Impact of marine fuels quality legislation on EU refineries at the 2020 horizon

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ABSTRACT

Legislative measures recently adopted by the International Maritime Organisation (IMO) pave the way for a dramatic reduction of the sulphur content of international marine fuels. Based on a 2020 reference scenario taking into account all expected product quality changes and demand change forecast, this report analyses the specific impact of marine fuel quality changes on EU refineries focussing on configuration, investments, energy consumption and CO_2 emissions.

KEYWORDS

Marine fuels, demand, call-on-refineries, energy consumption, CO_2 emissions, capital investment

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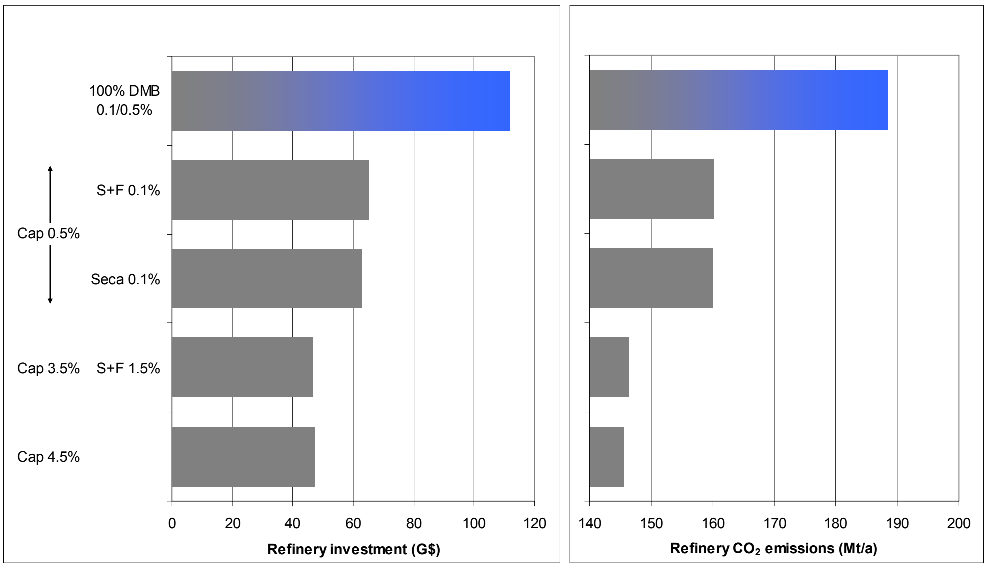
SUMMARY

In recent years there has been increased focus on the quality of marine fuels resulting in both international (International Maritime Organisation, IMO) and European legislation, the main feature of which has been the establishment of SECAs (Sulphur Emissions Control Areas) in the North Sea and the Baltic Sea. More recent debates in IMO have resulted in the adoption in October 2008 of measures for the progressive but drastic reduction of both the global sulphur cap and the maximum sulphur level allowed in SECAs. Although this is not included in the adopted IMO measures, there have also been calls for a wholesale migration of marine fuels from residual to (low sulphur) distillate fuels.

These effective and potential changes to the quality of marine fuels have to be seen in the context of numerous other changes affecting refineries in Europe both in terms of quality and of supply/demand. This integrated analysis is developed in a separate CONCAWE report [1].

This report focuses on the impact of marine fuels quality changes on EU refineries at the 2020 horizon, using the framework established in [1] in terms of supply/demand forecast and product quality changes. The analysis describes the changes that EU refiners would need to put in place in order for EU refineries to continue to produce the EU demand in quantity and quality.

Deep desulphurisation of marine fuels as implied by the recent IMO decision will have a profound impact on refineries worldwide and particularly in Europe. Comparison of different cases, all based on the same 2020 reference scenario, singles out the required configuration and operating changes to EU refineries to meet the new marine fuel quality constraints.



The industry is already facing potential investments of nearly 50 G$ to meet other demand and quality changes in the same time period. This IMO decision will increase this by another 10 G$. A switch to distillate fuel would be much more onerous, up to some 65 G$ additional investment on account of the already very tight middle distillate supply situation in Europe. Refinery CO_2 emissions follow a similar pattern with an increase of about 15 Mt/a (approximately 10%) to meet IMO specifications, reaching over 40 Mt/a in case of a switch to distillate fuel. It should be noted that these figures pertain to a fully optimised European scenario, including the option of deep desulphurisation of residual fuels.

