and these factors are used in this thesis to establish , compile and compare past annual mass emission values and to predict future emissions levels. Glover's work provides very useful data which demonstrates the success of the 1990's Environmental Legislation regarding the environmental advantages of the installation of the Three-Way Catalyst to reduce NO_X emission levels from petrol vehicle .The work clearly shows that there is a dramatic reduction in emission factors in grams / kilometer of between 63 % for small petrol cars on Urban roads and a 87 % reduction for large cars on motorways .The changing pattern of these monitored emission factors in terms of grams of pollutant / km of travel , kg / T , and grams / Gj for all vehicle categories are detailed in **Appendix 1** .
From Glover's work it can also established that NO_X emissions arising from passenger cars in 1994 account for over 60 % the NO_X mass emissions arising from the road transport sector, the remaining 40% was generated by the heavier diesel vehicles. It is also worth noting that the NO_X emissions from diesel passenger vehicles

is of the order of less than 50% of that of a petrol car fitted with a TWC and 10 % of a petrol car without a TWC which can be seen in **Appendix 1**.

9.1.2 Industry and Power Sector Emission Factors

Three major sources of research into NO_X emissions from the industrial and the power generating sectors were identified as:-

1.0 Walker, Warren Spring Laboratory Stevenage **(14)**
2.0 Corinair - European Commission **(15)**
3.0 Proops **(16)**

Empirically derived values for NO_X emission factors have been measured by :-
Walker et al **(14)** of the Warren Spring Laboratory who examined the smaller type of industrial and commercial steam raising boiler units using natural gas , gas oil , medium fuel oil, residual fuel oil , and bituminous coal . This work established emission factors for a range of boilers with different burner designs , configurations and firing rates .The Corinair Handbook **(15)** provided additional, useful and supplementary data on emission factors . A summary of the results outlined in **Table 17** show the average emission factor for each fuel . It also shows that as the chemical bonded nitrogen decreases in the fuel the emission factor in grams per Gj decreases. The results of this work demonstrates that the percentage chemically bonded nitrogen decreases in the following order :-
bituminous coal > residual oil > medium fuel oil > gas oil > natural gas

At the lower end of the above scale Walker **(14)** considers that any NO_X present in the combustion gases is considered to be formed by thermal fixation of the combustion air. The nitrogen content of coal is significantly greater than for the other fuels , however the higher content does not result in the highest emission factor on a weight basis i.e. grams emission / tonne as shown in Table17 . The calculated average emission factors for each fossil fuel in terms of grams / Gj outlined in Table **17** have been used in this thesis to establish the annual NO_X mass emissions for these sectors .

TABLE 17
Industry and Power Sector Emission Factors

		Bituminous Coal	Residual Fuel Oil	Medium Fuel Oil	Gas Oil	Natural Gas
Chemically bonded nitrogen	%	0.75 / 1.0	0.4	>0.3	trace	zero
Emission Factor kg / tonne		6.1	7.54	6.66	2.58	1.92
Emission Factor grams / Gj		250	176	155	57	51

*as received coal 11.7% moisture and 9.2 % ash

Another source of emission factor data was provided by Proops et al **(16)** and have been considered for comparison with **Walker (14)** . The paper examines and compares the NOx emissions and emission factors for larger power stations .The results show emission factors in grams / Gj are in the same descending order as established by Walker **(14)** i.e. coal (341grams / Gj) > fuel oil (231grams / Gj) > natural gas (62 grams / Gj) . There is a relatively good agreement between the two authors on emission values . The values in **Table 17** have been used in this thesis to establish current and future NO_X mass emission levels .

9.1.3 The Domestic Sector Emission Factors

A literature search into measurements available on NO_X emissions in this sector was undertaken to identify empirical data available on NO_X emission factors for the domestic sector. Just two sources of data were located the **USEPA (17) 1977** and **Corinair (18) 1989 .** The results of the measured emission factor were derived from a series of studies on solid fuels , household fuels and natural gas outlined in **Table 18.**

TABLE 18

NO_x Emission Factors for the Domestic Sector

FUEL	kg / tonne	grams / Gj
Anthracite / smokeless	4.8	201
Gas oil	2.6	60
Burning oil	4.5	96
Natural gas	-	56

9.2 Black Smoke Emission Factors

Solid emissions arising from the combustion of fuels may be measured as total particulates or as black smoke which is defined as suspended particulate matter of less than 15 micron .

Black Smoke is defined **(17)** as of sub- microscopic particles of carbon black as a result of incomplete combustion of fossil fuels . The extent of black smoke generated is dependent on many factors ; type of fuel ,burner design characteristics , age and level of burner maintenance and combustion control technology installed . For example an open coal domestic fire in early1970's with little control on combustion efficiency would generate very high levels of smoke emission compared with a modern day coal/ oil fired central heating system with sophisticated control equipment .

An extensive search was carried out to establish the empirical data available on smoke emission factors . Only two comprehensive sources of data were located both were carried out at the Warren Spring Laboratory by Keddie **(19)** and Timmis **(20)** . The standard method of monitoring black smoke emissions is based on a technique involving the sampling of volumes of gas through a filter at low extraction flows rates, the concentration of fine particles being estimated by measuring the blackness of the stain produced on the filter paper . For emissions of black smoke the emission factors are derived by multiplying smoke emission factors by filter soiling factors for the different fuels **(21)**. Over recent years a more positive technique has been employed to measure black smoke by the use of a size- selective sampler which extracts volumes of gas which collects only the smaller particles matter less than 15 micron diameter.

An analysis of the compiled data shows that in 1970 black smoke emissions arising from solid fuel represented over 80% of the total UK emissions which was generated by the domestic sector . The remainder of the black smoke arose from the combustion of petroleum products mainly from DERV. However by the late 1980' s coal accounted for only 43% of the black smoke emissions mainly due to to the reduced consumption of coal in the domestic sector , this decrease had been partly offset by increased emissions from diesel vehicles which currently emit over half of the national total of black smoke.

The emission factors used in this thesis to establish the total annual smoke mass emissions for each of the the energy consuming sectors are derived solely from the Keddie (**19**) and Timmis (**20**).

9.2.1 Road Transport Sector Smoke Emission Factors

In 1994 this sector accounted for over 50% of the black smoke generated in the UK compared with 10 % in 1970 (**3**) **.** It has been established empirically that the emission factor for road diesel fuel is 18 kg of black smoke / tonne of fuel compared with 0.645 kg / tonne for petrol (**19 and 20**) as demonstrated in **table 19**

TABLE 19

Black Smoke Emission Factor for Petrol and Diesel engined Vehicles

	kg/ tonne of fuel	grams / Gj
Petrol	0.645	13.0
Diesel	18 .0	418.0

It can be seen that diesel powered vehicles generate over 30 times more black smoke per unit of energy than petrol driven engines , and hence highlights the environmental impact of any increase in the diesel fuel consumption for the future .

9.2.2 Industrial Sector Black Smoke Emission Factors

The smoke emission factors determined by Keddie (**19**) have been used to establish the mass emissions arising from the industrial sector .The total particulates emissions were measured together with the fraction less than 15 micron defined as black smoke The results of the trials are shown below :-

Petroleum

For residual oil - fired installations the factor for total particulate emissions ranged from 0.2% for low capacity systems to 0.4 % by weight for large fired systems of the fuel input . Twenty five percent of the particulates were assessed to be under 15 microns , hence giving a black smoke emission factors in the range 12 to 24 grams / Gj of fuel input

For distillate oil- fired systems the factor for particulate emissions is taken as 0.05 % by weight, with 50% estimated as being under 15 micron diameter to give a smoke emission factor of 0.5 grams / Gj .

Solid fuel

For small installations with fuel input rates of less than 5,000 tonnes/ year the total particulate emission is taken as 1.0% by weight and using an estimate of 10% less than 15 micron the smoke emission factor was 23 grams / Gj of the fuel input.

For larger installations in excess of 180,000 tonnes / year the total particulate emission was taken as 0.5% by weight of the fuel input and using an estimate of 5% under 15 micron a smoke factor of 6 grams / Gj of fuel input was established.

A Summary of the particulate and smoke emission factors are outlined in **Table 20**

TABLE 20

Particulate and Black Smoke Emission Factors for the Industrial sector

	Particulate Emissions Factors		Black Smoke Factors < 15 micron diameter
Petroleum			
Fuel oil	kg / tonne	grams / Gj	grams /Gj
Residual (power stations)	1.0	40.0	5
Residual (industrial)	2-4.0	45-90	12-24
Gas oil	0.75	19.0	3
Distillates	0.5	12.0	6
Solid fuel			
Coal (small installations)	10.0	227.0	23
(larger installations)	0.5	113.0	6

9.2.3 Domestic Sector Emission Factors

The Black Smoke emission factors used in this thesis are based on the **Keddie(19)** and **Timmis (20)** monitoring survey in the domestic sector in 1978 and are outlined in **Table 21 .** It can be seen that domestic emission factors especially for coal are well above that reported for the industrial sector . Emission factor as high as 1200 grams / Gj were monitored when using very high volatile household coal operating with the poor combustion control of open fires , which largely accounts for the incredible high overall mass emission of particulates and smoke in the 1950's and 1960's . The emission factor for solid fuel has since declined following the extensive use of anthracite fuel which has an emission factor of 186 grams / Gj , but it still remains significantly above the values found in industry .The overall emission from the domestic sector has reduced very extensively due to the extensive use of central heating oil with low emission factor of 0.5 grams/ Gj and natural gas with a zero rated black smoke value.

TABLE 21

Black Smoke Emission Factors for the Domestic Sector

	kg / tonne	grams / Gj
Coal in open fires	40.0	1200.0
Solid smokeless	5.6	186.0
Burning oil- central heating	0.01	0.5

10 .0 Summary of Fossil Fuel Emission Factors

The average emission factor for each of the pollutants arising from each of the fossil fuels in grams / Gj is summarized in the following table . It can be concluded that firstly there is environmental benefit by switching , where it is technically feasible from coal to petroleum with regard to reducing the overall carbon dioxide and sulphur dioxide emissions . However the greatest potential environmental benefit is achieved by switching from both coal and petroleum to natural gas regarding carbon dioxide , sulphur dioxide , oxides of nitrogen and smoke emissions .Fuel consumed in the road transport sector is petroleum based and vehicles are not designed to function with natural gas , hence this sector cannot benefit as yet from the low emission levels associated with this relatively pollution free natural gas .

TABLE 22

The Average Emission Factors for all pollutants in Grams per Gj of Energy

	Natural Gas	Petroleum Non- Transport	Petroleum Transport		Solid Fuel
			petrol	diesel	
Carbon Dioxide	14,000""	20,000	18500	19000	24,000
Sulphur Dioxide	----	155* - 1427*	13	83	1,000^
Black Smoke	----	18	14	418	71
Oxides of Nitrogen	63""	140 - 250 "	553 "	1460"	54^ -181^

* range for gas oil to heavy fuel oil

^ range of coals from anthracite to bituminous

" range for gas oil to heavy fuel oil

"" North sea natural gas

" ranging from petrol cars and heavy diesel vehicles

SO_2 and CO_2 calculated on content and calorific value.

11.0 The Overall Changing Pattern of Atmospheric Emissions Arising from the Combustion of Fossil Fuel 1970 -1994

The changing pattern of the mass emission of the four major atmospheric pollutants ; carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke arising from the combustion of the three main fossil fuels during years 1970 and 1994 (1) are shown **in Table 23** and the percentage share of each of the four pollutants for years 1970 and 1994 are outlined in **Figure 11** . A brief analysis of these data in **Table 23** is summarized below which highlight the most salient conclusions . A more detailed assessment of the year by year changes is also undertaken in this chapter .

1. Solid fuel was the major contributor to carbon dioxide mass emission in 1970 , however in 1994 petroleum can be seen to have overtaken coal as the main source of carbon dioxide.

2. Solid fuel was also the major contributor to the mass emission of sulphur dioxide in 1970 and retained its number one position in 1994.

3. Petroleum products maintained their dominance as the major mass emitter of oxides of nitrogen through from 1970 to 1994.

4. In 1970 solid fuel accounted for the highest mass emission of black smoke , however by 1994 petroleum claimed the lions share of these emissions .

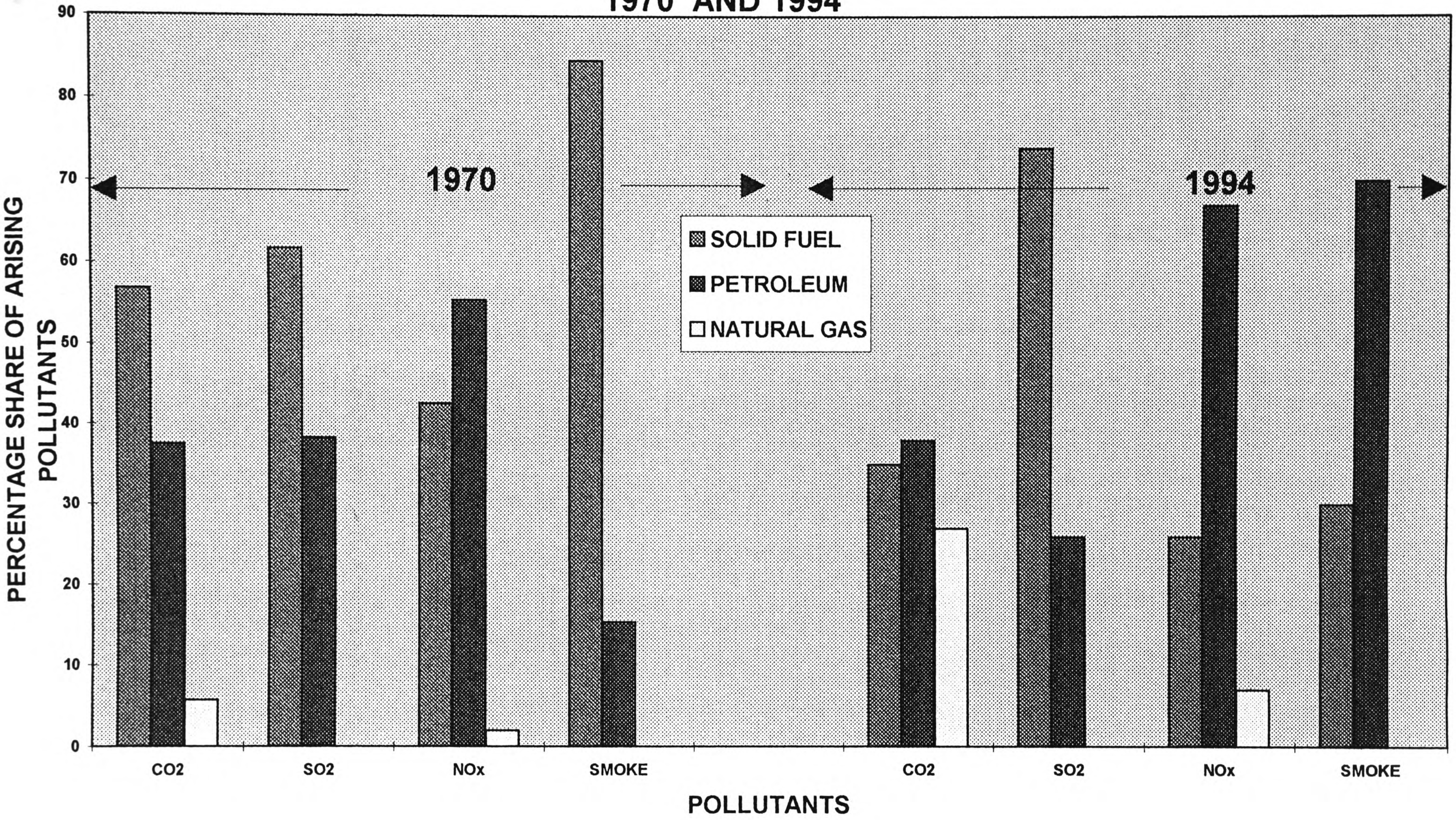
5. Natural gas was a minor contributor to carbon dioxide and oxides of nitrogen in 1970 and 1994 and a zero contributor to sulphur dioxide and smoke in both years.

TABLE 23
Mass Emission of Pollutants Arising from Fossil Fuels in 1970-1994

	Solid fuel		Petroleum		Natural gas		Total	
Tonnes / year	1970	1994	1970	1994	1970	1994	1970	1994
Carbon Dioxide 10^6	**<u>100</u>**	50	68	**<u>55</u>**	10	39	178	144
Sulphur Dioxide 10^3	**<u>3938</u>**	**<u>1992</u>**	2450	709	--	--	6388	2701
Oxides of Nitrogen 10^3	946	541	**<u>1230</u>**	**<u>1400</u>**	42	142	2218	2082
Black Smoke 10^3	**<u>826</u>**	117	150	**<u>268</u>**	--	--	976	385

bold and underlined print signifies major emitter in that year.

PERCENTAGE SHARE OF EMISSIONS ARISING FROM FOSSIL FUELS IN 1970 AND 1994



SOURCE : DIGEST OF ENERGY STATISTICS 1996

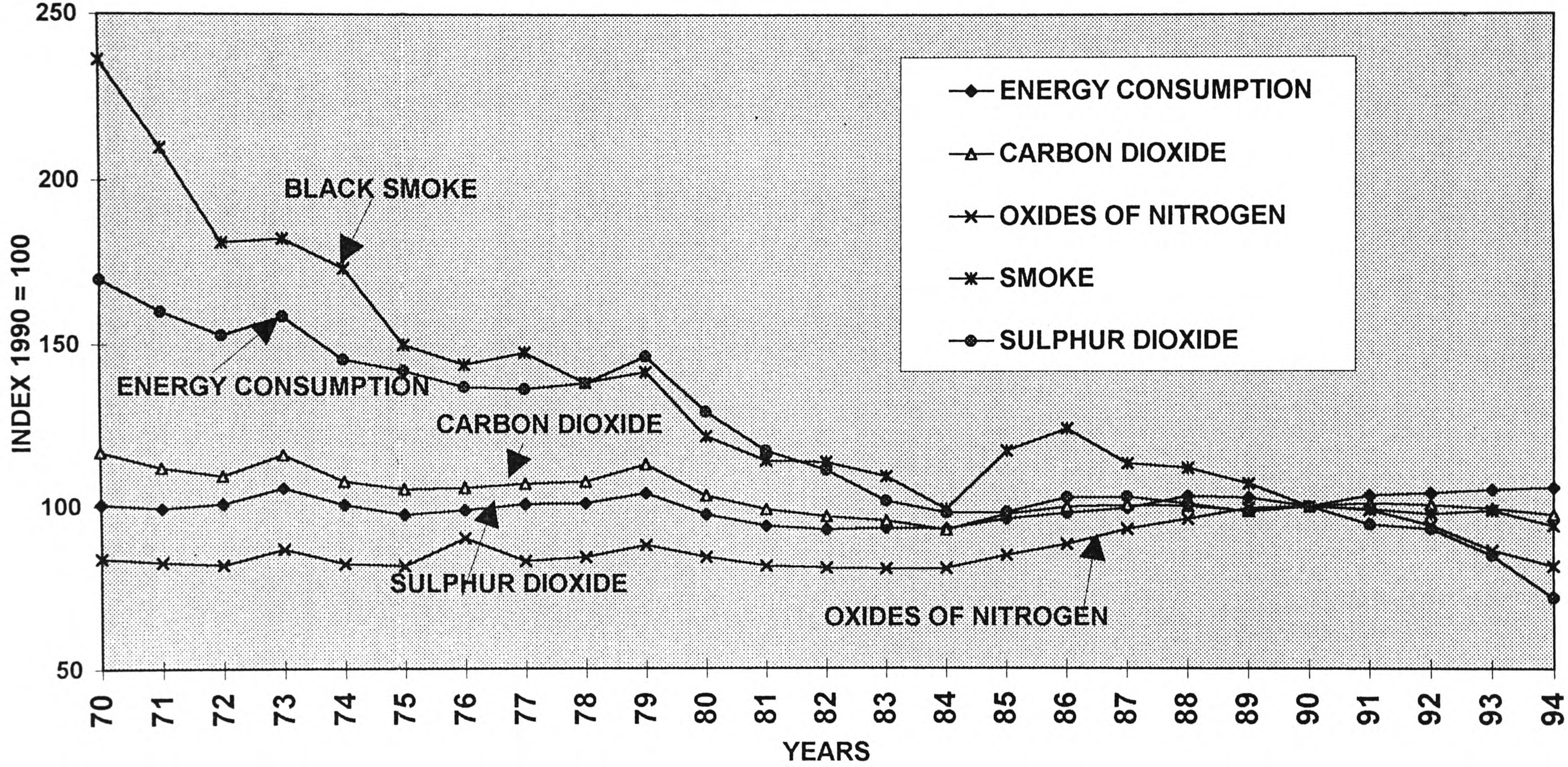
FIGURE 11

Clearly there has been a major overall downward trend in the level of emissions from the fossil fuels from 1970 to 1994 especially with regard to SO_2 and black smoke . The replacement of coal and petroleum by natural gas over this period has been the major reason for the decline in emissions by all the user sectors with the exception of transport , where there has been no fuel substitution and the demand for energy in this sector has expanded rapidly .

The overall relationships between the overall primary energy consumption , carbon dioxide (as carbon) , sulphur dioxide , oxides of nitrogen (as nitrogen oxide) and black smoke emissions over the period 1970-1994 are shown in **Figure 12** . It demonstrates very clearly the marked decline in black smoke and SO_2 emissions , the steady increase in NOx emissions up to 1990 , and the fluctuating but overall relatively constant CO_2 emissions against a background of a fairly stable demand for primary energy .

A further analysis of **Table 23** which is presented below provides a more detailed assessment of the changing pattern of mass emissions , the corresponding percentage of contribution of each pollutant compared with the changes in energy consumption each of the fossil fuels in years 1970 and 1994 are summarized in **Table 24** .

RELATIONSHIP BETWEEN ENERGY CONSUMPTION , CO_2 AS CARBON , SO_2 , BLACK SMOKE AND OXIDES OF NITROGEN EMISSIONS FROM 1970 - 1994



SOURCE : DIGEST OF ENERGY STATISTICS 1995 AND DIGEST OF ENVIRONMENTAL STATISTICS 1996

FIGURE 12

TABLE 24

The Changing Pattern of Mass Emissions and Percentage Contribution of Emissions in Years1970 and 1994

Fuel Type	changing mass emission 1970 to1994	change in % contribution 1970 to1994	change in energy consumption % 1970 to 1994
Solid Fuel			
Carbon dioxide	- 50 million tonnes	- 22.1%	)
Sulphur dioxide	- 1,946 thousand tonnes	-12.0 %	) - 45.5 %
Oxides of nitrogen	- 405 thousand tonnes	-16.7%	)
Black smoke	- 709 thousand tonnes	-54.0%	)
Petroleum			
Carbon dioxide	- 13.0 million tonnes	- 0.7%	)
Sulphur dioxide	-1741 thousand tonnes	- 12%	) -19.2 %
Oxides of nitrogen	+ 170 thousand tonnes	+11.9 %	)
Black smoke	+ 118 thousand tonnes	+ 54.1 %	)
Natural gas			
Carbon dioxide	+ 29 thousand tonnes	+ 21.4 %	) + 480 %
Oxides of nitrogen	+100 thousand tonnes	+ 4.8 %	)

The data in this table clearly shows :-
The downward trend in demand for solid fuel is reflected in the overall decline in the mass emissions all the pollutants arising from this fuel .

The decline in sulphur dioxide emissions arising from petroleum are attributed to reduced demand for this product coupled with the reduced consumption of high sulphur bearing fuel oils by the manufacturing and power generating industries and the dramatic increase in the demand for the light low sulphur bearing fuels used in the transport sector. The NO_x and black smoke emissions from the transport sector have increased due to the increase in road traffic.

The increase in carbon dioxide and oxides of nitrogen from natural gas is attributed to the 480 % increase in demand for this clean fossil fuel . However the whole environmental scene has benefited from this major transfer to natural gas over the 1970- 1994 period .

The changing trends of the individual pollutants carbon dioxide , sulphur dioxide oxides of nitrogen and black smoke are analyzed below :-

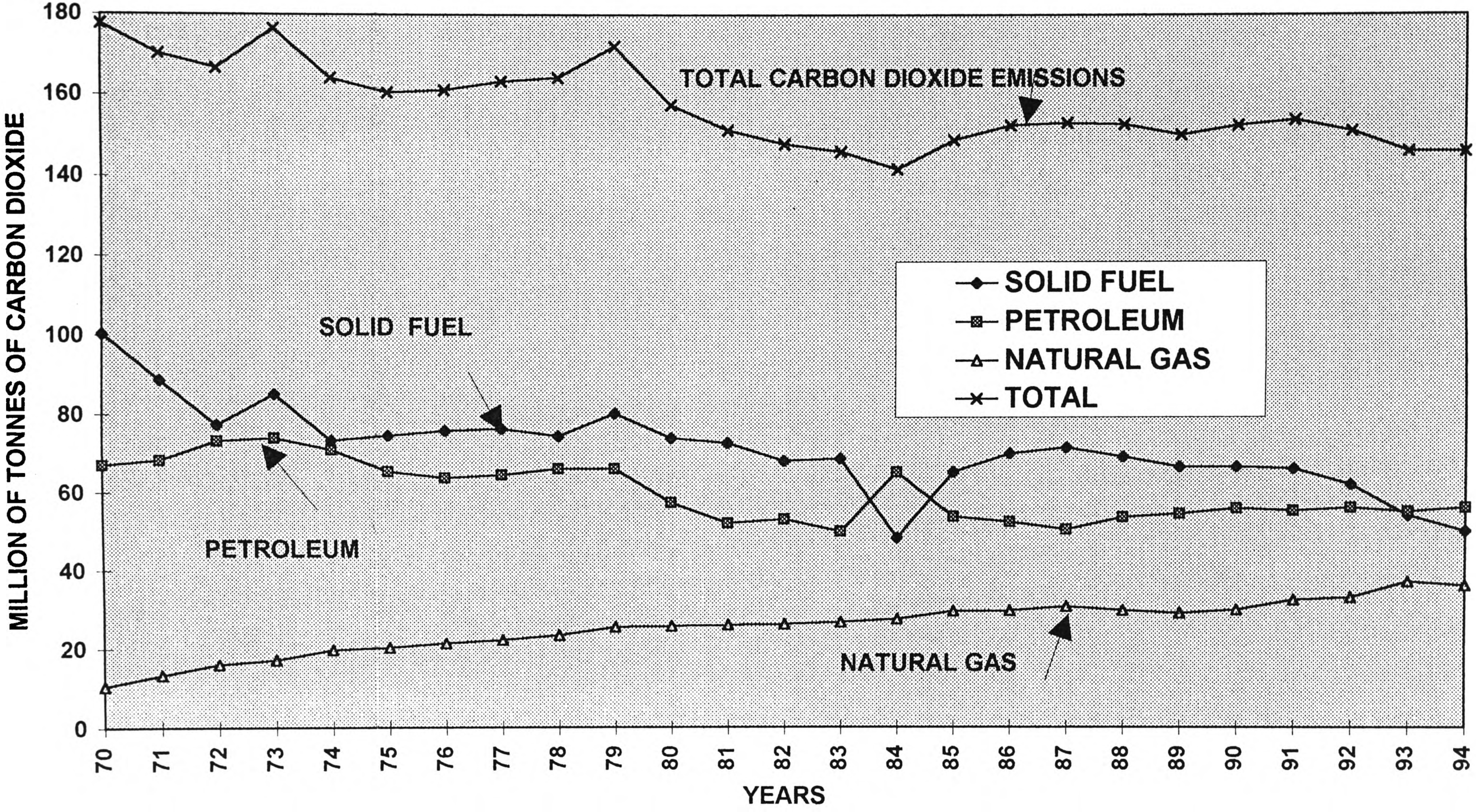
11.1 Carbon Dioxide Emissions .

The UK contributes about 2% of the global person made emissions of CO_2 which is currently estimated to range between 6000 - 8200 million tonnes per year (expressed as carbon)
Over the period 1970 to 1994 it can be seen from **Figure 13** that carbon dioxide emissions from combustion processes have declined by 19 % from 178 to 144 million tonnes , of the order of 0.75 % per year .The lowest emission level was reached in 1984 at 142 tonnes during the coal dispute when coal was replaced with oil in the power generation industry , which indicates the advantage of switching from solid fuel to fuel oil to achieve a lower CO_2 release per unit of energy consumed . The replacement of oil and solid fuel by natural gas which possesses a low carbon content per unit of energy has also contributed to the overall reductions in CO_2emissions .

Figure 14 shows a steady decline in the CO_2 emissions /unit of energy demand (emission factor) indexed to 1990 = 100 equivalent to an overall reduction of 18 % in this ratio over this period . This figure also demonstrates the decline in the mass emission of carbon dioxide in relation to the UK Gross Domestic Product from 518 tonnes per £ million of GDP in 1970 to 262 tonnes per £ million GDP by 1994 calculated on a 1990 factor cost .This clearly demonstrates that there was a decline in the emission / GDP ratio over this period despite the increased prosperity of the country in terms of spending power.

Figure 15 shows the annual estimated carbon dioxide (as carbon) emission factors for each of the fossil fuels in kg / Gj used in the **AEA (2)** annual environmental inventory and in this thesis . It can be seen that there is little fluctuations in the factors over the years .Despite using a single carbon content for each of the fuels for all years the estimated accuracy remains within +/- 5% .The trend is likely to be more reliable and hence an average value for these factors is used to predict future carbon dioxide emissions in **chapter 14 .**

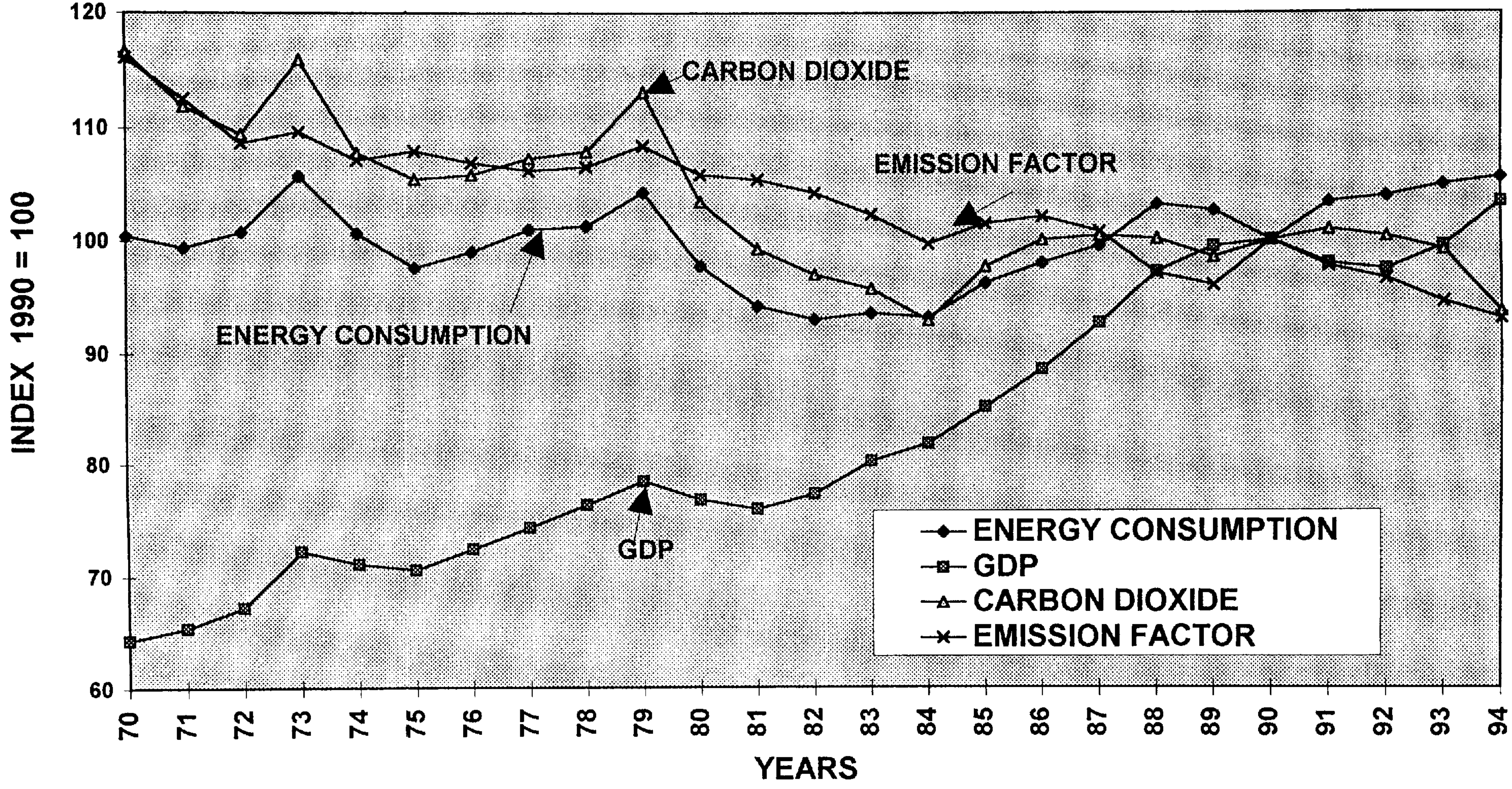
CARBON DIOXIDE EMISSIONS FROM FOSSIL FUELS 1970 - 1994



SOURCE : AEA NATIONAL ATMOSPHERIC EMISSIONS INVENTORY

FIGURE 13

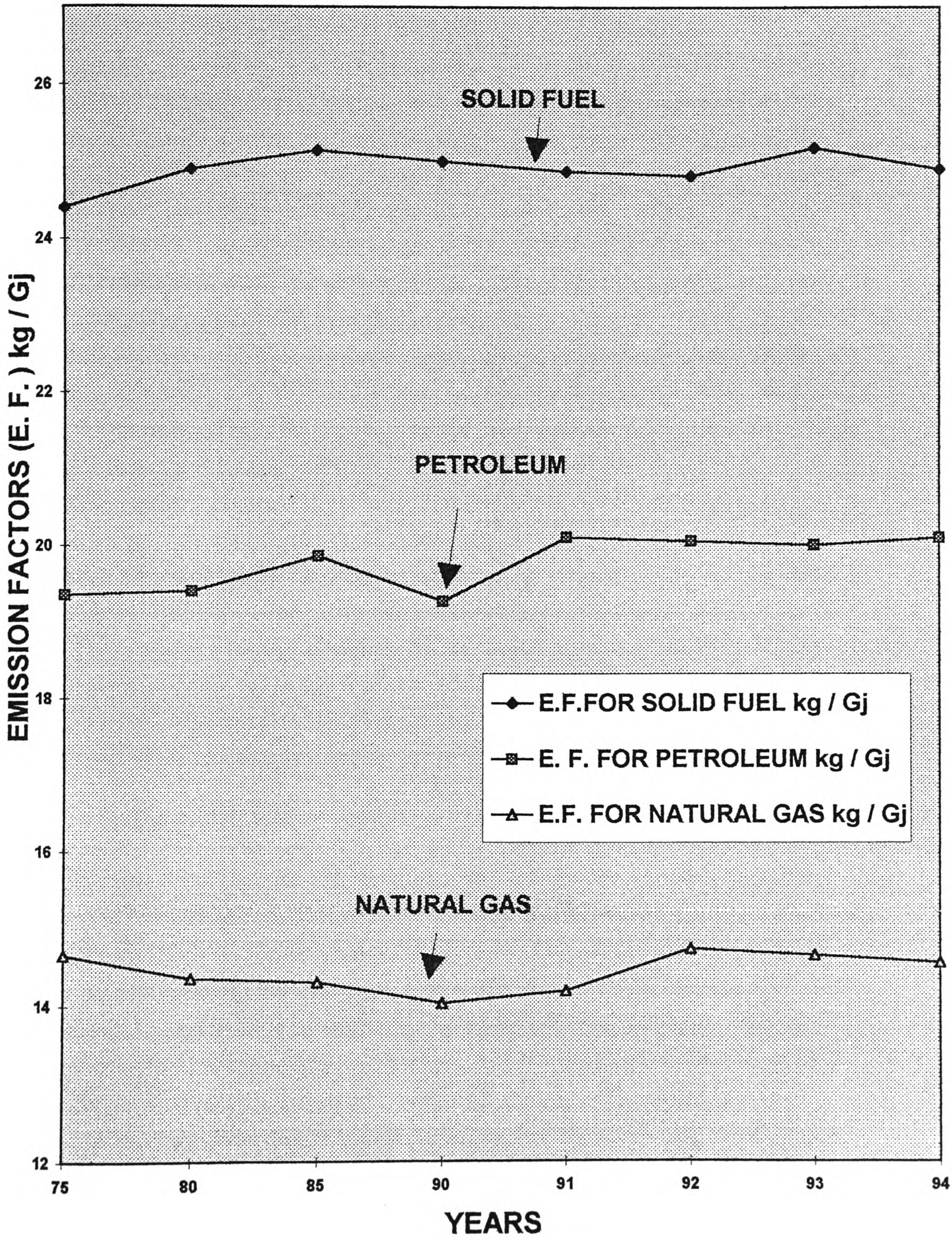
RELATIONSHIP BETWEEN ENERGY CONSUMPTION GDP , CARBON DIOXIDE EMISSION AS CARBON AND EMISSION FACTOR 1970 -1994



SOURCE : DIGEST OF ENERGY STATISTICS 1995 AND DIGEST OF ENVIRONMENTALSTATISTICS 1996

FIGURE 14

CHANGING PATTERN OF CO_2 EMISSION FACTORS FOR COAL , PETROLEUM , AND NATURAL GAS 1975 - 1994



SOURCE : AEA ENVIRONMENTAL ATMOSPHERIC EMISSION INVENTORY 1996

FIGURE 15

11.2 Sulphur dioxide emissions

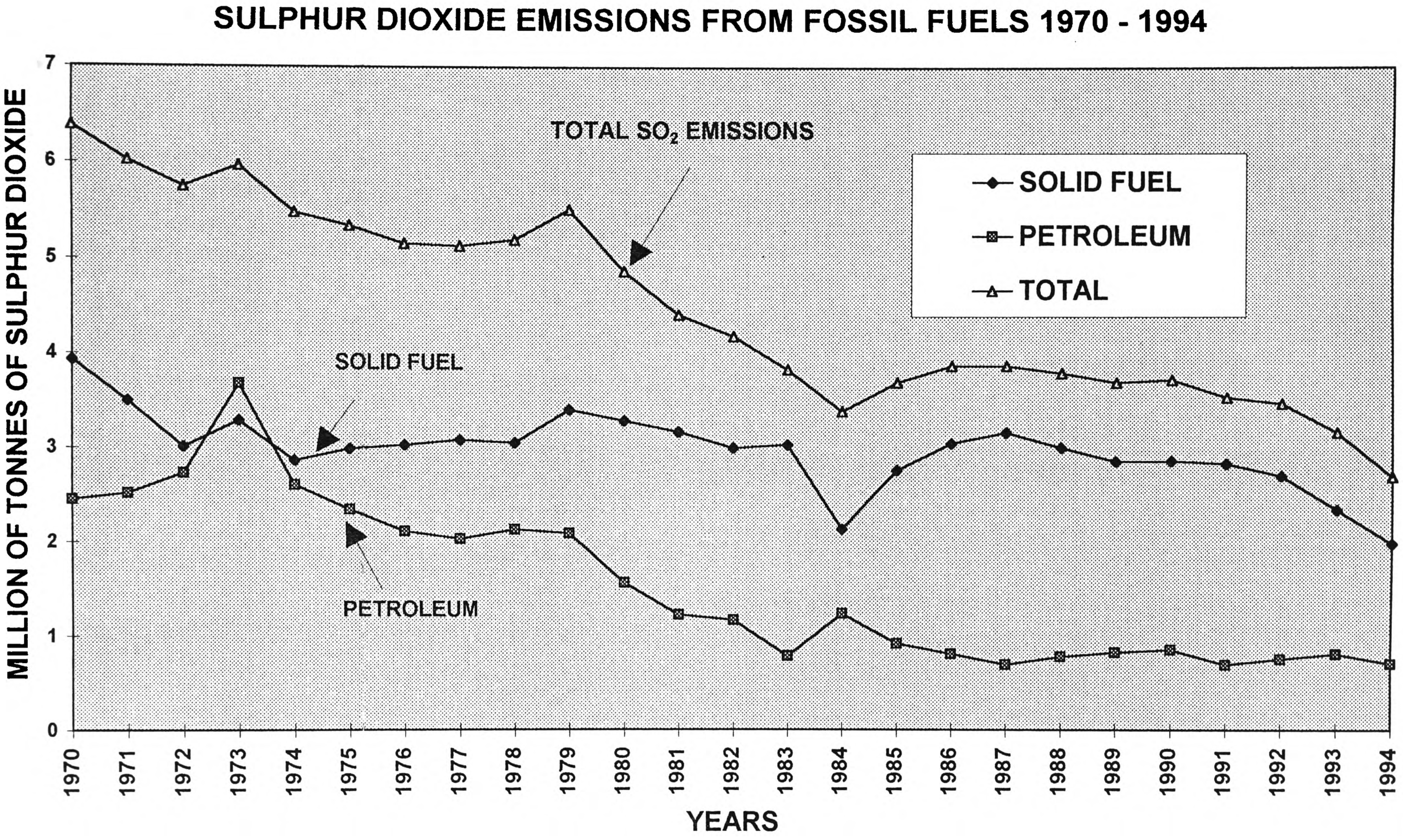
Globally SO_2 emissions from fossil fuel combustion have been seen to increase in the 20th century , this trend has been most evident in industrial developing countries. During the 1970 - 1994 period the SO_2 emissions in the UK as shown in **Figure 16** declined from 6.4 to 2.7 million tonnes a 58 % reduction equivalent to a 2.4 % annual fall . The emissions peaked in the early 1970's, but have shown a significant downward trend ever since. Sulphur dioxide emissions are generated by two of the fossil fuels ; solid fuel and petroleum products . It can be seen from **Figure 16** that the emissions arising from solid fuels remained relatively stable up to 1987 , but declined there after. However the emissions from petroleum steadily declined from 1970 to 1984 and were stable there after, which can be explained in both cases by the change in energy mix largely in fovour on natural gas . **Figure 17** shows the decline in the SO_2 emissions / energy unit (emission factor) indexed to 1990=100 which equated to a 53 % fall .The relationship between SO_2 emissions and GDP calculated at 1990 factor cost is demonstrates in **Figure17** in that , in 1970 the SO_2 emissions was 18.4 tonnes per £ million of GDP at 1990 prices , but by 1994 this had declined very dramatically to 4.8 tonnes per £ million of GDP .This can be accounted for by the reduced energy intensity in the manufacturing industry and the change in fuel mix to low polluting fuels that energy consumption at a greater rate than GDP .

