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Sulphur dioxide emissions from oil refineries in Europe (2010)

Environmental science for the European refining industry

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Sulphur dioxide emissions from oil refineries in Europe (2010)

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ABSTRACT

This report describes the results of the 2010 year survey into the sulphur pathways in European refining. This includes the distribution of sulphur in products, the capture and recovery of sulphur in refineries and the emission of sulphur oxides as part of the refining process. The archived results of surveys carried out for the years 1998, 2002 and 2006 are also included.

In 2010 the 63 refineries, considered in this report, processed crude and other feedstock equivalent to 68% of the European refinery throughput. The results confirm a downward trend in the sulphur content of major product streams, associated with a strong increase in sulphur recovered in the refinery process and a reduction of sulphur emitted from refinery operations.

The 2010 survey showed:

- A reduction in the amount of sulphur going out in products from ~37% of intake in 1998 to ~27% of intake in 2010.
- An increase in the amount of sulphur recovered from ~39% of intake in 1998 to ~56% of intake in 2010.
- A decrease in the amount of sulphur emitted to atmosphere from refinery operations from 7.2% in 1998 to 3.8% in 2010.

KEYWORDS

Emissions, oil industry, petroleum products, refinery, sulphur, sulphur dioxide, survey, crude

INTERNET

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SUMMARY

The Concawe Sulphur survey has been run at approximately 4 year intervals since 1979 and provides an overview of the distribution of sulphur across all of the main refinery product streams in relation to the refinery crude diet. Additionally it reports on sulphur emitted to atmosphere and sulphur recovered as a product.

The results of the survey show continued reduction in sulphur emitted to atmosphere with an overall strong increase in sulphur recovery. In 2010 an estimated 56% of the sulphur in the refinery intake is recovered as elemental sulphur compare to 45% in 2006 and 39% in 1998. A further 12% is sequestered in products that are not burned. The amount of sulphur emitted by refineries themselves has halved since 1998, this is due to less oil burning, a reduction in the sulphur content of internal fuels and investments in desulphurization of products and sulphur recovery process. The proportion of sulphur in products destined for combustion has decreased from 37% of intake in 1998 to 32.5% in 2006 and to 27% in 2010 reflecting the progress made to comply with fuel and air quality legislation.

The annually averaged sulphur content in the crude diet for Europe has increased from 0.91% in 2006 to 1.01% in 2010.

The sulphur content of produced fuels closely matches the market requirements of fuels regulated by international or EU regulations (e.g. Sulphur in Liquid Fuels Directive and the Directive on Automotive Fuel Quality).

1. INTRODUCTION

Concawe has reported the distribution of sulphur between refinery products and refinery emissions at 4 yearly intervals since 1979 by means of what is known as the Sulphur Survey report. (See references Concawe (1984) [1], Concawe (1986) [2], Concawe (1991) [3], Concawe (1996) [4], Concawe (1998) [5], Concawe (2002) [6], Concawe (2007) [7], Concawe (2010)[8])

The report provides information on the typical sulphur content of the main refinery product streams, the amount of sulphur recovered and the amount of sulphur emitted in the course of refining those products. Results from the Sulphur Survey are useful in assessing how the industry responds to regulation (e.g. on changing fuel specifications, environmental legislation, etc.).

2. REFINERY INTAKE AND OVERALL SULPHUR BALANCE

Refineries take in both crude oil and intermediate products for processing. The totals reported in the last four survey years compared with the total refinery intake in the EU-28, are given below. The Concawe surveys covered 73% of refinery input in 1998, 43% in 2002, 63% in 2006 and 68% in 2010. These survey results are therefore considered to be representative of the industry in 2010.

Table 1 Refinery hydrocarbon intake

	1998	2002	2006	2010
Number of refineries participating in survey	77[1]	46[2]	67	63[3]
Crude Intake, Mt	502	277	417	393
Other Intake, Mt	38	35	55	55
Total Intake, Mt	550	312	472	448
EU-28 Crude oil, feedstock and other hydrocarbons transformation input in refineries[4], Mt	751	726	478	658
Concawe/EUROSTAT %	73%	43%	63%	68%

The refinery overall sulphur intake and the distribution of sulphur output is shown in **Table 2** below. The categories are:

- products destined for combustion (fuels)
- products (non-combustion) where the sulphur remains in the product and is retained and not further converted (e.g. bitumen)
- sulphur recovered from refinery streams as elemental sulphur
- sulphur recovered in non-oil products (e.g. gypsum.)
- sulphur emitted from refinery processes and combustion

[1] Concawe Report 10/02 reports 79 refineries completing the questionnaire with a crude input of 507 Mt.
[2] Concawe Report 02/07 reports 47 refineries and a total intake of 331 Mt/a – one survey return appears to have been counted twice in that analysis and was removed when preparing Concawe report 1/10
[3] Two responses were not complete and 63 is the number of surveys taken into account in this report.
[4] Eurostat data. Downloaded 19-10-2015. v3.1.10-20150929-5608-PROD_EUROBASE. Crude oil, feedstocks and other hydrocarbons. Transformation input in refineries.

The largest sulphur output stream, for each year studied, is elemental sulphur from the sulphur recovery system. The next largest is the sulphur present in products.

The average sulphur content of the European crude intake increased to a value of 1.01% in 2010 compared to 0.91% w in both 2002 and 2006 and 0.97% w in 1998.

The sectoral sulphur mass closure in 2010 was 99.5% which is very good and better than for the last two surveys and similar to 1998[5]. The results for individual refinery balances are more varied due in part to sensitivity of the calculated balance using average S contents.

Table 2 Refinery sulphur intake and output in kilotonnes

		1998	2002	2006	2010
Intake	S in Crude kt(S)	4901	2515	3788	3965
	Other kt(S)	307	194	395	375
S content	Crude %	0.97	0.91	0.91	1.01
	Other %	0.81	0.55	0.72	0.68
Output	Products for combustion kt(S)	1926	809	1361	1185
	Products for non-combustion kt (S)	757	233	493	526
	Recovered as elemental sulphur kt(S)	2053	1289	1880	2426
	Recovered as other sulphur compounds kt(S)	71	149	9	18
Emitted at Refinery	All sources kt(S)	374	150	156	164
TOTAL	OUT kt(S)	5181	2629	3900	4320
	IN kt (S)	5207	2709	4183	4340
	RATIO %	99.5	97.0	93.2	99.5

5 Reported as 97.3% in Concawe report 10/02 with very slight difference in output 5122 c.f. 5181 kt(S)

To illustrate trends in time in the distribution of sulphur between the different output modes the S content is shown below as a percentage of the input.

Table 3 Fraction of sulphur intake going to different sources

		1998	2002	2006	2010
Output	Products for combustion	37.0	29.8	32.5	27.3
	Products not for combustion	14.5	8.6	11.8	12.1
	Recovered as elemental S	39.4	47.6	45.0	55.9
	Recovered as other S products	1.4	5.5	0.2	0.4
Emitted at Refinery	All sources	7.2	5.5	3.7	3.8
Balance		99.5	97.0	93.2	99.5

We conclude that the survey shows:

- a reduction in the amount of sulphur going out in products for combustion (fuel products) from ~37% of intake in 1998 to 27.3% of intake in 2010.
- an increase in the amount of elemental sulphur recovered from 39.4% of intake in 1998 to ~55.9% of intake in 2010.
- A decrease in the sulphur emitted to the atmosphere by refineries from 7.2% in 1998 to 3.8% in 2010, a comparable proportion to 2006.

The refinery emissions to atmosphere of oxidised sulphur arise from several combustion sources. The survey asks for the emissions from Stacks, Fluid Catalytic Cracking Units (FCCU), Sulphur Recovery Units (SRU) and Flares to be disaggregated and for remaining emissions to be categorised as Miscellaneous. The overall distribution of emissions from these sources is given in **Table 4** as a fraction of the refinery sulphur intake. It can be seen that the situation in 2010 is similar to that in 2006 with a small relative increase in stack emissions offset by a larger reduction in flaring emissions. A significant reduction has been achieved in sulphur emissions from the combustion stacks and from flaring. The emission from sulphur recovery has remained proportionately small despite the big increase in S recovered.

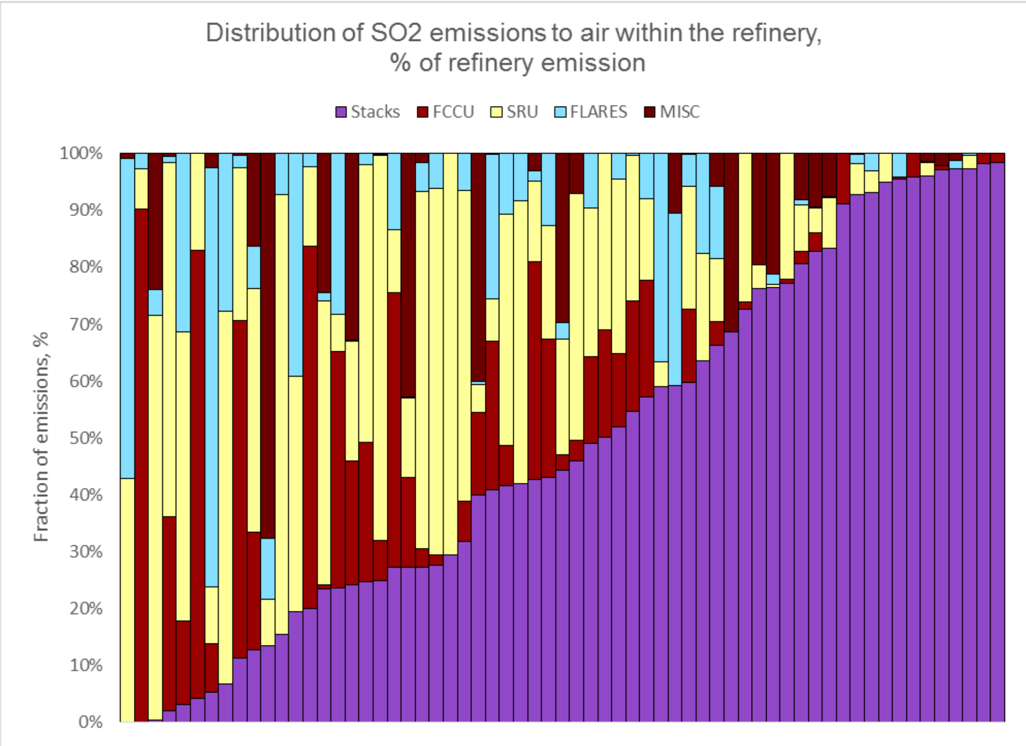
Table 4 Distribution of oxidised sulphur emissions between refinery sources as % of intake

Emissions from Combustion % of sulphur intake	1998	2002	2006	2010
Stacks	4.6%	3.1%	1.8%	2.3%
FCCU	0.4%	0.2%	0.4%	0.5%
SRU	0.8%	1.3%	0.6%	0.6%
Flares	1.0%	0.6%	0.8%	0.2%
Misc	0.4%	0.2%	0.2%	0.2%
All sources %S	7.2%	5.5%	3.7%	3.8%

The figures above are industry-wide aggregates. On a single refinery basis the apportionment of emissions is highly variable, as for example some refineries do not have a FCCU, some refineries are natural gas fired and have a low stack sulphur emission as a consequence, some have cokers which add to the miscellaneous emission etc.