The necessary investments would require a massive effort from the industry, especially when seen within the context of other calls for new installations for meeting quality specifications of other products, adapting to changes in supply/demand and complying with other regulatory constraints such as implementation of the IPPC and Large Combustion Plant Directive. Beyond the all important financial and economic aspects, the ability of the industry to mobilise sufficient material and human resources for such massive investments must be considered.

A high level comparison with studies by others shows that, although results differ at a detailed level, there is a common indication of the serious impact of desulphurisation of marine fuels and particularly of a migration to distillate fuels on the refining sector in terms of investment, energy consumption and CO_2 emissions.

Faced with the need to desulphurise residual streams refiners could choose instead to stop production of residual marine fuels and convert the residues into higher value products, primarily diesel and motor gasoline. The high investments required for desulphurisation of residual streams make this conversion alternative economically attractive. Indeed we were also able to confirm previous findings [2] according to which economics would favour conversion unless the price of low sulphur residual fuels approached that of gasoils. We found that the differential between gasoil and low sulphur residual marine fuel had to be reduced to between one third and one quarter of its original value to make production of the residual fuel attractive. This suggest that the real life impact of imposing very low sulphur marine fuels may be higher than what could be anticipated purely on the basis of the desulphurisation needs. It also highlights the fact that there is likely to be a cost trade-off for ship operators between using low sulphur fuel and installing on-board flue gas scrubbing facilities.

In a final section we show that the contribution of marine fuels to the total energy consumption and CO_2 emissions of refineries is a strong function of their desired quality and of the relative demand for the different grades. For Europe decreasing marine fuel demand can either increase or decrease energy consumption and CO_2 emissions depending whether the required grades are high sulphur residual fuels or low sulphur distillate fuel.

1. CONTEXT, BACKGROUND AND SCOPE

Over the years the oil refining system in the EU has developed and adapted to meet the evolving demand, in both qualitative and quantitative terms, while coping with an ever-changing supply of economically attractive crude oils.

The combination of changes in demand and crude supply requires constant adaptation of the refining tool, taking all factors into account including the availability of dependable import and export sources to "balance the books" under acceptable economic terms.

In recent years there has been increased focus on the quality of marine fuels resulting in both international (International Maritime Organisation, IMO) and European legislation, the main feature of which has been the establishment of SECAs (Sulphur Emissions Control Areas) in the North Sea and the Baltic Sea. More recent debates in IMO have resulted in the adoption in October 2008 of measures for the progressive but drastic reduction of both the global sulphur cap and the maximum sulphur level allowed in SECAs. While these measures essentially apply to international residual bunker fuels, distillate marine fuels are also affected with further restrictions for marine gasoil, through the obligation as of 2010 to use fuel with a maximum sulphur level of 0.1% while at berth and a gradual shift of inland marine fuels towards road diesel quality. Although this is not included in the adopted IMO measures, there have also been calls for a wholesale migration of marine fuels from residual to (low sulphur) distillate fuels.

These effective and potential changes to the quality of marine fuels have to be seen in the context of numerous other changes affecting refineries in Europe both in terms of quality and of supply/demand. This integrated analysis is developed in a separate CONCAWE report [1].

This report focuses on the impact of marine fuels quality changes on EU refineries at the 2020 horizon. These changes and their legislative background are detailed in *section 3*. The analysis describes the changes that EU refiners would need to put in place in order for EU refineries to continue to produce the EU demand in quantity and quality.

Starting from the situation before implementation of the SECA legislation in 2006, we developed a number of scenarios representing the gradual changes in residual marine fuel sulphur specification. All scenarios are considered in a 2020 environment i.e. with the supply/demand and the specifications of other products relevant to that year. The consequences for the EU refineries are reported in *section 4* in terms of new investments, total cost, energy consumption and CO_2 emissions.

Faced with the need to desulphurise residual streams refiners could choose instead to stop production of residual marine fuels and convert the residues into higher value products, mainly diesel, responding to the global market trend on transportation products towards more middle distillates. In a previous study [2] we showed that economics for EU refiners were likely to favour this conversion alternative rather than desulphurisation of residues. In *section 6* we have repeated this analysis in our new 2020 scenario to check whether these conclusions still hold.