Figure 18 demonstrates the changing pattern of the estimated SO_2 emission factors during 1975 to 1994 . The factor for coal remains relatively stable over this period , however there is a marked decline in the petroleum factor over the 1975- 1990 period . This is very largely due to the dramatic reduction in the demand for the high sulphur fuel oil consumed by manufacturing industry and the increase in the demand for road vehicle fuel which has a low sulphur content compared with industrial fuel oils .

11. 3 Oxides of Nitrogen emissions

Unlike SO_2 and CO_2 , the NO_x emissions have not shown a clear changing trend over the 1970-1994 period .However the change in energy mix , and also the increase in transport fuel has had a significant influence on NO_x emissions in the 1980's mainly due to the increase in the volume of road traffic . However the decline in the 1990 's as shown in **Figure 19** is accounted for by the introduction of the first UNECE NO_x Protocol aimed at returning NO_x emissions to 1987 levels by 1994 **(3)** and EEC legislation limiting NO_x emissions from power stations and road traffic .

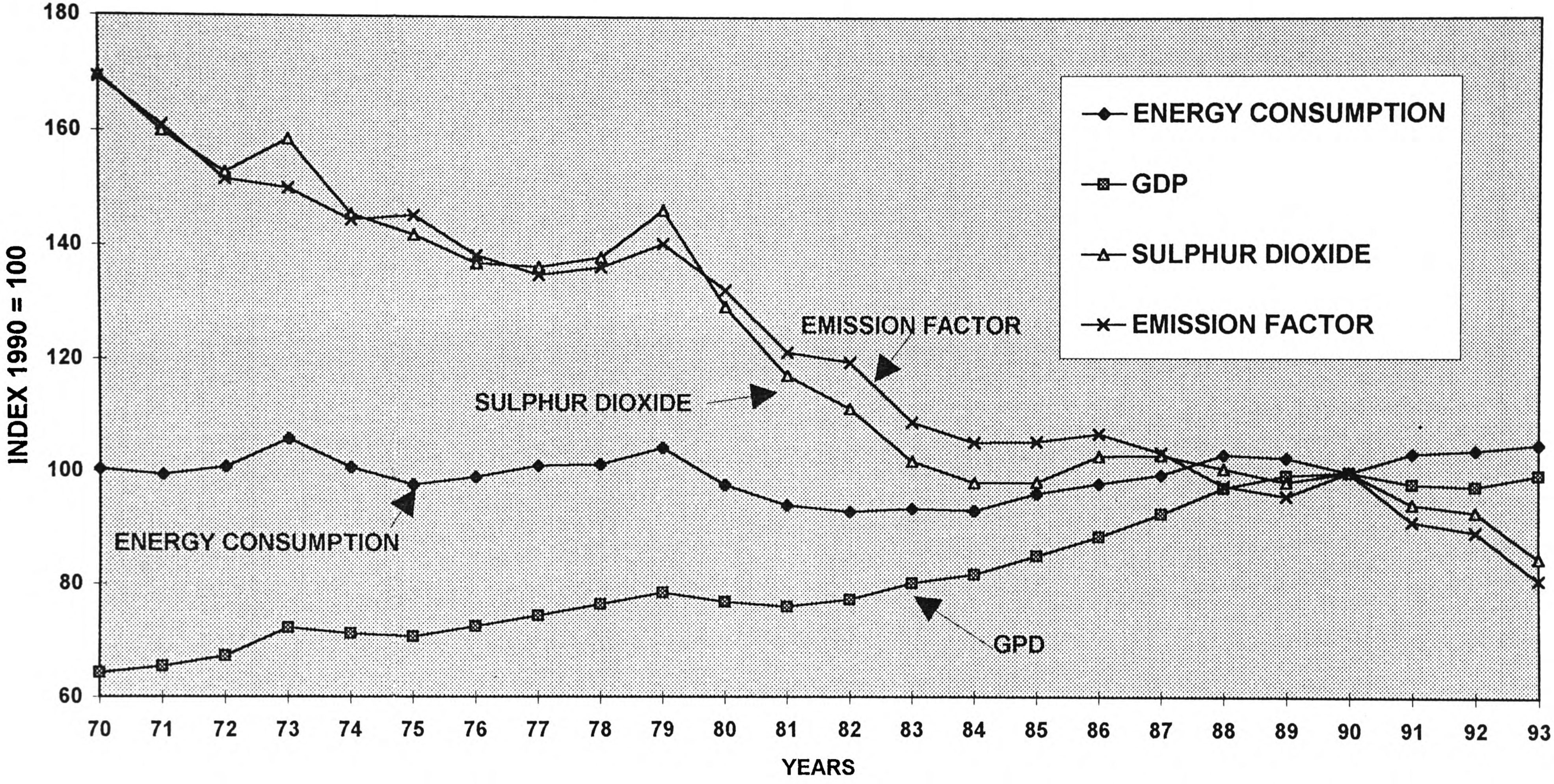
Further analysis of the data in **Figure 19** shows that there have been three distinct phases in the trends of NO_x emissions over the 1970-1994 period :-



SOURCE: AEA NATIONAL ATMOSPHERIC EMISSION INVENTORY1996

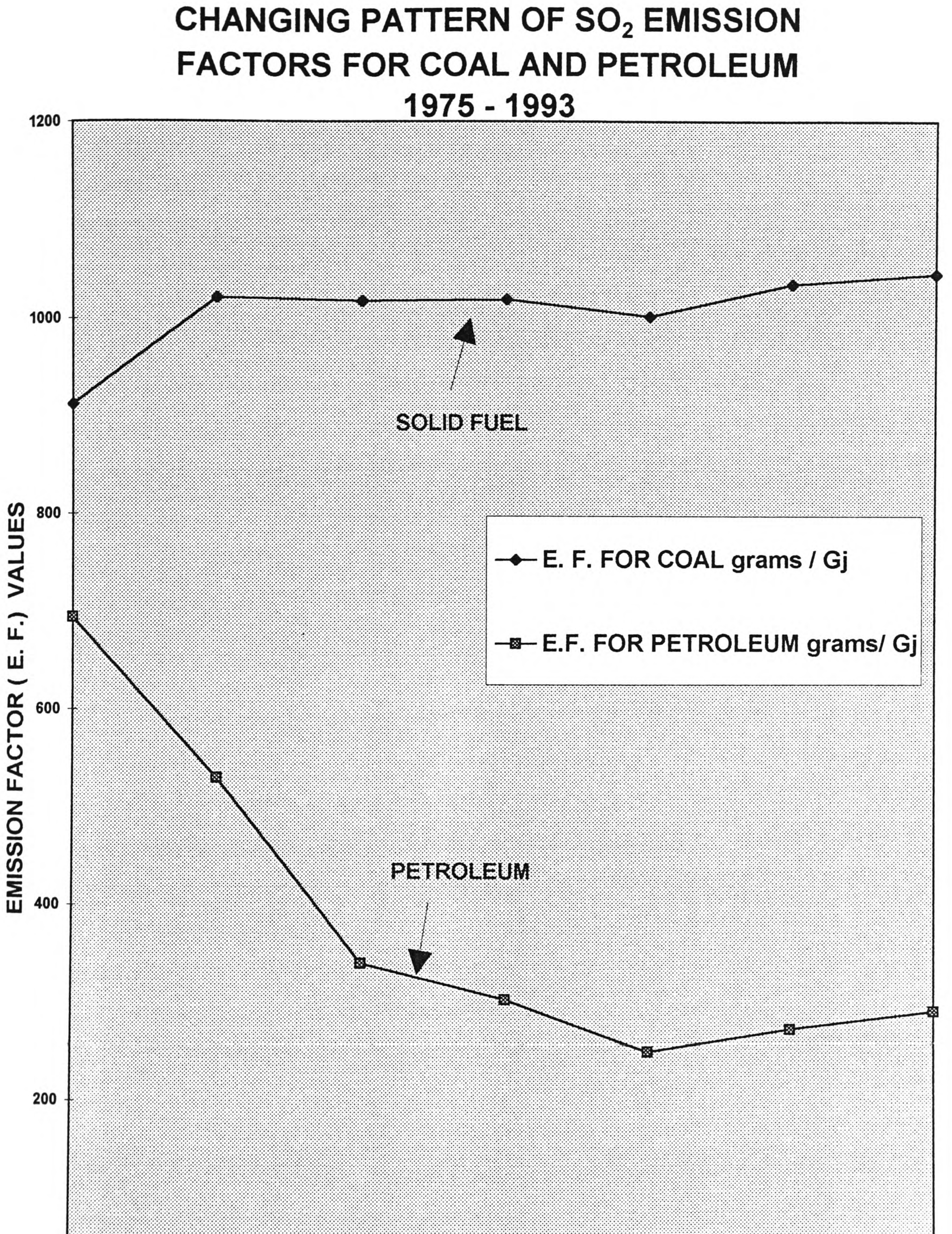
FIGURE 16

RELATIONSHIP BETWEEN ENERGY CONSUMPTION , GDP , SULPHUR DIOXIDE EMISSION , AND EMISSION FACTOR 1970 - 1994



SOURCE : DIGEST OF ENERGY STATISTICS 1995 AND DIGEST OF ENVIRONMENTAL STATISTICS 1996

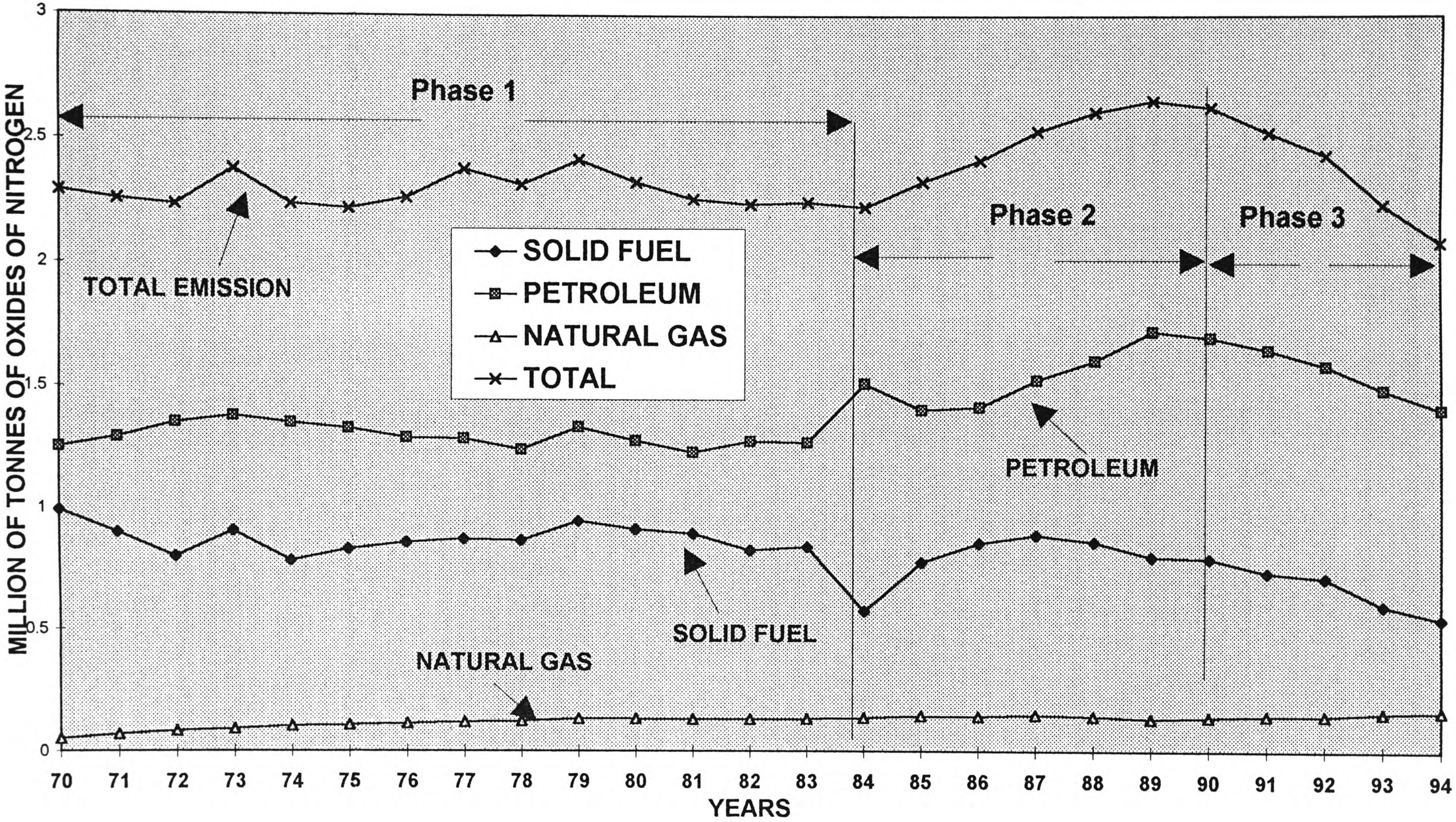
FIGURE 17



SOURCE : AEA ENVIRONMENTAL ATMOSPHERIC EMISSION INVENTORY 1996

FIGURE 18

OXIDES OF NITROGEN EMISSIONS FROM FOSSIL FUELS 1970 - 1994



SOURCE : AEA NATIONAL ATMOSPHERIC EMISSION INVENTORY

FIGURE 19

1.0 The 1970 - 1984 period shows a relatively static pattern of total NO_X emissions, and also for the individual fossil fuels ; coal , petroleum and natural gas.

2.0 During 1984 - 1990 a rapid escalation in emissions took place which is associated with the significant increase in the demand for road transport fuels .

3.0 The 1990 - 1994 period exhibits a rapid decrease in emissions which was equivalent to an 18 % fall , which can be partly attributed to the introduction of environmental legislation in 1992 / 3 .

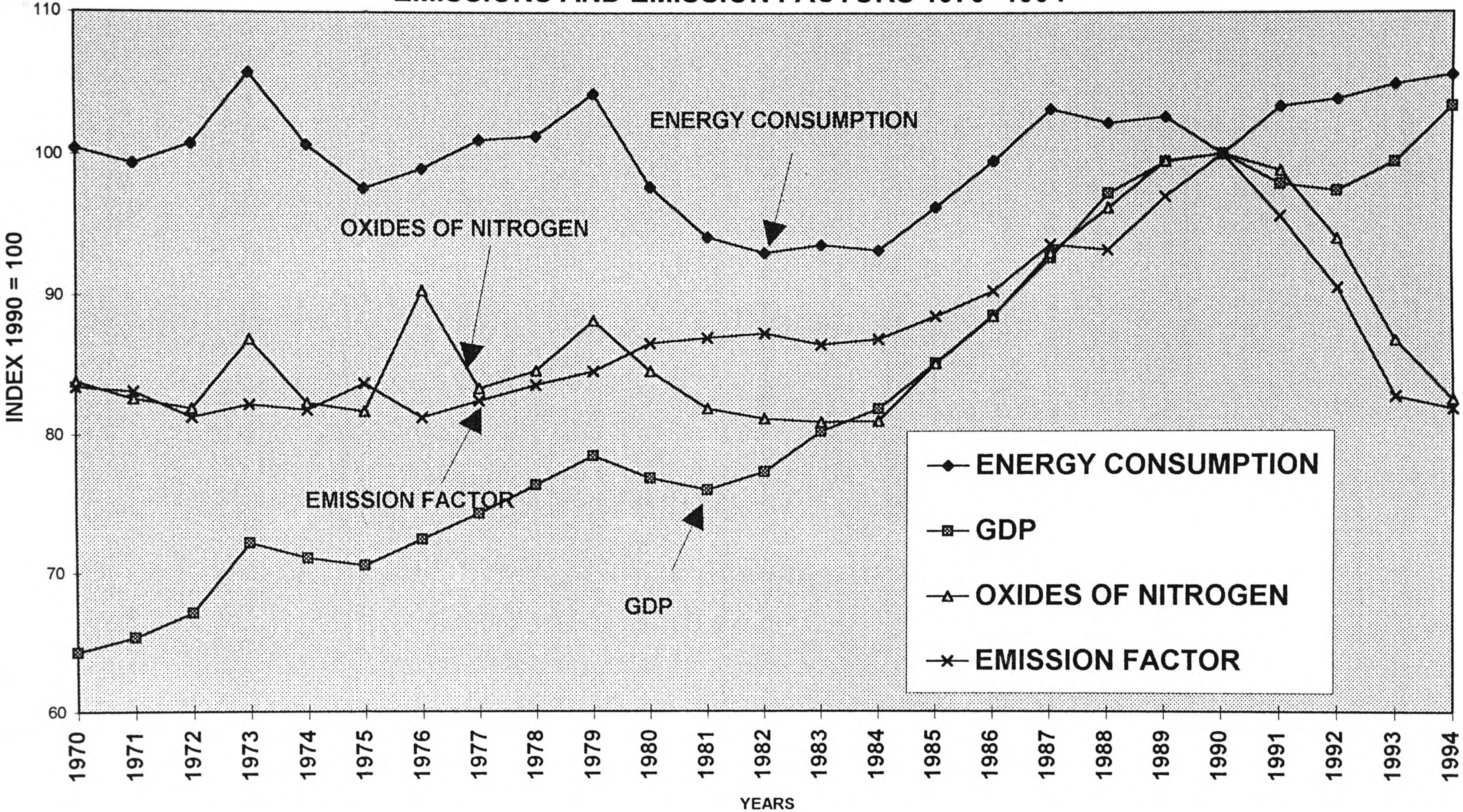
The relationship between energy consumption , NO_X emission and GDP at 1990 factor cost over the 1970-1994 period including emission factors indexed to 1990 are shown in **Figure 20**. This figure demonstrates the upward trend of the NO_X emission factor up to 1990 and there after a dramatic fall .The emission / GDP ratio was calculated to be equivalent to 6.6 tonnes of NO_X emissions per £ million of GDP at 1990 prices in 1970 this had decreased to 3.9 by 1994 , a significant decline despite the increased prosperity of the country .

Figure 21 shows the changing pattern of distance traveled by road vehicle sector in billions of km , the estimated mass of NO_X emitted and the calculated annual emission factor in terms of grams of NO_X / km of travel and grams / Gj of fuel consumption over the decade 1984- 1994 .Again it can be seen that the mass emissions and emission factor for NO_X peaked in 1989 / 1990 and declined there after in the 1990's despite the continuing increase in road traffic . This decline in the late 1990's is partly due to environmental control legislation measures and also the increase in the penetration of diesel passenger car which exhibit a lower NO_X emission factor than petrol cars **(Appendix 1) .**

11.4 Black Smoke Emissions

It can be seen from **Figure 22** that there was a substantial fall in black smoke emissions arising from fossil fuels over the 1970-1994 period , which is very largely accounted for by the reduction in the consumption of coal in the domestic sector. However the increased consumption of petroleum products in the form of diesel fuel resulted directly in an increased contribution to black smoke by the road traffic sector over this period .

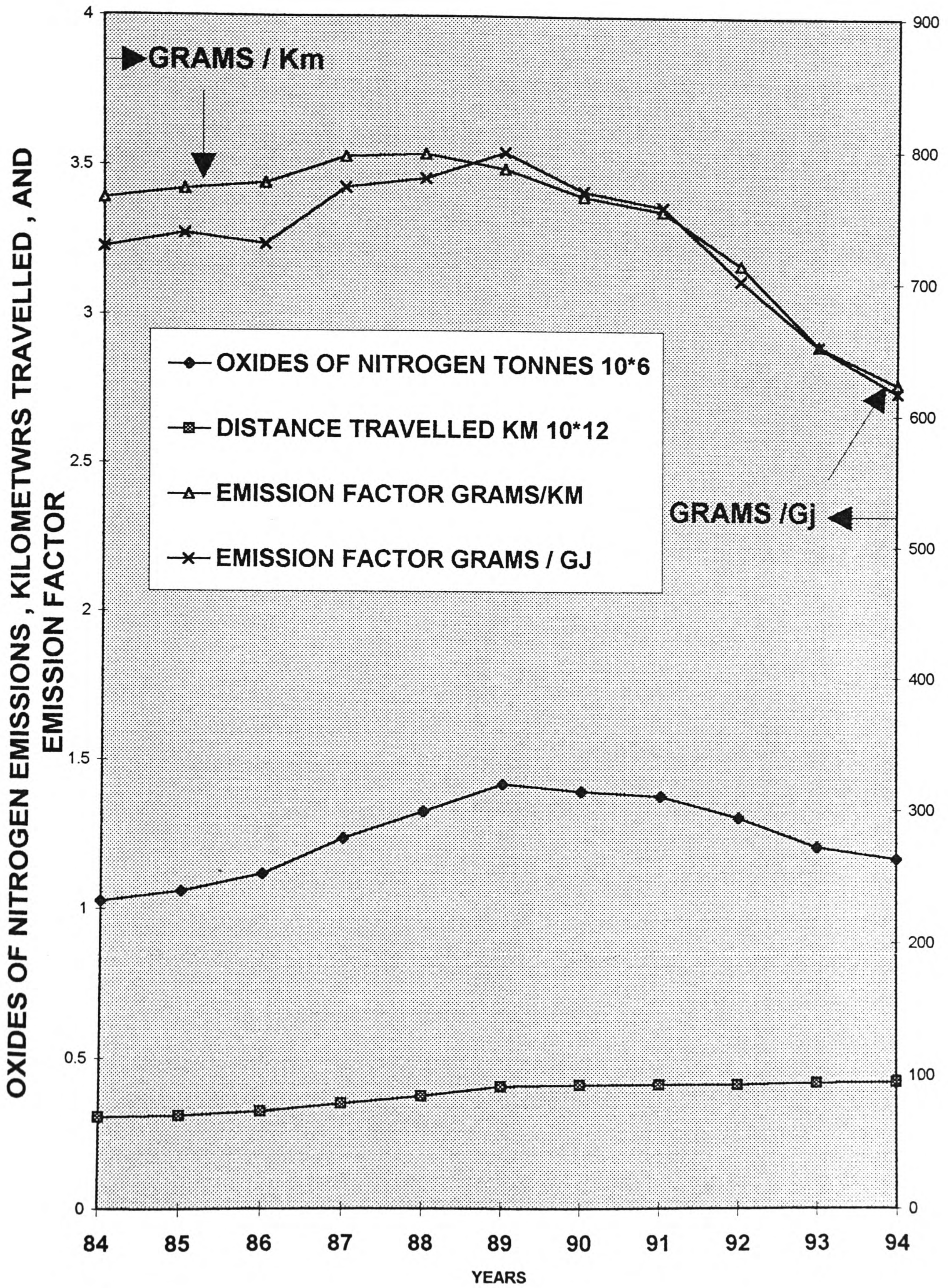
RELATIONSHIP BETWEEN ENERGY CONSUMPTION , GDP , OXIDES OF NITROGEN EMISSIONS AND EMISSION FACTORS 1970 -1994



SOURCE : DIGEST OF ENERGY STATISTICS 1995 AND DIGEST OF ENVIRONMENTAL STATISTICS 1996

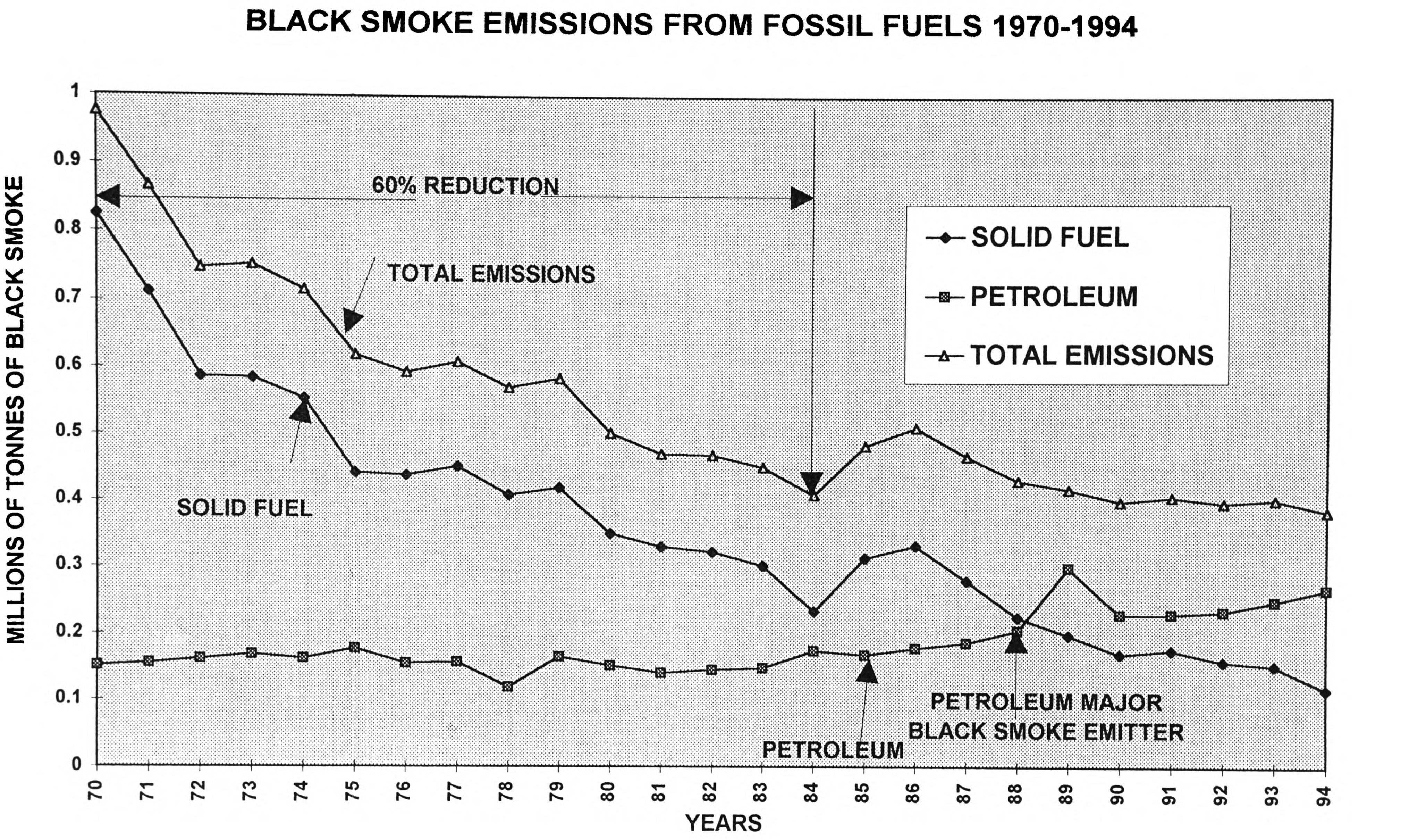
FIGURE 20

CHANGING PATTERN OF OXIDES OF NITROGEN EMISSION FACTOR IN THE ROAD TRANSPORT SECTOR



SOURCE : DEPT OF TRANSPORT STATISTICS GREAT BRITAIN 1995 / 1996

FIGURE 21



SOURCE : AEA NATIONAL ATMOSPHERIC EMISSION INVENTORY

FIGURE 22

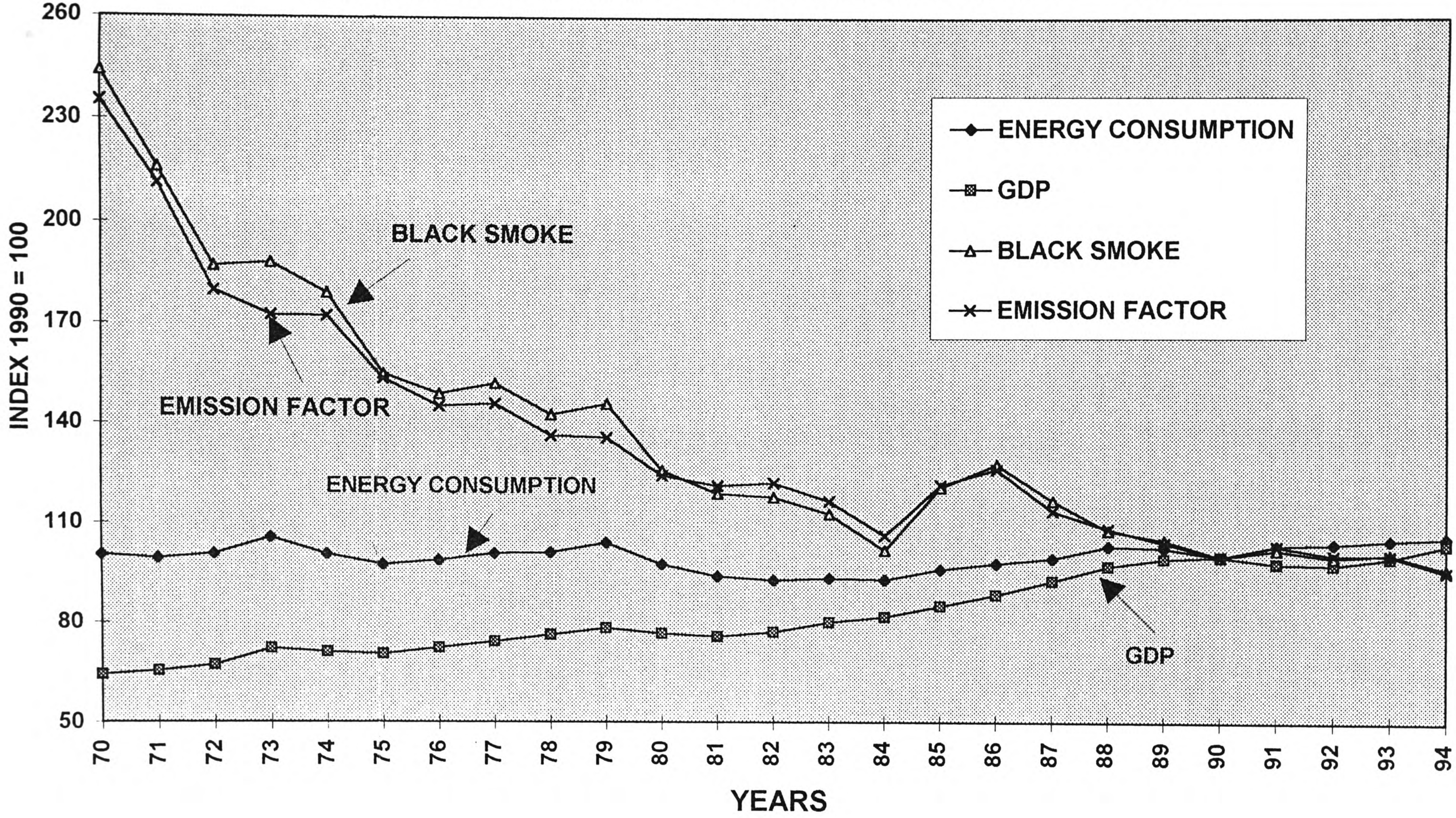
Figure 23 shows that the overall emission factor has declined by 57 % over the 24 years. However the increase in smoke from diesel traffic over this period has masked the full impact effect of the decline in smoke from the combustion of coal .This figure also demonstrates the marked decline in indexed relationship between the mass emission of smoke and GDP. In 1970 this value was 2.9 tonnes of smoke emission per £ million of GDP but by this had declined to 0.9 tonnes per £ million of GDP at 1990 prices by 1994 despite background of increased UK prosperity .

Figure 24 shows the changing pattern of the smoke emission factor in the road transport sector over the past ten years . Both the vehicle distance traveled based on billions of km per year and the total mass emission of smoke in million of tonnes have increased, giving rise to a 26 % overall increase in the emission factor as grams / km and grams / Gj over this period .
In 1970 the domestic sector accounted for over 80% of the UK emissions and up to 1989 this sector maintained its place as the major contributor of black smoke emissions, however by 1990 the transport sector had replaced the domestic sector as the major contributor and by 1994 the emissions from the transport sector were estimated to represent over 50% of that generated in the UK.

11.5 An Overview on the Changes in the Emissions Factors

Figure 25 summarizes the changing trends of the emission factors over the 1970-1994 period for the four pollutants . Clearly black smoke emissions have experienced the greatest reduction equating to 60 % by 1994 , this was followed by a fall in sulphur dioxide by 58 %and carbon dioxide by 19 % . The oxides of nitrogen increased steadily up to 1990 , but declined rapidly over the following four years . This is considered to be in response to legislation introduced to control emissions in the road traffic sector

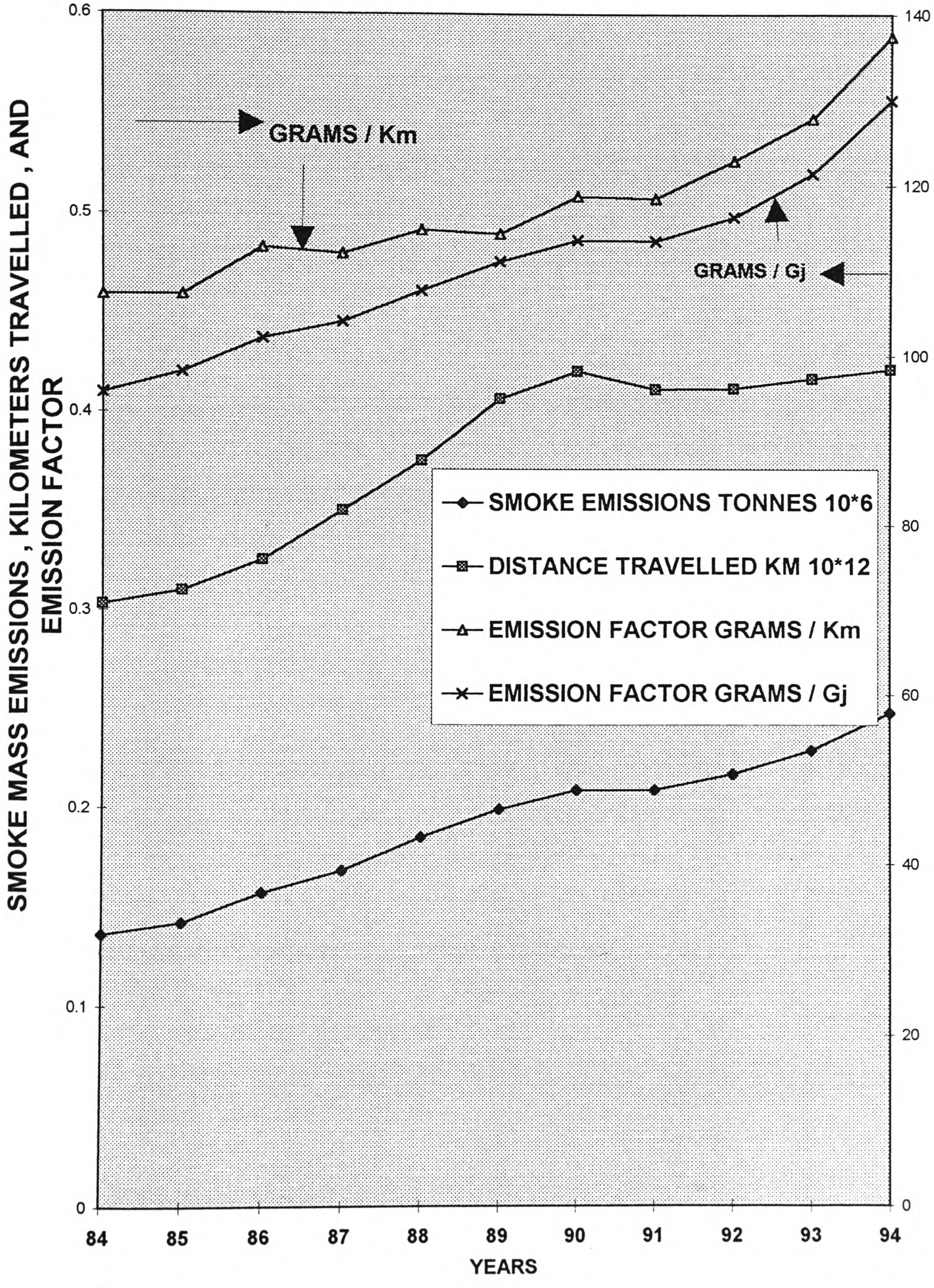
RELATIONSHIP BETWEEN ENERGY CONSUMPTION , GDP , BLACK SMOKE EMISSION AND EMISSION FACTOR 1970 - 1994



SOURCE : DIGEST OF ENERGY STATISTICS 1995 AND AEA EMISSIONS OF AIR POLLUTANTS 1996

FIGURE 23

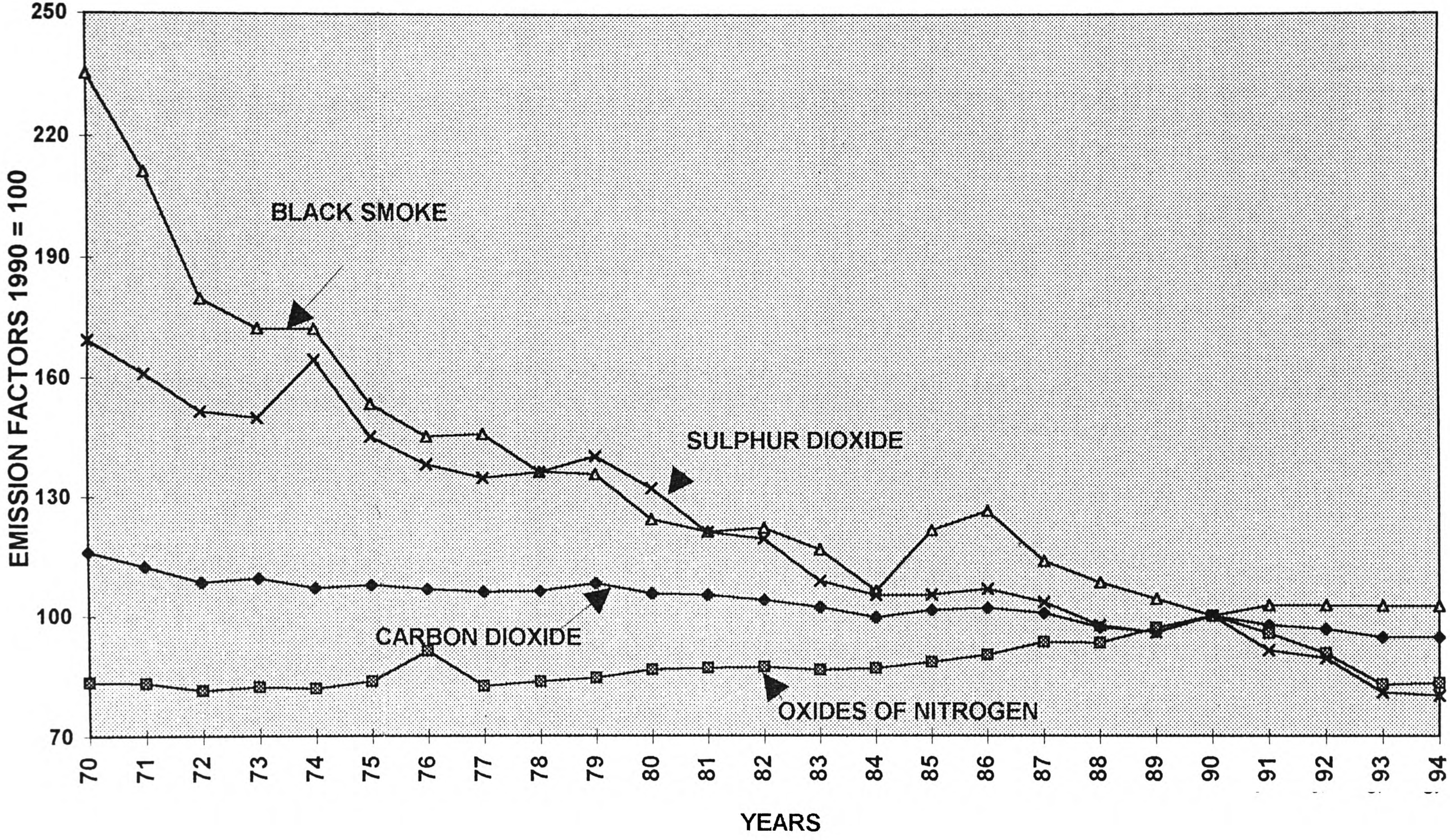
CHANGING PATTERN OF THE SMOKE EMISSION FACTOR IN THE TRANSPORT SECTOR



SOURCE : DOT TRANSPORT STATISTICS GREAT BRITAIN 1995 / 1996

FIGURE 24

THE CHANGING PATTERN OF ESTIMATED EMISSION FACTORS FOR CO_2, SO_2, NO_x, and Black Smoke 1970 -1994



SOURCE : DIGEST OF ENERGY STATISICS 1995 AND DIGEST OF ENVIRONMENTAL STATISTICS 1996

FIGURE 25

12.0 An Assessment of the Changing Pattern of Emissions Arising from the Major Energy Consuming Sectors

Table (25) outlines the estimated mass emission of pollutants arising from the individual energy consuming sectors which is based on the product of calculated or empirically derived emission factors and annual fossil fuel consumption (5) .It provides a basis for identifying the changing pattern in the emissions that have occurred during years 1970 and 1994 within the major energy consuming sectors .