This heterogeneity between refineries is shown for the year 2010 in **Figure 1**.

Figure 1 Distribution of refinery sulphur emissions between stacks, FCCU, SRU, flares and other sources. Results ordered by stack emission as fraction of total emission (2010).

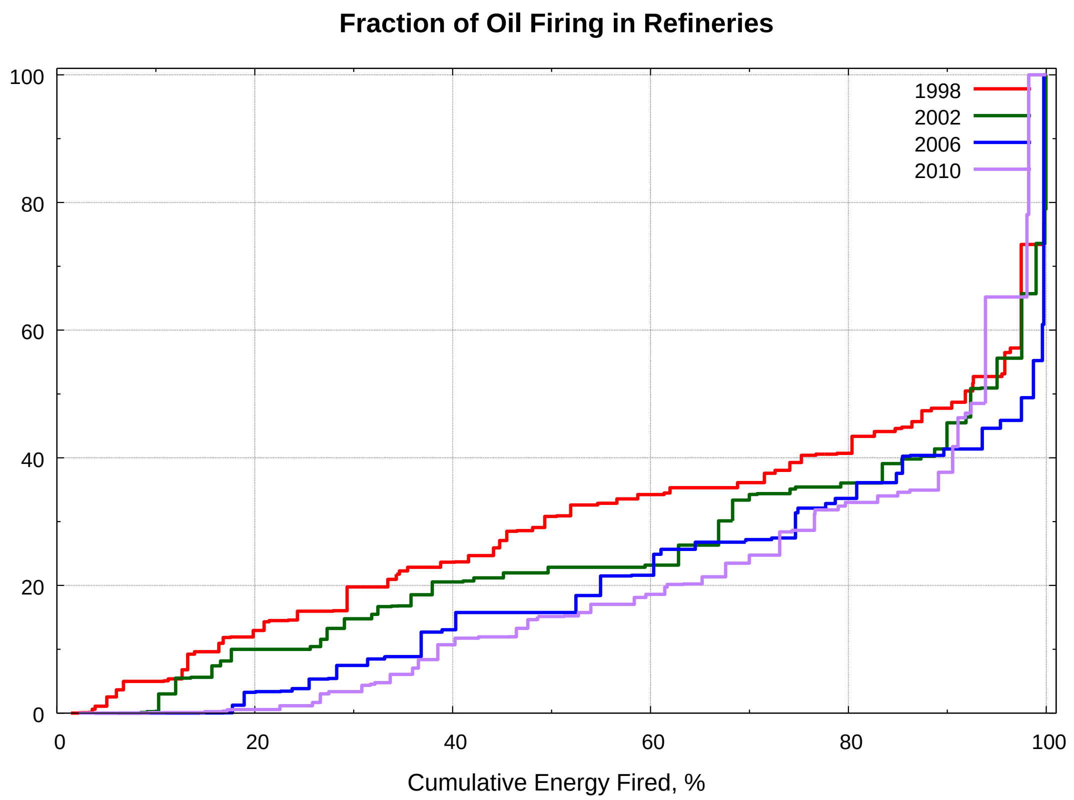


3. COMBUSTION EMISSIONS

Sulphur emissions as SO_2 from combustion units in a refinery are a direct consequence of burning refinery fuels. Refineries have specific configurations with a high level of interconnection between the combustion and process units. Because operation is adapted to suit changing conditions, such as an intake of a new crude feedstock or change in demand, the mix of fuels generated within the refinery site itself can also vary significantly in time. The main fuels used are refinery liquid fuel oil, refinery fuel gas and commercial natural gas. Sites with fluid catalytic cracker or FCC units also recover energy by burning carbon deposited on the catalyst (coke). Data on this thermal input is not considered by the survey. There are other combustible streams that may have a low heating value due to their high nitrogen or carbon-dioxide content. The category “other fuels” encompasses such usage.

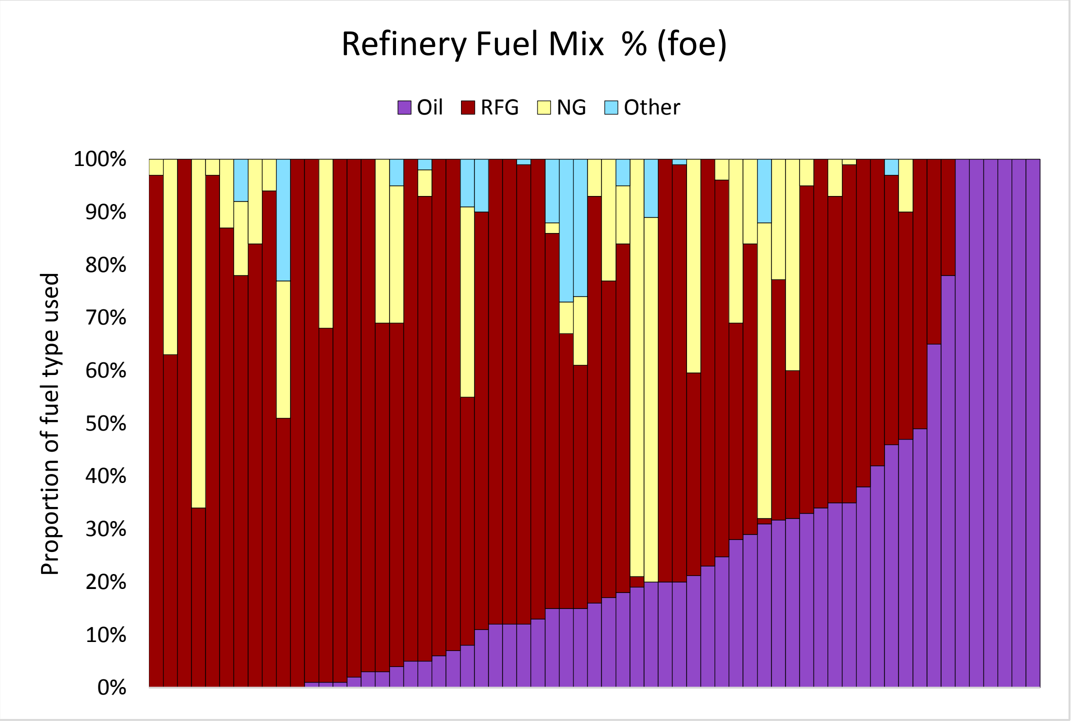
The amount of liquid fuel oil (namely oil firing) fired in refineries has been steadily decreasing as a result of emissions reductions imposed requirements by the EU and national regulations but also reflecting changes in refinery configuration to make a changed portfolio of products. **Figure 2** shows the evolution in oil use over the period 1998 to 2010. There has been a general reduction since 1998 and this is generally due to an increase in the use of refinery fuel gas. In 2010 only a few refineries have a high oil usage and these include specialist refineries (e.g for bitumen production) which have no gas-producing distillation units.

Figure 2 Oil firing as a fraction of overall refinery fuel used in the combustion units



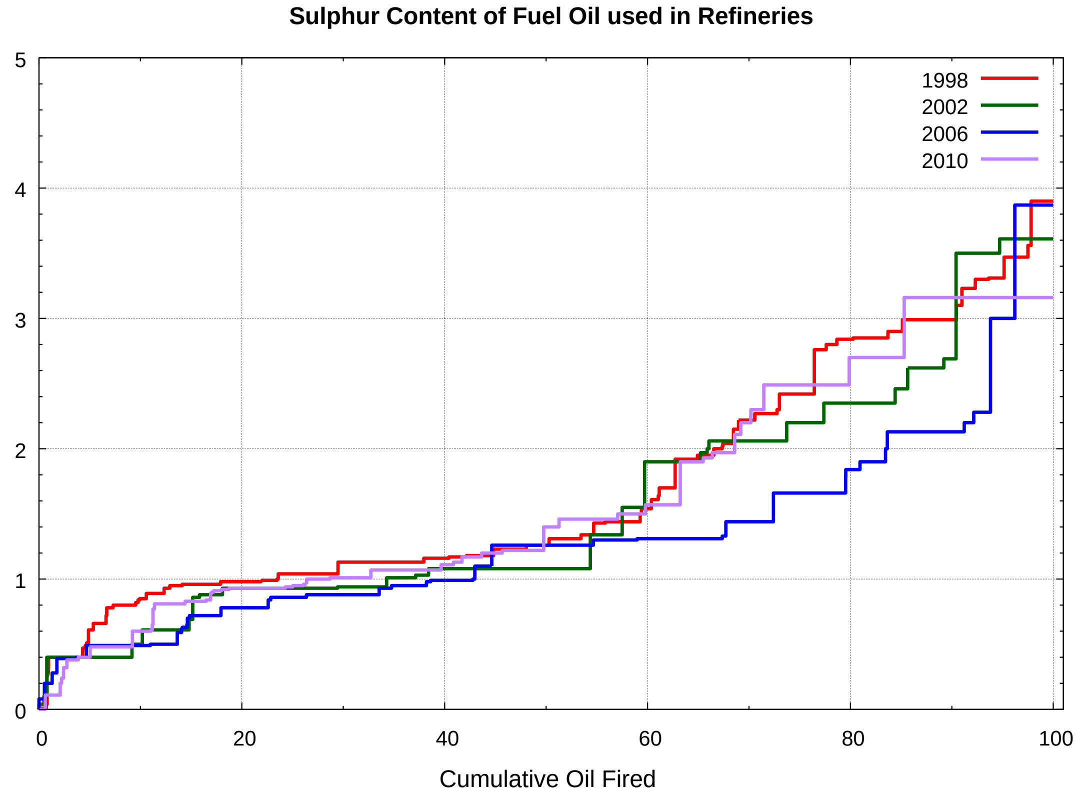
The proportions of fuels used in the refinery combustion units in 2010 is shown in **Figure 3**. Note that in many refineries the FCC is an important energy source but coke is not included as a “fuel” in this chart (or in earlier reports) because its oxidation takes place in the FCCU regeneration section. Any additional fuel supplied to an auxiliary CO boiler is included.