In relation to life cycle assessments (or, in the case of ships, so-called “Well-to-Hull” studies) the question is often raised as to the energy and carbon footprint marine fuels or, more specifically, how much energy and carbon emissions are attached to their production. Although this is a legitimate question, there is no single, simple answer. In *section 7* we have attempted to shed light on this by estimating the energy and CO_2 emissions associated with marginal marine fuel production.

2. MODELLING THE EU REFINING SYSTEM

This principal tool used for this study was the CONCAWE EU refining model. This model uses the linear programming technique to simulate the European refining system. The model has a library of process units operating modes (yields, product properties, energy use and costs). The EU-27 (+Norway and Switzerland) is represented by 9 regions (see **Table 1**). In each region the actual refining capacity is aggregated, for each process unit, into a single notional refinery. The diversity of actual crude oils is represented by 6 model crudes. Other specific feedstocks can also be imported. The model can produce all usual refinery products in various quality grades. Exchanges of key components and finished products between regions are allowed at a cost. Economic data is included in the form of feedstock prices, product values, logistic costs, refinery investment and operating costs. Although ethylene crackers and aromatics production plants belong to the petrochemical rather than refining industry, olefins and aromatics production is included in the model so that the interactions between the two sectors, which are crucial to the understanding and dynamics of the lighter end of the barrel (gasoline, naphtha, LPG), are represented in the modelling.

Estimating refinery investment costs is notoriously difficult. Even for notionally similar projects, costs tend to be heavily location dependent particularly when it comes to new plants in existing sites (which is virtually the only relevant scenario in Europe). There is a lack of consistency in what is considered as an integral part of the project and what is not, particularly when it comes to off-sites (so-called OSBL items), engineering costs and contingencies. Large real-life projects also invariably include extra items for improving/updating the refinery which makes comparison of what figures are publicly available difficult. Finally the cost of projects has significantly increased in recent years. Plant scale is also an issue. Our estimates are based on consensual industry all-in costs for each type of process units prorated to a level representative of 2007 costs. The total regional extra capacity identified by the model for a particular process is broken down into a number of realistic scale plants, consistent with the actual number of refineries in the region, and for which a reasonable cost estimate can be made.

Given a set of premises and constraints (product demands, crude and feedstocks availability, plant capacities and economic data), the model proposes an “optimised” feasible solution on the basis of an economic objective function. The model is carbon (and hydrogen) balanced and can therefore estimate the impact of changes in terms of CO_2 emissions from both refinery sites and modified fuels when used.

Table 1 The 9-regions of the CONCAWE EU refining model (EU-27+2)

Region	Code	Countries
Baltic	BAL	Denmark, Finland, Norway, Sweden, Estonia, Latvia, Lithuania
Benelux	BNX	Belgium, Netherlands, Luxembourg
Germany	GER	Germany
Central Europe	CEU	Austria, Switzerland, Czech, Hungary, Poland, Slovakia
UK & Ireland	UKI	United Kingdom, Ireland
France	FRA	France
Iberia	IBE	Spain, Portugal
Mediterranean	MED	Italy, Greece, Slovenia, Malta, Cyprus
South East Europe	SEE	Bulgaria, Romania

The model was calibrated with real data from 2005. The calibration included tuning of the "energy efficiency" of process plants to match actual overall energy consumption data and small adjustments to the actual plant capacities in order to ensure that the base case is feasible and not over-constrained. This was then back-casted to the 2000 demand for which the "existing capacities" were adjusted.

All cases were then run as independent pathways to the future, always starting from the 2000 base case and adding additional marine fuels quality constraints one by one. Comparison of future scenarios with the 2000 base case established the need for additional plant capacities, the total cost to refiners of meeting the demand as well as the impact on energy consumption and CO_2 emissions of the refineries.

This approach assumes perfect foresight into the developments under consideration and therefore perfect synergy between the different requirements in order to optimise investments for each combination of constraints. Accordingly, when migrating from one case to the next, we did not take into account any investment that may be required in one case and not used by the model in the next, under the assumption that such investment would not actually be made. This may be seen as optimistic but is justified by the fact that, with the exception the "all distillates" case at the end of the period, we have been looking at provisions that are either already known and planned for today or have been the subject of firm proposals.