Table (25)

The Contribution of the Individual Energy Consuming Sectors to Atmospheric Emissions

	POLLUTANTS			
	CO_2	SO_2	Black Smoke	NO_x
Major Sources of emissions	1970 (1994)	1970 (1994)	1970 (1994)	1970 (1994)
	million tonnes/year	thousand tonnes/ year	thousand tonnes/ year	thousand tonnes/ year
Power sector	56 (43.0)	**2895 (1752)**	31.0 (17.0)	805 (516)
Transport sector	19.0 (31.0)*	190 (109)	105 (245)*	**823 (1202)***
Domestic/ service sector	37 (30.0)	**801 (160)**	**810 (116)**	120 (106)
Industry Sector	66.0 (40.0)	**2500 (680)**	51.0 (23.0)	470 (314)
Total	178 (144)	6388 (2701)	997 (385)	2218 (2138)

The estimated total mass emissions from all pollutants ; carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke arising from the major energy consuming sectors have decline over the1970 to1994 period . With regard to the individual sectors it can also be seen that in the power, domestic/ service and industrial sectors all pollutants have declined .The transport sector due to the increase in fuel demand has increased its contribution of pollutants with the exception of sulphur dioxide which has declined .

The major changes in the emissions of pollutants arising from the four sectors have been identified in **Table 25** and highlighted below -:

1.0 The major reductions in sulphur dioxide are seen to occur in the industrial , power generating and the domestic sectors .

2.0 The domestic sector experienced a very significant fall in black smoke .

3.0 The transport sector has increased its carbon dioxide , black smoke , and an NO_X emissions.

Figure 26 compares the percentage changes that have occurred for each of the pollutants over the 24 year period and an analysis of the table provides the following assessment of changing trends :-

1.0 The power generating sector has remained the primary source of SO_2 emission over this period , however by 1994 the percentage contribution of this sector had increased very significantly to 65 % from 45% in 1970 .
It is noted that the emissions from industry had reduced to 25 % largely due to the demise of the fuel intensive industries like the iron and steel industry .

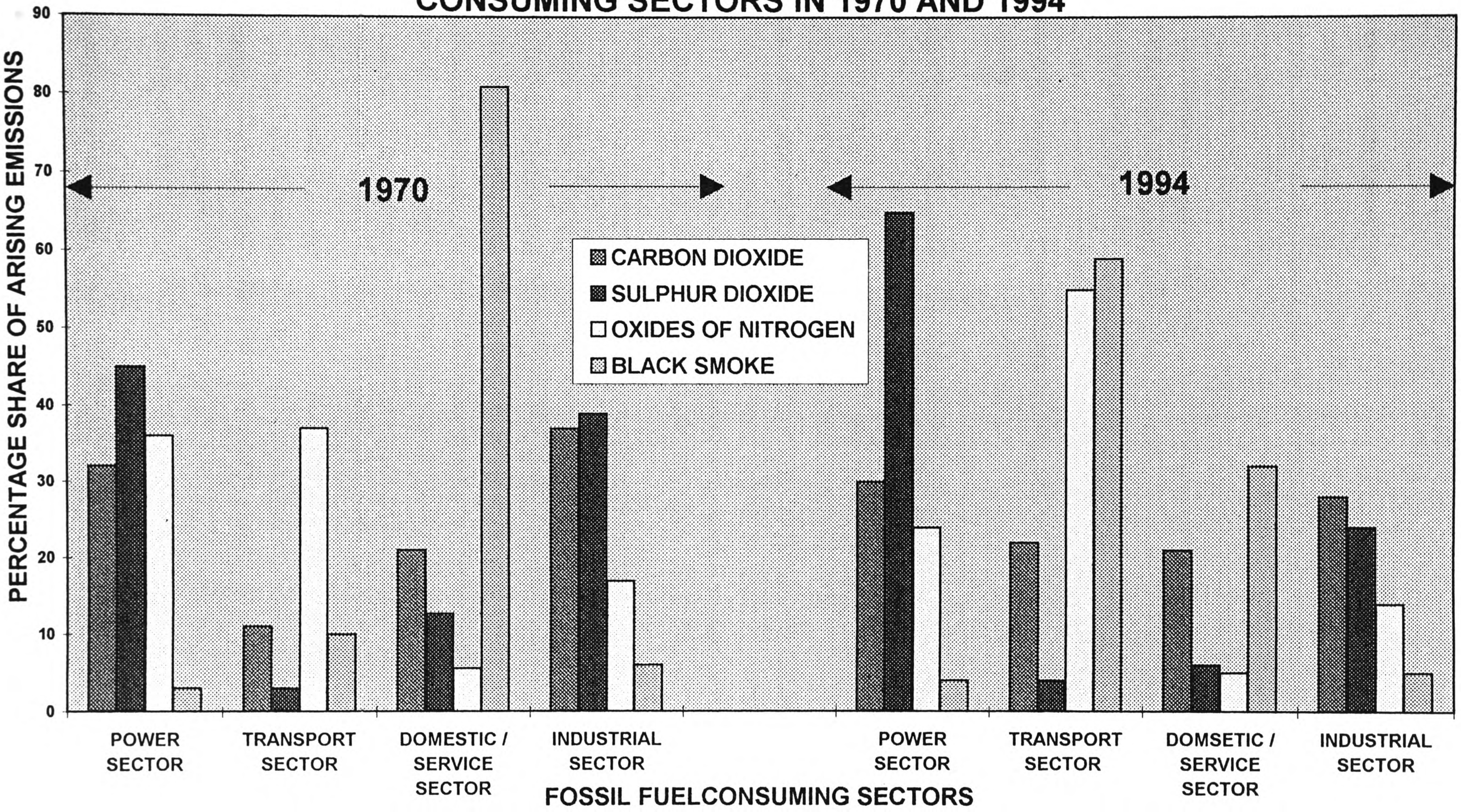
2.0 Black smoke arising from the domestic sector in 1994 accounted for 32 % of the total emission compared with 81 % in 1970 , which is attributed to the very sharp decline in the demand for coal in the domestic sector which is largely replaced by natural gas .

3.0 The road transport sector has remained the major emitter of NO_X which has steadily increased over the period and now accounts for well over over half of the total emitted .

4.0 In 1970 the industry sector generated the largest share of carbon dioxide , however by 1994 this had declined from 37 % to 27% , whereas the power generating sector retained its share of 30 % to become the major emitter.

A more detailed in depth study of the changing pattern of the four air pollutants arising from each of the energy consuming sectors is undertaken .

PERCENTAGE EMISSIONS ARISING FROM THE MAJOR FOSSIL FUEL CONSUMING SECTORS IN 1970 AND 1994



SOURCE : NETCEN ;CSO

FIGURE 26

12.1 Carbon Dioxide Emissions

Figure 14 has clearly demonstrated the changing pattern of the CO_2 emissions arising from the combustion of fossil fuel , which show a clear decline of 19 % over the 1970-1994 period . **Figure 27** traces the changing annual profiles of the emissions from the four energy consuming sectors . An overall assessment indicates a rapid decline in CO_2 from the industrial and power generating sectors , which is partly counter balanced by the increases from the domestic and transport sectors .

The power generating sector show a decline in CO_2 emissions of 23 % .This decline can be accounted for by :-

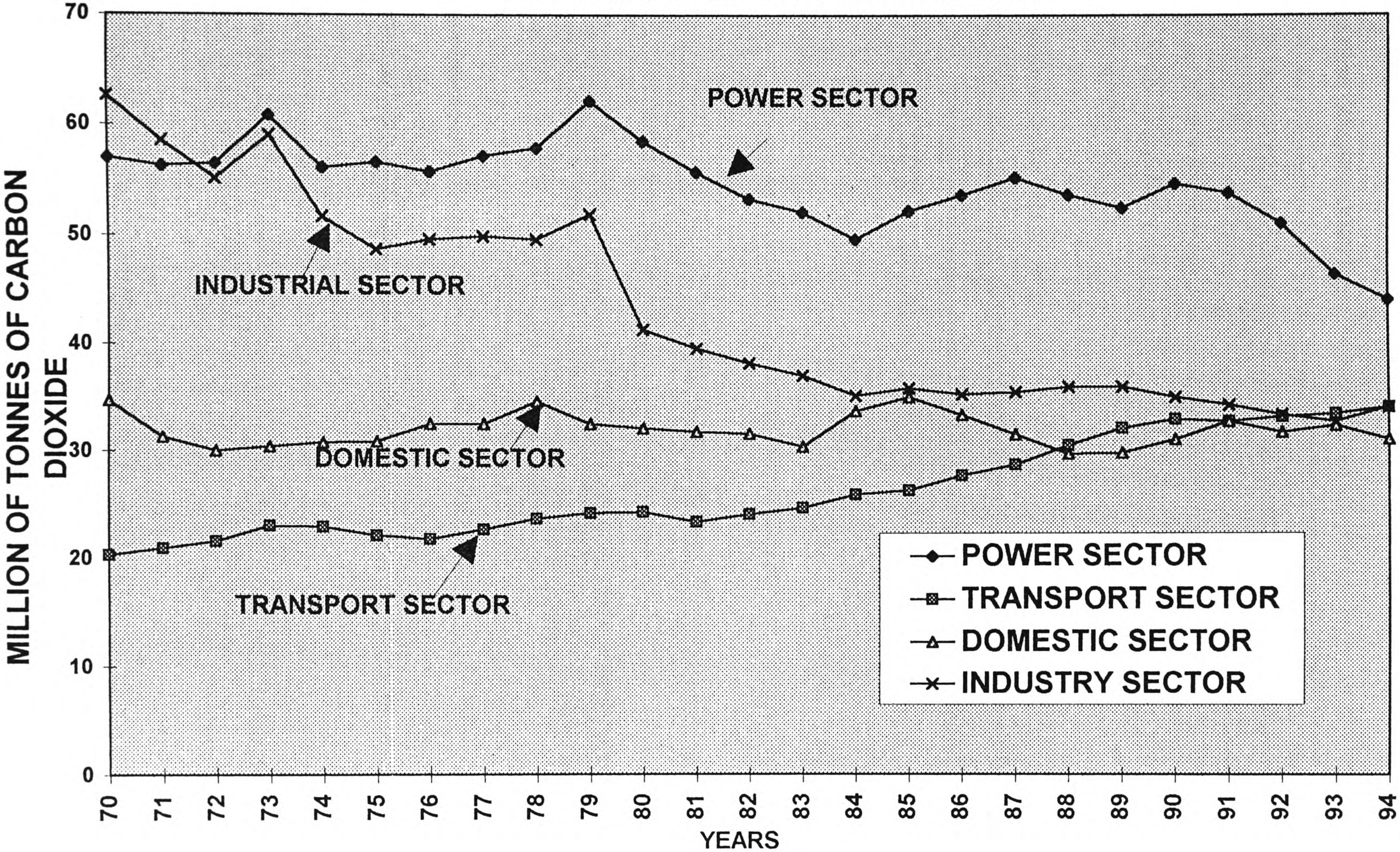
A 33 % reduction in coal consumption in this sector can be attributed to the introduction of Combined Cycle Gas Turbine (CCGT) power stations since 1990 .The CCGT stations operate with a high thermal efficiency of over 50% compared with coal fired operating plant which achieve up to 36 % conversion efficiency. The combination of utilizing natural gas which has a low carbon emission per unit of supplied energy and the CCGT station which operates within a high conversion efficiency resulting in an overall 50 % reduction in CO_2 per unit of generated power . Electrical generation from the nuclear power industry has partly replaced the power demand from conventional coal generation plant resulting in further reductions in CO_2 emissions .

The industrial sector CO_2 emissions have decreased by 46% .This can be accounted for by the decline in the demand for solid fuel and petroleum products which are classified as the high emitters of CO_2 being replaced by natural gas with a lower carbon emission factor , the lower level of manufacturing output and hence the lower demand for energy and finally the demise of the energy intensive industries like the iron and steel industry which operate with a very high consumption levels of solid fuel.

The transport sector CO_2 emissions increased by 78% over the 1970-1994 period . By 1994 the rapid expansion in road transport gave rise to a corresponding increase in CO_2 emissions , which accounted for over 90 % of the emissions arising from the transport sector. This sector in 1994 also accounted for 22 % of the total UK CO_2 emissions compared with 11% in 1970.

The domestic sector CO_2 emissions have remained relatively stable despite the decline in the use of solid fuel which possesses the highest carbon content per unit of

CARBON DIOXIDE EMISSIONS (AS CARBON) FROM ENERGY CONSUMING SECTORS 1970 - 1994



SOURCE : DIGEST OF ENVIRONMENTAL STATISTICS 1996

FIGURE 27

energy. This is attributed to the rapid expansion in the use of oil and natural gas central heating systems .

12.2 Sulphur Dioxide Emissions

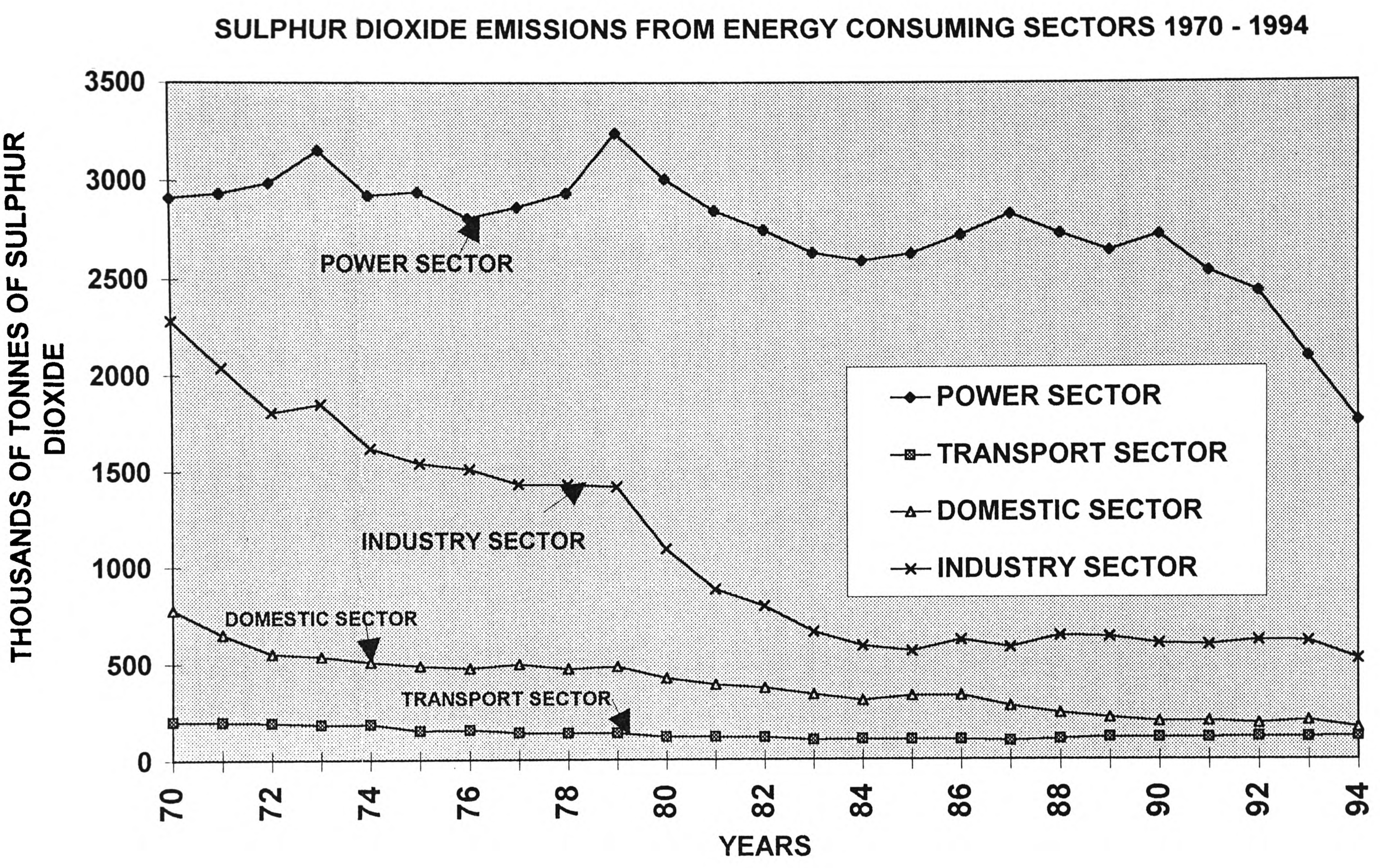
Figure **16** outlined the changing trend of SO_2 and demonstrates the dramatic fall in the overall sulphur dioxide emissions during the 1970-1994 period .This reduction is assessed to be 2 .7 million tonnes by 1994 equating to a reduction of 58 % overall fall .It can be seen from **Figure 28** the changing pattern of the emissions arising from the four major energy consuming sectors .

In the power sector the sulphur dioxide emissions have decline by 40% over the 1970-1994 period . This fall can be accounted for by the introduction of environmental legislation limiting emissions of SO_2 from Large Combustion Plant Sector , the introduction of major gas desulphurisation equipment (**22 and 23**) and the introduction of CCGT gas fired gas turbines.

The industrial sector exhibited a sharp fall in emissions over the period 1970 to 1985 there after it was stable . This trend has been influenced by the lower manufacturing output in the late 1970's , the improved energy efficiency, restructuring of industry especially the fuel intensive industries and the extensive use of natural gas replacing the high sulphur bearing fossil fuels .

The domestic sector has switched from coal to light fuel oil , natural gas and electricity consequently reducing sulphur dioxide emissions to 17% by 1994.

The transport sector emissions have declined by 40% since 1970 . Despite the increase in road transport and the consequential rise in total sulphur dioxide emissions, the decline in the consumption of fossil fuels in the other sectors of transport particularly heavy fuel in shipping and and coal in railway traffic which was replaced by diesel fuel the overall sulphur emissions in this sector have reduced . However it must be appreciated that even in 1970 during peak sulphur dioxide emissions arising from this sector it only represented 3 % of the total UK SO2 emissions.



SOURCE : DIGEST OF ENVIRONMENTAL STATISTICS 1996

FIGURE 28

12.3 Oxides of Nitrogen emissions

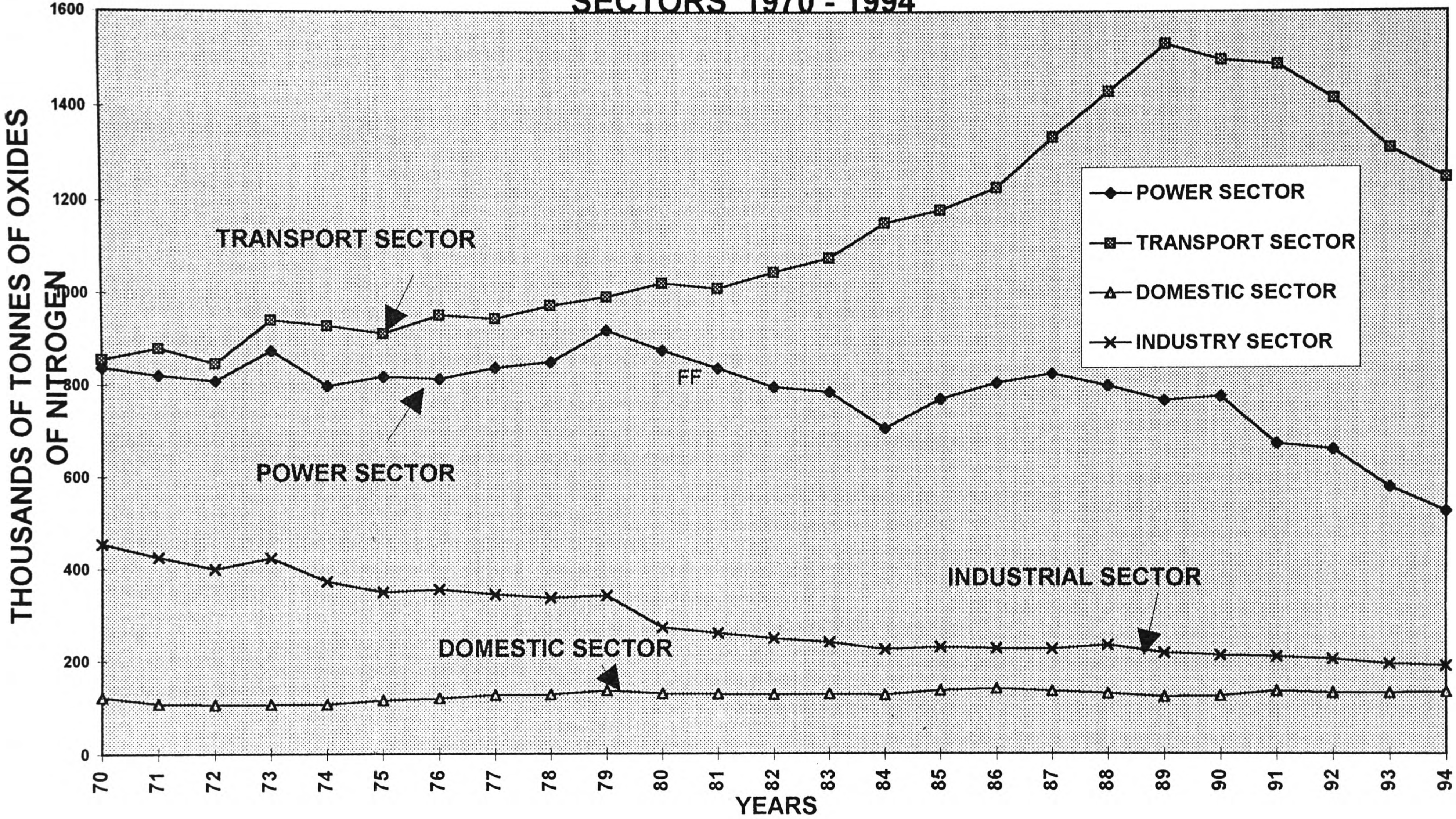
Over the 1970 - 1994 period the NO_X emissions peaked in 1990 and over the following four year period declined very dramatically .The overall decline between these years was a modest 6.0 % . However the emissions from the energy consuming sectors was relatively stable for a ten year period from 1970 to 1980 as demonstrated in **Figure 19** , but there after the emissions from the transport sector escalated but declined substantially from the power sector . The emissions arising from the combustion of petroleum in the form of road transport fuel increased while there was a notable down turn in the emissions from coal due to the decline in its use primarily in the domestic and industrial and to a smaller extent in the power generating sectors .

The transport sector increased its contribution by nearly 0.4 million tonnes of NO_X / year equating to an average annual rise of 2.0 % as shown in **Figure 29**. This can be clearly accounted for by the increase in road vehicle fuel demand of 98 % over the 1970-1994 period . Over the same period the mileage by road passenger vehicles increased by 117% **(7)** suggesting an increase in fuel efficiency . However during 1990-1994 there has been a sharp decline in NO_X emissions in the transport sector which can be partly accounted for by the introduction of the EEC legal requirement to install three- way catalytic converters to petrol vehicle exhausts in the early 1990's **(7)**. Glover (**13)** undertook measurements to quantify the effect of the TWC on reducing NOx emissions for three petrol engine capacities on national and urban roads .The results are outlined in **appendix 1** and compare the monitored emissions for petrol non - catalyst , petrol catalyst and diesel non - catalyst . Further analysis of the transport statistics data shows clearly the dramatic fall in the NOx emissions / kilometer travel ratio in the road sector in the 1990's which decline from 3.49 in 1970 to 2.77 grams / kilometer in 1994 .

Power sector NOx emissions have declined over the 1970-1994 period by over 0.28 million tonnes equal to an annual fall of 1.5% . This decline accelerated during the 1990- 1994 period equivalent to an annual fall of 6.4 % over this period ,which can be accounted for by the 25% reduction in consumption of solid fuel and the 54 % reduction in demand for fuel oil which were largely replaced by natural gas .

The industrial sector experienced a steady reduction in NO_X equivalent to 32 % over this period as shown in **Figure 19** , a reduction of 0.15 million tonnes by 1994.

OXIDES OF NITROGEN EMISSIONS AS NO_X FROM ENERGY CONSUMING SECTORS 1970 - 1994



SOURCE : DIGEST OF ENVIRONMENTAL STATISTICS 1996

FIGURE 29

This is largely due to improved production efficiency , restructuring of industry and the steady increase in the use of natural gas which expanded from 3% of the industrial market in 1970 to 33% in1994 .

The domestic sector is a minor contributor to NO_X emissions which have remained relatively constant over the 1970-1994 period .

12. 4 Black Smoke Emissions

Figure 22 shows a dramatic fall of 60 % in smoke emissions over the 1970-1994 period , a reduction of 0.6 million tonnes by 1994 . This is wholly attributable to the decline in the consumption of coal mainly in the domestic sector and to a lesser extent in the industry sector . However this decrease has been partly offset by increased emissions from diesel vehicles which currently emit over half the national total at 0.25 million tonnes by 1994 .

.

The domestic sector smoke emissions as shown in **Figure 30** have declined by 83 % from 0.77 million tonnes in 1970 to 0.093 million tonnes by 1994 . The domestic sector is clearly the principal reason for the major national decline in the smoke emissions over this period.

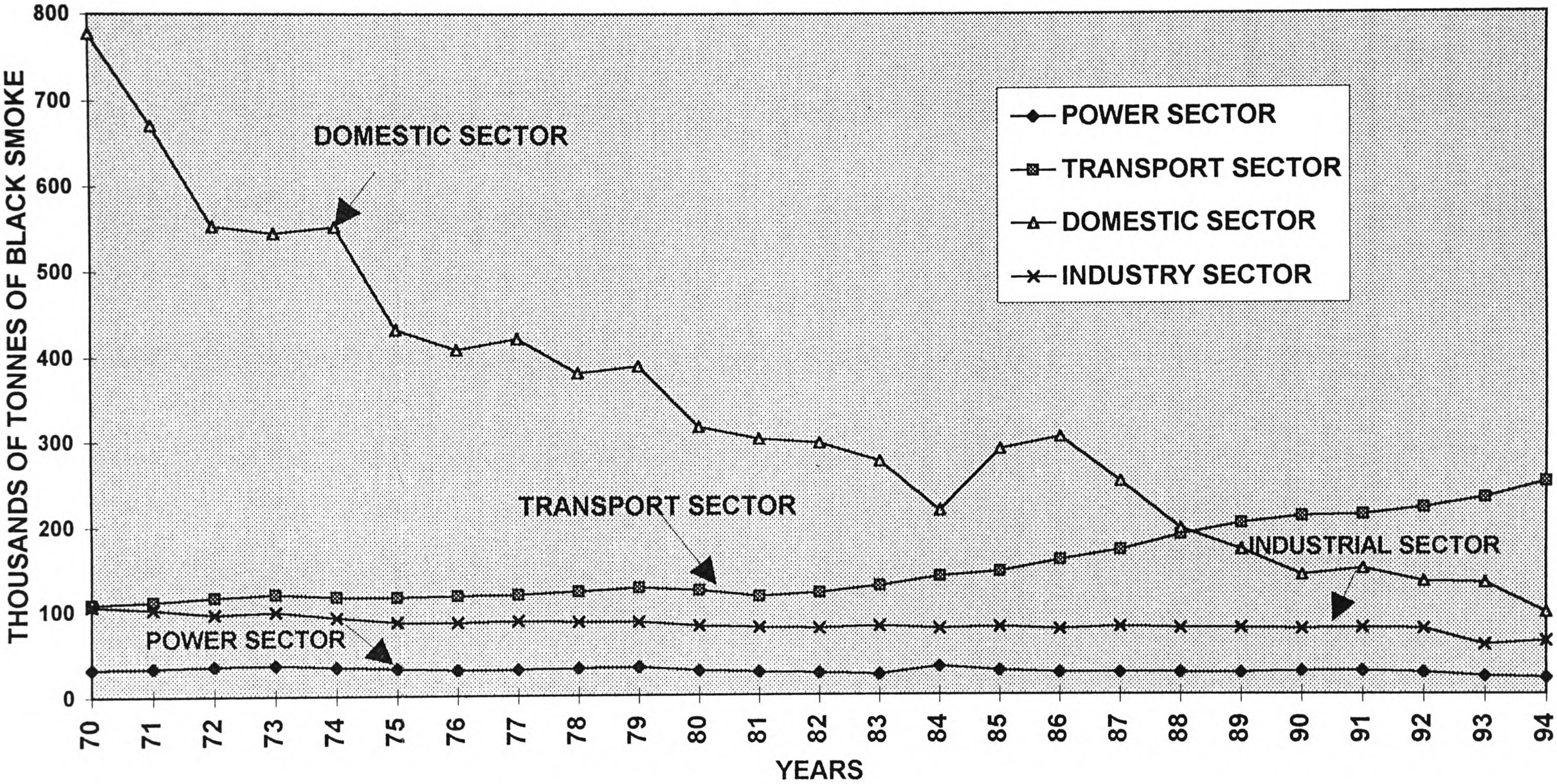
The transport sector in contrast to the domestic sector exhibited a 72 % increase in black smoke emissions over the same period .**Table 26** demonstrates the impact that the transport sector has had on the black smoke emissions over the past 25 years.

TABLE 26

The Impact of the Transport Sector on Black Smoke Emission in Thousands of tonnes 1970 to1994

Period	Total UK Black Smoke Emissions	Road Transport Black Smoke Emissions	Road transport Black Smoke Emissions as a % of the UK Total
1970	976	100	10.2
1975	890	109	12.2
1980	503	117	23.3
1985	485	141	29.0
1990	400	208	52.0
1994	385	247	64.0

BLACK SMOKE EMISSIONS FROM ENERGY CONSUMING SECTORS 1970 - 1994



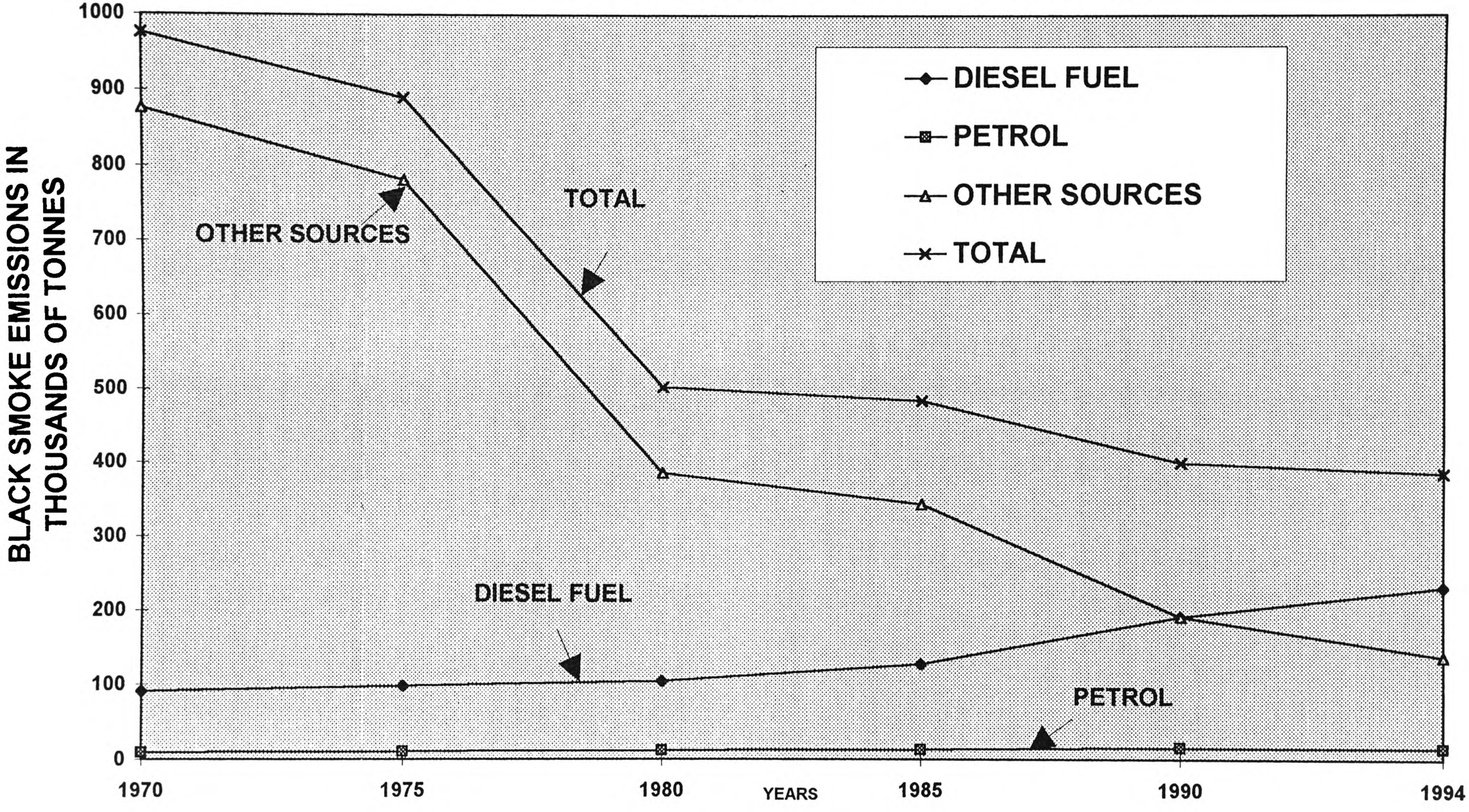
SOURCE : DIGEST OF ENVIRONMENTAL STATISTICS 1996

FIGURE 30

Energy demand in the transport sector is dominated by road transport of which diesel fuel currently accounts for 36% of the market share in the road transport sector in 1994 compared with 26 % in 1970 . It has already been shown in **Tables 15** and **16** that the black smoke emission factor for diesel fuel is in the order of 28 times that of petrol per unit of energy. The combination of increased demand for diesel fuel coupled with the higher black smoke emission factor accounts for the major rise in these emissions from the road transport sector **.**
Figure 31 demonstrates the changing scene of the contribution of black smoke emissions arising from petrol and diesel road vehicles . Both transport fuels showed a rise in emissions with the diesel sector being the dominant emitter .The remaining black smoke emissions in the 'other category' show a distinct decline in emissions . The contribution of petrol vehicles to these emissions is very small compared with the contribution from the diesel vehicles. By 1994 diesel vehicles accounted for 62 % of the black smoke emissions arising from fossil fuels which equate to 0.25 million tonnes .

The power sector level of black smoke emissions have declined by over 40% over the 1970-1994 period . There has been a steady decline over the 1970 -1990 years but a slight fall off in the following four years . This rapid decline is attributed to the increase in use of natural gas and the reduced consumption of fuel oil .However the average annual estimated emissions generated by this sector over the 1970-1990 period is the lowest of all the energy consuming sectors which represents only a few percent of the total national estimated emission despite the high consumption of solid fuel , which represent 67% of the total UK fossil fuel consumption . The average black smoke emission factor over this period was calculated to be a low value 323 grams / tonne of coal and 11 grams / Gj of coal , compared with the significantly higher values . industrial and domestic sectors as shown in **Tables 17 and 18** respectively . This tends to indicate that the modern power stations operate with a highly efficient combustion control system compared with other sectors to minimizing black smoke emissions .

THE CHANGING PATTERN OF BLACK SMOKE EMISSIONS FROM THE ROAD TRANSPORT SECTOR AND FROM THE REMAINING SECTORS



SOURCE : TRANSPORT STATISTICS GREAT BRITAIN 1996

FIGURE 31

13.0 Environmental legislation : The U. K. and EC regulations and World Agreements on Environmental Control

There has been 120 years of Government regulations , inspection and enforcement relating to air pollution control in the U.K.. The regulatory framework for the control of air pollution originated in the mid 19 th century when local and national legislation were formulated to prevent or abate the worst smoke emissions of Victorian factories . A classic example in recent times being the reduction in the emissions of smoke and sulphur dioxide leading to the London smog of the 1950's and early 1960's .During this period industrial smoke fell by 60 % and domestic emissions by 20% and in the following decade the industrial smoke problem was further reduced , with domestic emissions falling almost another 60 %.(**4**). The Government of the day gave high priority to protecting the environment , introduced major pieces of legislation in the form of two separate acts , the Clean Air Acts of 1956 (**24**)and 1968 (**25**) which were specific to the control of emission of black smoke from industrial or trade premises and included penalties for contravening the acts .

During the past 25-30 years a miriad of U.K. Legislation and E.C. Directives relating to air pollution control have been enacted and also a number of World Agreements have been reached in which the UK has participated . This thesis considers the influence of this legislation and agreements on emission control over this period . Some of the most recent influential Legislation and World Agreements on the control of atmospheric pollutants are listed below :-

1.0 Smoke and Sulphur Dioxide Control

European Community Directive 1983 on smoke and sulphur dioxide prescribes mandatory maximum values for ground level concentrations **(26).**

2.0 Sulphur Dioxide and NOx Control

The Council Directive (88/609/EEC) on the limitation of emissions of certain pollutants into the air from Large Combustion Plants **(27).**

EEC Directive 87 / 219 / EEC sulphur content of gas oil **(28).**

3.0 Carbon Dioxide Control

The UK Climate Change Programme published in 1994, set out in full UK policy and measures at returning emissions of each of the greenhouse gases to 1990 levels by the year 2000 (**29**)

4.0 Vehicle NO_x and Particulate Emission Control

EEC emission standards for passenger cars , light weight commercial vehicles, and heavy goods vehicles Council Directives 91/441/EEC **(30),** 93/59/EEC **(31)** and 91/ 542 / EEC **(32)**

13. 1 The Influence of Legislation and World Agreements are Assessed for each Pollutant

13.1.1 Carbon Dioxide

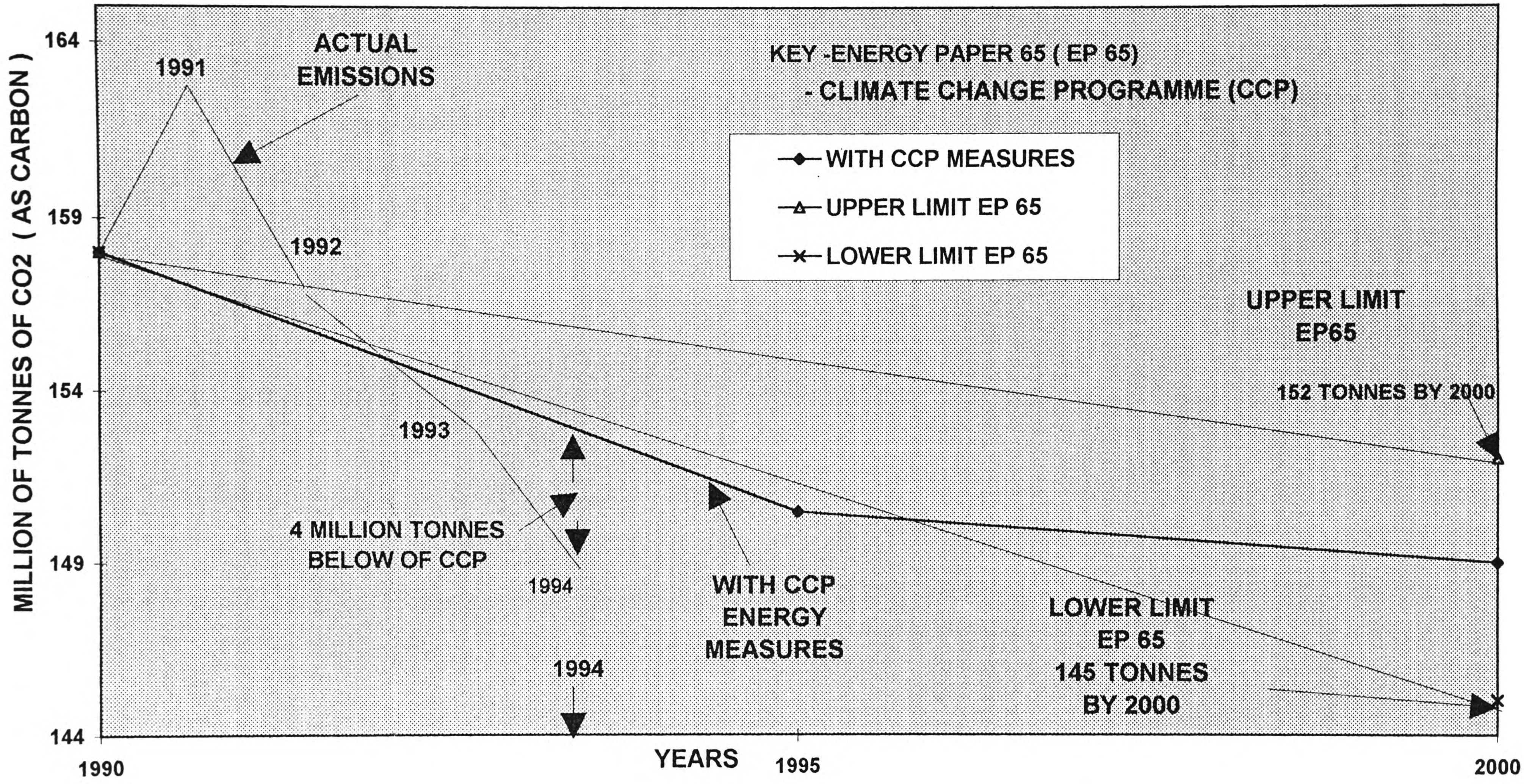
The UK Climate Change Programme 1994

The major influence on controlling carbon dioxide emissions over the 1970-1994 period has been the UK Climate Change Programme 1994 (CCP) **(33)** ,which sets out in full the UK policies and measures aimed at encouraging energy efficiency across all sectors of the economy in order to return to the 1990 level of 158 million tonnes (as carbon) by the year 2000 .