Figure 3 Refinery fuel mixes, 2010



The sulphur content of the oil used in refineries is shown in **Figure 4**. About 40% of oil fired has a sulphur content of 1% or less and this fraction has been remarkably consistent over the surveys. The 2010 data show an increase in the sulphur content of those fuels having more than 1% S, reversing the trend seen through 1998 to 2006. This is a likely consequence of a higher S crude feedstock and greater conversion of feedstock to products. The average S content of refinery fuel was 1.7% in 1998, 1.34% in 2002, 1.33% in 2006 and 1.63% in 2010.

Figure 4 Sulphur content of refinery fuel oil



A breakdown of fuel use by combustion plant size and fuel type is given in **Table 5**. The average S content of the fuels in each category is also given. The fuel proportions are expressed on a fuel oil equivalent basis. The situation in 2010 is very similar to that in 2006 if it is accepted that "other fuels" are gaseous. The proportion of these as a fraction of the total fuel mix in 2010 is more in-line with 1998 and 2002 suggesting that in 2006 some of these fuel streams may have been counted as part of the refinery fuel gas system. The proportion of energy used in the smaller combustion units fell from 25.9 in 2006 to 15% of the total, the same level as in 1998. It is not clear why there should be such a large adjustment between surveys. More specific stack information should be gathered in future surveys to avoid confusion in categorising emissions from stacks which are shared by < 50 MW and > 50MW combustion units or between combustion units and process units.

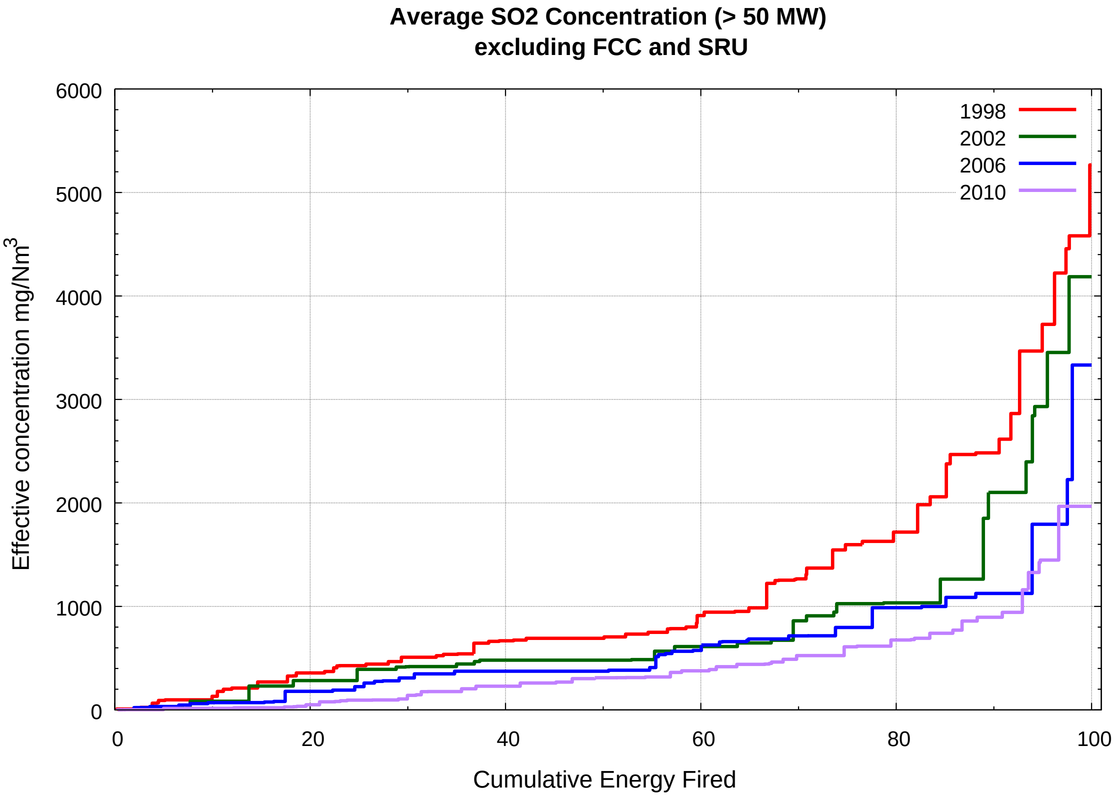
Table 5 Breakdown of energy use and of fuel sulphur content by fuel type and stack size

	1998		2002		2006		2010	
	Energy %	Fuel sulphur content %m	Energy %	Fuel sulphur content %m	Energy %	Fuel sulphur content %m	Energy %	Fuel sulphur content %m
Oil < 50MW	2.2%	1.73%	6.9%	0.75%	2.7%	0.95%	2.6%	0.94%
Oil > 50MW	26.3%	1.70%	16.7%	1.59%	16.5%	1.39%	18.1%	1.72%
All Oil	28.5%	1.70%	23.6%	1.34%	19.1%	1.33%	20.7%	1.625%
Gas < 50MW	12.6%	0.11%	29.3%	0.03%	22.7%	0.14%	11.8%	0.094%
Gas > 50MW	53.2%	0.07%	39.3%	0.04%	56.4%	0.05%	61.0%	0.063%
All Gas	65.8%	0.08%	68.7%	0.04%	79.2%	0.07%	72.8%	0.068%
Other < 50MW	0.3%	0.51%	2.9%	0.27%	0.5%	0.72%	0.6%	0.31%
Other > 50MW	5.4%	0.78%	4.8%	0.12%	1.2%	0.19%	5.9%	0.097%
All Other	5.7%	0.77%	7.7%	0.18%	1.7%	0.34%	6.5%	0.116%

To assess how changes in SO_2 concentration have occurred an estimate of the average concentration has been constructed for the large combustion plant (> 50 MW) using the annual emissions, assuming representative fuel types, the amount of fuel used and the typical dry flue gas volume (Nm^3/kg foe at 3% oxygen). These properties are set out in **Appendix 1** of Concawe report 10/01 [8]. The survey results are ordered by the value of the average concentration and plotted against the cumulative heat fired (foe) normalised by the total foe fired.

Figure 5 shows how the average LCP combustion stack concentration on refineries has evolved since 1998. The 2010 results show a continued downward trend essentially across all refineries (accepting that not all refineries are represented in each survey) with a very significant decrease from 1998.

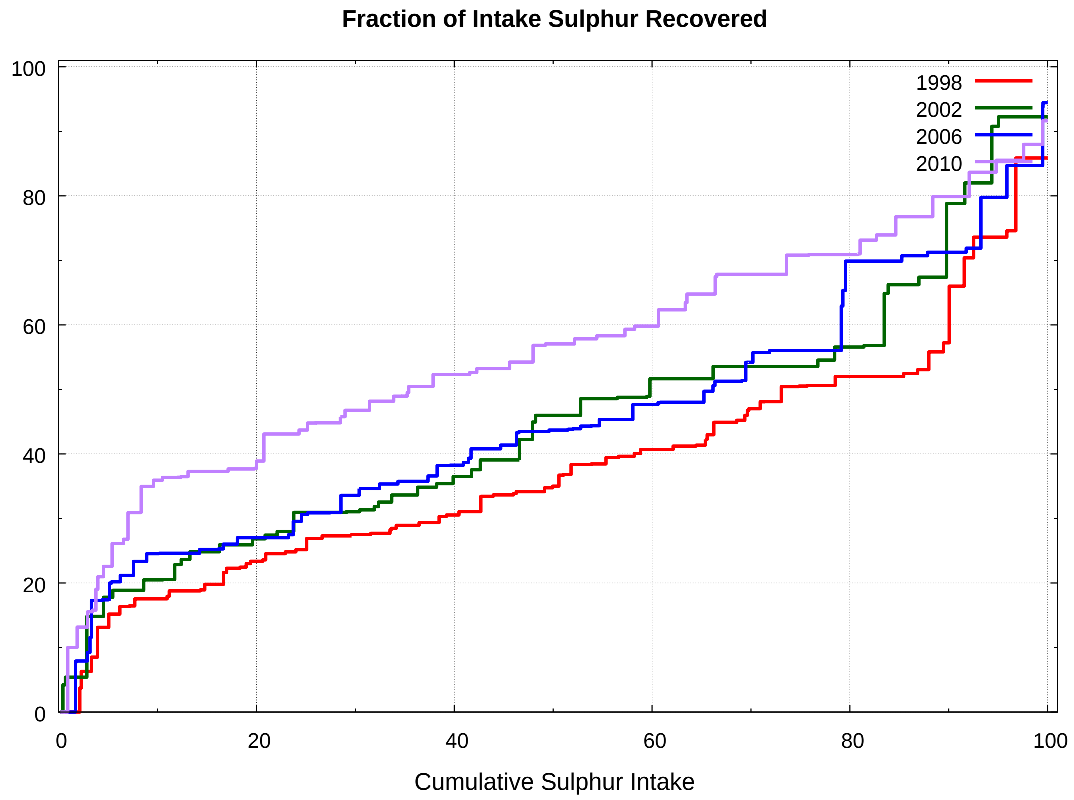
Figure 5 Estimated distribution of annual average LCP SO_2 concentrations



4. SULPHUR RECOVERY

The observed reduction in both refinery atmospheric emissions and in the product sulphur content, while maintaining throughput with a given crude slate, more or less with the same sulphur content, shows that sulphur recovery has improved. As shown in **Table 3**, the recovery in 1998 was calculated to be 39.4% of total sulphur intake, in 2002 to be 47.6%, in 2006 to be 45% and 55.9 % in 2010. This last increase is very substantial as can be seen from the distribution of recovery achieved on a per-refinery basis shown in **Figure 6.** The returns for 2010 give a different profile from previous years. There has been a great shift to increased recovery compared to 2006. Refineries have conducted investments in products desulphurization and recovery sulphur processes. This is clearly illustrated by the 2010 distribution.