As a rule the model was required to produce the stipulated demand from a given crude slate. Imports (mostly of middle distillates) and exports (mainly of gasoline) were kept constant throughout the study. Availability of other feedstocks, including natural gas either for hydrogen production or as fuel, was also kept constant. The main flexibilities were crude allocation to each region, intermediate and finished product exchanges and mainly investment in new process units (i.e. beyond the 2005 installed capacities). In line with considerations in *section 3.4* the crude diet was kept the same in all cases (45% light low sulphur, 55% heavy high sulphur) only one crude (Heavy Middle East) being allowed to vary to balance the requirements (e.g. for refinery energy consumption).

When running the model in this manner, the impact of absolute prices on the model response are somewhat limited as the model runs more in a "cost minimisation" than "profit maximisation" mode. This methodology also dispenses with the need to engage in price forecasts which are inevitably speculative and subject to criticism. Nevertheless a set of prices must be used. In this case we have used the average 2007 prices for North West Europe in all cases for both crude and products as detailed in **Appendix 1**.

One exception to the above methodology, i.e. where the model was left free to meet or not meet a maximum demand on the basis of economic considerations, is reported in *section 6* where the implications are also analysed.

All operating and investment cost figures in this report are meant to be in constant 2008 US$.

In this report, we concentrate on the global EU analysis. Although the model gives a full account of the outcome for each region, it is not possible to draw meaningful conclusions from regional changes between cases. This is because the model optimises the whole of Europe rather than each region separately. From one case to the other the regional crude diet as well as the level of component transfers between regions can vary significantly effectively moving the "goal post" in each individual case.

3. EVOLUTION OF OIL PRODUCTS SUPPLY DEMAND AND QUALITY IN EUROPE BETWEEN 2000 AND 2020

In the last decade the oil product market in Europe has undergone very significant changes. This will continue through the coming decade and towards the 2020 time horizon considered in this study. The changes stem both from the evolution of demand, particularly for road fuels but also from the relentless increase in the proportion of diesel and jet fuel, and from product quality changes brought about chiefly by environmental legislation across the spectrum of fuel grades.

In this section we first consider the timeline of product quality changes brought about by new legislation. We then consider the evolution of demand using forecasts essentially based on results of consultancy firm Wood Mackenzie's (WM) "Global Outlook" as elaborated in 2007. This excludes petrochemicals (i.e. light olefins and aromatics) for which data was obtained from CEFIC[1]. Finally we briefly discuss the EU crude supply situation and its likely evolution over the period.

3.1. ENACTED MARINE FUELS LEGISLATION AND RECENTLY ADOPTED MEASURES

Emissions from international shipping are regulated by the International Maritime Organisation (IMO), established in 1948 under a United Nations Convention. Air pollution requirements are covered in Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78). This Annex was added in 1997 and entered into force in May 2005 following ratification of the addition by a quorum of IMO Member States. The key regulation in this Annex impacting on marine fuels is Regulation 14 on Sulphur Oxides and Particulate Matter. This regulation aims to limit SOx emissions by specifying that the sulphur content of any fuel oil used on-board ships shall not exceed 4.5%. In addition, the regulation allows the creation of so-called Sulphur Emission Control Areas (SECAs), where the sulphur content of the fuel has to be limited to 1.5%. Alternatively, approved emission abatement equipment may be used to reduce flue gas SOx concentration to a level equivalent to using 1.5% S fuel.

The Baltic Sea became the world's first SECA, effective May 2006, followed by the North Sea effective November 2007. No further SECAs have been established since, bit it is widely expected that the US and Canada will submit an application for SECAs on their East and West Coast shortly. Such SECAs could become effective in the 2013 time frame.

Shortly after entry into force of Annex VI, IMO initiated a process to review the air pollution requirements, and this culminated in the adoption in October 2008 of a revised Annex VI. This revision, which is expected to enter into force on July 1, 2010, will trigger significant changes to marine fuels specifications in the next decade and beyond. First, the sulphur level in SECA area will be reduced to 1.0% as of July 2010 and to 0.1% as of January 2015. Furthermore the global sulphur cap will be reduced to 3.5% as of January 2012 and to 0.5% as of January 2020, subject to a review in 2018. If the 2018 review reveals that sufficient fuel supply will not be available by 2020, the implementation date for the 0.5% global cap will become January 2025. In all cases, approved emission abatement equipment may be used to achieve equivalent emissions.