Figure 32 provides a comparison between the emission reduction in CO_2 emissions outlined in the CCP energy improvement programme to be adopted 1990-2000 and the actual CO_2 emissions achieved over the 1991 - 1994 period . It can be seen in this figure that the actual emission level by 1994 was 4 million tonnes below the CCP line for that year . It can be understood why the 1995 DOE progress report **(33)** contained the statement that "the UK is confident of meeting its current commitment under the Climate Change Convention" since the report projects that the CO_2 emission level will be comfortable within a band of 6-13 million tonnes of carbon (4-8%) below 1990 levels by the year 2000 as demonstrated in **Figure 32 .**

This rapid reduction in CO_2 emissions between 1991 and 1994 is attributed to two major factors :-

IMPACT OF THE UK CLIMATE CHANGE PROGRAMME MEASURES ON CARBON DIOXIDE EMISSIONS



SOURCE : CLIMATE CHANGE UK PROGRAMME DOE 1995

FIGURE 32

1 The introduction of Combined Cycle Gas Turbine Stations with a capacity of 12 GW to replace conventional coal fired power stations result in a lower level of CO2 emission due to the use of natural gas which possesses a much lower carbon content than
coal and the higher operating thermal efficiency with CCGT stations The overall saving equates to 50% reduction in carbon dioxide per unit of output.

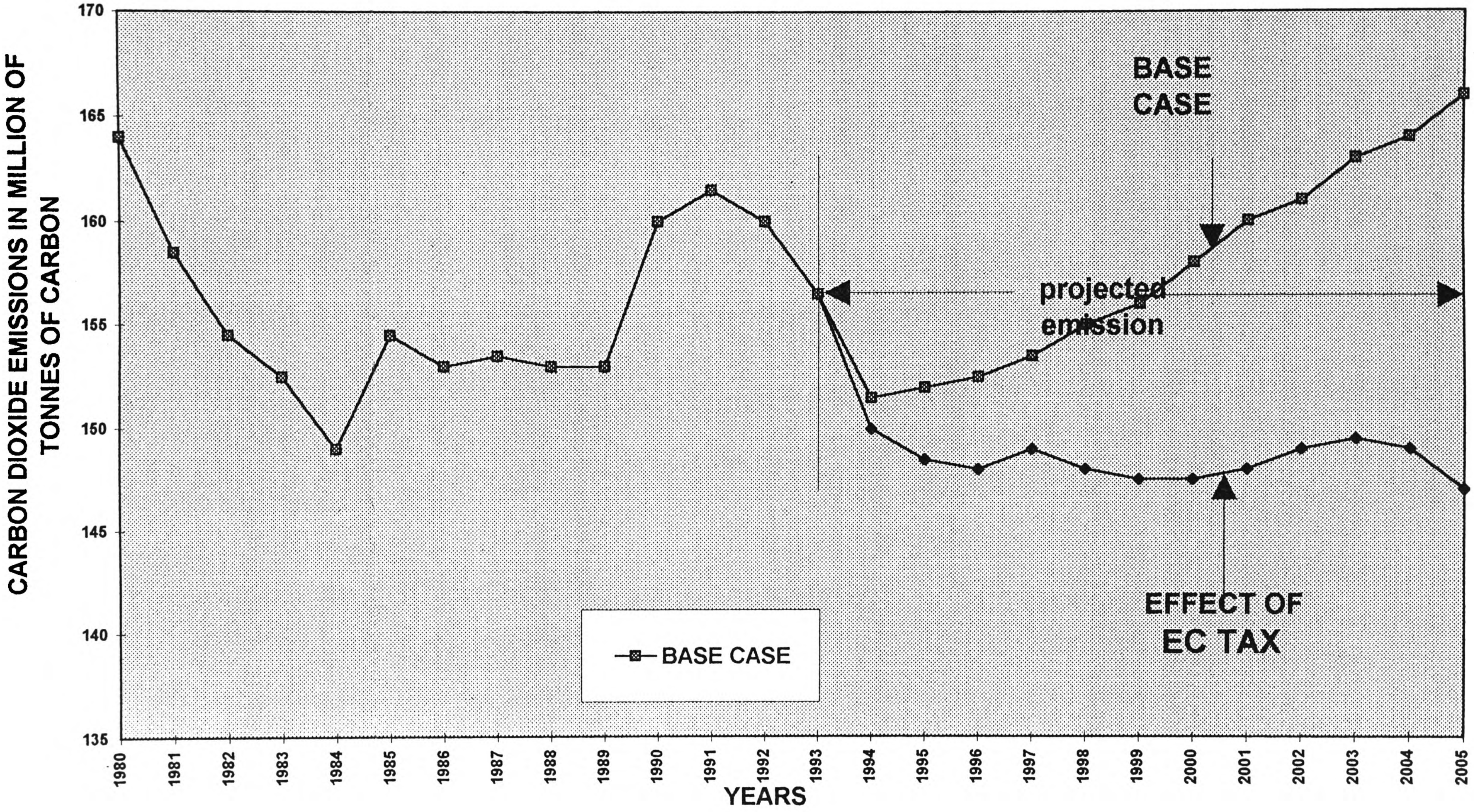
2 An increase in nuclear power output of 6.3 % between 1990 and 1994 which accounts for 26.0 % of the total power generation in 1994 . Hence reducing the demand for power and the associated emissions of CO_2 from conventional power stations fired with fossil fuel .

PowerGen plc annual environmental review supports the downward trend taking place in the power generating sector . It claims in the report **(34)** a steady and successful 14% reduction in CO_2 emissions in its operation over the 1990-1994 period due to a combination of the introduction of the CCGT plants and improved efficiency .

13.1.2 UK Carbon / Energy Tax

A carbon / energy tax has been proposed by the European Commission to start at US $ 3 per barrel oil equivalent in 1993 , rising to US $ 10 in 2000 **(35)**. It was envisaged that the tax would be indexed in line with inflation from 1993 ; it was assumed that after year 2000 the tax would stay at US $ 10 . The tax rates would be allocated across fuel consumption i.e., 50% in accordance with calorific value and 50% in accordance with carbon content .
The effects of this tax on the UK economy has been assessed at the Cambridge University Department of Applied Economics using a large scale energy- environment - economy model **(35).** The projections of the model are shown **in Figure 33** which demonstrate the impact of EC tax on carbon dioxide emissions up to the year 2005 The base case which does not include the projected effects of CCP energy improvement schemes , and hence shows a dramatic increase in emissions between 1994 and 2005 from 151 to 166 million tonnes of carbon in contrast to the DOE report (33) **.** However the implementation of this proposed tax would have achieved a stable CO_2 emission over the 1994- 2005 period and by 2005 the emissions could have reduced to147 million tonnes a fall of 0.4 millions tonnes below the 1990 level.

THE IMPACT OF EC CARBON TAX ON CARBON DIOXIDE EMISSIONS UP TO THE YEAR 2005



SOURCE : ENERGY POLICY 1993

FIGURE 33

The overall effect of the CCP measures coupled with the influence of the EC tax on fuel would have resulted in a total reduction of 28 million tonnes of CO_2 emissions over the 1990 - 2000 period i.e. 9 and 19 million tonnes respectively .
Although this tax provides a significant potential for reducing carbon dioxide , it has been abandoned (**36**) following the refusal of the EC ministers to endorse the proposal in 1993 .Disagreement over the contribution of the poorer EC Member States to the tax brought about the proposal's rejection .Nevertheless for completeness it has been considered necessary to evaluate the implications of such a tax and assess the scale of the reductions in emissions .However the EU could implement this proposal sometime in the future and hence its potential effect on the UK CO_2 emission scene should be kept under constant review.

13.2 The influence of Legislation on Sulphur Dioxide Emissions

Four major pieces of environmental legislation have been enacted to control sulphur dioxide during the 1970 - 1994 period :-

Firstly The Control of Pollution Act of 1974 included regulations under section 76 to limit the sulphur content of oil fuel defined as any liquid petroleum product produced in a refinery and later the EC Directive 87 / 219 EEC setting a limit of 0.3% on sulphur content of gas oil used as domestic fuel .

Secondly in 1980 a European Council Directive 80 / 779 / EEC **(26)** was enacted which came into force in 1983 prescribing mandatory maximum values for ground level concentrations of smoke and sulphur dioxide .

Thirdly an EEC Directive has been enacted imposing legislative limits on the sulphur content of petrol and diesel fuels . In 1990 the standards requirements were 0.1 % for petrol and 0.3 % for diesel . By 1994 the legislation would further reduce the permissible sulphur content for diesel from 0.3% to 0.2% and by 1996 both petrol and diesel will have a maximum of 0.05 % sulphur . However the road transport sector only accounts for 4% of the total sulphur and therefore these measures would have only a marginal effect on the overall UK emission levels .

Fourthly in 1990 a European Council Directive was enacted to limit the sulphur dioxide emissions into the air from large combustion plant (**37**) with thermal inputs equal to or greater than 50 MW .In response to this Directive the UK prepared a National action plan for the reduction of SO_2 emissions from these plants (**27**) in the period 1991 to 2003 which are outlined in **Table 27**.and in **Figure 34.**
The plan was designed to limit the overall emissions from these plants from a base line in 1980 by 15% in 1987 , 21% in 1993 , 45 % in 1998 and 63 % by 2003 which is detailed in Table 27 .

TABLE 27
Base Year 1980
UK's Proposed National Plan to reduce SO_2 emissions

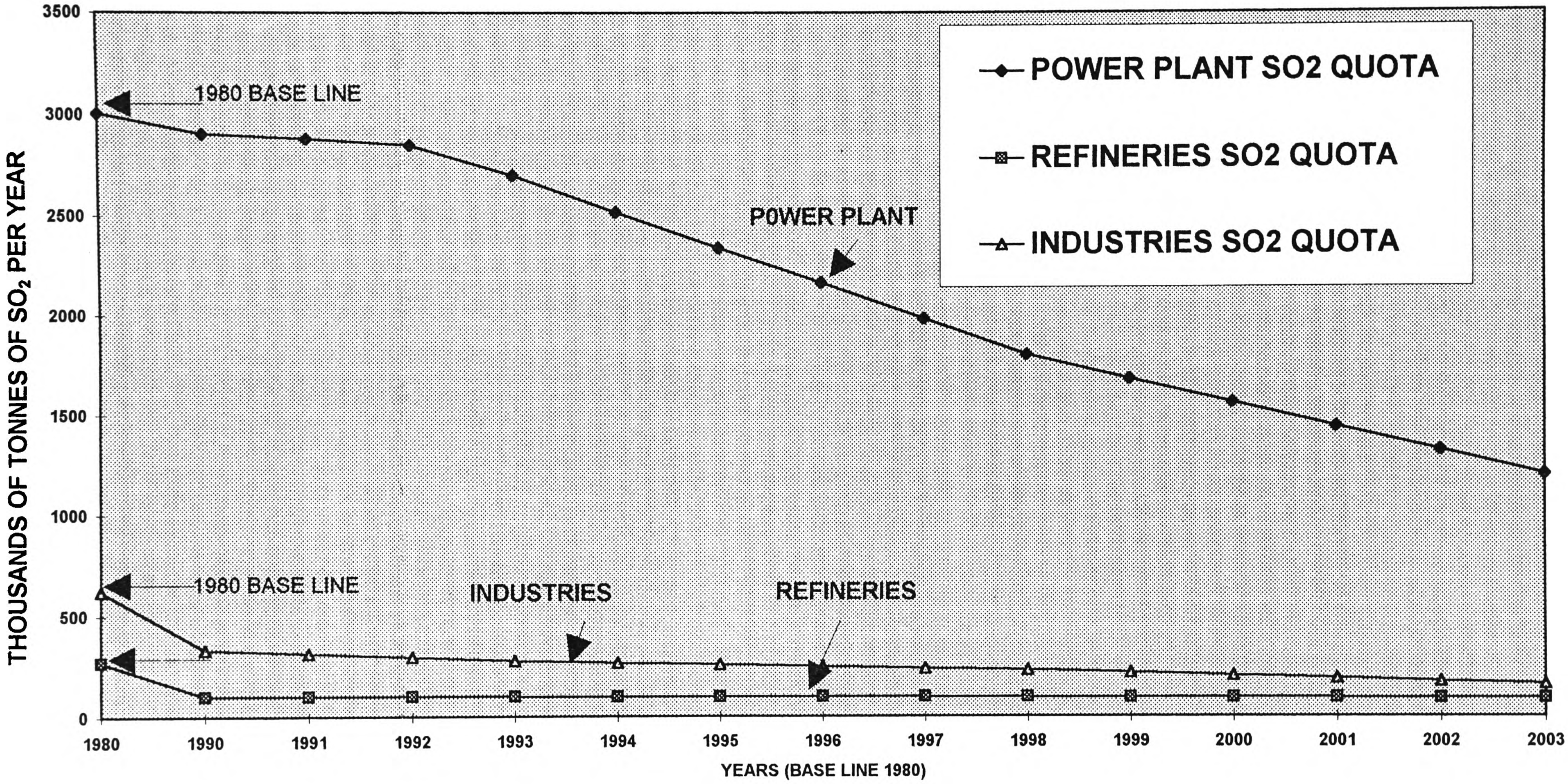
	1980	1987		1993		1998		2003	
	k tonnes	k tonnes	% red	k tonnes	% red	k tonnes	% red	k tonnes	% red
Power stations	3007	2830	5.9%	2700	10 %	1803	40 %	1202	60%
Refineries	282	162	49.0 %	100	63%	95	65 %	90	66 %
Industry	600	307	43.0 %	276	56 %	230	63 %	160	74 %
Overall	**3895**	**3299**	**15 %**	**3076**	**21 %**	**2128**	**45 %**	**1452**	**63%**

The National plan proposed a possible total reduction of emissions from three sectors:- , power plants , oil refineries and other industries equivalent to 2443 k tonnes by the year 2003 a 63% overall fall .
Figure 35 outlines the level reductions that have been achieved over the 1980- 1994 period and demonstrates how these actual estimated emissions values compare with the annual emission quotas . It can be seen that in 1994 the SO_2 emissions were 49 % below the 1980 baseline level 9 % ahead of the 1998 EC target level.
The following measures were adopted as part of the National action plan to achieve these emission levels (**27**).

The electricity supply industry(ESI)

1. Retro - fitting 8 Gigawatts flue gas desulphurisation equipment (FGD) on existing coal fired stations designed to remove more than 90% of SO_2 in the waste gas stream.

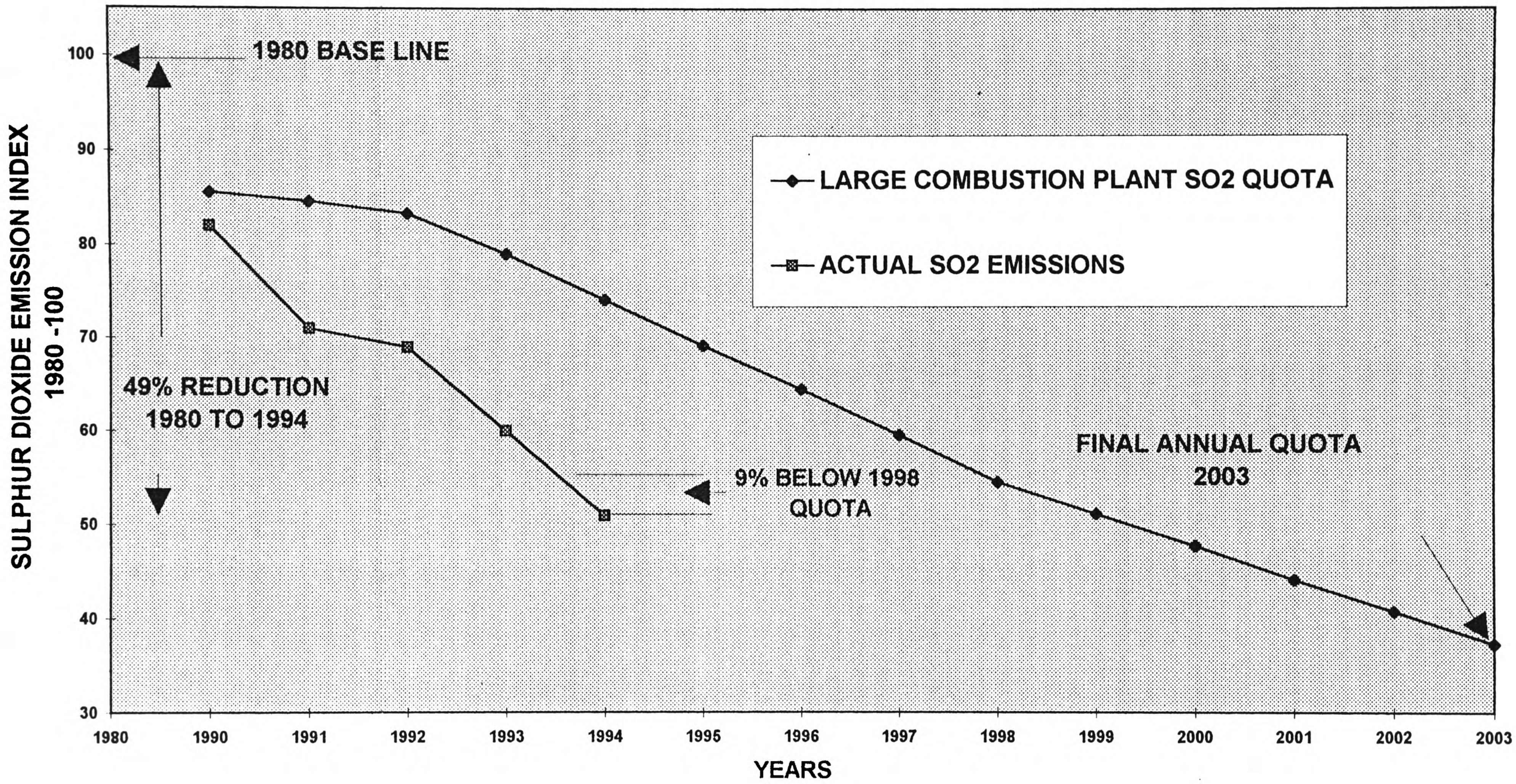
UK NATIONAL PLAN FOR REDUCING SULPHUR DIOXIDE EMISSIONS FROM LARGE COMBUSTION PLANT DURING 1990 - 2003



SOURCE : DEPARTMENT OF THE ENVIRONMENT 1990

FIGURE 34

ACTUAL SULPHUR DIOXIDE EMISSION VALUES FROM LARGE COMBUSTION PLANT COMPARED WITH THE UK NATIONAL PLAN VALUES



SOURCE : EEC DIRECTIVE1990 AND DEPARTMENT OF THE ENVIRONMENT 1990

FIGURE 35

2. Switching to new low - polluting plant , notably Combined Cycle Gas Turbines (CCGT) This will provide a two stage improvement , by using natural gas a lower polluting fuel and the higher efficiencies achieved with CCGT power stations.

3. The use of low- sulphur coal in existing coal- fired power stations.

<u>The oil refineries</u>

The directive states that the oil refineries should not increase SO_2 emissions over those of 1987 i.e. 162 ktonnes per annum.

<u>Other industries</u>

An annual 3.3% reduction would be achieved by up- grading existing plant to new standards and natural plant closure i.e down to 160 k tonnes by the year 2003

Powergen Ltd have reported a significant overall reduction of 22.6 % in SO_2 emissions over the 1990-1994 period **(34)** , which supports the findings of the thesis that there is a specific downward trend in SO_2 emissions from the power sector.

Figure 16 demonstrates the overall decline in sulphur dioxide emissions . It is difficult to quantify exactly the improvement that can be attributed to enactment of this legislation since other factors such as the recession in manufacturing industry in 1979 as shown in **Figure 28** and the extended use of natural gas have played an important part in the fall in these emissions . However there has been a significant fall in these emissions in the power generating sector which can only be attributed largely to the implementation of the National Plan **(27).**

13.3 The Influence of Legislation on Oxides of Nitrogen Emissions

The total emissions of oxides of nitrogen peaked in 1989/1990 , but there after declined as shown in **Figure 19 .** This can be attributed to three pieces of environmental legislation.

Firstly the UK commitment under the first UNECE Protocol **(47)** to return its emissions to 1987 levels of 2.56 million tonnes by 1994 and this target was achieved in 1994 since then it has declined well below this target level .

Secondly an EEC Council Directive was enacted in 1988 (**37**) to limit the emissions of oxides of nitrogen from Large Combustion Plant over the 1993 to 1998 period taking 1980 as the base line . In response to this Directive annual NO_X emission targets for each of the power generating sectors were agreed and are formally set out the UK's National Plan outlined in the **Table 28** and in **Figure 36**.

TABLE 28
Base Year 1980

UK' s Proposed National NO_X Emission Targets

	1980	1987	1993		1998	
	ktonnes	ktonnes	ktonnes	% red	ktonnes	% red
Electricity supply	897	820	757	16%	622	31 %
Refineries	43	34	32	26 %	27	37 %
Other industries	187	141	118	37 %	100	47 %
Overall	1127	995	907	21 %	749	35 %

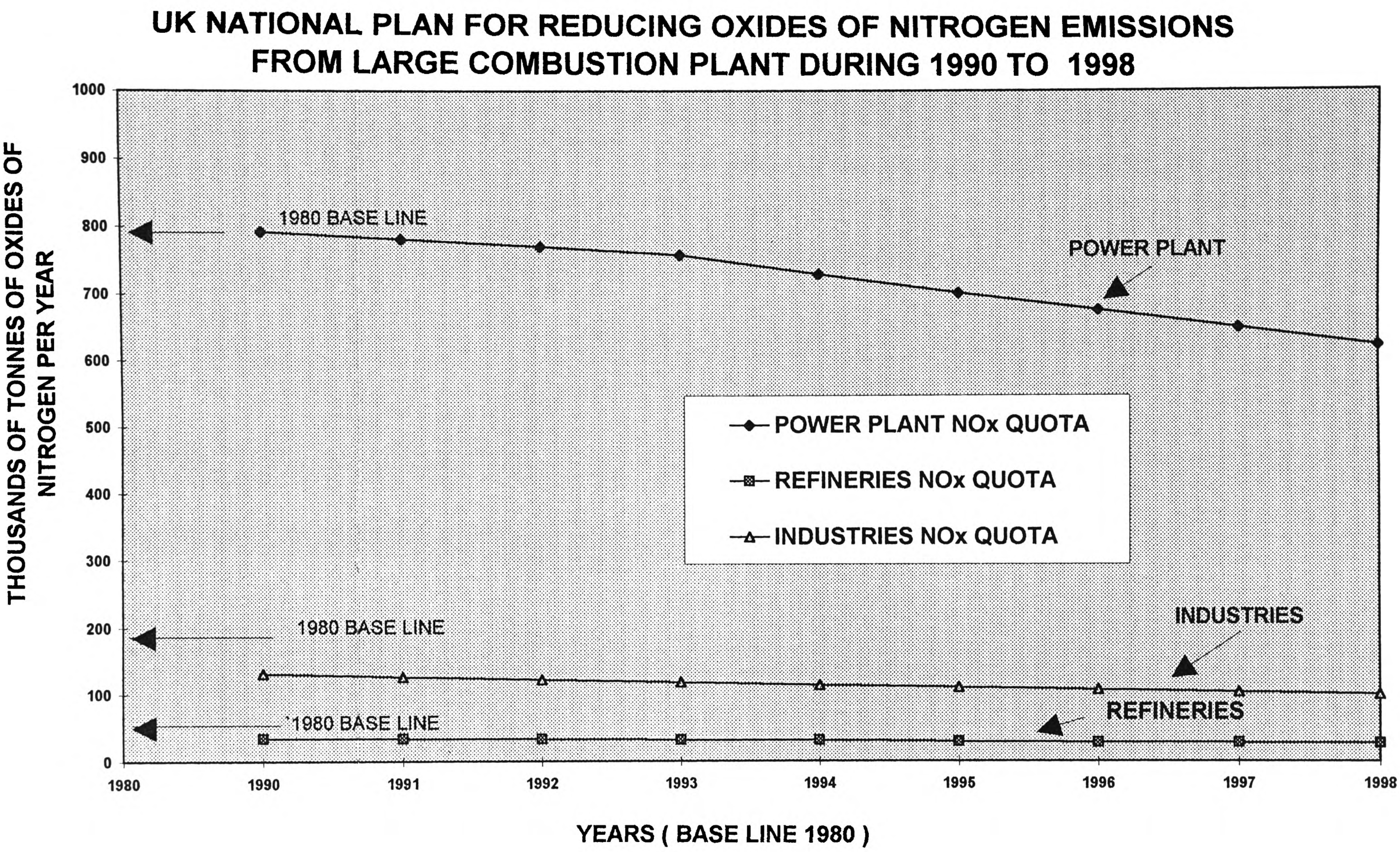
The overall reduction proposed in the a National Plan was 378 kilo tonnes by 1998 from the 1980 base line.

Figure 37 demonstrates the remarkable reductions that have been achieved in these sectors over the 1980 -1994 period . In 1994 the emission level was 45% below the 1980 level and 12% below the 1998 i.e. 5 years in advance of that required in the Directive .

The measures outlined in the National Plan and adopted in the strategy are presented below

The Electricity Supply Industry in England and Wales

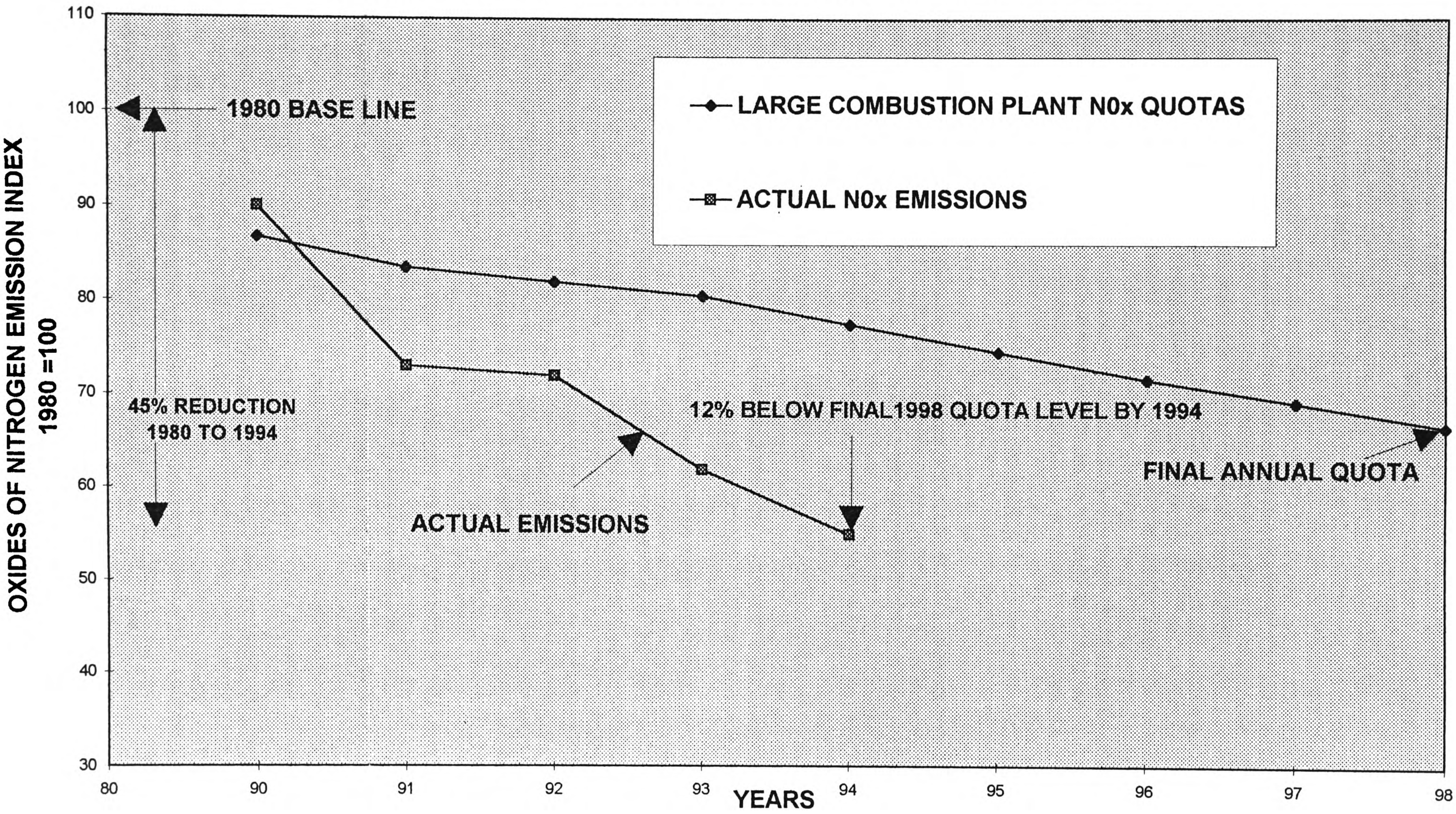
The fitting of low-NO_X burners to the Electricity Supply Industries major coal - power stations commenced in 1987. Typically low NO_X burners achieve reductions in NO_X of between 35 and 45 % (**27**) . **Figure 37** clearly demonstrates the effectiveness of this low - NO_X installation programme .



SOURCE : DEPARTMENT OF THE ENVIRONMENT 1990

FIGURE 36

ACTUAL OXIDES OF NITROGEN EMISSION VALUES FROM LARGE COMBUSTION PLANT COMPARED WITH THE UK NATIONAL PLAN VALUES



SOURCE :EEC DIRECTIVE 1990 AND THE DEPARTMENT OF THE ENVIRONMENT 1990

FIGURE 37

Oil refineries
Emission limits of NO_X are based on the principle that no oil refinery should increase its emission over those in 1987.

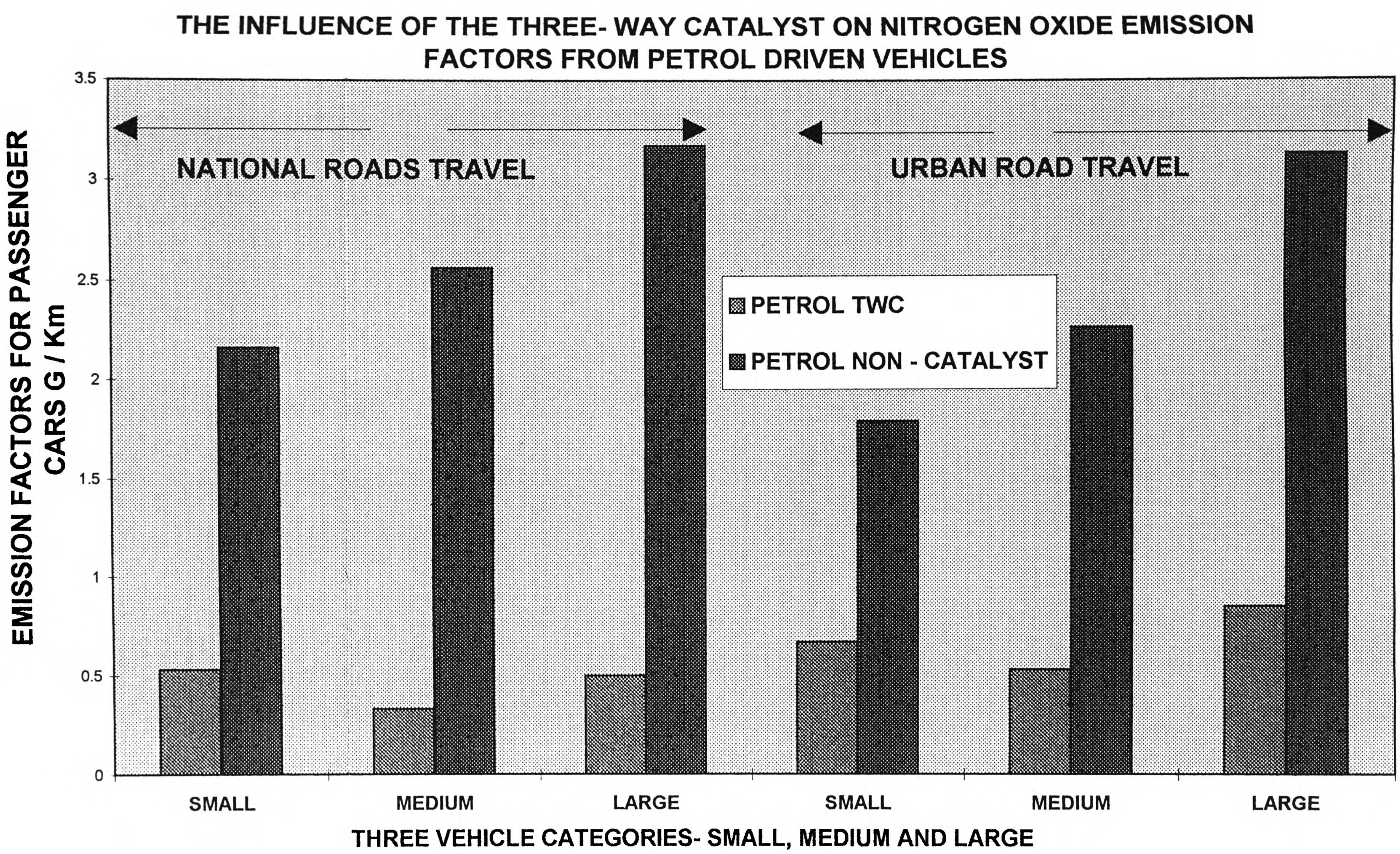
Other Industry
For other industries the emission quotas will be meet by an annual reduction of 3.3% through the normal upgrading of existing plant to new standards and normal plant closure.

Figure 37 compares the actual estimated NO_X emission levels against the quota values outlined in the UK Plan (**27**) The 1994 emissions are 45% below the 1980 baseline and lower than the quota target value set for 1998.

PowerGen's plc 1995 annual environmental report and accounts document has confirmed the downward trend in NO_X in the power generating sector and outlined a 27.4 % reduction in NO_X in its operating plant over the 1990-1994 period **(34)**

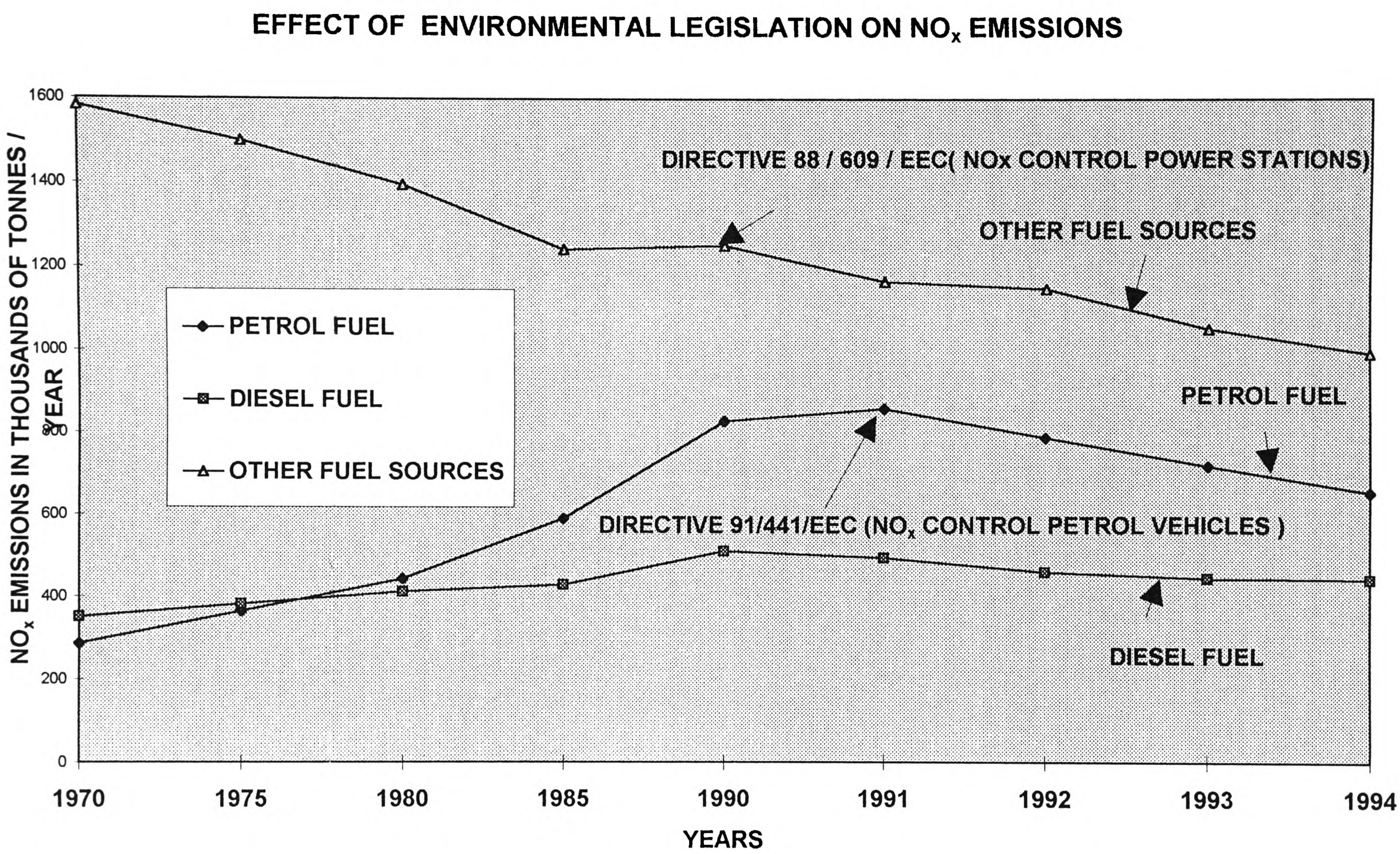
Thirdly the introduction of the EEC Directive 91/441/EEC was enacted in 1992 with the objective of reducing oxides of nitrogen from passenger cars in the road transport sector .The legislation requires the installation of a three - way catalyst (TWC) to petrol driven vehicles to reduces the exhaust emissions .The Department of Transport's Transport Research Laboratory (**38**) has undertaken measurement trials to quantify the decline in emissions with the TWC for three different engine capacities and three different road types.
Figure 38 summarizes the TWC trial results and clearly shows that the implementation of the Three- Way Catalyst on petrol passenger cars will have a major effect on the oxides of nitrogen emission factor . The factor has been declining since 1989 , however the rapid acceleration in the decline in the emission factor over the period 1991 to 1994 as shown in **Figure 21** can be attributed to the installation of the TWC units in new petrol cars , since the trials undertaken **(Appendix1)** show a reduction of between 73 to 83 % of NO_X emissions per kilometer of travel can be achieved .It is also interesting to note that the emission factor increases with engine size per kilometer of travel .

The overall effect of NO_X legislation measures have been assessed in this chapter and are outlined in **Figure 39** . The decline in the UK NO_X emissions can be attributed to a number of reasons as already discussed in this thesis . However a significant



SOURCES : DEPT of TRADE INDUSTRY AND THE DEPT OF TRANSPORT 1994

FIGURE 38



SOURCE : DEPTARTMENT OF TRADE and INDUSTRY . AND THE DEPARTMENT OF TRANSPORT 1994.

FIGURE 39

contributory factor is considered to be the wide installation of low - NO_x burners on coal fired power stations as directed by the EEC . The power sector in 1990 accounted for over 30% of the total emissions of NO_x , hence the legally enforced use of these low- NO_x burners has provided considerable scope for a reduction in the power sector which has already been reflected in a major downward trend in the UK NO_x emissions.

The EEC Directive on NO_x from petrol engines can be seen in **Figure 39** to have had a major effect on the emission level in the early 1990's despite the 4% increase in petrol engine usage over this period .By 1991 the increase in emissions were halted and reversed and a rapid decline is seen over the 1991-1994 period as more newly registered petrol driven passenger cars were fitted with the TWC units .