Figure 6 Distribution of sulphur recovered

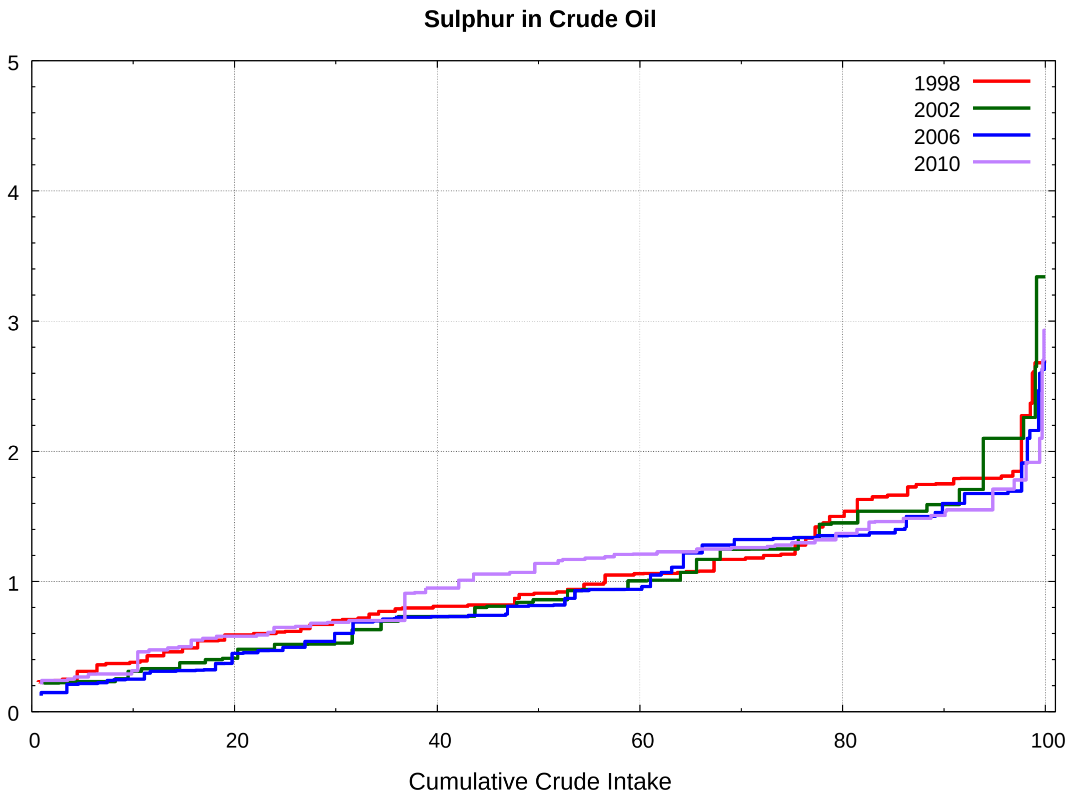


5. DISTRIBUTION OF SULPHUR IN STREAMS

Nearly 30% of the sulphur entering the European refineries still leaves in the fuel product streams so it is of interest to examine the overall distribution of sulphur in these streams and in the crude intake.

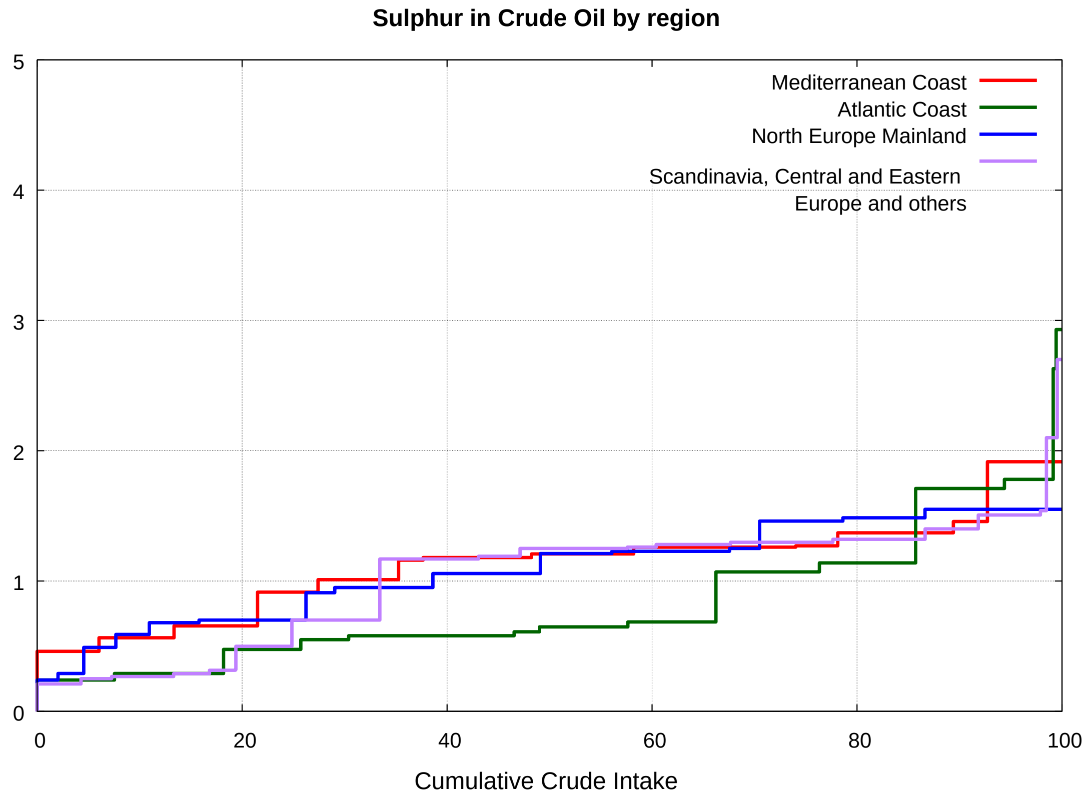
Figure 7 shows that the annually averaged crude slate for sulphur for Europe has hardly changed between 1998 and 2010. This is to be expected because refineries are designed to cope with a relatively narrow crude diet and crude will be procured to meet this requirement. The average crude sulphur content in 2010 is 1.01%, slightly higher compared to 0.91% in 2006 and 2002. About 40% of refinery throughput is lower sulphur crude. A small fraction of refineries specialise in treating high sulphur crude, although since 1998 there appears to be a trend to sweeten the annual average crude diet in the 20% of crude with the highest sulphur content (crudes with a sulphur content above ~1.4%).

Figure 7 Distribution of sulphur in crude oil



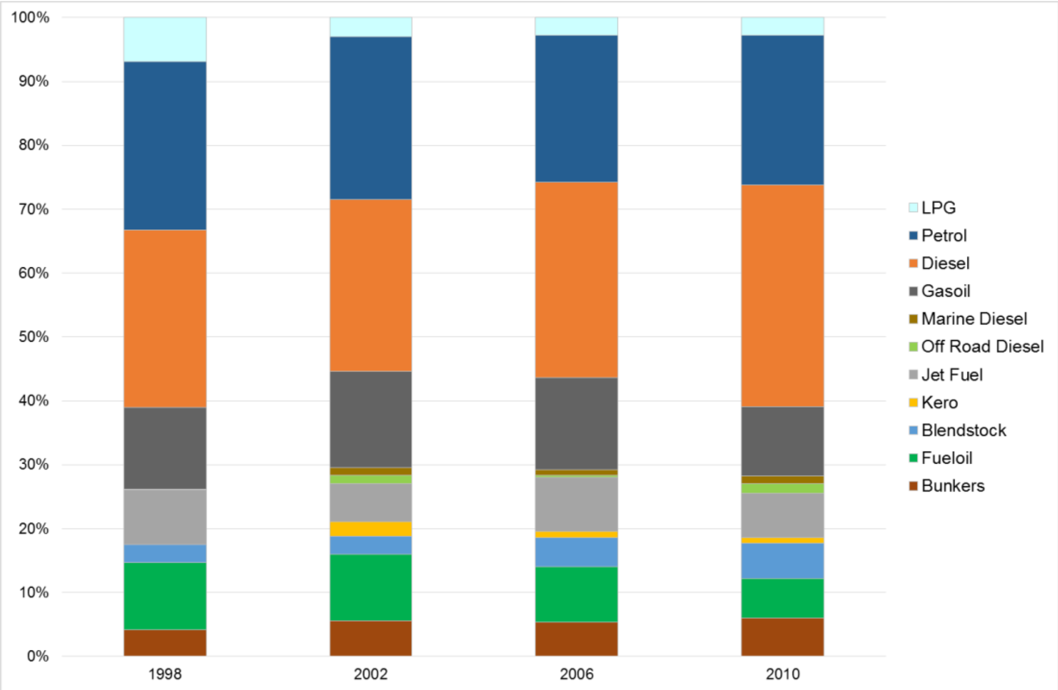
Previous reports presented a breakdown of the Sulphur content of crude oil according to the geographic location of the refineries to show if there are systematic differences. The breakdown separates refineries situated in the Mediterranean area, those with an Atlantic coastline and those likely to take in crude through the northern European mainland ports and waterway. Central and eastern European refineries and refineries in outlying areas including Scandinavia are gathered into a fourth category. Results for 2010 are shown in **Figure 8**. They show that, relatively speaking, the refineries with access to the Atlantic coast processed a greater proportion of low S feedstock.