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[1] European Council of Chemical Industry Federations

In addition to the IMO regulations, the European Union has established its own requirements in a revision of the Sulphur in Liquids Fuels Directive in 2005 (2005/33/EC). The Directive aligns European legislation with the IMO requirements for the North Sea and Baltic SECAs. In addition it imposes the use of 1.5% sulphur fuel by all ferries calling at European ports within territorial seas, exclusive economic zones and pollution control zones as of August 2006. As of January 1, 2010 marine fuels for inland waterway vessels and for all ships at berth may not contain more than 0.1% sulphur. In line with the IMO convention, emission abatement technology may be used by ships to achieve equivalent emissions, subject to authorisation.

The Directive also imposes a maximum of 0.1% sulphur in gasoil for land and marine use, and limits the sulphur content of any marine gasoil sold in Europe to 0.1% as of January 1, 2010. The EU Commission was due to report on this Directive and to make proposals for revision by 2008. However, this has not happened yet, as the Commission delayed its review until after the completion of the IMO deliberations.

3.2. OTHER PRODUCT QUALITY LEGISLATION

Pressure on the quality of petroleum fuels has been relentless for many years. The already implemented reductions of marine fuels sulphur content and the further momentous changes to come were described in *section 2* above. Besides this, all fuels have been affected although road fuels have arguably been the subject of most of the attention over the past say 20 years. Although the majority of road fuels related changes have already or will soon be implemented, a number of already legislated measures are still due to enter into force in the next few years.

“Fuels Quality Directive” (FQD)

The various dispositions of Directive 98/70/EC promulgated as a result of the first Auto-Oil programme came into force between 2000 and 2005 affecting road fuels. The second Auto-Oil programme resulted in a first revision, including the introduction of sulphur-free road fuels (<10 ppm). A further revision currently under discussion introduces further limits on road fuels, non-road mobile machinery fuels and inland waterways fuels.

“Sulphur in Liquid Fuels Directive” (SLFD)

Directive 1999/32/EC affects heating oil, industrial gasoils and inland heavy fuel oils.

Table 2 shows the chronological sequence of specification changes of various fuel products, including marine fuels, from the mid 90s through to 2020 as implied by agreed or proposed legislation. **Appendix 2** shows the detail of the specifications and corresponding quality targets used in the model, the difference representing the usual level of operating quality margins that refineries have to use in order to ensure on-spec products.

Table 2 Chronology of specification changes

Year	Product(s)	Legislation	
2000	Gasoline / Diesel	Directive 98/70/EC on fuels quality: Auto Oil 1 phase 1	150/350 ppm S in gasoline/diesel + other specs
2000	IGO/Heating oil	Directive 1999/32/EC on sulphur in liquid fuels	Heating oil 0.2% S
2003	HFO	Directive 1999/32/EC on sulphur in liquid fuels	Inland HFO 1% 1S
2005	Gasoline / Diesel	Directive 98/70/EC on fuels quality: Auto Oil 1 phase 2	50 ppm S in gasoline/diesel + 35% aromatics in gasoline
2006-7	Marine fuels	Marpol Annex VI, Directive 2005/33/EC on the sulphur content of marine fuels: sulphur restrictions in Baltic and North Sea SECAs and for EU ferries	1.5% S in marine fuel for SECA & Ferries
2008	IGO/Heating oil	Directive 1999/32/EC on sulphur in liquid fuels (includes marine gasoils used in EU waters)	Heating oil 0.1% S
2009	Gasoline / Diesel	Directive 98/70/EC on fuels quality: Auto Oil 2	10 ppm S in gasoline/diesel
2009	Gasoline / Diesel	Fuels Quality Directive proposal: Non-road diesel specification and diesel PAH limit	8% m/m PAH in road diesel 10 ppm S in non-road diesel
2010	Marine fuels	IMO: Sulphur restriction in SECAs Also includes restriction for ships at berth	1.0% S in marine fuel for SECAs 0.1% S for ships at berth
2011	Marine diesel	Fuels Quality Directive proposal: Inland waterways diesel	10 ppm S in gasoil for inland waterways
2012	Marine fuels	IMO: Global sulphur cap	3.50% S in all marine fuels
2015	Marine fuels	IMO: Sulphur restriction in SECAs	0.1% S in marine fuel for SECAs
2020	Marine fuels	IMO: Global sulphur cap	0.5% S in all marine fuels
	Marine fuels	*Substitution of all marine fuels by distillates at <0.5% sulphur*	