13.4The Influence of Legislation on Black Smoke Emission Control

Black smoke emissions have fallen significantly as a result of legislation including the 1956 and 1968 Clean Air Acts and EEC Directives eliminating domestic coal combustion in many urban.areas .
The mass emission of black smoke from coal has declined by 86 % from 0.825 million tonnes in 1970 to 0.117 million tonnes in 1994 partly as a result of the implementation of legislation , which was instrumental in influencing the switch to cleaner fuels including smokeless fuel , lighter petroleum products and natural gas .
Pearce (**39**) concluded following epidemiological studies that health damage appears to be related to particle matter of less than 10 micron diameter , i.e. PM 10. The major source of PM10 particulates in 1970 arose from the domestic sector and accounted for 40% of the total , whereas this percentage had reduced significantly to 14% by 1994 **(2)** . The road transport sector generated the major share in 1994 equivalent to 25% of the total particulate matter , due largely to the increase in the diesel vehicle traffic **(5)** .However the total PM 10 particulates have been reduced by 53 % over the 1970-1994 period in line with the total black smoke at 58% . This reduction in PM10 can be largely attributed to the same factors that reduced the black smoke emissions ie Environmental legislation measures .

14.0 Future Projections for Energy Demand and Mix and also Atmospheric Emissions up to the Year 2020.

It has already been shown **in Table 4** that the combustion of fossil fuels is by far the major contributor to atmospheric pollutants considered in this thesis and that any change in the UK's future energy demand and mix would effect on the UK's overall atmospheric pollution . This chapter presents and analyses the future emissions for years 1990 to 2020 period , which are based on the product of predicted energy demand and mix for this period outlined in the DTI Energy Paper 65 **(40)** and the emission factors derived or from empirical data established in this thesis .

14.1 Projected Primary Energy demand 1990-2020

Ever since the 1950's official projects have been undertaken by government departments to produce estimates of future energy demand **in 1995 (40) 1992 (41) and in 1990 (42) .** Extensive investigative work resulting in many technical papers on forecasting energy demand has been carried out by a number of researchers including Kouris 1976 **(43)** Wigley 1984 **(44)** and Hsioa 1985 **(45)** .Most researchers forecast future energy consumption by employing the energy - econometric modeling approach using historic energy trends , assuming future energy prices and GDP / income level .

The most comprehensive recent example of energy - econometric modeling is undertaken in the Energy Paper 65 **(40)** . It develops energy models which forecast energy demand and energy mix on a disaggregated basis approach for the four energy consumers separately ; industry , domestic , transport and power generating sectors . The results of the modeling were published in the Energy Paper , however the basis on which the final energy demand equations were selected from the 160 econometric equations developed by the modeling was not available for analysis.. However the predictive ability of such energy - econometric models have been well established by Blakemore et al **(46)** .These models were developed for the manufacturing and domestic sectors and were shown to exhibited highly statistical significant coefficients for GDP/ income , manufacturing output , disposable income and energy price determinants .The chosen model for each sector exhibited good predictive ability, suggesting the effects of market forces in terms of GDP / income and energy prices were quantifiable and could be used to forecast future energy demand **Appendices 2 and 3.**

The statistical relationship developed by Blakemore (46) when using the energy - econometric technique for forecasting energy demands for each of the energy consuming sectors is shown below .

The chosen model equation for prediction for the manufacturing industry is shown below :-

$$\log E = 2.725 + 0.6478 \log Y - 0.2426 \log P$$

$$'t'\ (6.219) \qquad 't'\ (-2.847)$$

$$R^2 = 93.07 \qquad F = 8.105$$

The selected model equation for the domestic sector is outlined below :-

$$\log E = 2.465 + 0.6862 \log PDI \quad -0.2278 \log P$$

$$'t'\ (8.273) \qquad 't'\ (-2.593)$$

$$R^2 = 94.80 \qquad F = 2.613$$

E = Energy Demand Y= Manufacturing Output P = Energy Price

DPI = Disposable Personal Income 'R^2 't' and F statistical determinants

It is important not to underestimate the uncertainties inherent in projecting the future path of energy demand .Therefore to improve the accuracy of forecasting the Energy Paper 65 (40) examined a set of six different scenarios which included three UK plausible growth levels in the economy and a low and high world fossil fuel price for crude oil , coal , and gas for five year periods from 1990 to 2020 which are outlined in tables 29 and 30 .

The assumptions for each scenario are :-

TABLE 29
U K Economic Growth Assumptions up to 2020

High Growth	2. 85 %
Central Growth	2.35 %
Low Growth	1.75 %

TABLE 30

World Fossil Fuel price assumptions up to 2020 (£ / Gj)

	Crude oil		Steam Coal		Gas	
	low	high	low	high	low	high
1990	2.33	2.33	4.815	4.815	1.73	1.73
1995	1.50	2.00	4.00	4.50	1.60	2.0
2000	1.50	2.50	4.50	5.00	2.0	2.6
2005	1.50	1.75	4.56	5.115	2.2	28.8
2020	1.50	3.50	5.00	6.00	2.5	3.70

The six senarios considered are defined as following :-

Low GDP - Low energy price (L / L)
Low GDP - High energy price (L / H)
Central GDP - Low energy price (C / L)
Central GDP - High energy price (C / H)
High GDP - Low energy price (H / L)
High GDP - High energy price (H / H)

The results of this energy predictive modeling work are outline in **Figure 40**, it can be seen that the future primary energy demand increases for all six scenario . The base case in 1990 was 220.8 millions toe equivalent . The model predicted that this would increase to 253.4 million toe for the L / H scenario and to 298.7 million toe for the H / L scenario by the year 2020 equivalent to a 15 % and 34% increase respectively.

14.2 Carbon Dioxide Projected Emission 1990-2020

Based on the projected energy demand and mix values in Energy Paper 65 (**40)** and the appropriate emission factors established in this thesis for each of the fossil fuels , mass emission calculations for the period over the 1990 -2020 period has clearly shown in all six scenarios there is an overall increase in carbon dioxide emissions which is demonstrated in **Figure 41** This figure also shows that there are two distinct emission patterns over this period -:

Between 1990 and 2000 the projections suggest a downward trend in emissions followed by a very pronounced increase up to the year 2020. The reason for the downward trend is largely attributed to the adoption of CCP energy saving measures and changes in energy mix in the power generating sector . The demand for coal in this sector is forecast to decline by over 40% by 2000, being replaced by a 32 % increase in

PROJECTED UK PRIMARY ENERGY DEMAND UP TO 2020 BASED ON SIX SELECTED SCENARIOS IN ENERGY PAPER 65

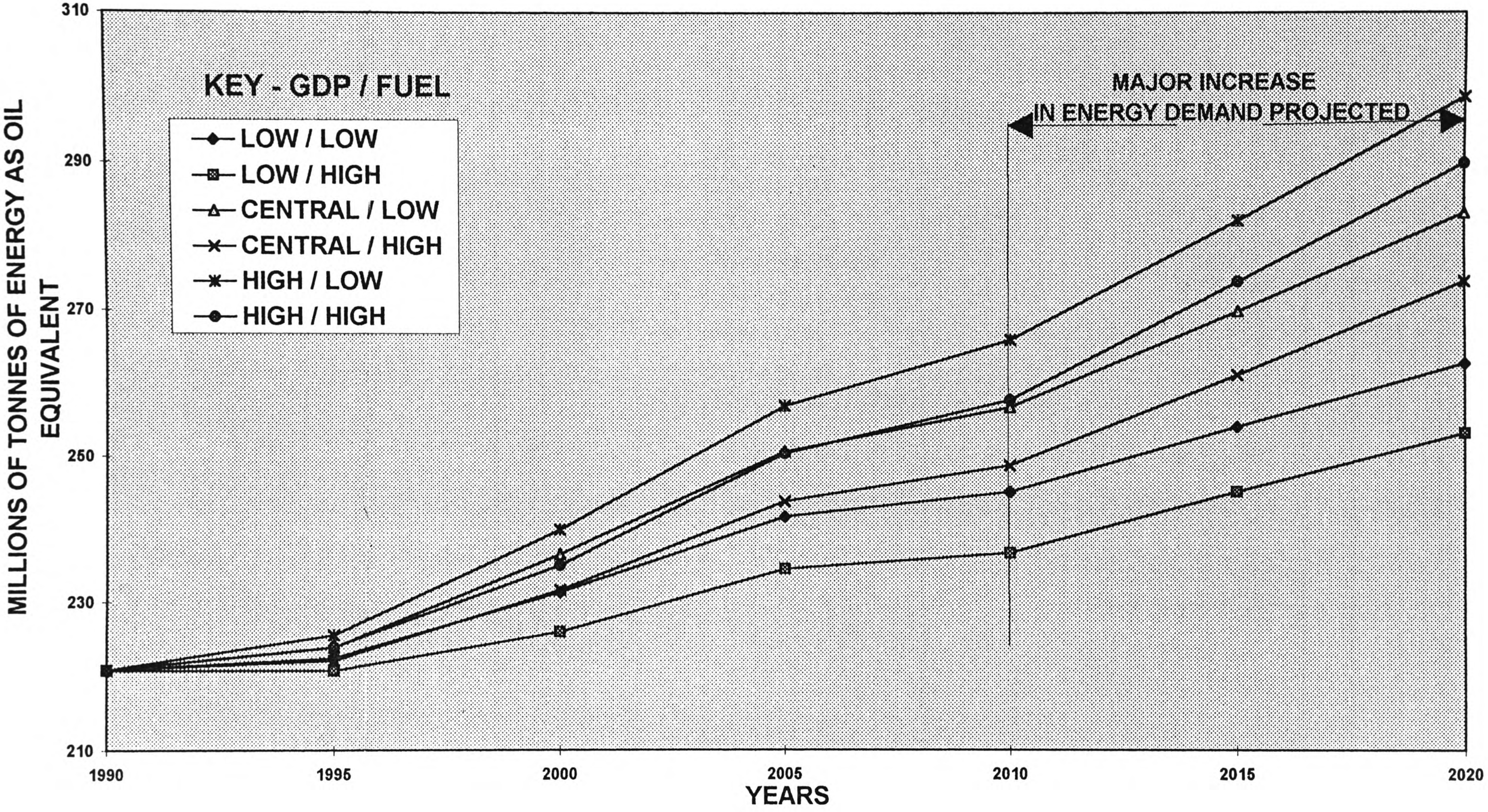
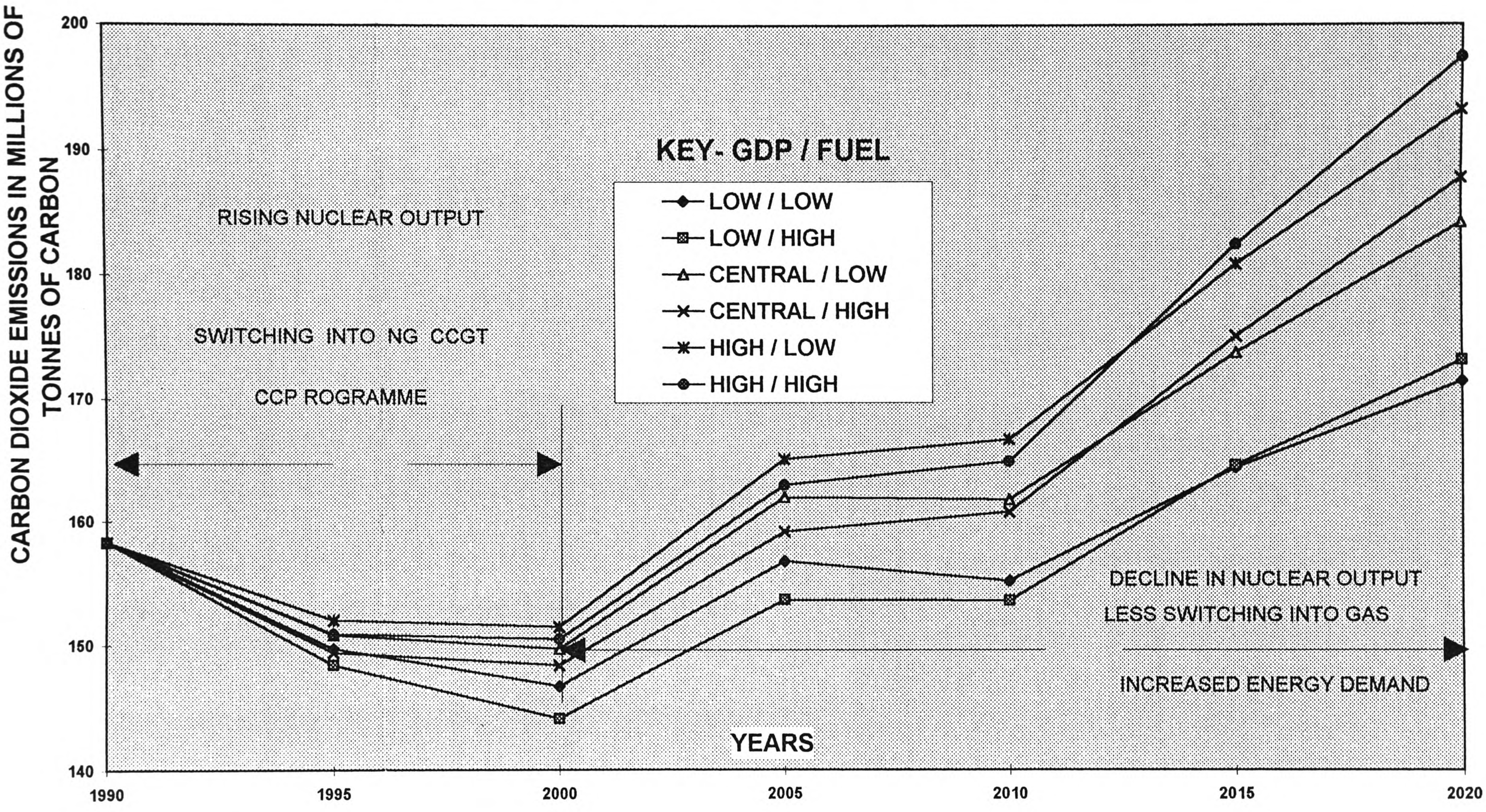


FIGURE 40

PROJECTED CARBON DIOXIDE EMISSIONS BASED ON THE SIX SCENARIOS IN THE ENERGY PAPER 65



SOURCE : DTI ENERGY PAPER No 65

FIGURE 41

the demand for natural gas in Combined Cycle Gas Turbines and a 13 % increase in nuclear power or power imports .This change in energy mix would equate to an average annual reduction of 12 million tonnes of carbon dioxide by the year 2000 .

In contrast , from 2000 to 2020 an upward trend in emissions in all scenarios is projected , which can be accounted by a combination of factors :-

1.0 The decommissioning of nuclear power stations would result in reduced power output , necessitating additional power generation from fossil fuel stations .

2.0 The leveling off in the overall use of natural gas with the exception of the power generating sector which continues to increases its share of the market in this sector as a fuel for CCGT.

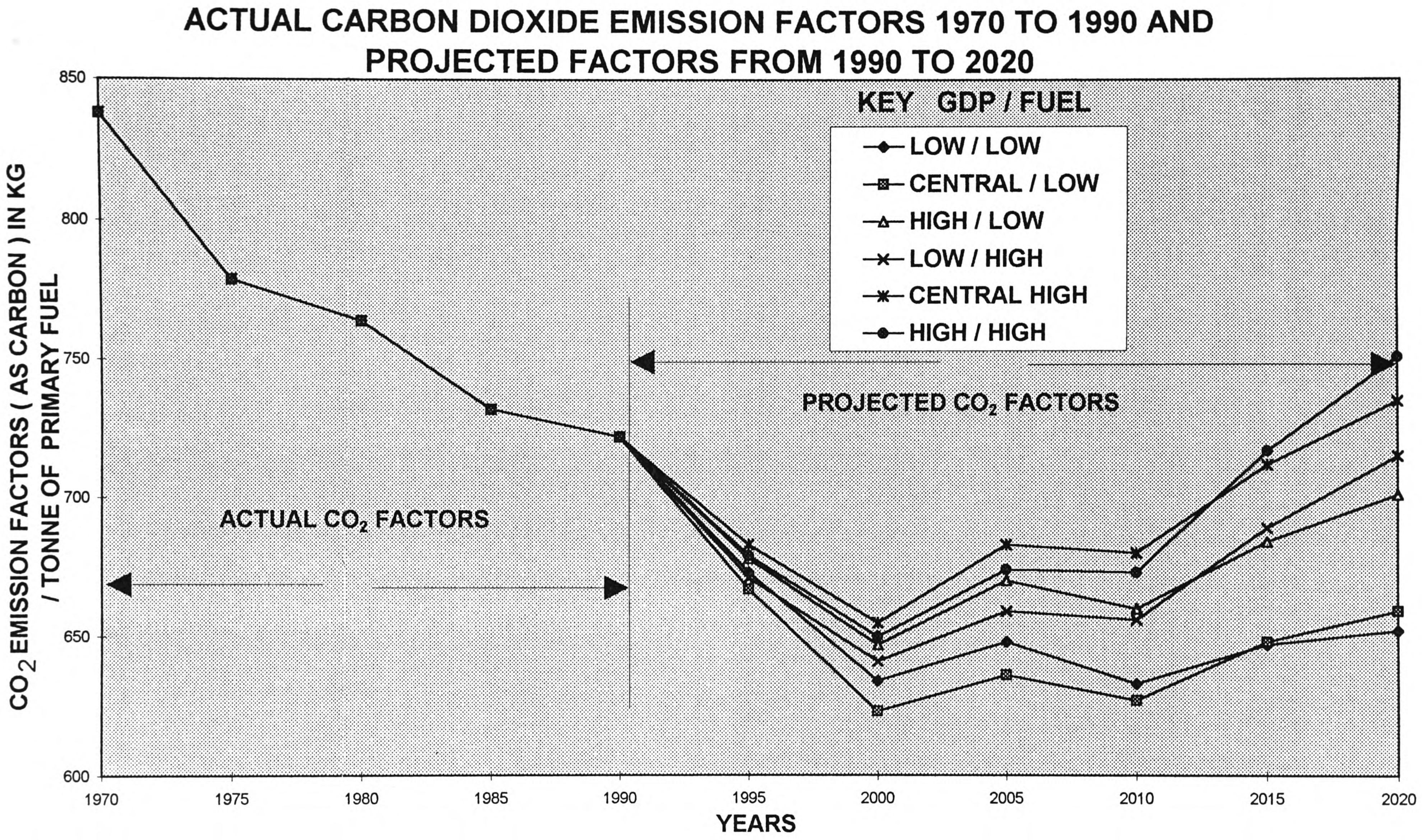
3.0 The IGCC power station would by this time be considered technically and commercially viable and could be fired with coal or oil , hence increasing the overall demand for these fuels .

Figure 42 shows the corresponding sharp decline in the CO_2 emission factor up the the year 1995 and the the same rate of decline is projected up the the year 2000 . There after there would be an overall substantial increase for all scenarios up to the year 2020.

The total changing trends of carbon dioxide emissions over the the 1990 - 2020 is predicted to increase by 26 million tonnes under the CL scenario which is taken to represent the mean values for six scenarios in Energy Paper 65 **(40).** It is important to establish the predicted distribution of these emissions arising from the individual energy consuming sectors over this period . An analysis has been undertaken and is outlined in **Figure 43** , and summarized as follows :-

The the rapid decline in emissions from the power generating sector over the 1990-2000 period and the very significant reversal in this trend over the 2000 -2020 period , the reasons for which have been fully discussed in this thesis.

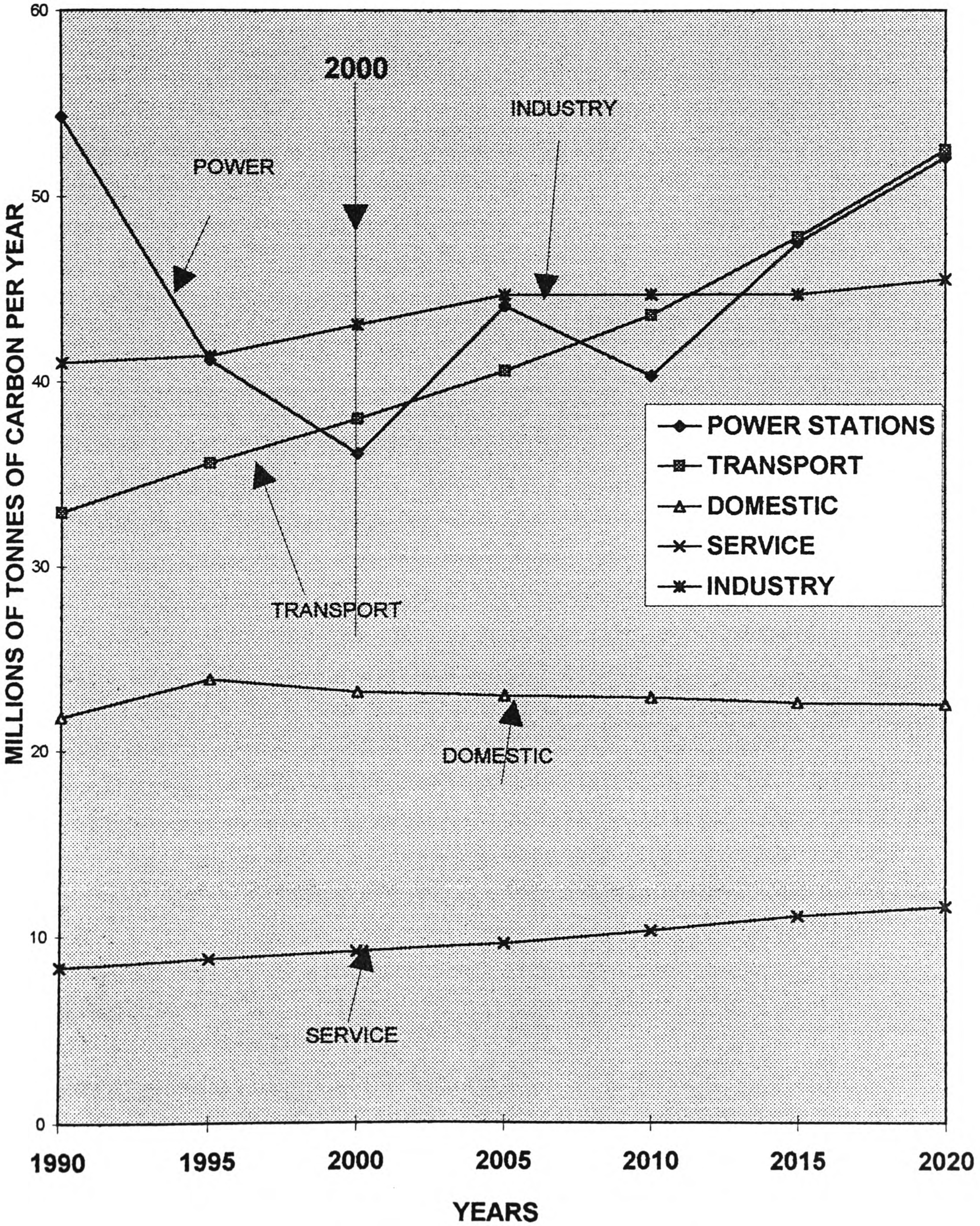
There are modest increases in the emissions from the industrial and service sectors .



SOURCE : ENERGY PAPER 65 DTI

FIGURE 42

PREDICTED CARBON DIOXIDE EMISSIONS ARISING FROM ENERGY CONSUMING SECTORS 1990 - 2020 UNDER SCENARIO CL



SOURCE :DOE ENERGY PAPER 65

FIGURE 43

The road transport sector shows a rapid increase in emissions and by 2020 represents the major share of CO_2 of the total emissions .

The emissions from the domestic sector is predicted to decline slightly

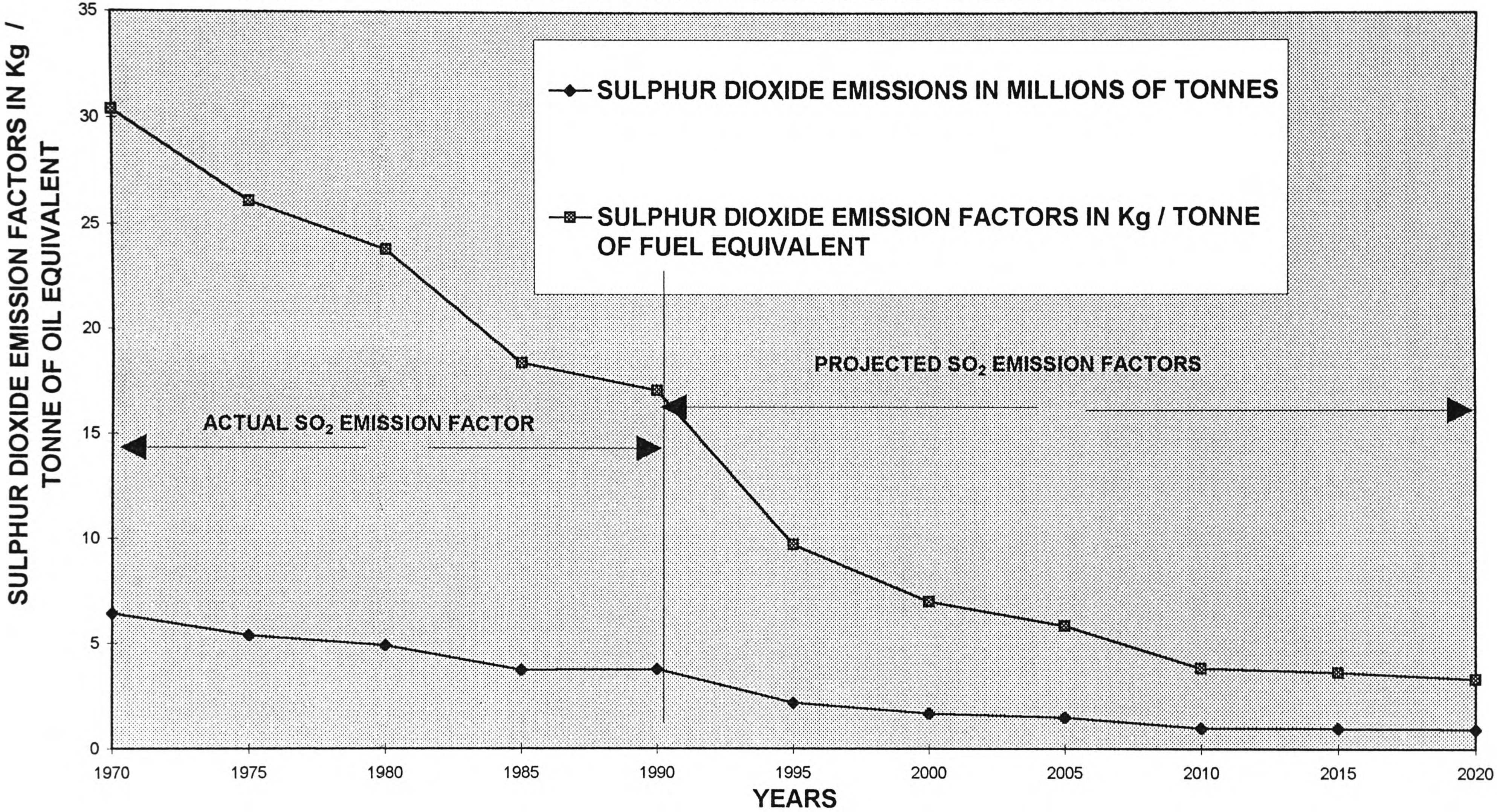
14.3 Sulphur Dioxide Projected Emissions 1990-2020

In contrast to the forecast of a steady increase in CO_2 emissions between 1990 and 2020 , the projected SO_2 emissions which are also calculated using future energy demand and mix outlined in the Energy Paper 65 **(40)** and the appropriate emission factors established in this thesis , indicate an overall decline for the full 1990 - 2020 period of 75 % as shown in **Figure 44** , despite the increase in primary energy demand ranging from 15.0 and 35.0 % predicted for this period .
It can be seen from **Figure 44** which considers the CL prediction scenario **(40)** that the fall in SO_2 emissions can be analyzed in two periods 1990 - 2000 and 1990 - 2020 :-

The predicted changing trend of SO_2 arising from the main energy consuming sectors is shown in **Figure 45**, which clearly demonstrates that 98% of the total decline in SO_2 can be attributed to the power sector , most of which occurs in the 1990 - 2000 period. The predicted change in fuel mix in the power sector during 1990 - 2000 will account for this major decline in SO_2 emissions. The change comprises a major reduction in coal consumption with a lesser reduction in petroleum consumption , but a significant increase in demand for natural gas , plus higher nuclear power and imports of electrical power from nuclear sources is shown in **Figure 46** . The overall effect will result in a decline in the sulphur dioxide emission factor from 17 to 8.0 kg of sulphur dioxide per tonne of oil equivalent during 1990-2000 as shown in **Figure 44.**
However the decline in the sulphur dioxide emission factor during the total 1990-2020 period can be seen to be very significant with a reduction in the emission factor from 17 to 3.3 kg of sulphur dioxide per tonne of oil equivalent . This fall is associated with the reduced oil and coal utilization mainly on power stations , the introduction of natural gas CCGT plants also by the power sector and the introduction of FGD units on power generating plant which operate with a sulphur dioxide reduction efficiencies in excess of 90%

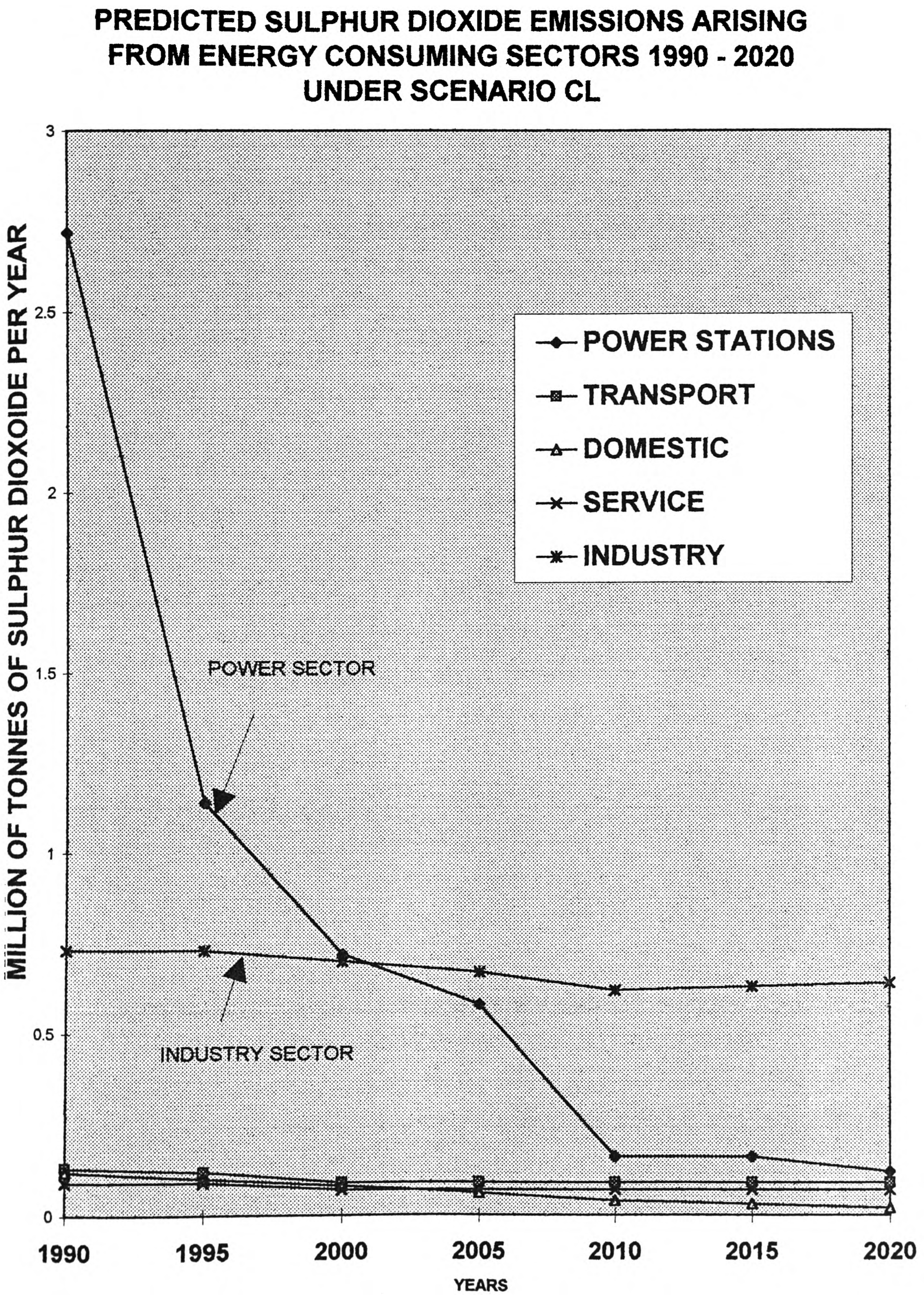
Figure 47 provides a comparison between the projected decline in SO_2 calculated from Energy Paper 65 (40) and the SO_2 reduction the UK is committed to in the Second Sulphur Protocol for the period 2000 - 2010 . The Protocol requires a reduction of 50% by 2000 , 70% by 2005 and 80% by 2010 based on the 1980 baseline

ACTUAL SULPHUR DIOXIDE EMISSION FACTORS 1970 TO 1990 AND PROJECTED FACTORS FROM 1990 TO 2020 FOR SCENARIO CL



SOURCE : ENERGY PAPER 65 DTI

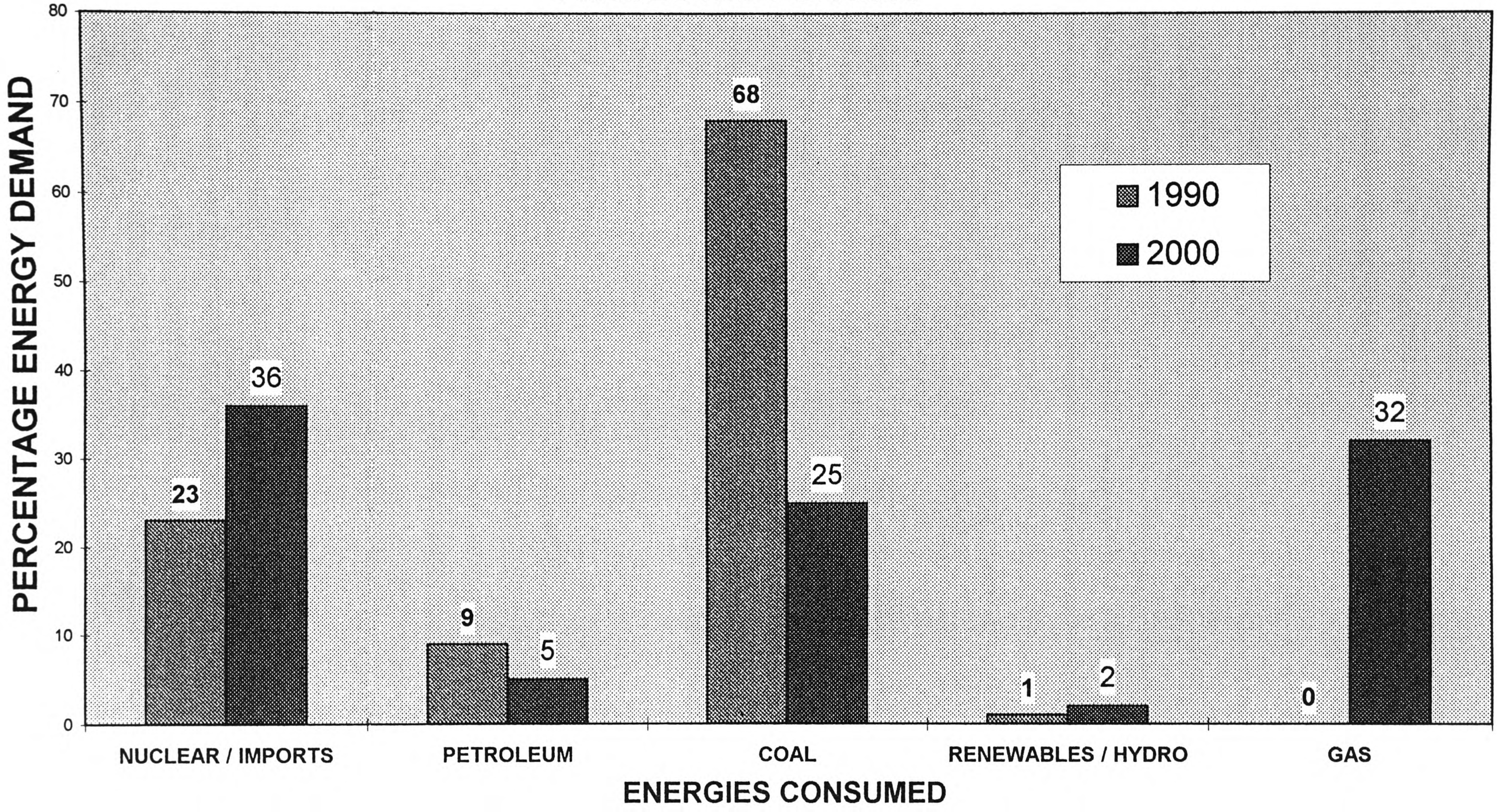
FIGURE 44



SOURCE : DOE ENERGY PAPER 65

FIGURE 45

ENERGY DEMAND BY THE POWER GENERATION SECTOR 1990 AND PROJECTED FOR 2000



SOURCE : DoE CLIMATE CHANGE PROGRAMME

FIGURE 46

Figure 47 clearly shows that the projected reduction figures agree very closely with the Protocol targets set for the for the year 2010 .

14.4 Oxides of Nitrogen Projected Emission 1990-2020

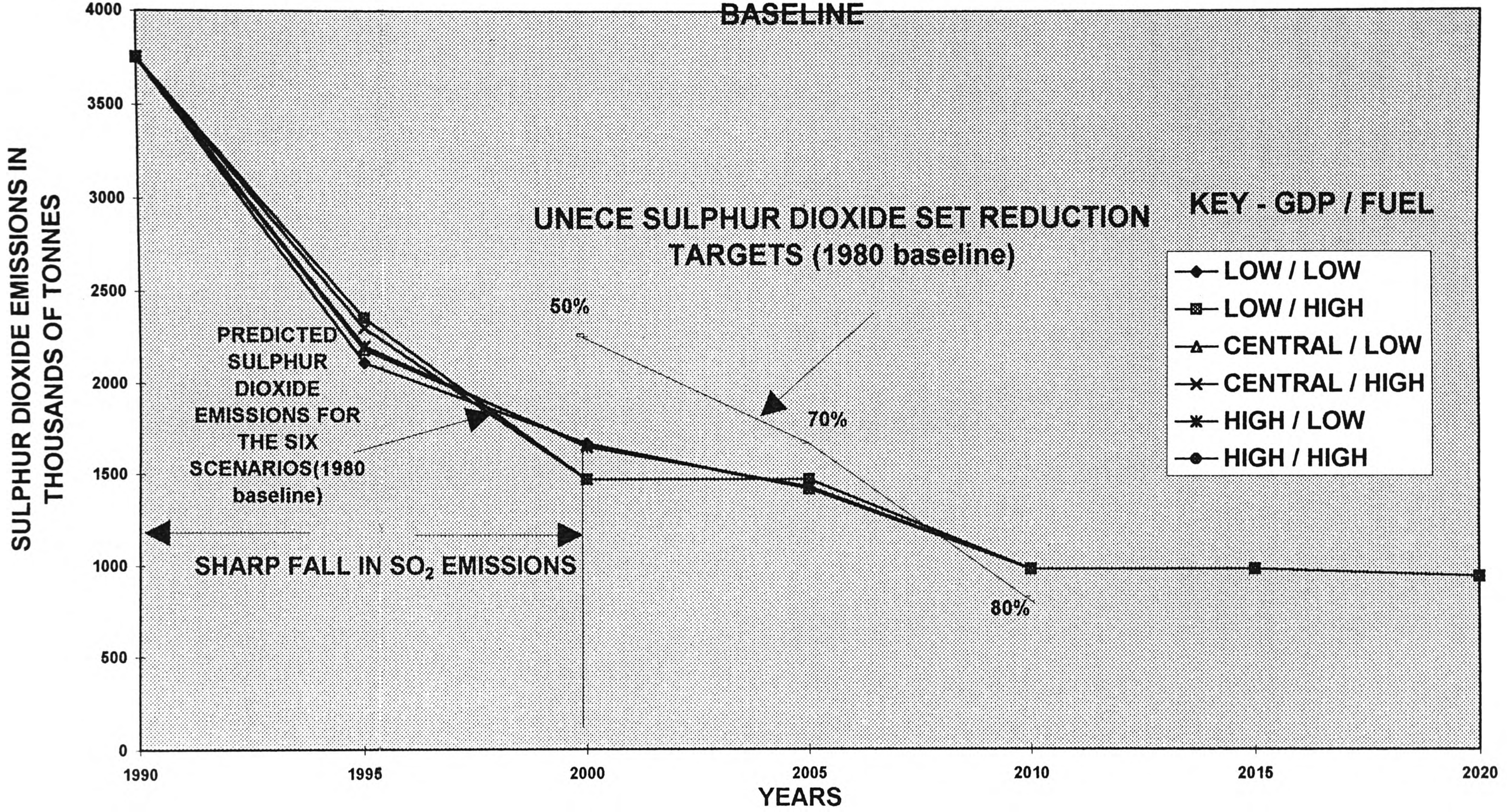
The transport sector's energy demand is projected in the Energy Paper 65 (**40**) to grow very significantly by between 1.3% to 2.2% per annum over the 1990-2020 period largely due to greater car ownership and increased air travel . It has been demonstrated in this thesis that in 1994 , 73 % of the transport sector acconted for over 50% of the NO_X emissions and the power generation sector at 24% .The emissions from both these sectors are predicted to decline in the future due to the legislation enacted in the mid 1990's which are discussed below :-
Since 1990 NO_X emissions from the road transport sector have declined as shown in **Figure 29** this is partly due to the enforcement of the EEC Legislation to install catalytic converters on new passenger car vehicles from 1992 (**30**) and stricter regulations on truck exhaust emissions (**32**) , despite the significant increase in passenger road traffic over this period . Hence the adverse effect of the projected increased road traffic on NO_X emissions will be tempered in the future by the legal requirement that all new petrol vehicles which will be fitted with installed catalytic converters resulting in an overall decline in NO_X emissions .