Figure 8 Regional variation in the sulphur content of crude 2010



The product slate obtained from the four surveys is shown in **Figure 9**. In 1998 the marine diesel, off road diesel and kerosene streams were not disaggregated. The main refinery products are road transport fuels, heating gasoils, aviation fuel and heavy fuels (fuel oil and bunkers).

Figure 9 Product slate from 1998 to 2010, proportion by mass %



5.1. ROAD AND TRANSPORT FUELS

In sulphur survey reports before Concawe report 10/01 the road diesel component was not presented as a separate item with the explanation that disaggregation was not reliable. Instead all gasoil items were combined and reported as a general gasoil pool. In this report the on-road diesel and heating gasoil streams have again been disaggregated although we must introduce the caveat that there may be some unappreciated inadequacies in the reporting from previous years. The generalised gasoil pool is reported for consistency with reports before 2006 and comprises the combination of the above with off-road diesel and marine gasoil streams but these latter are minor contributors overall.

Figure 10 Distribution of sulphur in gasoline

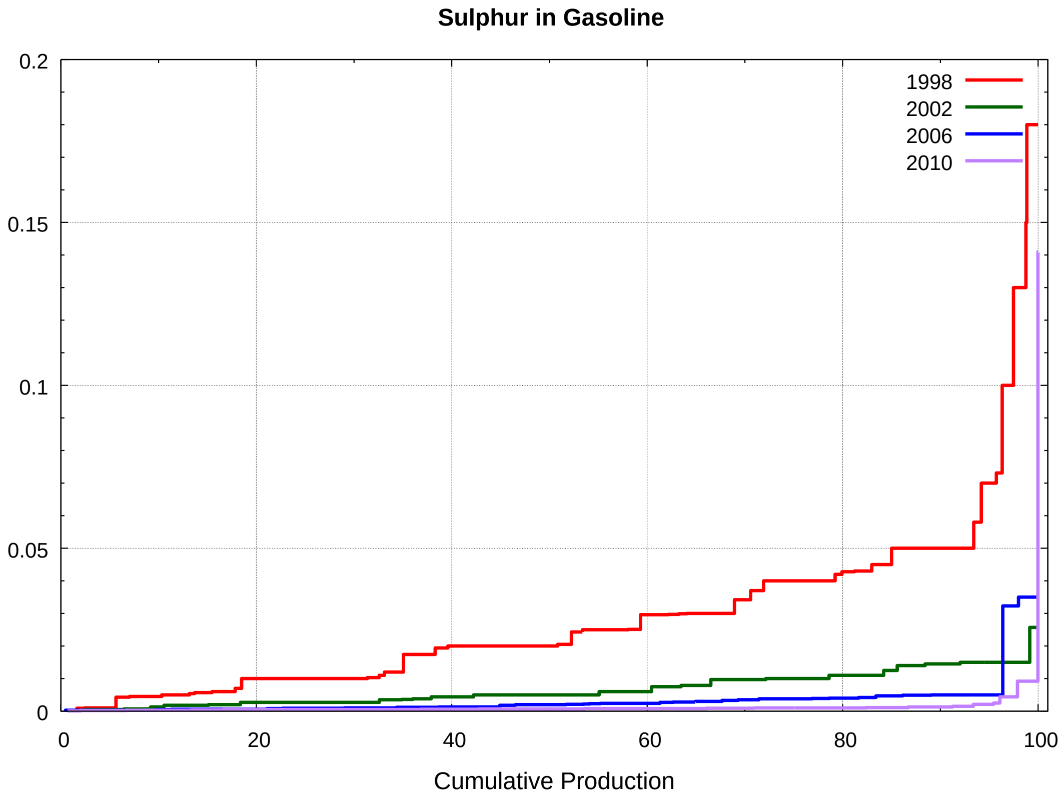


Figure 10 shows the evolution of sulphur in produced gasoline. The concentration decreases in line with legislative requirements. In 2006 95% of production had a sulphur content of 50 ppm or lower and 30% less than 10 ppm. In 2010 over 85% of gasoline produced had an S content < 10 ppm. The survey includes products for export.

Figure 11 Distribution of sulphur in on-road diesel

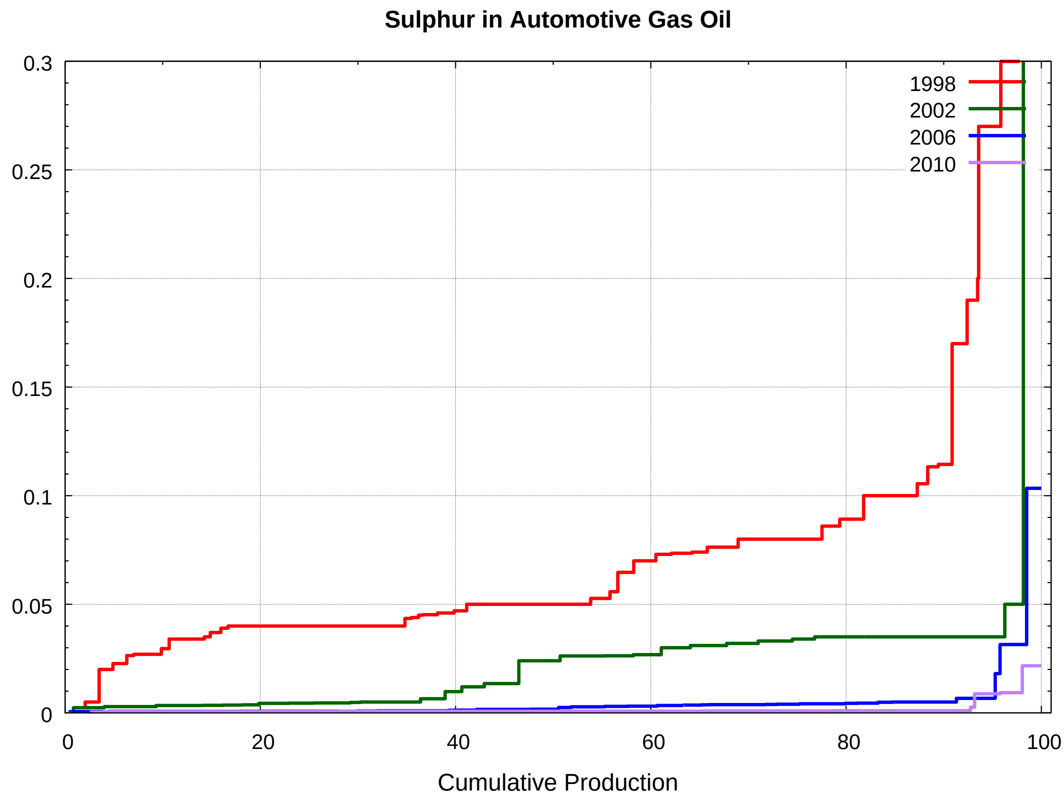


Figure 11 shows the distribution of sulphur in on-road diesel. As for gasoline the changes reflect the requirements of the EU market which required from 2005 the maximum sulphur content of diesel to be 50 ppm and that by 2009 the maximum sulphur content is 10 ppm. Of the production in 2010, 93% had a sulphur content below 10 ppm. The survey includes products for export.

Figure 12 Distribution of sulphur in marine fuel oil

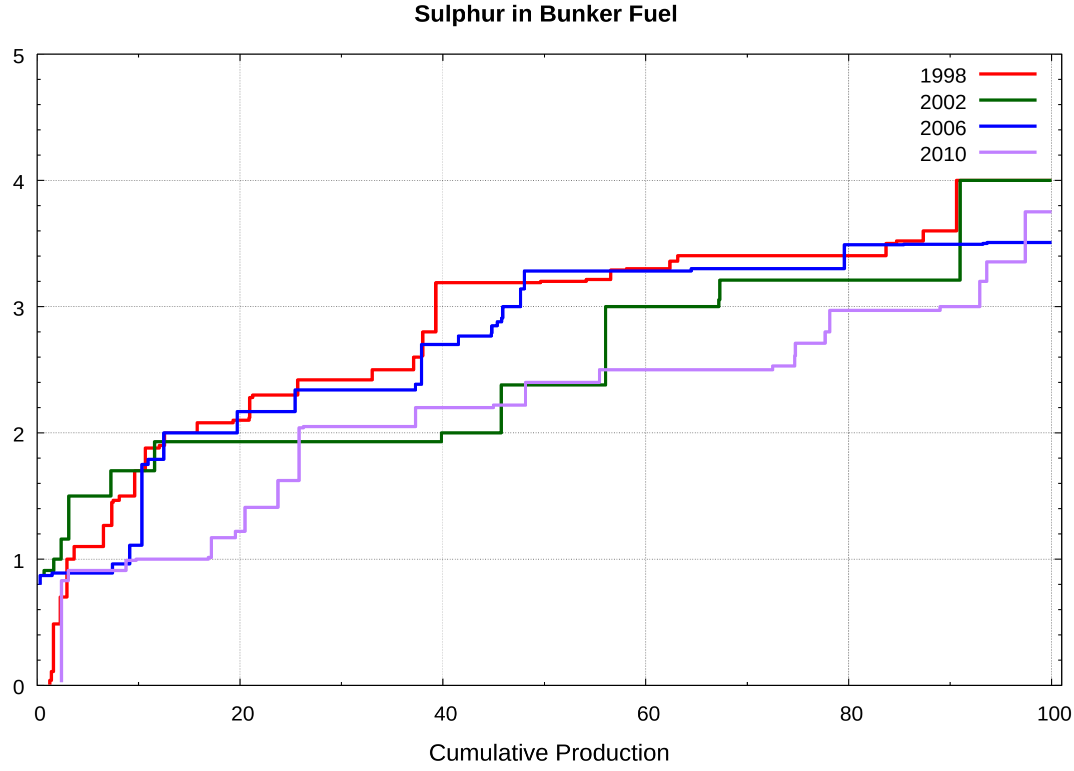


Figure 12 shows the distribution of sulphur in marine bunker fuels where there has been a substantial change since 2006. Not all refineries produce marine bunker fuel and the number of responses for marine fuels was 44 in 1998, 17 in 2002, 27 in 2006 and 26 in 2010. The distribution for 2002 show lesser values than for 1998 and for 2006 which is likely due to the smaller number of respondents in 2002.