The emissions arising from power stations have declined by 35% between 1990 and 1994 partly due to the introduction of the CCGT . The scenarios in Energy Paper 65 (**40**) assume in their predictions that output from the CCGT would be increased by between 16 and 18 GW by 2000 and hence displace power that would normally be generated by the high NO_X emitting coal- fired .Using the Proops emission factors **(16)** it can been calculated that this would achieve a reduction of 0.4 million tonnes of NO_X by the year 2000 .

14. 5 Black Smoke Projected Emission 1990-2020

The demand for energy in the transport sector is predicted in the Energy Paper 65 **(40)** to increase by between 1.3 and 2.2 % annually by the year 2020 .The demand for DERV which is the major contributor to black smoke is expected to rise faster than for petrol in this sector.

PROJECTED SULPHUR DIOXIDE EMISSIONS BASED ON THE SIX SCENARIOS IN THE ENERGY PAPER 65 COMPARED WITH UNECE SET TARGETS BOTH FROM 1980 BASELINE

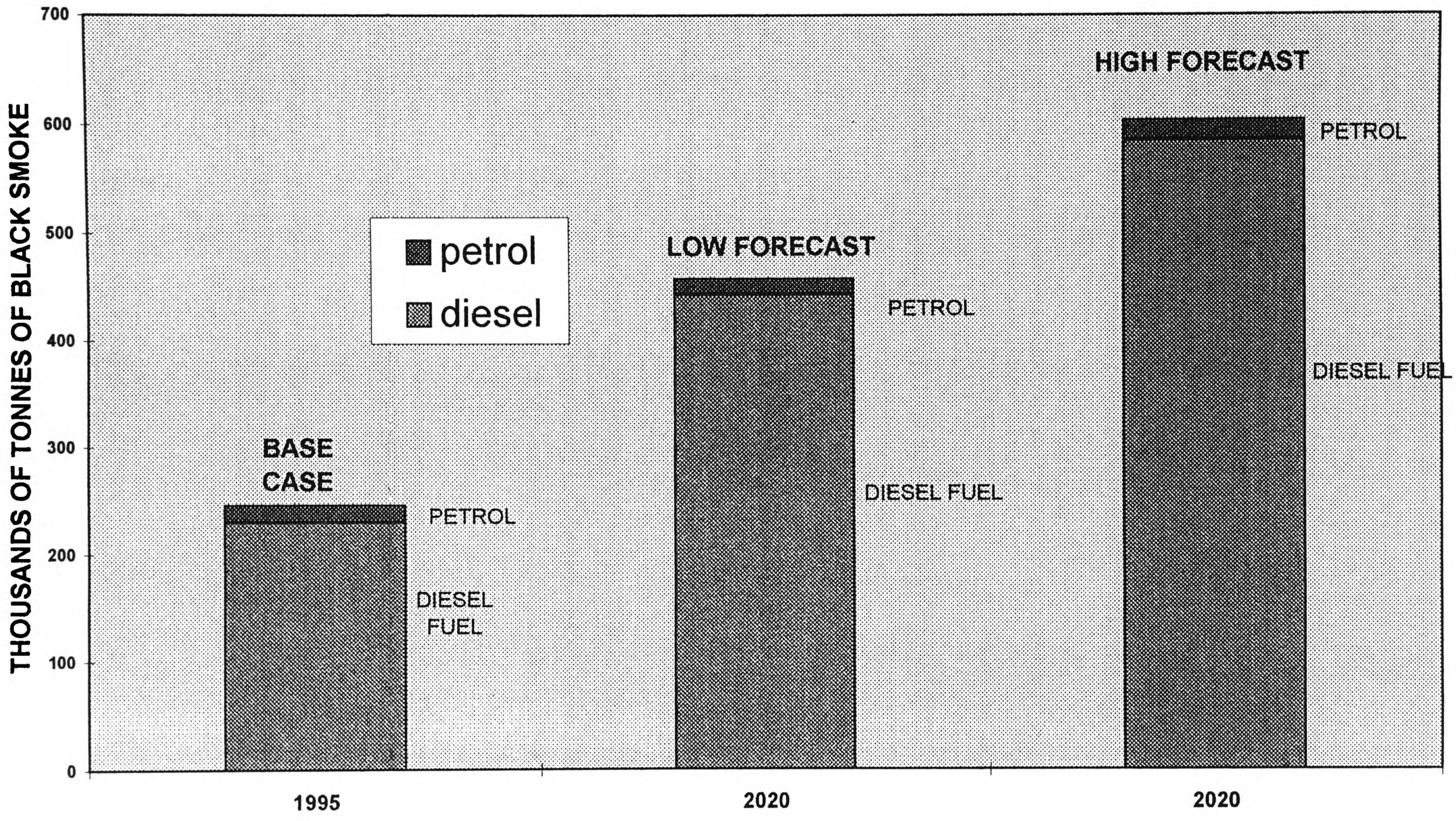


SOURCE : ENERGY PAPER 65

FIGURE 47

Based on the product of emission factors established for petrol and DERV in this thesis and the projected energy demand for years1995 and 2020 in Energy Paper 65 **(40)**, a forecast of the mass emission of black smoke arising from the road transport sector has been predicted for low and high scenario energy demand forecasts, assuming no further black smoke emission control legislation measures are introduced. The results of these predictions are presented in **Figure 48**. It can be seen that over the 1995 - 2020 period that diesel fuel would dramatically increases its share of generated smoke in the road transport sector and the actual projected emission for diesel fuel would increase by 300% over the 1995 - 2020 period.

PROJECTED BLACK SMOKE EMISSIONS FROM PETROL AND DIESEL FUEL IN THE ROAD TRANSPORT SECTOR BY 2020



SOURCE : ENERGY PAPER 65 AND AEA NATIONAL ATMOSPHERIC INVENTORY

FIGURE 48

15 Future Options for Further Reductions in Emissions.

This thesis has highlighted the major factors that have contributed to the overall reduction in emissions over the 1970-1994 period . This research work has also provided a fund of useful background information with regard to additional possible measures that could be adopted in the future to further reduce emissions especially in the power generating sector. In 1994 this sector was established to be the major source of sulphur dioxide and carbon dioxide accounting for 65 % and 30 % respectively of the total UK emissions and NOx emissions constituted 24% of the total UK emissions , which was only exceeded by the transport sector .This accounts for the EEC and UK Government enacting stringent legislation on the generating sector . This chapter focuses on the possible reductions that could be achieved in this sector by extending the use of low emitting fossil fuel such as natural gas and the use of new advanced clean coal technology.

However the take- up of these options will depend on a number of factors both economic and technical some of which are highlighted below :-

1.0 Any future fuel utilization strategy aimed at minimizing emissions will be largely influenced by the relative cost of each fuel , the guarantee of secure continuous supply and the cost of environmental control measures to be adopted to comply with UK and EU future emission regulations.

2.0 Advanced new clean coal technology offers environmental improvements and improved thermal efficiency . However its future viability will largely depend on Research funding available from the government and industry to develop these more thermally efficient schemes for use on a commercial scale.

3.0 Future expansion of the nuclear industry is dependent on the guaranteed safety of operation and decommissioning costs of nuclear power generators .

Taking these considerations into account the following emission reducing options are available for future possible adoption .

15.1 Extending the Switching to Lower Air Polluting Emitting Fossil Fuels.

Switching to lower carbon and sulphur fossil fuel where it is commercially and technically viable , provides an opportunity to reduce the mass emission of carbon dioxide and sulphur dioxide , especially to natural gas which has the lowest specific CO_2 and oxides of nitrogen emission rates of all the fossil fuels and zero SO_2 and black smoke emissions .This switching approach has already been shown in the past to be environmentally beneficial . However its continued adoption is strongly influenced by the final relative cost of the fuel at the burner and the practicability of its application

15.2 Extending the use of Natural Gas and the Adoption of Clean Coal Technology in the Power Generating Sector to Reduce Emissions .

Over the 1970-1994 it has been shown that the power generating sector has been a major emitter of air pollutants and in 1994 in its contribution to carbon dioxide , oxides of nitrogen and sulphur dioxide . Over 73% of the fossil fuel utilized in this sector was solid fuel already established to be the major generator of these emissions . Hence it is not suprising that the UK and indeed the whole of the EU is considering investing in clean coal technology to achieve the existing and even more stringent environmental emission standards under consideration for the future . Hence an urgent drive is underway within the EU to clean up one of the dirtiest fuels by financially sponsoring research and plant trials to assess the potential of new technologies **(47).** Proops et al **(16)** have examined the possible environmental benefits of adopting three types cleaner technologies applicable to the power generating sector which are summarized below .

15.2.1 The Combined Cycle Gas Turbine (CCGT).

Power produced from natural gas increased from zero in 1990 to a value equal to 10 % of the total electrical power generated by the industry in 1994 .
It has already been established that natural gas , which is used in the CCGT generates lower emissions of CO_2 and NO_x and virtually no sulphur dioxide or black smoke per unit of energy consumed in comparison with coal and petroleum . In addition CCGT stations operate with a energy conversion factor up to 53 % (**16**) compared with 38-38 % for the conventional coal fired station which strengthens the environmental case for the switching to the CCGT .

The National Grid responsible for transportating power around the counrty revealed its plans in May 1997 to further increase extend its use of natural gas by doubling its gas fired gas turbine capacity over the period 1997 / 8 - 2000 / 1(**48**) .The CCGT generating capacity using natural gas would be equivalent to 27GW, compared with 24 GW of conventional coal capacity by the year 2000 **(48)**.

Figure 49 shows this proposed change in generation policy in favour of additional CCGT capacity to meet future power needs in the 21st century .Based on these power generating figures and the emission factors established by Proops **(16)** it has been calculated that this strategy will result in a decline of 2 % in CO_2 , 29 % in SO_2 and 15 % in NO_x over the 1990-2000 period , despite the overall increase in the generating capacity .

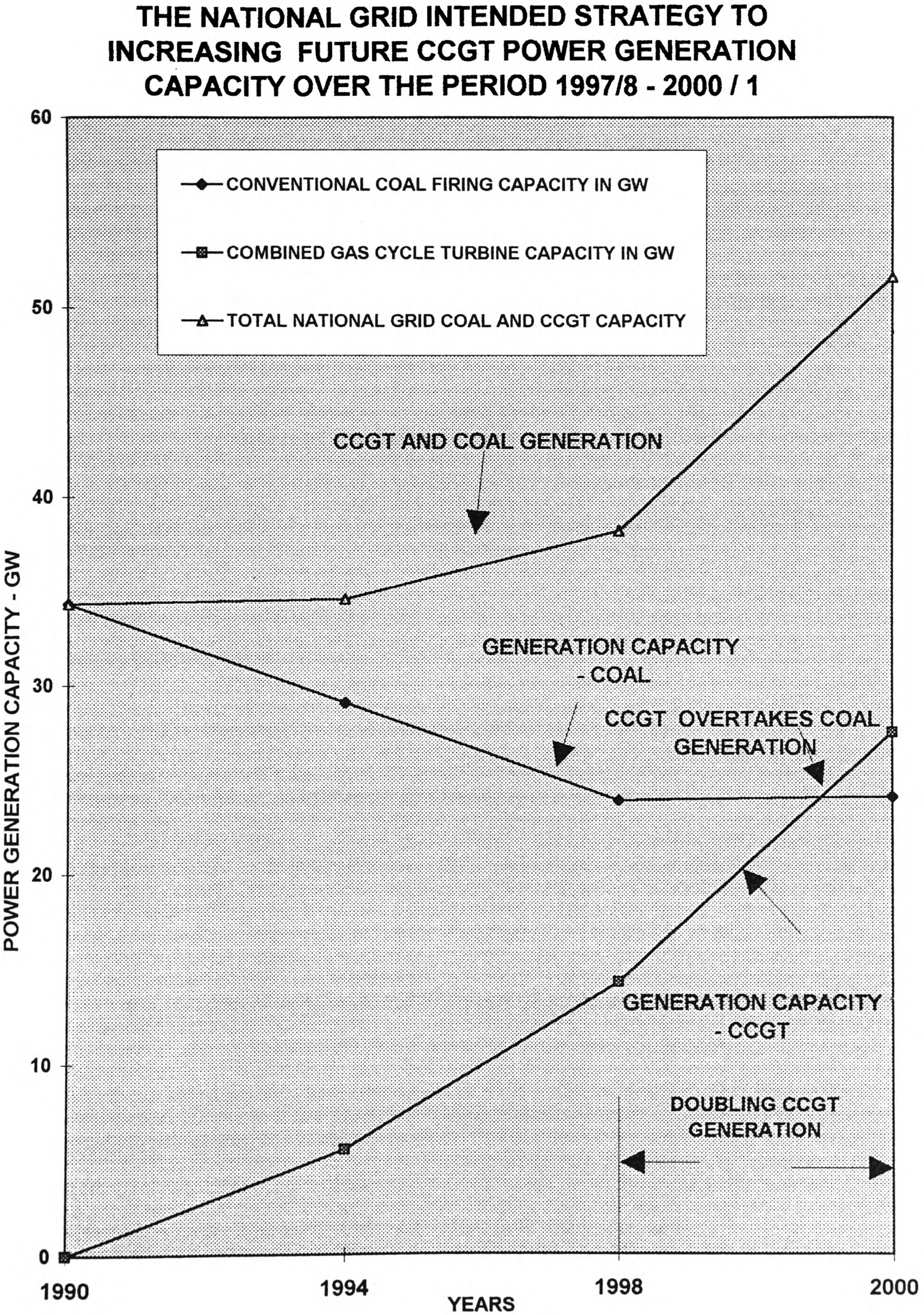
15.2.2 Supercritical coal (SUPC).

The most direct substitution for coal burning technology is the supercritical coal which burns coal with a conversion efficiency of 42% and when coupled with equipment to remove SO2 from the flue gas presents a significant environmental benefit **(16)**

This system is in the development stage and at present is not considered as a commercially acceptable venture .However it has considerable environmental potential. and its possible adoption should be kept under review .

15.2.3. The Coal - Fired Integrated Gasification Combined Cycle (IGCC).

The IGCC system is widely recognized as the cleanest method available for turning coal into electricity . In the gasification process , a feedstock fuel of coal or oil is heated with steam and oxygen and pollutants are removed before the combustion process. However the clean- up comes at a high price and is not likely to prove cost effective in the near future **(47)** .



SOURCE : DAILY TELEGRAPH MAY 1997

Figure 49

An assessment of its potential as a an effective means of reducing pollutants has been undertaken **(49)** and compared with the emissions from the conventional coal fired system as shown below :-

Pollutants	Percentage reductions in pollutants
Sulphur dioxide	An increased reduction of 9.99 % (from 90 to 99.9 %) compared with the conventional coal fired system operating with SO_2 scrubbers.
NO_x	A 600 % reduction compared with typical low NO_x burners currently employed on conventional coal fired power station plants
Particulate	More than a 33.3% improvement by incorporating post combustion control.

A number of these systems have been identified as operating on a commercial basis around the world.

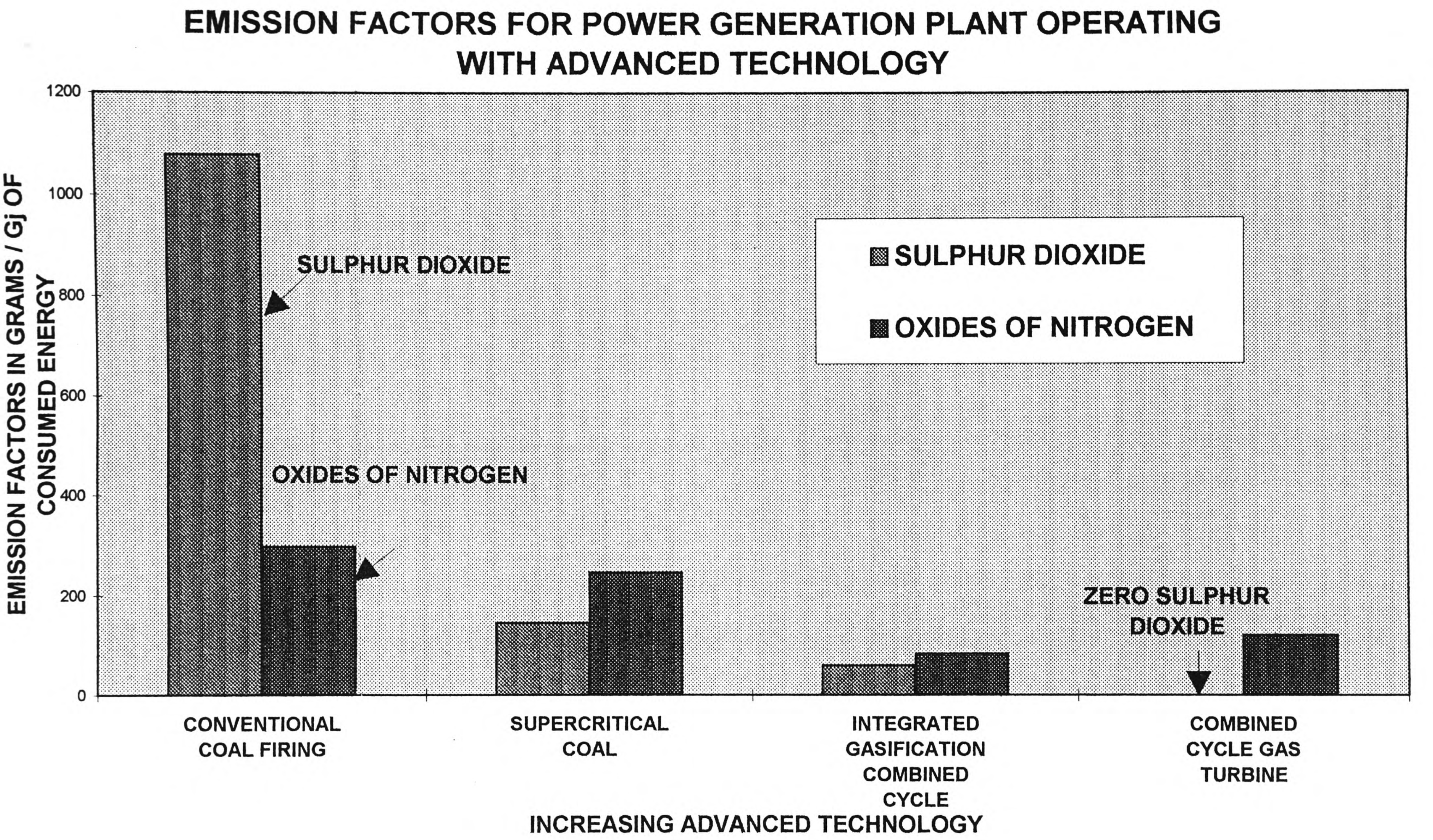
A 250 MWe unit has been operating on coal in Holland since 1994, and a 262 MWe unit is also operating on coal since 1995 , and monitoring tests have recorded conversion efficiencies in excess of 50% , for coal - based electric power generation **(50)**.

Proops **(16)** has evaluated the environmental benefits of operating the three improved technology systems compared with the conventional coal fired system Table 31 summarizes these findings. **Figure 50** demonstrates clearly that the CCGT system provides the best overall environmental advantage of the fossil fuel options with a 64 % reduction in CO_2 , a 100% reduction in SO_2 and an 80% reduction in NO_x per unit of power generation

TABLE 31

Emissions Factors for New Technology Compared with Old Coal Stations based on kt of Pollutant / TWh of electrical output

	kt / TWh		
	CO_2	SO_2	NO_x
Conventional coal firing	1113	13.9	4.50
CCGT	403	00	0.86
IGCC	759	0.5	0.7
SUPC	795	1.3	2.20
Nuclear and renewable	00	00	00



SOURCE : PROOPS ENERGY POLICY 1996

Figure 50

15.3 The further use of Nuclear Energy.

The potential for reductions in emissions using a non fossil fuel consuming power generating system such as nuclear power stations is shown in **Table 32 .** Nuclear energy could replace base load fossil electricity generation **(16)** and thus contribute significantly to reducing emissions generated by conventional power stations . However the expansion of the nuclear industry has stalled during the two past decades and a reversal will only be generally acceptable if the safety of reactor operation together with the disposal of radioactive waste reaches acceptable standards

15.4 The Challenge for Renewable Energies

The use of tidal , wave , wind and solar energies have the same potential for reducing atmospheric pollution similar to the nuclear industry but where as the load factor for a fossil fuel fired plant would be in the order of 65-70 % , non fossil would be significantly less i.e. the Severn Barrage would not be above 23 % due to tidal conditions , wind energy would be highly variable depending on wind speed and location of the installation .

The total renewable capacity commissioned by the end of 1994 has been established to be 325 MW of generation , equivalent to 0.44 million tonnes of fuel oil per year or 0.5% of total fuel used in the power generating sector **(50**). The UK Climate Change Programme **(29)** includes the broad aim of working towards increasing this to1500 MW of new renewable generating capacity by the year 2000 . This would only account for less than 2% of total power generating fuel by the year 2000 and would result in a very minor reduction in the future overall UK emission level .

15.4 Estimation of Reductions in Emissions From the Power Generating Sector by 2020.

The estimation of reduced emissions in the power generating sector is based on the projected energy mix for this sector up to the year 2020 outlined in the Energy Paper 65 **(40)** which is summarized in **Table 32** , and the emission factors for CO_2 , SO_2 and NO_x per unit of power generated for conventional coal / oil , IGCC and CCGT systems established by Proops **(16)** are outlined in **Table 31.**

TABLE 32

The Changing Pattern of Power Generated by the Different Generating Systems by 2020 (predicted in Energy Paper 65 **(40)**)

Generating systems	% Power Generation 1990 (actual)	2020(predicted)
	%	%
Conventional coal / oil firing	**82***	10
Nuclear power	17	1.5
Renewable energy	1	6.5
CCGT	0	**55.0***
IGCC	0	**27.0***
	100 .0	100.0

The Energy Paper 65 **(40)** predicts a 40 % increase in power generating capacity by the year 2020 , together with the percentage contribution from each type of generating system which is outlined in **Table 32 .** By 2020 advanced technology in the form of CCGT and IGCC will be used to generate 80% of the power , compared with 80% by the conventional coal fired system in 1990 . A large potential exists for a significant reduction in emissions and it has been calculated that even with the inceased level of power demand , this generating strategy would result in a reduction of 22 % in CO_2 (as carbon) , 82 % of SO_2 and 60 % of NO_x (as NO_2) by 2020 , equivalent to 15.0 million tonnes of CO_2 (as carbon) , 2.5 million tonnes of SO_2 and 0.6 million tonnes of NO_x (as NO_2) per annum from this power generating sector.

This additional level of reductions in emissions in the power sector assuming it is achieved by the year 2020 , coupled with the reductions already achieved through legislation , the switching to natural gas and improved thermal efficiencies , would have a very profound effect on the future overall mass emission of carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke emissions arising from the UK.

Conclusions

1 This thesis has demonstrated that the combustion of fossil fuel is by far the major source of man made atmospheric pollutants , and the following percentages indicate the current contribution of these emissions by fossil fuels .

Carbon dioxide 97%
Sulphur dioxide 99%
Black smoke 91%
Oxides of nitrogen 95 %

It is widely accepted that these pollutants can give rise to a wide range of problems in the atmosphere and at ground level including : acidic pollution , photochemical pollution , toxic pollutants , the green house effect and smoke pollutants . Some broad estimates of the damage cost of these pollutants have been outlined .Although it is recognized that there are significant uncertainties in quantifying such costs .

2 Research into the changing trends of the total UK primary energy demand has shown that there has only been a marginal increase in overall consumption over the 1970-1994 period , however there has been a major change in the mix in energy . The consumption of solid fuel and petroleum had markedly declined over the 1970-1994 period by 47 % and 17.6 % respectively and replaced by natural gas and primary electricity mainly from the nuclear source which have increased by 481% and 211 % respectively . This strategy of switching to these lower or zero atmospheric polluting primary energies will be shown to be very significant in the changing trends of the estimated atmospheric emissions .

3.0 A detailed analysis of the changes in energy consumption trends by the major energy user sectors , defined as the user sectors which comprise the industrial , domestic transport and service sectors and the power generating sector has been undertaken

3.1 The overall fossil energy demand by the final user sector classified as the industrial , transport , domestic and service sectors have exhibited different characteristics of energy demand and energy mix consumption patterns over the period 1970 to 1994 . The change in energy mix in these sectors has been shown to have play a major role in influencing the level of emissions . Each sector with the exception of the transport sector exhibited the same pattern of a switch from coal to natural gas.

3.1.1 The industry sector is the only sector to experience a fall in the demand for fossil fuel , this 40% decline can be accounted for by a 67% reduced demand for solid fuel and a 69% for petroleum , however the natural gas increased by a factor of nearly 7 to achieve a 33 % share of the industry sector . The change in the final mix of fuel in favour of natural gas together with the decline in overall energy demand in this sector has been shown to have had a significant influence on the mass emissions of pollutants.

3.1.2 The domestic sector has increased its fossil fuel demand by 16% . There was a decline of 79% in the demand for solid fuel and to a lesser extent of 9% in petroleum however this was offset by the 220% increase in demand for natural gas This swing again in favour of natural gas is shown to have a very significant influence on the overall UK emission scene by 1994.

3.1 .3 The transport sector 's demand for petroleum has increased by 80 % , which is wholly accounted for by the increase in the demand for road transport fuel Much of the increase of this fuel is associated with the increased demand for DERV fuel.

3.1.4 The service sector has shown less than 1% increase in fossil fuel demand but a substantial increase in the market share for natural gas.

3.1.5 Overall the final energy users sectors has experienced a 71% decline in demand for solid fuel over the period 1970-1994 equivalent to 3 million tonnes of oil per annum , whereas the natural gas demand increased by 285 % equivalent to 3.6 million toe per annum over the same period . The demand for petroleum changed by only 3.5 million toe in the order of a 5% increase The environmental benefit of increased utilization of natural gas coupled with the relatively low emission levels associated with this fuel is demonstrated to have had a major effect on the environment .

3.2 The power generating sector is another major consumer of fossil fuel which has experienced a change in energy mix in favour of natural gas at the expense of the other fossil fuels solid fuel and petroleum . Solid fuel demand declined by 6.0 million toe per annum equivalent to 13.4 % reduction and petroleum by over 9 million toe per annum by a staggering 70% . This deficit was replaced by 9.7 million tonnes of oil equivalent of natural gas and a significant increase in primary electricity from nuclear power .

This switch in favour of the lower and zero polluting fuels in this sector is shown to have had a major influence on emissions .

4.0 Based on calculations using fuel analysis data and / or published empirical data, emission factors defined as the mass of pollutant per unit of energy as tonnes and Gj were established for carbon dioxide , sulphur dioxide , oxides of nitrogen and black smoke generated from solid fuel , petroleum products and natural gas .These emission factors were used to estimate annual mass emissions of each pollutant over the 1970-1994 period and to predict future emissions.

4.1 With regard to the estimate of carbon dioxide emission factors , calculations using the fuel carbon content and calorific value has shown that solid fuel emits the highest level of CO_2 , followed by petroleum ,and the lowest emitter being natural gas .The variation in emission factors for carbon dioxide were examined over the 1975-1994 period and have proved to be relatively static .The major influence on the emission factor has been the change in the energy mix .

4.2 The calculated sulphur dioxide emission factors are also based on the product of sulphur content and heat content of the fuel . The highest value in terms of grams / Gj are shown to exhibited by solid fuels with petroleum possessing slightly lower values . North sea natural gas is credited with virtually zero sulphur content. An assessment of the changing trends of sulphur dioxide emission factors over the 1975 to 1994 period has shown that for solid fuel it has been relatively stable , whereas for petroleum products there has been a dramatic decline over the 1975-1991 period, primarily due to the lower demand for the high sulphur bearing heavy fuel oil by manufacturing industry and an escalation in the demand for the low sulphur road transport fuel. The Protocol on the reduction of sulphur dioxide emissions adopted in 1985 required a cut in the total SO_2 emissions of 30% by 1993 based on 1980 levels . The UK achieved a reduction of 37% by the end of 1993 .

4.3 The estimation of oxides of nitrogen emission factors for the fossil fuels were based on empirical data generated largely by government research establishments .The factors are dependent on a number of conditions including nitrogen content in the fuel , combustion condition ie excess air value, combustion temperature , firing rate and type of burner , and hence can only be established empirically. An assessment of emission factors over the 1970-1994 period has clearly shown that a progressive and steady increase in emissions has occurred over the period 1970 to 1990 . However a rapid decline over the 1990-1994 period took place , which is associated with EU Legislation restricting emissions from large combustion plant and with the installation of three- way catalyst petrol driven road vehicles . The Sofia Protocol adopted in 1988 concerning the control of NO_x emissions committed the UK to reduce emissions to their 1989 level by 1994 . The UK met this target .

4.4 The estimation of black smoke of emission factors are also based on empirical data published by research establishments . The studies provided extensive emission information on a the different types fossil fuels under a range of operating conditions. It has been shown that there has been a dramatic fall in the emission factor over the whole of the 1970-1994 period which is wholly attributed to the decline in the utilization of coal which is the major contributor to the UK smoke emissions . The European Community are énacting legislation to come into force by 2000 involving additional abatement measures to further reduce Black Smoke emissions by 30 % .

5.0 It has been established that there has been a clear and continuing downward trend in the total mass emission of carbon dioxide , sulphur dioxide and black smoke . The emission trends for oxides of nitrogen are less clear , the emissions were stable for most of the 1970-1994 period but increased in the late 1980's .The most remarkable changes were observed to take place with sulphur dioxide and black smoke , where the emissions were reduced by 50% , whereas with carbon dioxide and oxides of nitrogen, reductions were more modest at 13.5% and 5.0 % respectively .

6.0 The changing patterns of atmospheric emissions arising from the four major energy consuming sectors has been estimated for the 1970-1994 period . The analysis has shown that :-

6.1 An overall annual reduction of 15% in CO_2 emissions has been established which can be accounted for largely by the 23% and 46% decline of fossil fuel demand in the power generation and industrial sectors respectively , but in contrast the emission contribution by the transport sector has increased by 68 % over the same period due to the increase in activity in this sector . The emissions arising from the domestic sector have been relatively stable . The implementation of the Climate Change Programme energy improvement scheme (CCP) has been instrumental in lowering energy demand which in turn has had a major effect on minimizing carbon dioxide emissions .

6.2 The total sulphur dioxide emissions fell dramatically by 58% , this major decline is due to a 10% reduction in the demand for solid fuels and fuel oil fossil fuels by the power generation sector , a change in energy mix to sulphur free natural gas and the increase in the use of primary energy from the nuclear and hydro electricity sectors.

The installation of FGD units on power plant waste gas exhaust systems have also made major reductions in sulphur dioxide emissions . The decline in the demand for solid fuel and petroleum products in the manufacturing sector and the increased demand for the zero rated natural gas has made a major reduction in the total emissions from this sector . The displacement of the conventional energies , particularly solid fuel and heating oil by natural gas in the domestic has also contributed to the significant fall in sulphur dioxide emissions.

6.3 The overall NO_x emissions have changed relatively little decreasing by a modest 5.0 % in contrast to the other pollutants which have all experienced significant declines in emissions . Only the transport sector is seen to increase the level of NO_x emissions which is attributed to the dramatic increase in road travel over the 1970-1990 period .

6.4 Black smoke emissions have been identified to plummet by 60% over the 1970-1994 period. By far the principal reason for this dramatic reduction is associated with the decline in the demand for coal in the domestic sector and also the replacement of coal and heating oil by natural gas in this sector .

7.0 UK and EU environmental legislation coupled with Government Agreements on the control of pollutants have been shown to be effective in reducing emissions arising from fossil fuels .

7.1 The UK Climate Change Programme set out the measured aims at reducing emissions of greenhouse gases by 2000 to the 1990 levels . It has been shown that the implementation of the programme has reduced emissions and with the current trend, it is predicted that the carbon dioxide emission levels will be 6-13 million tonnes of carbon below the 1990 levels by the year 2000 .

7.2 This research work has identified four pieces of environmental legislation which were enacted over the 1970-1994 period and have had a major impact on sulphur dioxide emissions . It is difficult to quantify the exact reductions in mass emissions achieved by this legislation since major changes in energy mix have also taken place over the same period . However the implementation of the EEC Directive regarding emissions of SO_2 from Large Combustion Plant appears to have a direct effect on emissions .

7.3 Three pieces of legislation were brought into force during this period both appear to have greatly influenced NO_x emissions especially the EEC Directive emissions from Large Combustion Plant . It has been shown that over the period 1990 to 1994 there has been a significant fall in NO_x from the power generating sector , which is coincident with the enforcement period of the Directive . Secondly the EEC regulations restricting NO_x emissions from petrol driven road traffic by the installation of three - way catalysts had also accelerated the decline in NO_x emissions.

7.4 The research has shown the effect of a number of major Environmental Acts and EEC Directives on black smoke mass emissions , which have resulted in a decline in emissions from the domestic market due to a decline in the demand for high sulphur bearing bituminous coal which have been largely replaced burning oils and natural gas .

8.0 This thesis has undertaken to forecast future levels of emissions up to the year 2020 .Many energy demand models have been developed over the years by employing the energy -econometric modeling technique . The research has shown that the most comprehensive predictive energy - econometric model was produced by the DOE in 1994 , which is contained in an Energy Paper 65 and examines six scenarios with different GDP and energy price values in the predictive analysis .

8.1 The predicted increase in primary energy demand range from between 15 % for low growth and high fuel prices to 35 % for high growth and low energy prices.

8.2 The demand for coal is predicted to decline progressively in all scenarios over the 1990-2020 period , but to a greater extent in the low fuel price cases .In contrast natural gas and petroleum dominate total primary demand in the low energy price scenarios , while their dominance is less marked in the high price cases , reflecting the recovery in coal use after 2010.

9.0 The implications for atmospheric pollution were predicted for all scenarios .

9.1 The carbon dioxide emissions are predicted to increase by a minimum of 3.8% and to a maximum of 8.9 % by 2020 despite the substantially greater increase in energy demand .This can be accounted for by the continued decline in the demand for coal which is predicted to be replaced by the petroleum and natural gas which have lower CO_2 emission factors than coal . The predicted fall in electrical power due to the closure of some nuclear plant by 2020 will involve additional fossil fuel by the conventional power generators to achieve the increased demand for power .

9.2 The sulphur dioxide emissions are predicted by 2020 to decline by 75% by the year 2020 , this is accounted for by the decline in demand for coal , increased use of natural gas by combined cycle gas turbines together with increased use of FGD units on power generating stations.

9.2 In 1994 over 50% of NO_x and black smoke was generated by road traffic . Petrol has been shown to be the major generator of NO_x and diesel the major producer of black smoke .With the predicted expansion in road traffic of between 1.3% and 2.2 % per annum over the 1990-2020 period .The future mass emissions of these pollutants will depend on the relative growth in the demand for petrol and diesel .The energy demand model has indicated that in the longer term 2000 - 2020 emissions of NOx from the combustion of motor spirit will be basically flat , while emissions from DERV increase significantly reflecting its greater penetration in the transport fuel market .

10 It has been shown that significant reductions in emissions can be achieved in the power generating sector by the increased use of CCGT systems and by adopting new and improved energy technology . Three of these technologies have been critical examined ; the natural gas fired combined cycle gas turbine (CCGT) , the supercritical coal system (SUPS)and the coal fired integrated gasification combined cycle system (ICCC). The CCGT system which operates with an efficiency of over 50% has been shown to have significantly increased its share of the market over the 1990 - 1994 period and generate only 36 % of CO_2, 0% of SO_2 and 19 % of NO_x per unit of power of that produced by the conventional coal fired power station .
The new coal technology IGCC and SUPS systems operate with thermal efficiencies in a band of 42-45 % compared with 34-35 % for the conventional coal fired system and generate only 68% of CO_2 , 4% of SO_2 and 16% of NO_x of the coal fired system per unit of power produced . However they are less advanced technically and commercially than the CCGT system , but when fully developed they could offer considerable reductions in emissions over the conventional coal fired syste

APPENDIX 1

APPENDICES

Appendix 1

Comparison of NO_X Emissions from Passenger petrol and diesel Cars

(A) Petrol driven cars without three way catalyst.
(B) Petrol driven cars with installed three way catalyst.
(C) Diesel driven cars without catalyst.

Emission Factors

Vehicle Category and Driving Cycle		grams / km			kg / T			grams / Gj		
		(A)	(B)	(C)	(A)	(B)	(C)	(A)	(B)	C)
Small	National	2.16	0.53	0. 42	38.9	11.2	3.77	868	250	84
	Urban	1.79	0.67	0.42	26.5	12.0	4.76	592	268	106
Medium	National	2.56	0.33	0.67	40.9	5.25	4.36	913	117	97
	Urban	2.26	0.53	0.70	28.3	7.2	3.74	632	160	83
Large	National	3.17	0 50	0.91	37.4	6.13	3.54	835	137	79
	Urban	3.13	0.85	0.94	27.4	9.0	4.30	612	200	96

Density of petrol 0.74 kg / l Density of diesel 0.84 kg / l

NO_X Emissions from Heavy Diesel Vehicles

	grams / km	kg / t	grams / Gj
LGV			
National	1.25	184	412
Urban	1.35	187	419
HGV			
National	13.06	411	917
Urban	14.69	454	1014
Buses			
National	15.86	427	952
Urban	16.20	423	944

APPENDIX 2

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UK Energy Market: An Analysis of Energy Demands. Part I: A Disaggregated Sectorial Approach

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ABSTRACT

An econometric model has been used in a disaggregated approach to study the effect of energy demand for the Manufacturing Sector (1960–1987) and Domestic sector (1970–1987) respectively. The chosen model in each sector exhibits highly statistical significant coefficients for GDP, output, disposable income and energy price determinants. The GDP income elasticity was shown to be prominent in all models. The chosen model for each sector exhibited good predictive ability suggesting that it could be used for forecasting.

1. INTRODUCTION

The application of econometric models using an aggregate approach has been examined. In this study, an awareness that the difference in energy use cannot be fully explained in the aggregate model means that this difference must be explained on a sector-by-sector basis. To illustrate this, sectorial modelling of two major sectors of the UK economy have been examined. These include the manufacturing sector and domestic sector. Models based on these have been used to interpret in more detail the reasons for change in the energy-demand structure. Static and dynamic models, on the basis of energy supplied and useful energy, have been used in this disaggregated sectorial approach.

Analysis of energy demand has been undertaken for the following conditions:

(i) The manufacturing sector over the period 1960-1987, the real manufacturing output, real aggregate energy prices and energy

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consumption indexes in the demand model are based on two time periods:

1960–1979, indexed to 1970 ≡ 100
1973–1987, indexed to 1985 ≡ 100

(ii) The domestic sector over the period 1970–1987, the real disposable income, real aggregate energy prices, and energy consumption indexed to 1985 ≡ 100.

2. THE APPLICATION OF ECONOMETRIC MODELS TO THE MANUFACTURING SECTOR 1960–1979 (1970 ≡ 100)

An analysis of the energy demand in the manufacturing sector is undertaken over the same period as the overall energy demand study.[1]

The real aggregated energy-price data used in the statistical analysis are based on information compiled by the European Community[2] which calculates on the basis of annual changes in energy product and changes in the price of individual energies on an annual basis in order to compile an overall energy-price index each year over the period 1960–1979.

2.1 Energy Consumption, Aggregate Energy price and Manufacturing Output Relationship on a Supplied Energy Basis

The data in Fig. 1 show two distinct energy-price phases during 1960–1979. The pattern of energy consumption, economic activity and energy-price changes can be seen to be very similar to that occurring with the UK overall energy scene.

Period 1: (1960–1973)

The real price of energy consumed by industry steadily declined over this period: this contributed in part to the dramatic increase in industrial output and energy consumption. However, Fig. 1 also clearly shows a continuing reduction in energy consumption in relation to GDP over this period, reflecting the manufacturing industry's positive move to a lower-energy-intensity phase.