In 2010, the median sulphur content is 2.4% which is consistent with the international IMO sulphur monitoring in bunker fuels and 97% of produced fuels have a sulphur content below 3.5%S which is the world-wide specification applicable in 2012 and which can be achieved by blending.

In 2010 there was a requirement for the sulphur in fuel burned in sulphur Emission Control Areas to be 1% (or below). Some 18% of bunker production met this requirement which was a substantial increase compared to 2006.

Figure 13 Sulphur distribution in jet fuel and kerosene

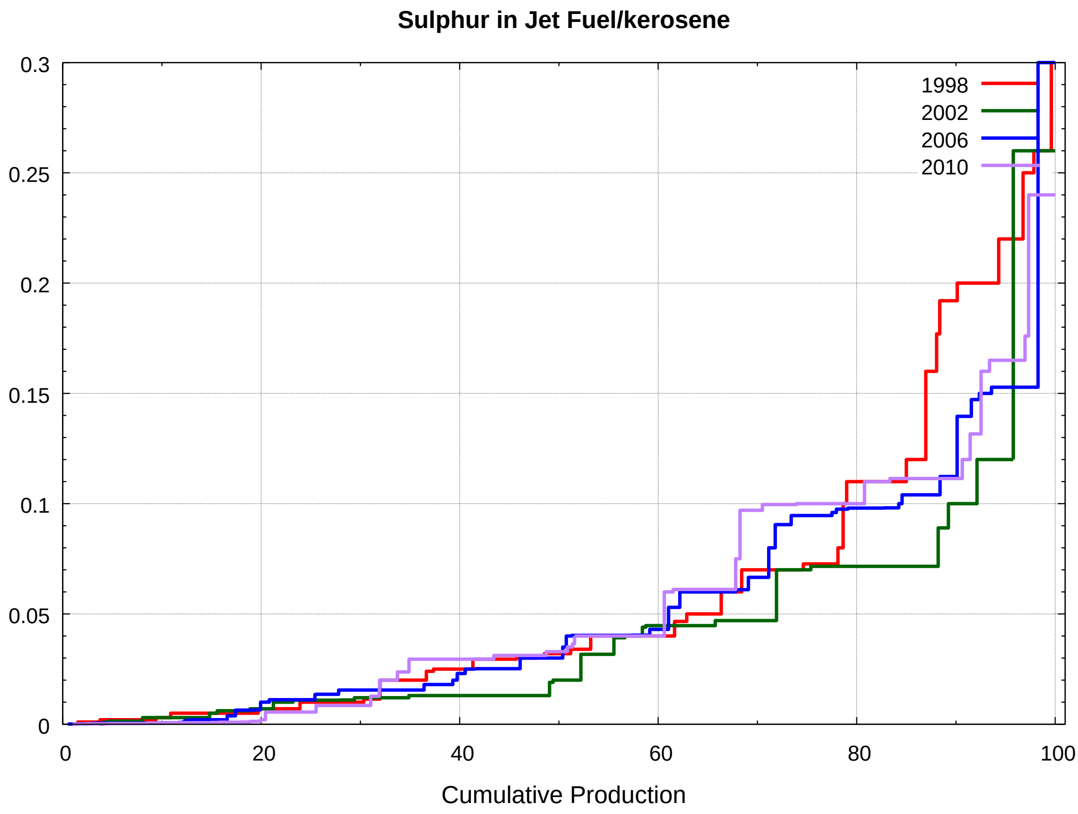


Figure 13 shows the distribution of sulphur in jet fuel and kerosene. All production covered by the survey in 2010 meets the world-wide specification for Jet fuel of 0.3% and overall the distribution of S contents is similar to that in 2006. As remarked in Concawe report 10/01, the 2002 results may reflect the lower participation rate rather than significant change.

5.2. FUEL OILS

Figure 14 shows the distribution of sulphur in gasoils used for heating purposes. The EU sulphur limit was 0.2% sulphur (up to 2000) and decreased to 0.1% in 2008. The survey shows very little evolution in the distribution since 1998 to 2006 and then a very large change in response to specification, about 94% is less than 0.1%.

Figure 14 Distribution of sulphur in heating gas-oil

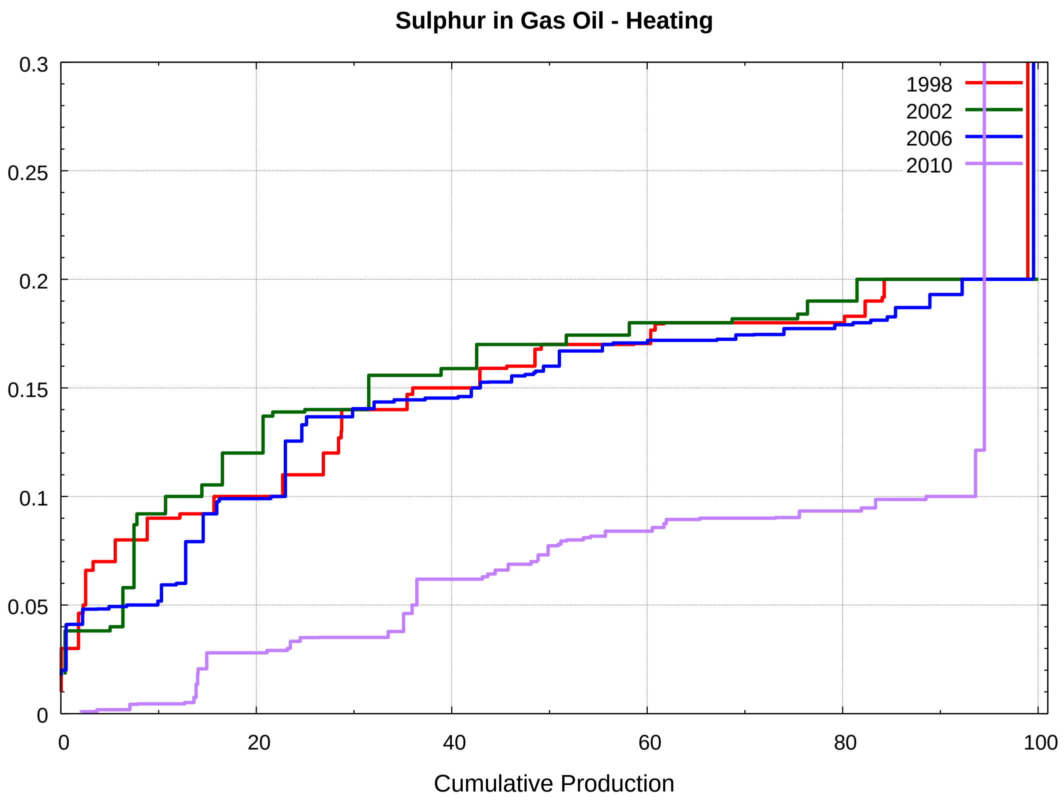
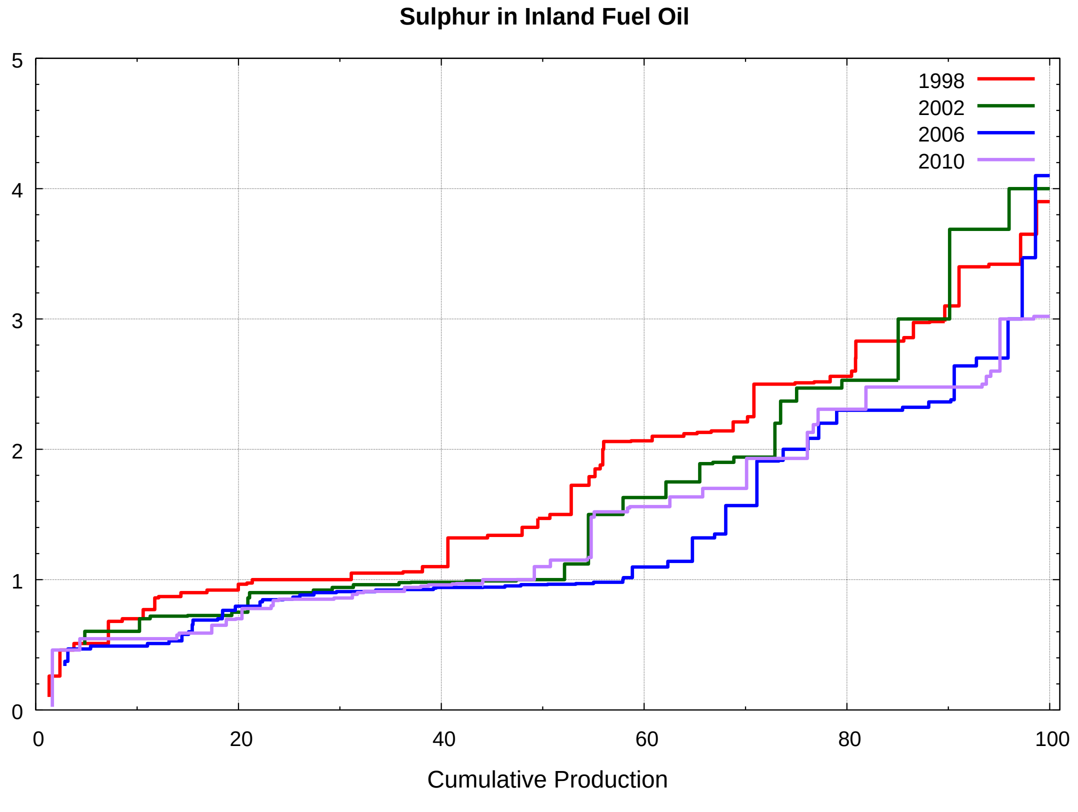