Period 2: (1973–1979)

Following the dramatic increase in fuel oil prices in 1973, manufacturing output growth was seriously curtailed and this was accompanied by an even greater reduction in energy consumption, as is clearly shown in Fig. 1, which again reflected the continuing lowering of energy intensity

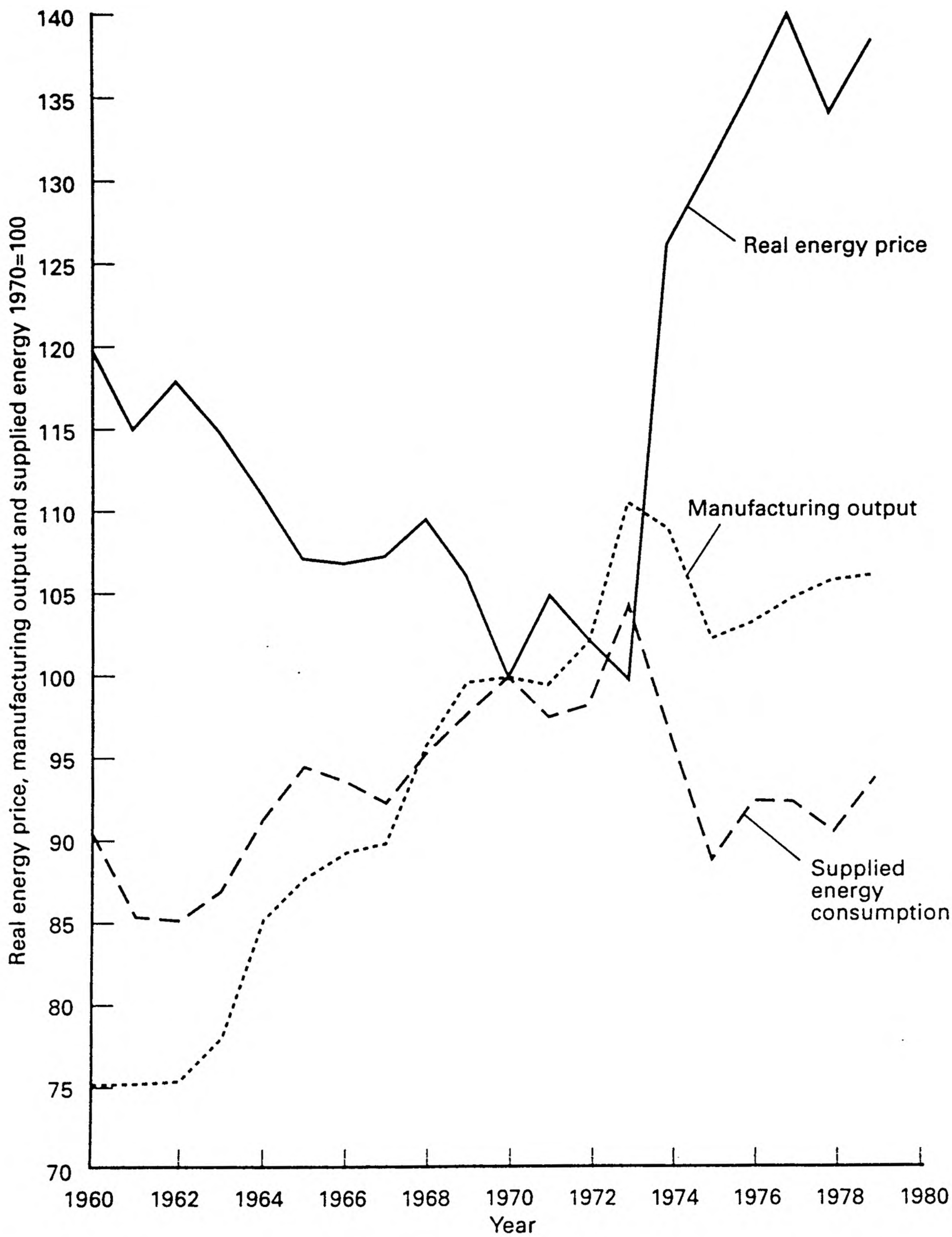

Fig. 1. Relationship between real energy price, manufacturing output, and supplied energy consumption 1970 ≡ 100 (*Sources:* Energy Consumption—Annual Digest of United Kingdom Energy Statistics 1960–1980. Manufacturing Output-Central Statistical Office, United Kingdom National Accounts 1960–1980, Energy Price—Statistical Office of the European Communities—Synthetic Annual Energy Price Index for the UK 1960–1980).

over the 1973–1979 period. Hence the increase in energy would be expected to be a major determinant in the energy-demand model.

Variables	% Change over the period 1973–1979
Energy price	+ 40%
Manufacturing output	−4·0%
Energy consumption	−9·7%

2.2 Model results based on supply energy

The results of the computer model provide the following for manufacturing output (Y), energy price (P), lagged variables (E_{t-1} and T), and energy consumption in the form of supplied energy (E).

Model 1

$$\log E = 2{\cdot}272 + \log 0{\cdot}6508\ E_{t-1} - 0{\cdot}1441 \log P$$
$$\text{`}t\text{'}\ (4{\cdot}584) \qquad \text{`}t\text{'}\ (-2{\cdot}074)$$
$$R^2 = 66{\cdot}11 \qquad F = 4{\cdot}301$$

Model 2

$$\log E = 4{\cdot}790 + \log 0{\cdot}4251 \log Y - 0{\cdot}3400 \log P$$
$$\text{`}t\text{'}\ (7{\cdot}907) \qquad \text{`}t\text{'}\ (-8{\cdot}473)$$
$$- 0{\cdot}1269 \log E_{t-1}$$
$$(-1.079)$$
$$R^2 = 93{\cdot}44 \qquad F = 62{\cdot}53$$

Model 3

$$\log E = 2{\cdot}731 + \log 0{\cdot}6539 \log Y - 0{\cdot}2599 \log P$$
$$\text{`}t\text{'}\ (4{\cdot}221) \qquad \text{`}t\text{'}\ (-4{\cdot}432)$$
$$- 0{\cdot}1869 \log E_{t-1} - 0{\cdot}5427 \log T$$
$$\text{`}t\text{'}\ (-1{\cdot}595) \qquad \text{`}t\text{'}\ (-1{\cdot}652)$$
$$R^2 = 94{\cdot}61 \qquad F = 2{\cdot}731$$

In model 1, the 't' statistics of the coefficients are significant enough. However, the regression coefficient is very low with a poor explanatory ability. It is also of importance that in the static model No. 1 manufacturing output is not one of the main determinants.

The explanatory properties of models 2 and 3 are very similar. The output of the manufacturing sector and the energy price are the main determinants in the model. In terms of size of the output and price coefficients, and significance of 't' values, both models compare favourably. However, model 3 possesses the highest R^2 value at 94·61. The inclusion of lagged energy consumption and time trend has added

TABLE 1
Supplied Energy Consumption (in 10^5 therms) for Manufacturing Industry

Year	*Actual*	*Prediction*	*Error as % of actual*
1961	20 994	20 961	−0·16
1962	21 035	20 986	−0·23
1963	21 430	21 405	−0·12
1964	22 516	22 664	+0·66
1965	23 306	22 960	−1·48
1966	23 084	22 960	−0·54
1967	22 763	22 960	+0·87
1968	23 529	23 751	+0·94
1969	24 121	24 319	+0·82
1970	24 689	24 492	−0·80
1971	24 072	23 874	−0·82
1972	24 269	24 417	+0·61
1973	25 775	25 751	−0·10
1974	23 800	23 578	−0·93
1975	21 949	22 640	+3·20
1976	22 837	22 788	−0·22
1977	22 813	22 516	−1·30
1978	22 368	22 813	+1·98
1979	23 183	22 640	−2·30

little to the explanatory properties of the dynamic models 2 and 3, since in statistical terms their values are insignificant.

2.3 Predictive ability of the econometric energy model

A predictive ability assessment has been made of the energy demand model 2. The percentage error is shown to be within a very narrow band; 85% of the predicted values were within ± 1·5%. The equation clearly demonstrates good predictive quality and as such could be used for forecasting.

2.4 Variations in the model elasticity

The model using supplied energy has been further analysed to establish the variations in the output and real energy price coefficients over the 1960–1979 period using a moving-point approach. Beginning from the 1960–1973 period, and moving the date one year each time, seven sets of data are formed which include 14 observations.

The results of the computer econometric model are shown in Table 2 and clearly demonstrate that the statistical significance of the output and energy price elasticities of energy demand are high, and the coefficients have the proper sign. The effect of increasing aggregate energy prices in

TABLE 2
log E = a + b log Y + c log P

Period	a	b	('t')	c	('t')	R^2	F
1960–1973	3·832	0·3930	(5·790)	−0·2267	(−1·918)	97·56	2·405
1961–1974	4·127	0·3886	(18·27)	−0·2857	(−6·896)	98·13	47·55
1962–1975	4·720	0·3603	(11·56)	−0·3853	(−8·423)	95·33	70·94
1963–1976	4·487	0·3655	(8·986)	−0·3404	(−8·148)	92·29	66·39
1964–1977	4·342	0·3702	(6·711)	−0·3139	(−8·029)	88·44	45·04
1965–1978	4·412	0·3737	(5·453)	−0·3325	(−8·282)	87·11	29·74
1966–1979	4·060	0·4347	(5·473)	−0·3176	(−8·275)	86·95	29·95
Overall 1960–1979	4·790	0·4251	(7·907)	−0·3400	(−8·473)	93·44	62·53

1973/74 is clearly reflected in significant increases in the statistical significance of the price elasticity of energy demand in the period 1961–1974.

2.5 Econometric model results based on useful energy

The following energy-demand models as the useful energy basis were produced for the manufacturing industry over the 1960-1975 period. As with the supplied energy basis, the main determinants of the energy model came out as manufacturing output and energy price in model 2 with the correct signs, significant '*t*' values, and very similar coefficient values.

The regression analysis using useful energy provides the following relationship, which in terms of size of coefficients, R^2 and '*t*' values, is very similar to that produced using supplied-energy values.

Model 2 (energy consumption based on useful energy)

$$\log E = 4{\cdot}8104 + 0{\cdot}4270 \log Y - 0{\cdot}3412 \log P$$
$$`t' \ (7{\cdot}942) \qquad `t' \ (-8{\cdot}492)$$
$$- 0{\cdot}1319 \log E_{t-1}$$
$$`t' \ (-1{\cdot}121)$$
$$R^2 = 93{\cdot}48 \qquad F = 62{\cdot}53$$

3 THE APPLICATION OF ECONOMETRIC MODELLING TO MANUFACTURING INDUSTRY SECTOR OVER THE 1973–1987 PERIOD BASED ON 1985 ≡ 100

In contrast to the previous section, which analysed energy demand during one movement in energy price over the 1960–1979 period, this section analyses the changing energy structure over four major changes in energy prices for the 1973–1987 period.

3.1 Energy consumption, energy price and manufacturing output relationships

The summary in Table 3 clearly shows that the changes in real energy prices have had a major influence on manufacturing output and energy consumption.

Figure 2 shows that supplied-energy consumption responds very positively to any change in real energy prices, whereas output can be seen to

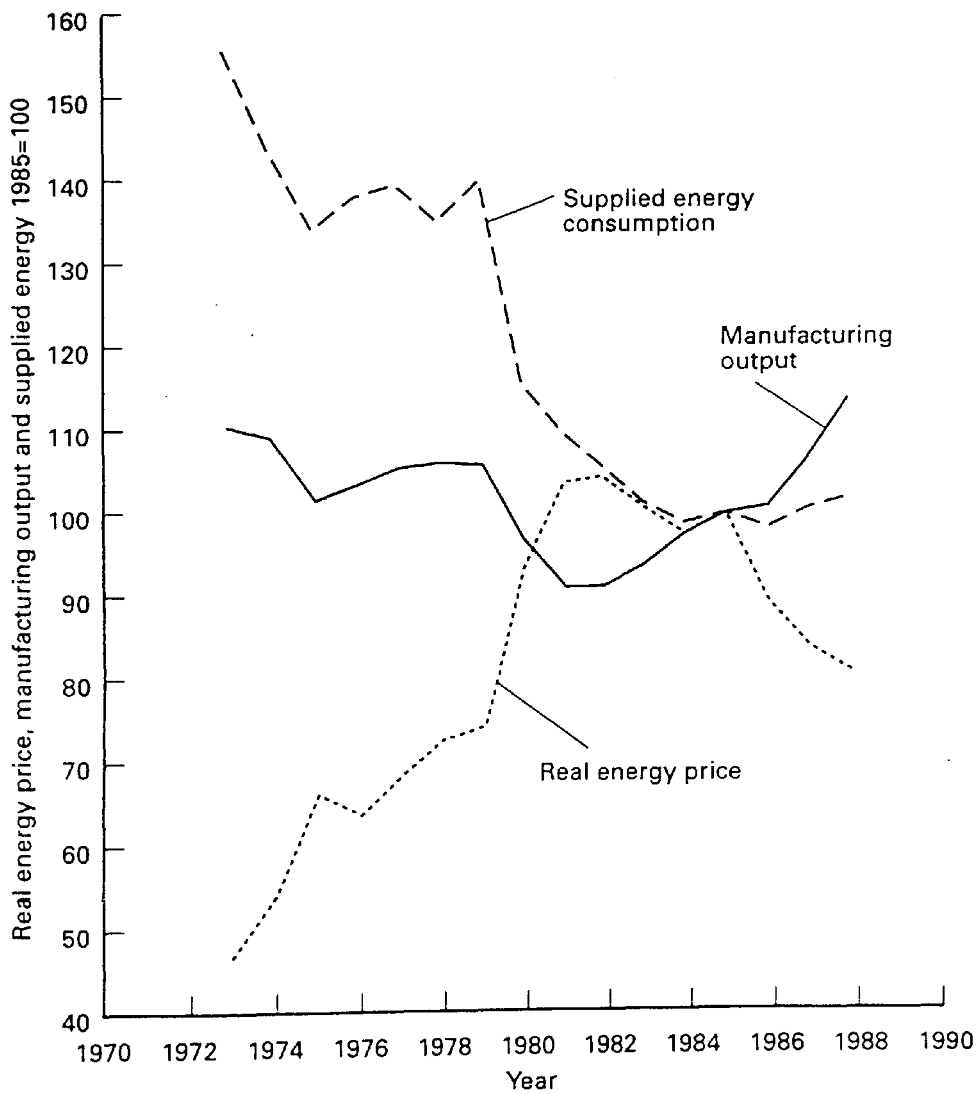

Fig. 2. Relationship between real energy price, manufacturing output, and supplied energy consumption 1985 ≡ 100 (*Sources*: Energy Consumption Index—Annual Digest of United Kingdom Energy Statistics 1970–1988, Manufacturing Output Index—Central Statistical Office, United Kingdom National Accounts 1973–1988, Energy Price Index—Department of Energy—Energy Trend Statistical Bulletin (Fuel price index relative to producer price index of materials)).

TABLE 3

Period	*% Change in real energy price*	*% Change in output*	*% Change in energy consumption*
1973–1982 (major price increase)	+124	−17·5	−32·4
1982–1987 (major price reduction)	−22·5	+25	+3·4
Overall 1973–1987	+74·0	+3·1	−34·7

have responded to a lesser extent. Energy price changes in 1973, 1979, 1982 and 1985 resulted in an immediate change in energy demand. The increase in energy price in 1979 gave rise to a sudden and significant fall in manufacturing output.

3.2 The results of the computer model provides the following relationships:-

Manufacturing output (Y), energy price (P), lagged variables (E_{t-1} and T) and energy consumption as supplied energy (E).

Model 1

$$\log E = 2{\cdot}725 + 0{\cdot}6478 \log Y - 0{\cdot}2426 \log P$$
$$`t\text{'}\ (6{\cdot}219) \qquad `t\text{'}\ (-2{\cdot}847)$$
$$R^2 = 93{\cdot}07 \qquad F = 8{\cdot}105$$

Model 2

$$\log E = 5{\cdot}588 + 0{\cdot}5205 \log Y - 0{\cdot}2340 \log P$$
$$`t\text{'}\ (2{\cdot}324) \qquad `t\text{'}\ (-2{\cdot}648)$$
$$- 0{\cdot}5021 \log E_{t-1}$$
$$`t\text{'}\ (-0{\cdot}6485)$$
$$R^2 = 93{\cdot}32 \qquad F = 0{\cdot}4205$$

Model 3

$$\log E = 8{\cdot}783 + 0{\cdot}8917 \log Y - 0{\cdot}1452 \log P$$
$$`t\text{'}\ (1{\cdot}180) \qquad `t\text{'}\ (0{\cdot}4362)$$
$$+ 0{\cdot}3096 \log E_{t-1} - 2{\cdot}250 \log T$$
$$`t\text{'}\ (1{\cdot}093) \qquad `t\text{'}\ (-1{\cdot}351)$$
$$R^2 = 94{\cdot}14 \qquad F = 1{\cdot}392$$

Model 1 provides the highest coefficient values for output and energy price with the correct signs, and with significant 't' values, and a demand model equation with a high regression analysis, with the best explanatory capability. The inclusion of the lagged energy consumption and time term in the dynamic models 2 and 3 has added little to the explanatory ability of the models, because both variables have low 't' values and can be regarded as insignificant and only the static model has any applicability to the explanation of energy demand over this period.

4 THE PREDICTIVE ABILITY OF THE ECONOMETRIC DEMAND MODEL

To assess the predictive ability of the manufacturing industry's econometric energy demand model for the period 1973–1988, the computer was programmed to compare the actual annual energy-consumption values with the predicted values: the results and the error as a percentage of the actual are shown in Table 4.

The four major changes in energy prices with their dramatic effect on energy consumption and influence on manufacturing output has given rise to large errors in predicting the energy consumption, i.e. only 20% of the predictions were within ± 1·5%. However, the demand equation possesses high statistical 't' values for output and price, and a high correlation coefficient.

TABLE 4
Supplied Energy Consumption (in 10^6 therms) for the Manufacturing Industry, 1973–1988

Year	*Actual*	*Prediction*	*Error as % of actual*
74	17 660	18 911	+7·08
75	16 495	16 924	+2·60
76	16 949	16 311	−3·76
77	17 145	16 495	−3·79
78	16 618	16 393	−1·51
79	17 206	15 882	−7·70
80	14 202	14 962	+5·35
81	13 466	13 196	+2·00
82	12 950	12 730	+1·70
83	12 411	12 546	+1·09
84	12 117	12 485	+3·04
85	12 264	12 411	+1·20
86	12 055	12 105	+0·41
87	12 338	12 239	−0·80
88	12 509	12 730	+1·77

4.1 Model results based on useful-energy consumption

The changing trends in manufacturing output, energy price and energy as useful energy is shown in Fig. 2.

The regression results using energy clearly show that the static model again has the best explanatory and statistical properties. Despite the difference in the coefficients between the supplied energy and useful energy demand models, both are statistically sound and possess high regression coefficients.

Model 1

$$\log E = 2{\cdot}027 + 0{\cdot}7254 \log Y - 0{\cdot}1682 \log P$$
$$`t' \ (7{\cdot}800) \qquad `t' \ (-2{\cdot}889)$$
$$R^2 = 93{\cdot}31 \qquad F = 8{\cdot}435$$

5 THE APPLICATION OF ECONOMETRIC MODELLING TO THE DOMESTIC SECTOR OVER THE PERIOD 1970–1987 (1985 ≡ 100)

5.1 Energy cost as a percentage of real disposable income

The demand for energy in the domestic sector depends on the consumer's relative preference for energy and other goods. The other goods are categorised into 9 specific groups and their percentage as a total of the disposable income is outlined in Table 5.[3] It can be seen that the total

TABLE 5

Items of Expenditure in the Disposable-Income Basket	*% Consumer Expenditure at 1985 Market Price*		
	1978	*1988*	*% Change*
Food (household expenditure)	15·8	12·8	−19·0
Alcoholic drink	8·2	6·6	−19·5
Tobacco	4·6	2·7	−41·3
Clothing and footwear	5·9	7·3	+23·7
Housing	15·0	14·4	−4·0
Household goods and services	6·7	7·0	+4·5
Transport and communications (less fuel)	11·7	14·5	+24·0
Recreation, entertainment and education	8·5	9·4	+10·6
Other goods and services	14·1	17·1	+21·1
Fuel, power, petrol and oil	9·5	8·1	−15·0

expenditure on fuel, power, petrol and oil only represents a relatively-small proportion of the total basket of disposable income. The table also shows that this figure fell from 9·5 to 8·1% over the immediate ten-year period, i.e. a fall of 15·0%. Most of the growth in consumer expenditure is associated with clothing, footware and transport activity.

Over the 1970–1983 period, domestic energy prices increased by 28% and consumers may have preferred to spend more money on home insulation and more efficient consuming appliances, thereby reducing the direct use of, and also expenditure on, energy.

5.2 Energy consumption, energy price and disposable income relationship

Figure 3 clearly shows that the domestic energy consumption/real disposable income ratio had fallen dramatically over the 1960–1989 period, which is largely as a result of substitution by more efficient fuels, and more efficient energy appliances, and the increased use of electricity despite the higher cost.

The real disposable income can be seen to have steadily increased by 40% over the 1970–1988 period (Fig. 4) despite four major changes in the real price of energy in the domestic sector. This is not unexpected in light of the relatively low level of expenditure on energy as a percentage of total disposable income. The influence of an increase in real energy prices on the overall consumer level of expenditure would be expected to be marginal.

5.3 An analysis of model results based on supplied energy

The energy consumption of the domestic sector is analysed relating the demand to such factors as real personal disposable income (*PDI*) of the sector: real energy price (*P*) in the sector in the static model and lagged energy consumption and time dependents are included in the dynamic model. The models were produced by using the iterative least-squares technique.

Model 1

$$\log E = 2{\cdot}465 + 0{\cdot}6862 \log PDI - 0{\cdot}2278 \log P$$
$$\text{'}t\text{'}\ (8{\cdot}273) \qquad \text{'}t\text{'}\ (-2{\cdot}593)$$
$$R^2 = 85{\cdot}10 \qquad F = 6{\cdot}722$$

Model 2

$$\log E = 1{\cdot}286 + 0{\cdot}384 \log PDI - 0{\cdot}3042 \log P$$
$$\text{'}t\text{'}\ (1{\cdot}270) \qquad \text{'}t\text{'}\ (-2{\cdot}654)$$
$$+\ 0{\cdot}6341 \log T$$
$$\text{'}t\text{'}\ (1{\cdot}034)$$
$$R^2 = 86{\cdot}23 \qquad F = 1{\cdot}070$$

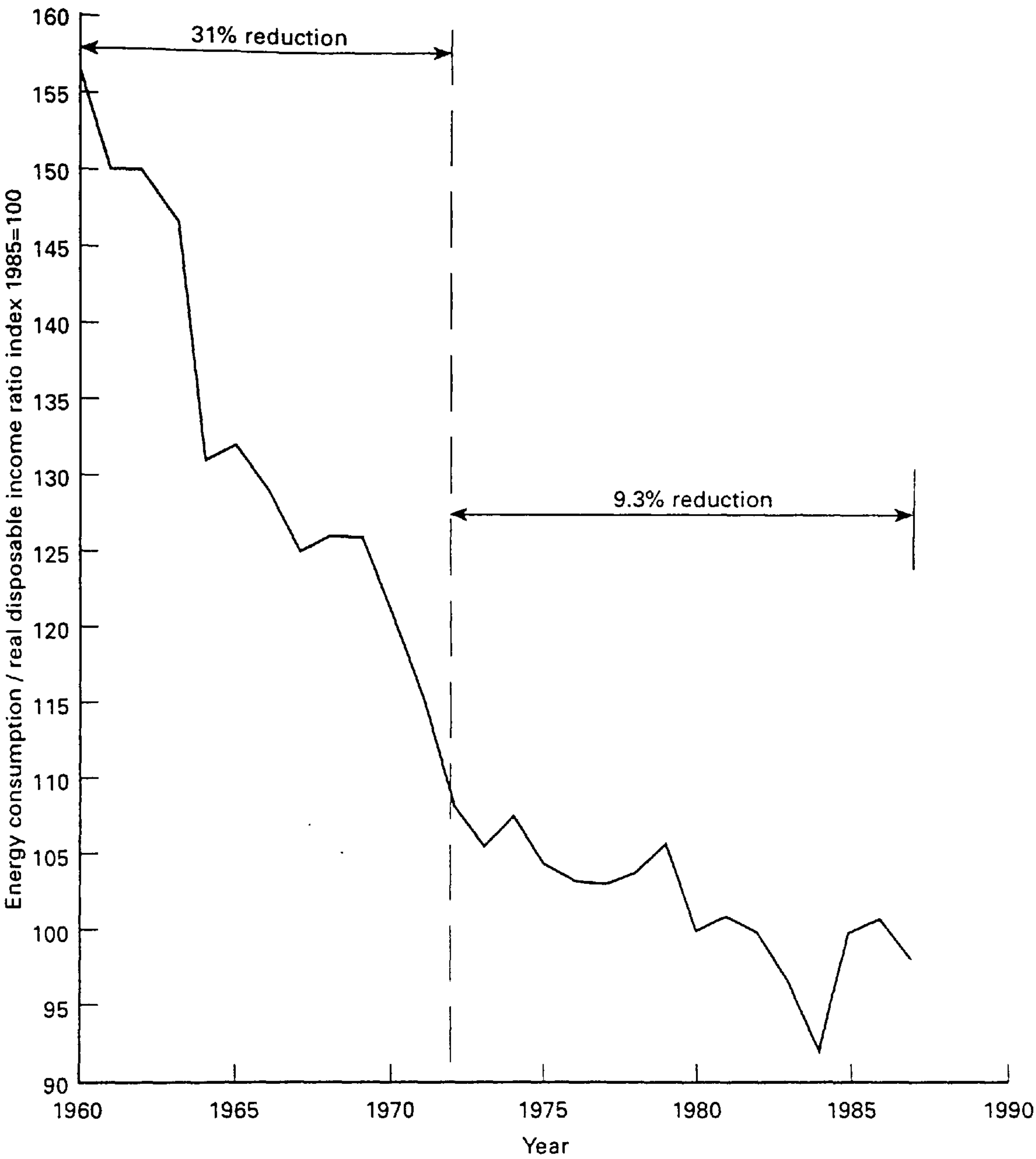

Fig. 3. Domestic energy consumption/real disposable income 1985 ≡ 100. (*Source:* Annual Digest of United Kingdom Energy Statistics 1960–1987).

Model 3

$$\log E = 1{\cdot}217 + 0{\cdot}3848 \log PDI - 0{\cdot}2849 \log P$$
$$`t\text{'}\ (1{\cdot}233) \qquad `t\text{'}\ (-2{\cdot}294)$$
$$+\ 0{\cdot}1052 \log E_{t-1} + 0{\cdot}5253 \log T$$
$$`t\text{'}\ (0{\cdot}5065) \qquad `t\text{'}\ (0{\cdot}7876)$$
$$R^2 = 86{\cdot}52 \qquad F = 0{\cdot}2566$$

The static and dynamic models show that energy demand is positively proportional to real disposable income in the domestic sector and negatively proportional to real aggregate domestic energy price.

The static model possesses high explanatory properties in terms of size

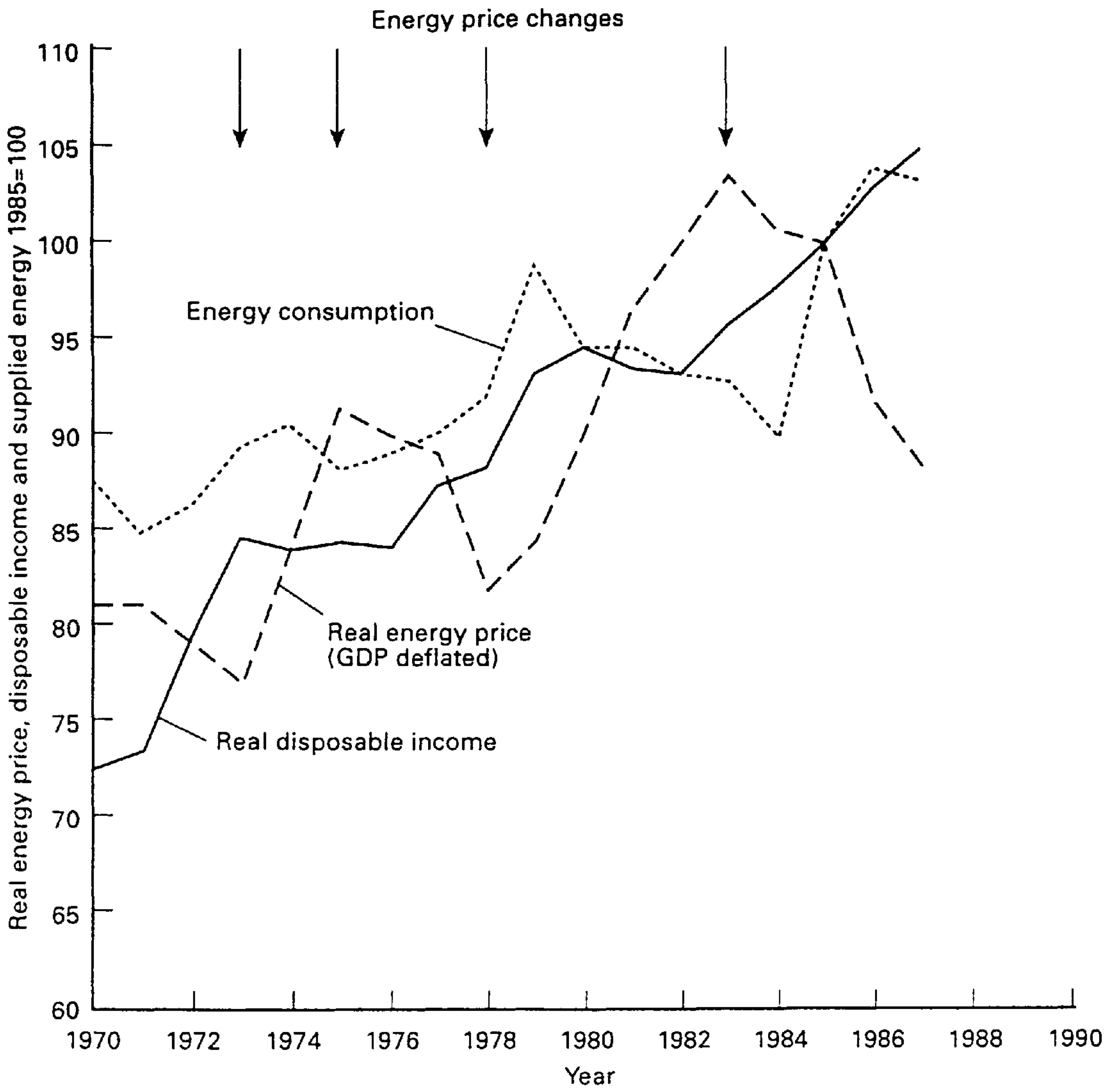

Fig. 4. Relationship between real energy price, real disposable income, and supplied energy consumption 1980 ≡ 100 (*Sources:* Energy Consumption and Real Disposable Income—Annual Digest of United Kingdom Energy Statistics 1970–1987, Energy Price—Energy Trends, Department of Energy Statistical Bulletin).

of output, price elasticities, regression coefficients (R^2) and the significant values of 't'. The inclusion of lagged energy variables and time trend in the dynamic model has produced an adverse effect and reduced the statistical significance of the main determinants, income and price, as shown in models 2 and 3.

5.4 Predictive ability of the econometric model

To establish the predictability of the econometric static model

$$\log E = 2{\cdot}465 + 0{\cdot}6862 \log PDI - 0{\cdot}2278 \log P$$
$$\text{'}t\text{' } (8{\cdot}273) \qquad \text{'}t\text{' } (-2{\cdot}593)$$

the computer program was extended to provide actual and predicted

TABLE 6
Supplied Energy Consumption (in 10^6 therms) for the Domestic Sector

Year	*Actual*	*Predicted*	*Error as % of actual*
1971	14 160	14 009	−1·06
1972	14 394	14 594	+1·39
1973	14 911	15 162	+1·68
1974	15 095	14 878	−1·44
1975	14 711	14 661	−0·34
1976	14 544	14 761	+1·92
1977	15 045	15 111	+0·44
1978	15 362	15 663	+1·96
1979	16 498	15 963	−3·24
1980	15 813	15 980	+1·06
1981	15 796	15 613	−1·16
1982	15 579	15 512	−0·43
1983	15 496	15 560	+0·41
1984	15 028	15 913	+5·90
1985	16 698	16 114	−3·50
1986	17 349	16 982	−2·11
1987	17 249	17 466	+1·26

energy demands for each year over the period 1970–1987: the results are shown in Table 6.

5.5 Variations in the model disposable income and energy price elasticities

To assess the changing trends of disposable income elasticity with regard to aggregate energy demand in the domestic sector over the 1970–1987 period under analysis, a moving-point approach has again been used. Beginning with the 1970–1987 period and moving data one-year each

TABLE 7
Domestic Sector Aggregate Energy Demand Model for the Moving Data Approach

Period	*a*	*b*	*('t')*	*c*	*('t')*	R^2	*F*
1970–1982	2·771	+ 0·4636	(4·901)	−0·0728	(−0·6939)	76·68	0·4815
1971–1983	2·449	+ 0·5947	(6·939)	−0·1441	(−1·961)	85·95	3·845
1972–1984	2·327	+ 0·7054	(4·698)	−0·2171	(−1·989)	71·75	3·956
1973–1985	2·4305	+ 0·6837	(4·114)	−0·2183	(−1·920)	65·31	3·687
1974–1986	2·505	+ 0·7832	(6·193)	−0·3332	(−2·956)	79·48	8·738
1975–1987	2·499	+ 0·7480	(6·994)	−0·2971	(−2·828)	83·15	7·995

time, giving 6 average coefficients based on 13 observations, shown in Table 7.

The results listed in Table 7 illustrate that the real disposable-income elasticities of energy demand for each of the six data sets possess highly significant '*t*' values. The energy price elasticities were shown to be statistically significant following the dramatic increase in aggregate energy prices in 1974.

5.6 Model results based on useful energy

The energy-demand models have been programmed to include energy consumption on the basis of useful energy. The dynamic model shown below exhibits the best explanatory properties of the models analysed with regard to the size of the disposable income and energy price elasticities, '*t*' values and

$$\log E = 1{\cdot}858 + 0{\cdot}8422 \log PDI - 0{\cdot}1439 \log P$$
$$`t\text{' } (4{\cdot}991) \qquad `t\text{' } (-2{\cdot}011)$$
$$+ 0{\cdot}2601 \log E_{t-1}$$
$$`t\text{' } (1{\cdot}617)$$
$$R^2 = 96{\cdot}77 \qquad F = 2{\cdot}613$$

The lagged energy coefficient, due to the low level of statistical significance indicated by the low '*t*' value, is not a major determinant in the energy demand model and here the model is classified as a static model.

CONCLUSIONS

The changing trends in the UK energy consumption could not be explained fully in aggregate and hence the two major sectors of the UK economy, manufacturing and domestic, were analysed in detail separately via econometric models to assess the UK energy-demand structure.

The choice of econometric equation to represent energy demand in each sector was based on the following equation properties:

(i) The highest correlation coefficient (R squared),
(ii) The elasticities with the significant '*t*' values and highest number,
(iii) The model with the largest number of determinants.

The chosen models in each sector are shown to exhibit highly statistically-significant coefficients for GDP, output, disposable income and energy price determinants.

The GDP–income–disposable-income elasticity is shown to be the most prominent one in all models. This is manifested in both the size of the elasticity and its statistical significance.

Changes in the real price of energy produced significant opposite responses in energy demand as demonstrated by the negative value for the price coefficient in all models. This effect is most clearly demonstrated for the manufacturing industry over the period 1973–1988 when four major price changes occurred.

The chosen model for each sector exhibited good predictive ability, suggesting that market forces in terms of GDP, manufacturing output, disposable income and energy price could be used for forecasting.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to R. Morgan and P. Luffrum of the Department of Business and Administrative Studies for helpful discussions.

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APPENDIX 1

TABLE A1
Energy Prices Indices Used in the Econometric Modelling Equations

1 *GDP* *(1973 = 100)* *1960 1979*		*2* *Industry* *(1970 = 100)* *1960 1979*		*3* *Industry* *(1985 = 100)* *1974 1988*		*4* *Domestic* *(1985 = 100)* *1973 1988*	
1960	115·8	1960	120·3	1974	54·1	1973	46·6
1961	114·4	1961	114·9	1975	66·0	1974	54·1
1962	115·1	1962	117·9	1976	63·5	1975	66·0
1963	113·7	1963	115·0	1977	68·3	1976	63·5
1964	112·9	1964	111·1	1978	72·5	1977	68·3
1965	109·6	1965	107·1	1979	74·1	1978	72·5
1966	109·8	1966	106·9	1980	93·4	1979	74·1
1967	110·9	1967	107·3	1981	103·7	1980	93·4
1968	113·0	1968	109·7	1982	104·4	1981	103·2
1969	110·7	1969	106·2	1983	100·8	1982	104·4
1970	108·9	1970	100	1984	97·4	1983	100·8
1971	112·8	1971	105·0	1985	100	1984	97·4
1972	105·3	1972	102·2	1986	89·3	1985	100
1973	100	1973	99·8	1987	83·8	1986	89·3
1974	125·4	1974	126·5	1988	78·4	1987	83·8
1975	131·2	1975	131·0			1988	80·9
1976	136·5	1976	135·7				
1977	144·2	1977	140·5				
1978	132·6	1978	134·5				
1979	141·0	1979	139·0				

1. The price index is the weighted average of energy prices deflated *by GDP deflator* (coal, oil, gas and electricity) for industry, household and petrol.
2. This index also takes account of trends in the pattern of consumption, i.e. the substitution of one form of energy by another in industry and the changing price of individual energies and provides an annual weighted-index of energy mix and individual energy prices *GDP deflated.*
3. This index is based on a fixed energy cost mix for coal, heavy fuel oil, gas and electricity for 1985 and *GDP deflated* to provide an annual price index for industry.
4. The price index is the weighted average of energy consumption of individual energies and changing energy prices *GDP deflated* for the domestic sector.

APPENDIX 3

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UK Energy Market: An Analysis of Energy Demands. Part II: Application of Econometric Models to the UK Sector

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ABSTRACT

An analysis of econometric energy demand models developed earlier has been carried out. The analysis examined models for coal, gas, electricity and fuel oil for both manufacturing and domestic sectors over the period 1973–87 for the manufacturing sector and 1970–87 for the domestic sector. The models were used to make predictions of the annual energy demand in both sectors over a 5-year period, assuming various output-energy price scenarios.

NOTATION

E Energy consumption as supplied energy —$\times$ 10^6 therms; indexed to base years 1970 ≡ 100 and 1985 ≡ 100.

P Energy price (real price) —deflated to base years 1970 ≡ 100 and 1985 ≡ 0 (coal, oil, gas and electricity); manufacturing industry indexed by producer price index domestic sector indexed by retail price index.

PDI Personal disposable income —£ $\times$ 10^6; index of income 1970 ≡ 100, 1985 ≡ 100.

Y Manufacturing output—£ $\times$ 10^6; index of industrial production at constant factor cost 1970 ≡ 100, 1985 ≡ 100

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THE STATISTICAL SIGNIFICANCE OF THE ENERGY PRICE COEFFICIENT IN THE ECONOMETRIC ENERGY DEMAND MODEL

During the 1970s, the UK experienced a major increase in the price of crude fuel oil, which was followed closely by increases in the price of other energies. The following analysis shows the dramatic increase in the statistical significance of the '*t*' value for the energy price coefficient following the major increase in energy price for the overall UK economy and manufacturing industry.

The overall economy 1960–79

Figure 1 shows that, when the real energy price was steadily declining during the 1960–73 period, the statistical significance of the energy price coefficient was low (the '*t*' value assuming 5 degrees of freedom at the 5% significant level being well below 2) for the eight overlapping periods 1960–66 to 1967–73. However, when the 1968–74 overlapping period was included in the analysis (energy prices having increased in 1974), the statistical significance of the energy price coefficient increased very dramatically, i.e. a '*t*' value in excess of 2.

The manufacturing industry 1960–79

A similar pattern emerges for the manufacturing industry as shown in Fig. 2. The statistical significance of the energy price coefficient increased substantially when the 1968–74 overlapping period was included in the analysis, again confirming the sensitivity and the statistical significance of the energy price coefficient in the econometric energy demand model to a major change in energy price.

THE DEVELOPMENT OF ECONOMETRIC ENERGY DEMAND MODELS FOR INDIVIDUAL ENERGIES (COAL, GAS, ELECTRICITY AND FUEL OIL) FOR THE MANUFACTURING AND DOMESTIC SECTORS DURING THE 1973–87 PERIOD

During 1970–87, the overall demand for energy declined as a result of many influencing factors including the dramatic increase in the real price of energies in 1973 and 1979—see Figs 3 and 4.