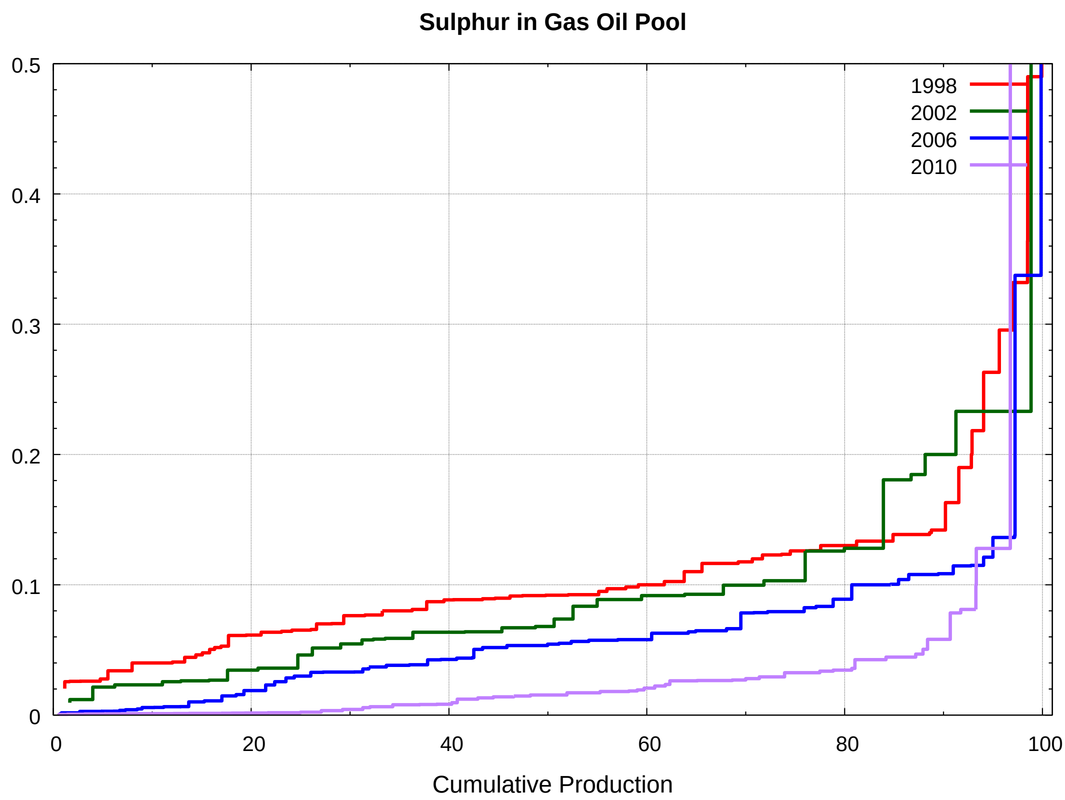
Figure 15 shows the distribution of sulphur in fuel oil. Under the terms of the Sulphur in Liquid Fuels Directive, since 2003, heavy fuel oil must have a maximum sulphur content of 1% for general use in Europe. Fuel oil having a sulphur content greater than 1% but less than 3% can be used under permit, in installations with appropriate emissions abatement equipment, or it may be exported. **Figure 15** shows that the fraction of production meeting this specification increased from ~ 30% in 1998 to 50% in 2002 to over 60% in 2006. 2010 data show that 100% of the production is now below 3% sulphur content and that the production of fuel oil below 1% sulphur content is around 50%.

Figure 15 Distribution of sulphur in fuel oil



For completeness with previous surveys the sulphur content of the overall gasoil pool is shown in **Figure 16**. The sulphur content is evaluated as the weighted average of all the gasoil streams (heating oil, automotive diesel, off-road diesel and marine gasoil). The results show a progressive reduction since 1998 and a substantial change between 2006 and 2010 attributed to the 10 ppm automotive diesel and 0.1% heating oil, off-road and marine gasoil sulphur specifications. The overall pool has 93% of production less than 0.1% averaged sulphur content.

Figure 16 Sulphur in the overall gasoil pool



5.3. OTHER

The sulphur content of produced butane and propane is shown in **Figure 17**. No results are available for 1998. The 2010 and 2002 results are very similar and 2010 shows less production above 0.2 ppm than in 2006.

Figure 17 Sulphur content of LPG

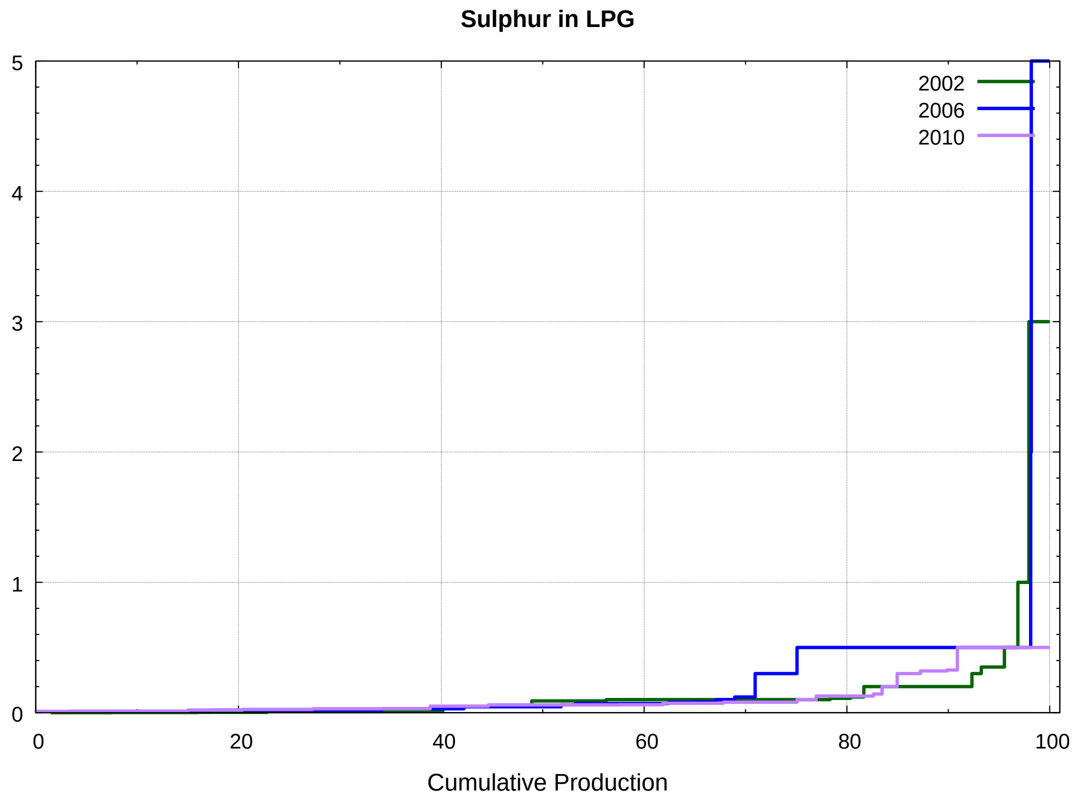
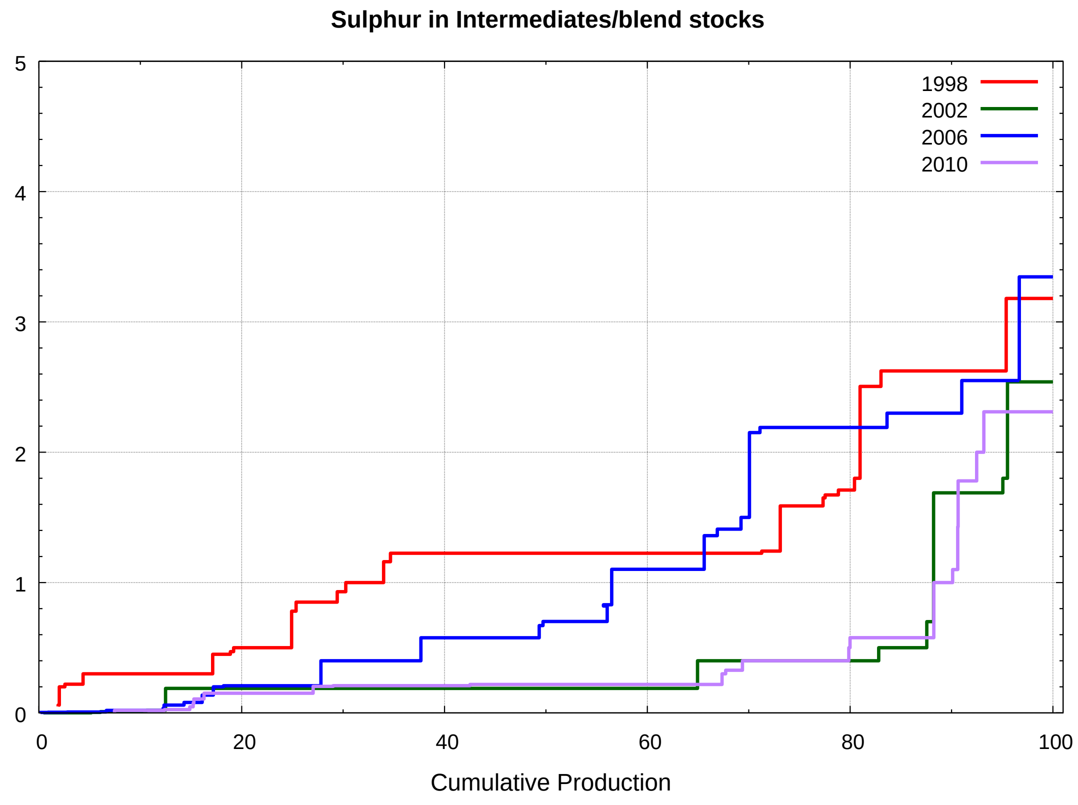


Figure 18 shows the distribution of sulphur in intermediates and blend stocks. In Report 1/10 it was noted that the 2002 returns seemed to be out of line with the 1998 and 2006 however, in 2010 a similar distribution was reported. It is possible that the year by year variation represents demand and opportunity in both domestic and export markets rather than structural change.

Figure 18 Sulphur content of intermediates and blend stocks



6. CONCLUSIONS

The sulphur survey response for the year-end 2010 has been analysed and its results shown together with the responses for previous surveys in 1998, 2002 and 2006. A common methodology was used.

The 2010 survey used responses from 63 refineries compared[6] to 67 in 2006, 46 in 2002 and 77 in 1998. The refinery intake from these 63 refineries is equivalent to 68% of the EU refinery throughput in 2010.

The survey provides an overview of the distribution of sulphur between the refinery products, the recovery of sulphur in the refinery process and the emission to atmosphere from refineries.

The period 1998 to 2010 has seen the following trends:

- A reduction in the amount of sulphur going out in fuel products from ~37% of intake in 1998 to ~27% of intake in 2010.
- An increase in the amount of sulphur recovered as elemental sulphur from ~39% of intake in 1998 to ~56% of intake in 2010.
- A decrease in the amount of sulphur emitted to atmosphere from refinery direct use from 7.2% in 1998 to 3.8% in 2010.

- These results confirm a downward trend in the sulphur content of major product streams associated with a strong increase in sulphur recovered in the refinery process.

- The sulphur content of produced fuels closely matches the market requirements of fuels regulated by international or EU regulations such as Sulphur in Liquid Fuels Directive and the Directives on Automotive Fuel Quality (e.g. road fuels with 10 ppm max sulphur in both gasoline and diesel starting in 2009, 0.1% sulphur content for heating gasoils, 1% sulphur content of inland fuels and marine fuels in sulphur control areas.)

Additionally:

- The sulphur content of the overall crude slate has slightly increased over this time period. There remains a distinct geographic variation in the sulphur content of crude processed.
- The product slate has changed with an increase in the overall proportion of middle distillates, especially on-road diesel and a decrease in gasoline production.
- Refineries continue to reduce the amount of liquid fuel burned internally and the sulphur content of this fuel increases indicating deeper conversion to useful products. Refinery fuel gas supply is supplemented with natural gas to a high degree in some refineries.

[6] Number of returns used in the analysis.

7. GLOSSARY

FCCU	Fluid Catalytic Cracking Units
Foe	Fuel oil equivalent
LCP	Large Combustion Plant
LCPD	Large Combustion Plant Directive
OECD	Organisation for Economic Co-operation and Development
SRU	Sulphur Recovery Units

8. ACKNOWLEDGEMENTS

Concawe would like to express its gratitude to all its member companies whose contribution to the survey has made this work possible.

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APPENDIX 1. METHODOLOGY

This Appendix is reproduced from report 1/10 for the convenience of the reader. Specific data referred to on fuels is from 2006.

The survey form comprises an Excel spreadsheet distributed to member companies. The spreadsheet comprises 12 worksheets of which 7 are data entry forms and the others contain contextual and summary information. The survey requests inputs and outputs that allow a hydrocarbon and sulphur balance on the refinery to be made. Sulphur emissions through combustion are identified on a per stack basis using the size categories of the Large Combustion Plant Directive.

Fuel use is standardised on an energy rather than a mass basis using a fuel-oil equivalent figure. In previous reports a lower heating value of 40.24 MJ/kg was used for the oil; a value of 52.3 MJ/kg was used for gases and a value of 16.1 MJ/kg was used for the fuel category "other". These figures were based on a 1998 analysis of fuel streams. As discussed below, these have been used again here for consistency and lack of a better approach.

One change to the survey in 2006 is that it sought data on internal fuel consumption in both mass and in energy units. All respondents provided mass data but only a few provided energy data. Some used global conversion factors (constant energy content for liquids, gas and other fuels), others reported different energy contents for fuels by combustion plant size. We note that the survey uses annual total emissions and so either total mass or total energy may comprise use of different fuels over the year.

The distribution of reported heating values for each survey fuel category (liquid, refinery gas, natural gas, other) is shown in **Figure A1**. This has been calculated by dividing the reported energy use by the reported fuel consumption in each reported category and counting the heating values falling into 2 MJ/kg wide bands. Average values have been calculated on both a weighted (amount of energy used) and on an unweighted (number of data points) basis. Results of the averaging are given in **Table A1**.

The fuel oil values are narrowly distributed about a weighted value of 42.03 MJ/kg (41.29 MJ/kg unweighted) which is slightly larger than the foe value of 40.24 MJ/kg used previously and is close to the IEA standard conversion of 41.86 MJ/kg.

The natural gas value is lower than for pure methane perhaps reflecting the high inert (N_2) content of some natural gases. The average value of 47.97 (46.2) MJ/kg is lower than the value used previously for gas of 52 MJ/kg. The refinery fuel gas value was surprisingly small 37.3 (41.81) MJ/kg on average but it is apparent that some low energy fuels were included in this category and this has depressed the mean value. These lower energy fuels would be better assigned to the category "other". Heating values assigned to gaseous fuels ranged from below 18 MJ/kg to above 54 MJ/kg.

Similarly it seems that two types of "other" fuel are in use having heating values that are very low (10 – 14 MJ/kg) on the one hand and high (44 MJ/kg) on the other hand. The average is 18.29 (34.06) MJ/kg fuel which compares well with the previously used value of 16 MJ/kg.

Figure A1 Distribution of heating value by fuel type, 2006 survey

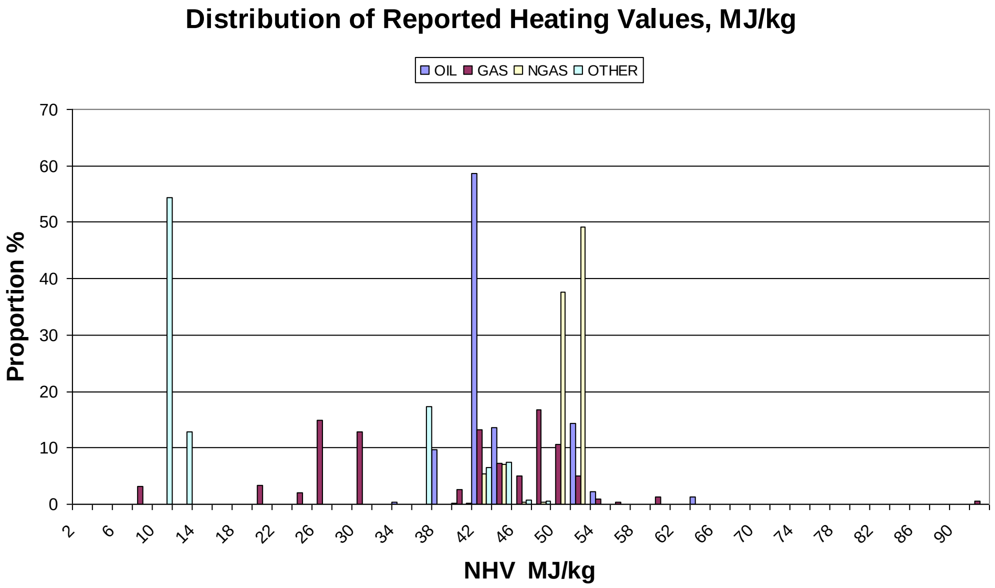

Table A1 Average lower heating values by fuel type (2006 report) compared with previous reports

Fuel	Lower Heating Value MJ/kg		
	weighted mean	unweighted mean	Used in this and earlier reports
Oil	42.03	41.29	40.2
Refinery Fuel Gas	37.34	41.81	52
Natural Gas	47.97	46.2	52
Other	18.29	34.06	16

To perform the survey analysis it is necessary to have a simple method of comparing fuel use in terms of energy content. The data collection was not adequate for this purpose and it was decided to retain the historic heating values, having also advantages of backward compatibility.

The assumptions will result a small margin of error in the estimate of total energy use. They may affect the refinery position in ranked charts but, because refinery name are not used in the study this has no consequence.

We note that the definition of fuel oil equivalent (foe) used in the sulphur survey analysis is different to the IEA definition (40.24 c.f. 41.86 GJ/t). In this appendix we use the standard value of 41.86 GJ/t.

The other aspect of fuel quality is the need to estimate combustion air requirements for the different fuels in order to determine equivalent bubble concentrations.

The commonly used conversion that the Large Combustion Plant Emission Limit Value of 1700 mg/Nm^3 for SO_2 corresponds to a fuel oil containing 1% sulphur by weight gives a dry combustion product volume of 11.67 Nm^3/kg fuel.

Values for dry flue gas volume used in previous reports (converted to the standard foe at 41.86 MJ/kg) were 12.5 for oil, 11.67 for both Refinery Fuel Gas and Natural Gas and 28.8 Nm^3/kg for “other” fuels. These compare well with calculations for some typical refinery fuels.

Table A2 Dry flue gas volume (3% excess oxygen) for several fuels. All on a fuel oil equivalent basis of 41.86 MJ/kg

Fuel Type	Lower Heating Value GJ/t	Standard Flue Gas Volume Nm^3/kg (foe)	Comment
Refinery Fuel Oil	39.7	12.6	H/C = 1.5 mol ratio.
Refinery Fuel Gas	47	11.67	Alkane mixture (10% C4)
Refinery Fuel Gas	49.7	11.4	Alkane mixture with 40% H2
Natural Gas	50	11.66	Methane
Natural Gas	39.2	11.86	13.7% Nitrogen, typical Benelux
FCC Coke	38	12.3	Low hydrogen
FCC Coke	40.7	11.9	High hydrogen
Low Joule Gas	4.19	16.94	High Nitrogen H2/CO mix
Low Joule Gas	1.88	27.0	5% HC

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