The econometric equations developed for the two major energy-con-

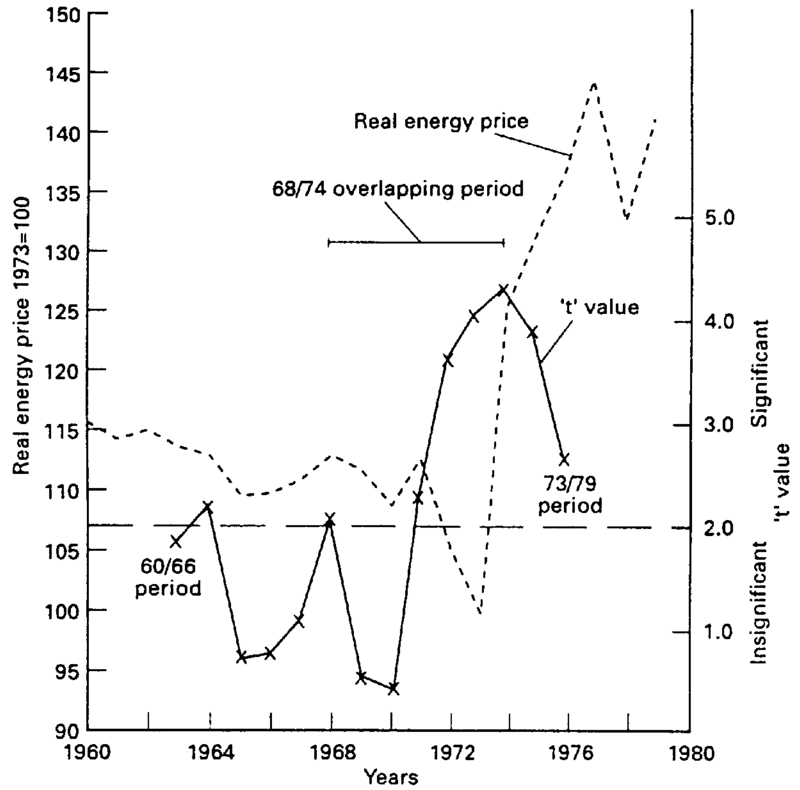

Fig. 1. Overall UK economy 1960/66—1973/79 statistical significance '*t*' of energy price in the econometric model (14 seven-year overlapping periods).

Overall UK economy 1960–79
14 seven-year overlapping econometric equations

R^2	F level		
94·17	0·4531	1960/66	$\log E = 7{\cdot}344 + 0{\cdot}07658 \log y - 0{\cdot}6841 \log P$
			(0·6731) (−1·921)
93·16	0·8605	1961/76	$\log E = 7{\cdot}300 + 0{\cdot}7824 \log y - 0{\cdot}6763 \log P$
			(0·9276) (−2·361)
84·48	27·22	1962/68	$\log E = 3{\cdot}185 + 0{\cdot}2923 \log y$ Insignificant
			(5·218)
80·09	20·11	1963/69	$\log E = 2{\cdot}687 + 0{\cdot}4071 \log y$ Insignificant
			(4·485)
92·16	1·533	1964/70	$\log E = 4{\cdot}038 + 0{\cdot}5843 \log y - 0{\cdot}4523 \log P$
			(6·468) (−1·238)
91·10	4·120	1965/71	$\log E = 5{\cdot}420 + 0{\cdot}6165 \log y - 0{\cdot}7768 \log P$
			(6·561) (−2·030)
88·09	0·2914	1966/72	$\log E = 2{\cdot}644 + 0{\cdot}5675 \log y - 0{\cdot}1418 \log P$
			(4·980) (−0·5398)
92·88	0·2172	1967/73	$\log E = 2{\cdot}305 + 0{\cdot}6064 \log y\ 0{\cdot}1069 \log P$
			(+3·977) (−0·4660)
			Energy price increase 1973
91·71	5·634	1968/74	$\log E = 3{\cdot}084 + 0{\cdot}5007 \log y - 0{\cdot}1708 \log P$
			(6·040) (−2·374)
84·71	13·631	1969/75	$\log E = 3{\cdot}786 + 0{\cdot}4133 \log y - 0{\cdot}2361 \log P$
			(3·756) (−3·690)
83·41	12·88	1970/76	$\log E = 3{\cdot}547 + 0{\cdot}4639 \log y - 0{\cdot}2318 \log P$
			(3·588) (−4·107)
85·63	18·33	1971/77	$\log E = 2{\cdot}539 + 0{\cdot}6632 \log y - 0{\cdot}2143 \log P$
			(4·460) (−4·281)
83·05	15·31	1972/78	$\log E = 2{\cdot}609 + 0{\cdot}6468 \log y - 0{\cdot}2136 \log P$
			(3·913) (−4·054)
74·72	6·495	1973/79	$\log E = 1{\cdot}228 + 0{\cdot}9429 \log y - 0{\cdot}2100 \log P$
			(3·255) (−2·549)

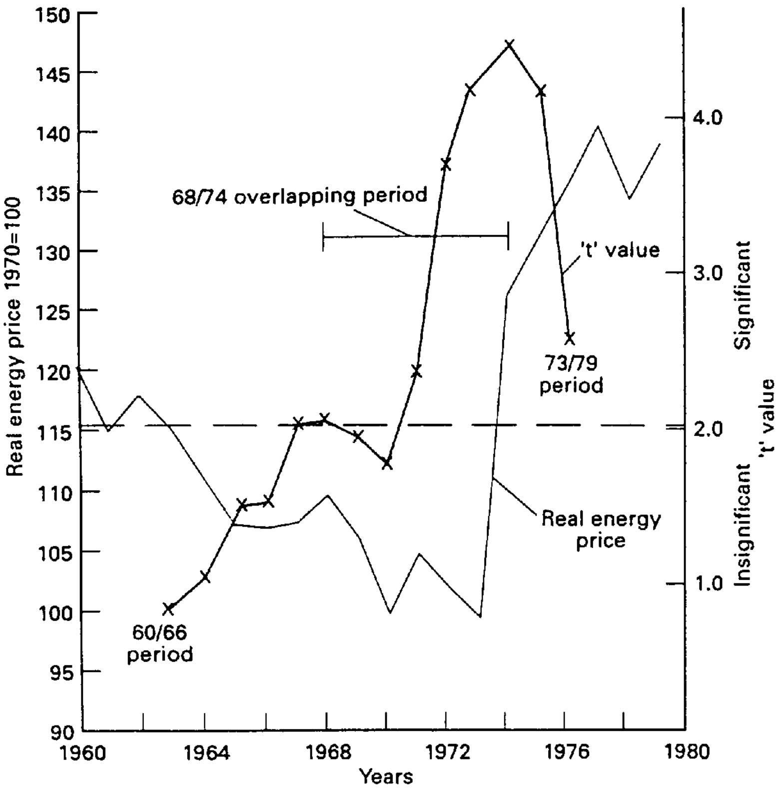

Fig. 2. Manufacturing industry 1960—1979· Statistical significance 't' of energy price in the econometric model (14 seven-year overlapping periods)·

Manufacturing industry 1960–79
14 seven-year overlapping econometric equations

R^2	F level		
96·26	0·1345	1960/66	$\log E = 1{\cdot}242 + 0{\cdot}6215 \log y - 0{\cdot}1095 \log P$ (3·563) (−0·3668)
95·37	1·018	1961/67	$\log E = 5{\cdot}267 + 0{\cdot}3160 \log y - 0{\cdot}3160 \log P$ (1·377) (−1·009)
94·89	2·212	1962/68	$\log E = 4{\cdot}728 + 0{\cdot}36622 \log y - 0{\cdot}3885 \log P$ (3·708) (−1·487)
93·80	2·251	1963/69	$\log E = 4{\cdot}751 + 0{\cdot}3459 \log y - 0{\cdot}3776 \log P$ (3·840) (−1·500)
91·74	4·219	1964/70	$\log E = 4{\cdot}774 + 0{\cdot}3347 \log y - 0{\cdot}3717 \log P$ (3·571) (−2·054)
89·19	4·307	1965/71	$\log E = 4{\cdot}872 + 0{\cdot}3309 \log y - 0{\cdot}3892 \log P$ (3·574) (−2·075)
93·15	3·612	1966/72	$\log E = 4{\cdot}099 + 0{\cdot}3975 \log y - 0{\cdot}2894 \log P$ (4·535) (−1·900)
96·78	2·987	1967/73	$\log E = 3{\cdot}499 + 0{\cdot}4867 \log y - 0{\cdot}2485 \log P$ (5·920) (−1·728)
			Energy price increase 1973
91·71	5·634	1968/74	$\log E = 3{\cdot}084 + 0{\cdot}5007 \log y - 0{\cdot}1708 \log P$ (6·040) (−2·374)
84·71	13·61	1969/75	$\log E = 3{\cdot}786 + 0{\cdot}4133 \log y - 0{\cdot}2361 \log P$ (3·756) (−3·690)
83·41	12·88	1970/76	$\log E = 3{\cdot}547 + 0{\cdot}4639 \log y - 0{\cdot}2318 \log P$ (3·588) (−4·107)
85·63	18·33	1971/77	$\log E = 2{\cdot}539 + 0{\cdot}6632 \log y - 0{\cdot}2143 \log P$ (4·460) (−4·281)
83·05	15·31	1972/78	$\log E = 2{\cdot}609 + 0{\cdot}6468 \log y - 0{\cdot}2136 \log P$ (3·913) (−4·054)
74·72	6·495	1973/79	$\log E = 1{\cdot}228 + 0{\cdot}9429 \log y - 0{\cdot}2100 \log P$ (3·255) (−2·549)

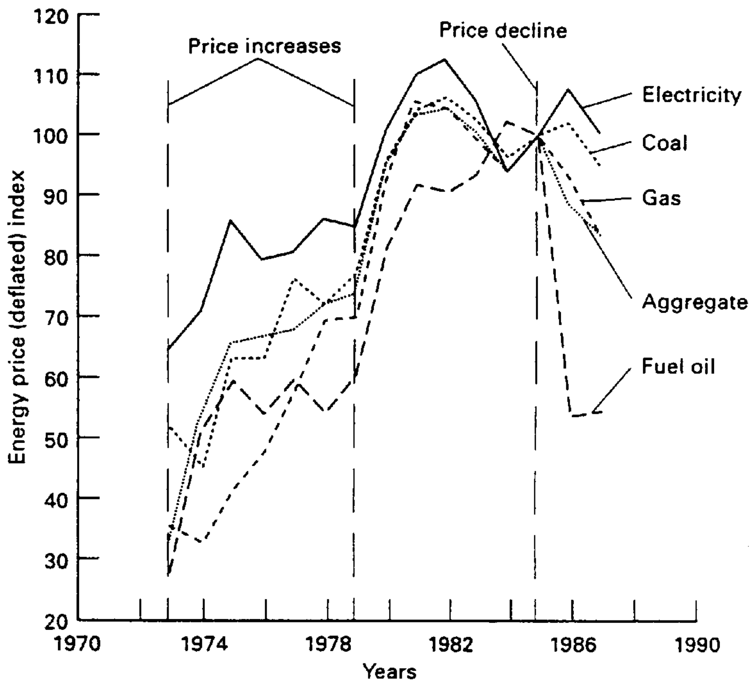

Fig. 3. Industrial sector: deflated energy price index (base year 1985 ≡ 100).

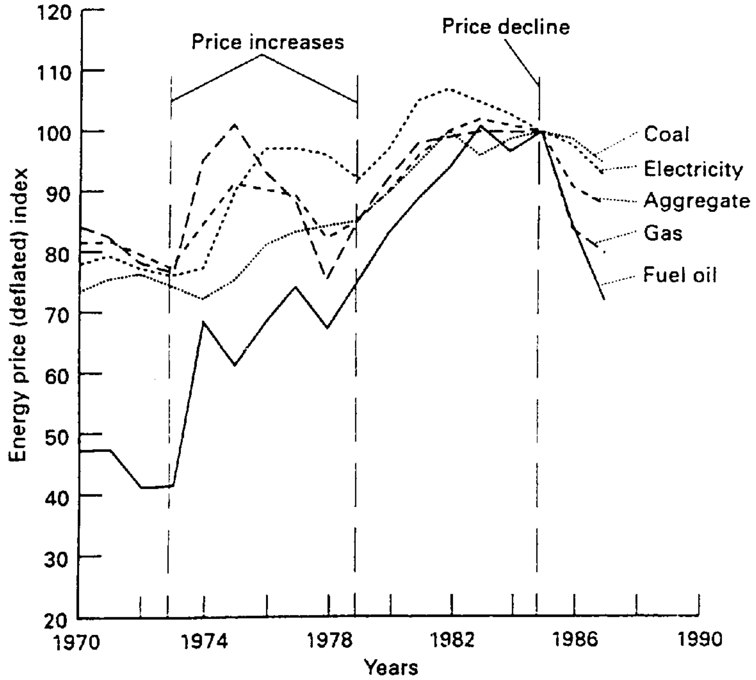

Fig. 4. Domestic sector: deflated energy price index (base year 1985 ≡ 100).

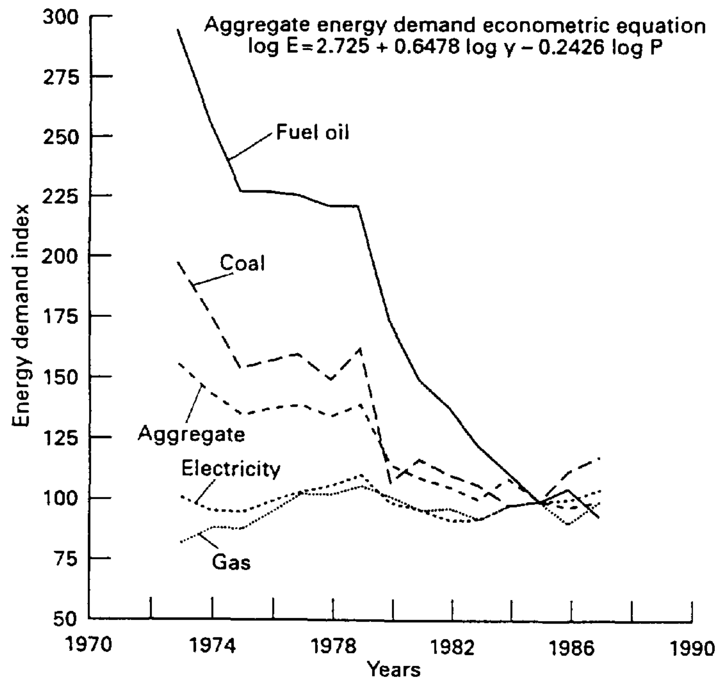

Fig. 5. Industrial sector: energy demand index (base year 1985 ≡ 100).

suming sectors in the UK economy, namely manufacturing and domestic, during 1970–87, exhibited positive signs for the energy-output coefficient and negative signs for the energy-price coefficients as shown below:

Manufacturing sectors

$$\log E = 2{\cdot}725 + 0{\cdot}6478 \log Y - 0{\cdot}2426 \log P$$

Domestic sectors

$$\log E = 2{\cdot}465 + 0{\cdot}6862 \log \mathrm{PDI} - 0{\cdot}2278 \log P$$

As a further stage of the analysis, econometric equations have been developed for each of the individual forms of energy (namely, electricity, gas, fuel oil and coal). The energy-demand equation outlined in Figs 5, 6 and 7 for the manufacturing sector and in Figs 8, 9 and 10 for the domestic sector show that widely different values and different signs for energy output (disposable income) and energy-price coefficients occur, depending on changing trends in the individual energy demand, which can be as a result of interenergy substitution, energy price increases and output or disposable income as shown below.

Manufacturing sector

Energy-demand decline

$$\text{Fuel oil} \quad \log E = 7{\cdot}996 - 0{\cdot}6875 \log P$$
$$\text{Coal} \quad \log E = 8{\cdot}123 - 0{\cdot}7362 \log P$$

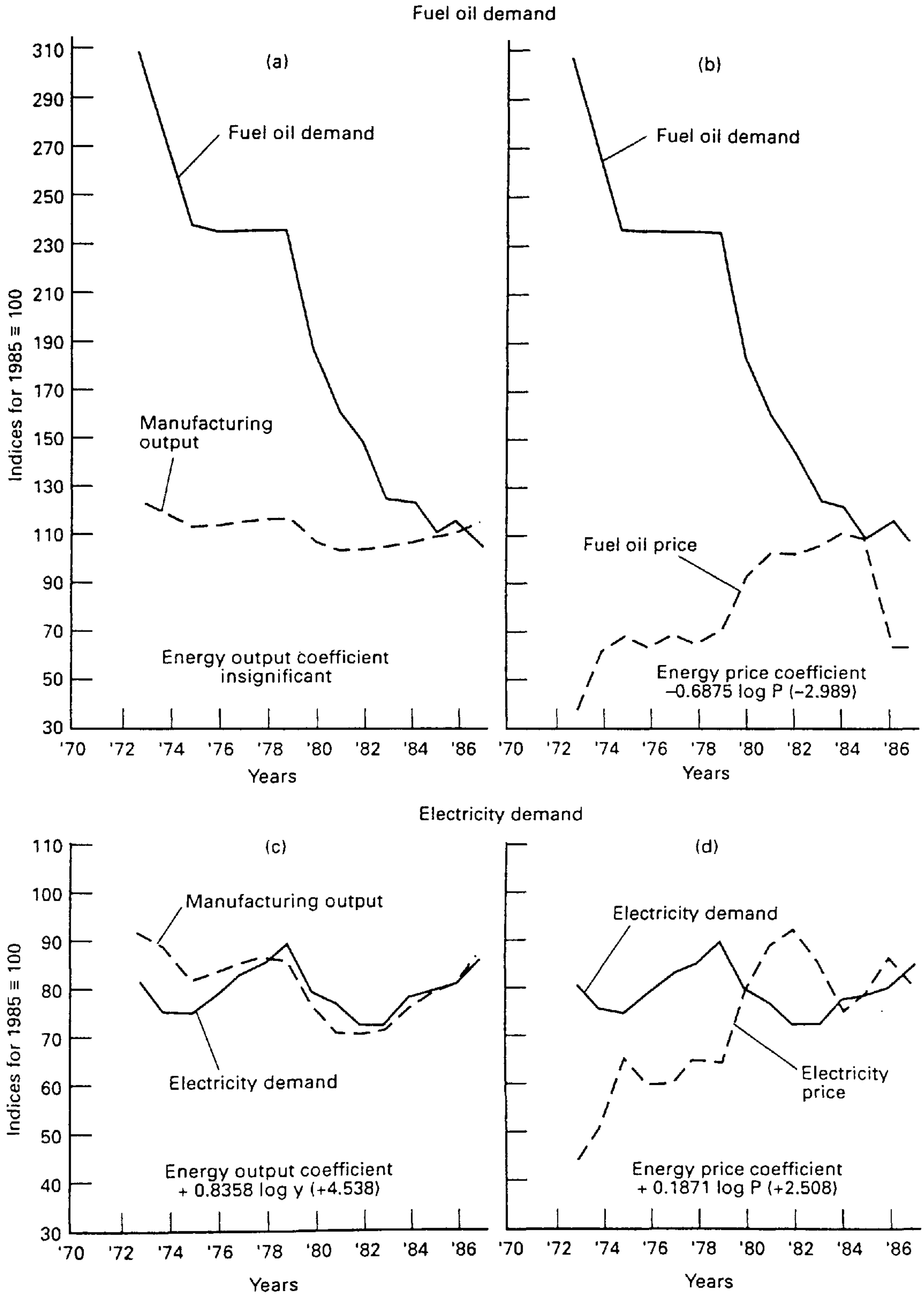

Fig. 6. Manufacturing industry sector: fuel-oil demand.

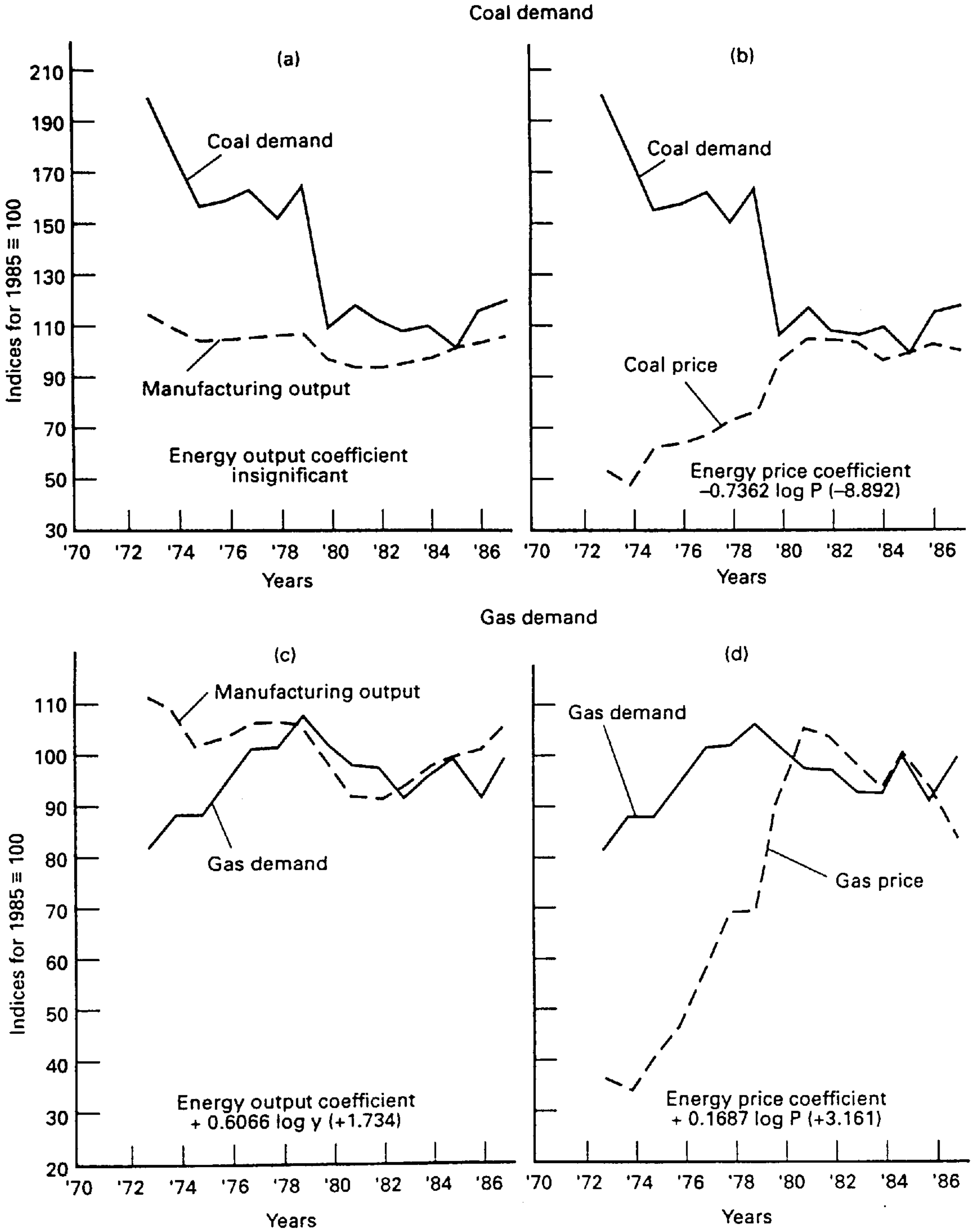

Fig. 7. Manufacturing industry sector: coal demand.

Energy-demand growth

Gas $\log E = 1{\cdot}047 + 0{\cdot}6066 \log Y + 0{\cdot}1687 \log P$

Electricity $\log E = -1{\cdot}022 + 0{\cdot}8358 \log Y + 0{\cdot}1871 \log P$

Domestic sector

Energy-demand decline

Fuel oil $\log E = 8{\cdot}502 - 0{\cdot}4124 \log \text{PDI} - 0{\cdot}4283 \log P$

Coal $\log E = 17{\cdot}202 - 1{\cdot}578 \log \text{PDI} - 1{\cdot}186 \log P$

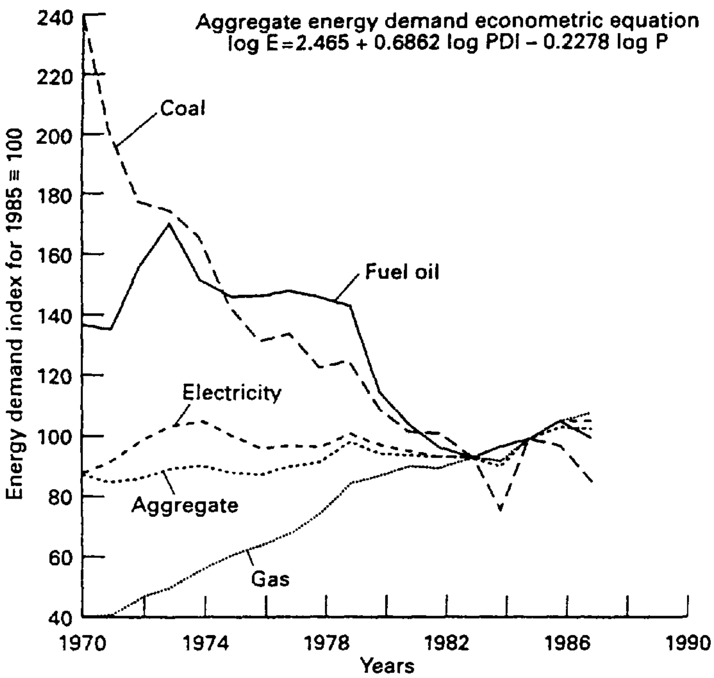

Fig. 8. Domestic sector: energy demand index (base year 1985 ≡ 100).

Energy-demand growth

$$\text{Gas} \quad \log E = 10{\cdot}371 + 2{\cdot}914 \log \text{PDI} + 0{\cdot}3462 \log P$$
$$\text{Electricity} \quad \log E = 4{\cdot}490 + 0{\cdot}4461 \log \text{PDI} + 0{\cdot}4261 \log P$$

These individual econometric energy models have clearly demonstrated that:

(a) Where a significant rate of decline in energy demand occurs despite an increasing real disposable-income, the sign preceding the disposable income coefficient is shown to be negative for coal and fuel oil demand for the domestic sector (Figs 9(a) and 10(a).

Where there is a major decline in energy demand as in the case of coal demand in the domestic sector, the energy disposable income coefficient is shown to be high at 1·578 with a negative sign.

(b) When the rate of energy demand is very high compared with disposable income as demonstrated by gas demand in the domestic sector, the energy disposable-income coefficient has a positive sign and a very high value of 2·914 (Fig. 9(c)).

(c) When the fall in the rate of energy demand is well in excess of the rate of increase in energy price, the energy disposable income coefficient is high at 1·186 with a negative price as demonstrated by the coal demand in the domestic sector (Fig. 9(b)).

(d) When the decline in demand for energy is significant, but the output is relatively stable and hence does not influence energy demand, the statistical significance of the energy-output coefficient is low as demonstrated by the fuel, oil and coal demands in the manufacturing sector (Figs 6(a) and 7(a)).

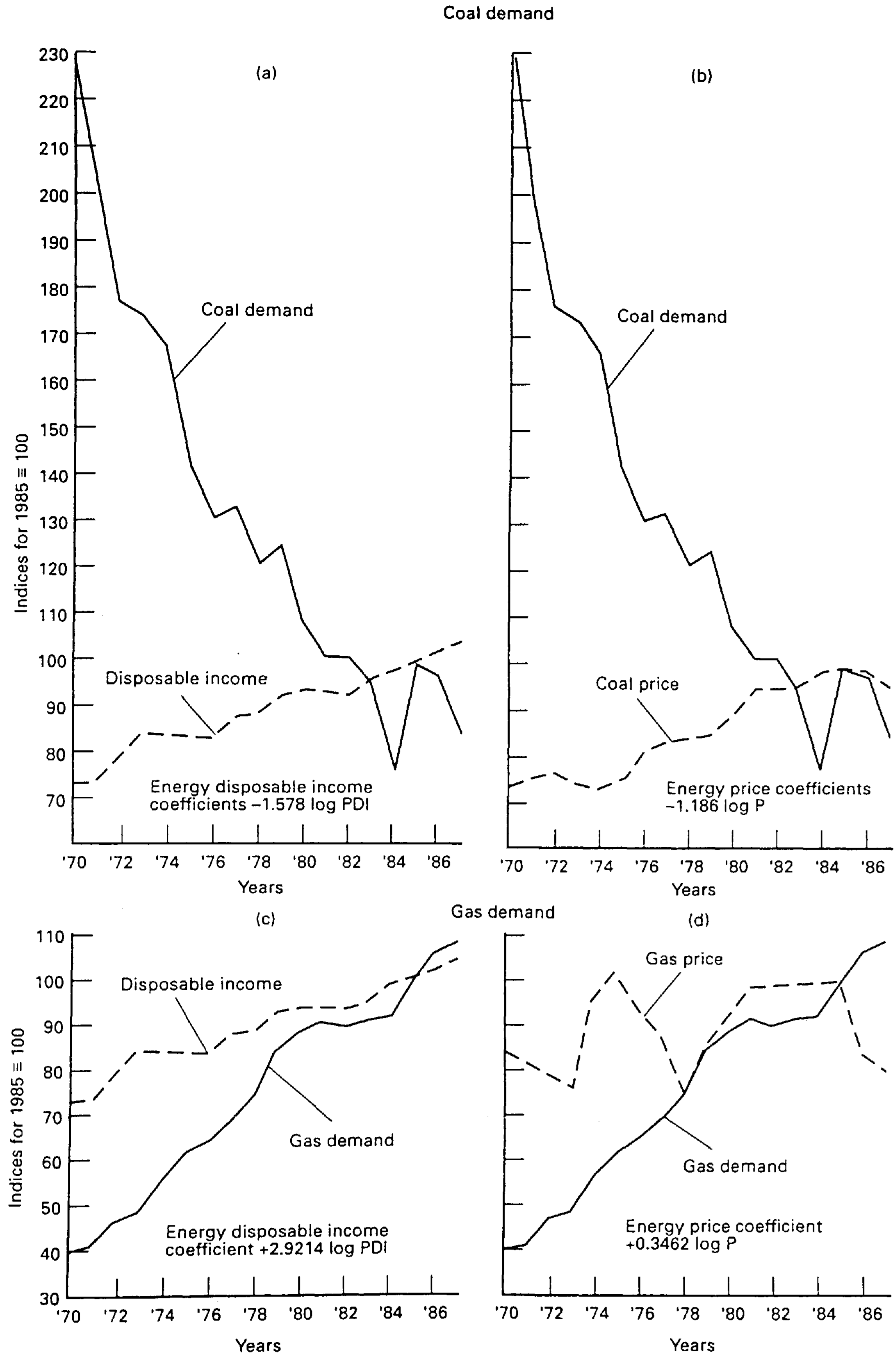

Fig. 9. Domestic sector: coal demand.

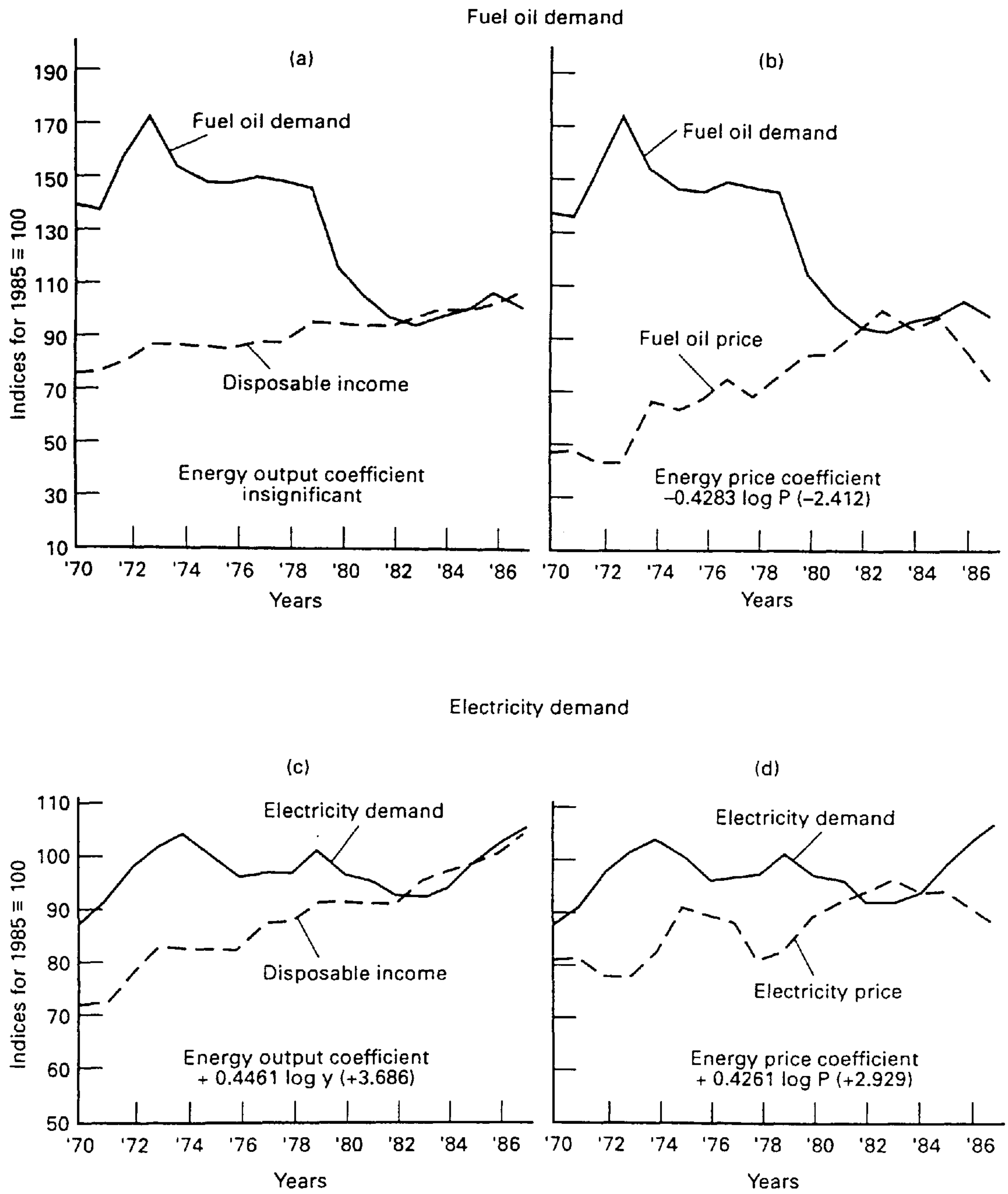

Fig. 10. Domestic sector: fuel-oil demand.

USING THE DEVELOPED ENERGY ECONOMETRIC MODELS TO PREDICT FUTURE ENERGY-DEMANDS OVER A 5-YEAR PERIOD

Future energy demands have been predicted for the two major energy-demand sectors in the UK economy over the period 1988–93, using the model equations developed for 1970–87.

The following four scenarios were selected:

Scenario 1: 4% annual increase in manufacturing output or disposable income with the aggregate energy price unchanged.

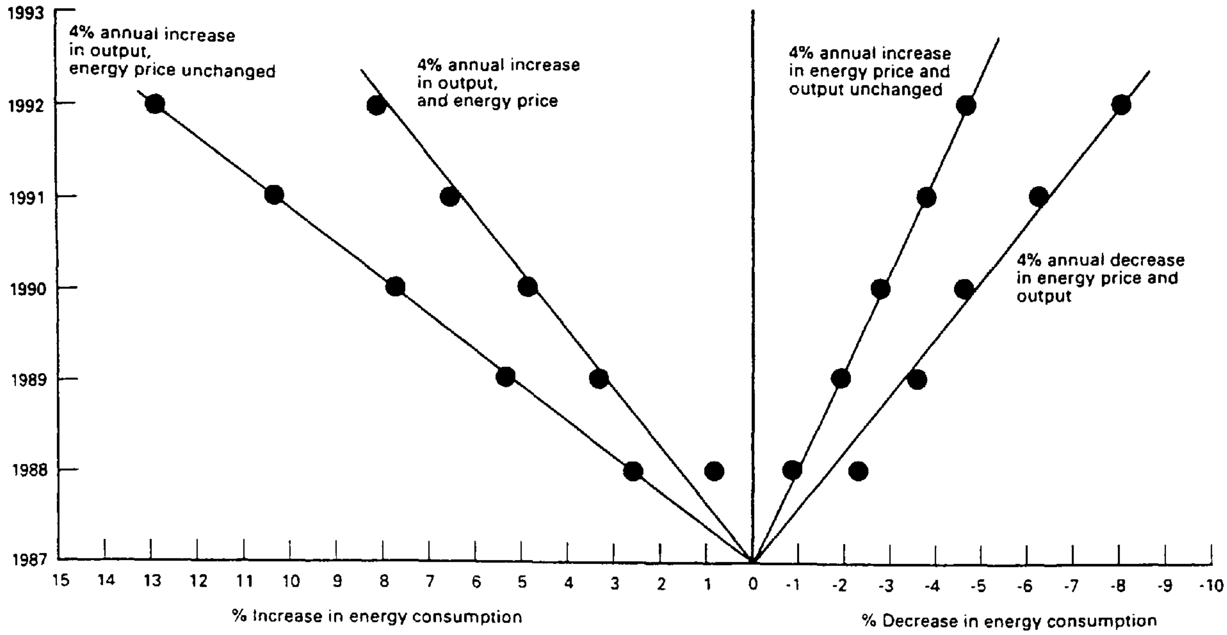

Fig. 11. Predicted energy consumption from 1973 to 1988: data for manufacturing industry—over 5 years (log E = 2·725 + 0·6478 log y − 0.2426 log P).

Scenario 2: 4% annual increase in manufacturing output or disposable income including a 4% annual increase in aggregate energy price.

Scenario 3: 4% annual increase in aggregate energy price with manufacturing output or disposable income unchanged.

Scenario 4: 4% annual decrease in manufacturing output or disposable income and a 4% annual decrease in energy price.

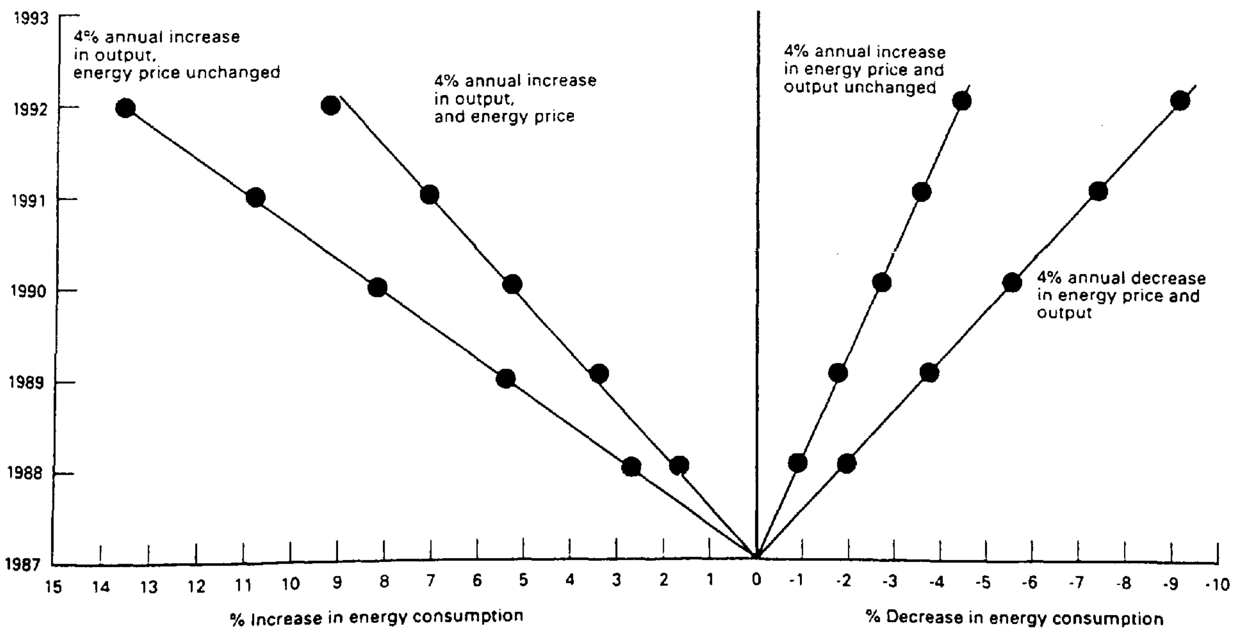

Fig. 12. Predicted energy consumption from 1970 to 1987: data for domestic sector over 5-year period (log E = 2·465 + 0·6862 log PDI − 0·2278 log P).

The overall predicted demand for the 5-year period is shown below:

	Manufacturing Industry (Fig. 11)	Domestic Sector (Fig. 12)
Scenario 1	+12·93%	+9·63%
Scenario 2	+8·16%	+9·20%
Scenario 3	−6·80%	−9·11%
Scenario 4	−4·60%	−4·52%

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Nomenclature

CCGT	combined cycle gas turbine
CCP	Climate Change Programme
CH	central GDP growth - high fuel prices
CL	central GDP growth - low fuel prices
CO_2	carbon dioxide
DERV	diesel engine road vehicle
DoE	Department of Environment
DTI	Department of Trade and Industry
EC	European Community
EP 58	Energy Paper 58
EP 59	Energy Paper 59
EP 65	Energy Paper 65
ESI	electricity supply industry
FGD	flue gas desulphurisation
GDP	gross domestic product
GW	gigawatts
HH	high GDP growth - high fuel prices
HL	high GDP growth - low fuel prices
IGCC	integrated gasification combined cycle
LCPD	Large Combustion Plant Directive
LH	low GDP growth - high fuel prices
LL	low GDP growth - low fuel prices
MtC	million tonnes of carbon
MW	megawatts
NAEI	National Atmospheric Emissions Inventory
NO_x	oxides of nitrogen (as nitrogen dioxide)
SO_2	sulphur dioxide
toe	tonnes of oil equivalent
UNECE	United Nations Economic Commission for Europe
SUPC	Supercritical coal
IGCC	integrated gasification combined cycle
TWC	Three - Way Catalyst
EEC	European Economic Community
HMIP	Her Majesty's Inspectorate of Pollution
Gj	Giga joules
kg	Kilo grams
km	Kilometers
CV	Calorific Value
WRL	Warren Spring Laboratories
O_2	oxygen
PM	particulate matter

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