Table 2 also includes an “all distillates” case where all residual marine fuels would have to be replaced by distillates of a quality as per **Appendix 3** consistent with the grade known as DMB. Although this has not been legislated by IMO, such an option was extensively discussed during the MARPOL Annex VI review process.

3.3. PRODUCT DEMAND AND CALL ON REFINERIES

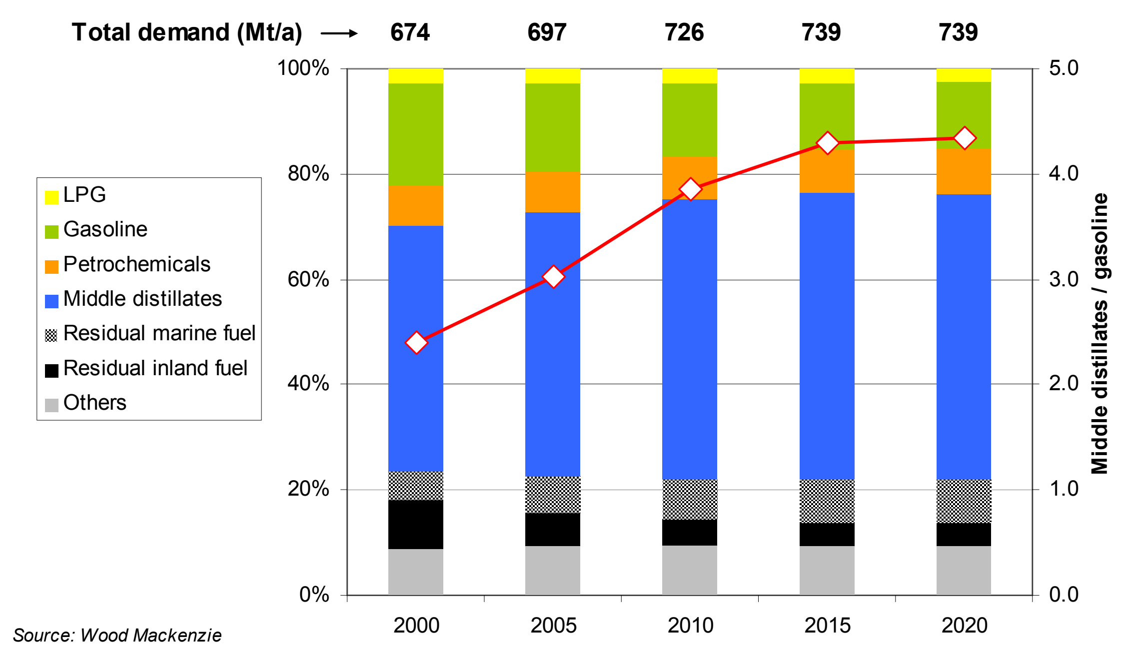
For many years European petroleum product demand has been shaped by three main trends

- Slow rate of growth of total demand,
- Gradual reduction of demand for heavy fuels and concomitant development of markets for light products,
- Within the light products market, a relentless increase of demand for “middle distillates” particularly automotive diesel and jet fuel, and a slow erosion of motor gasoline demand.

These trends are expected to continue as illustrated in **Figure 1** (a more comprehensive table is also included in **Appendix 4**). Total demand in EU-27+2, still sustained by growth in the new Member States in the early years, is expected to flatten from 2015.

The figure also shows the historic and predicted evolution of the ratio between middle distillates and gasoline demand, showing a steady increase until at least 2015. The Wood MacKenzie data suggests levelling out of this ratio thereafter as the trend towards ever more diesel cars slows down and eventually reverses. Many parameters will play a part in determining the actual outcome. Where cars are concerns this includes the relative success of gasoline vehicle fuel economy improvement technologies and of diesel vehicle after treatment technologies. Other crucial developments will be the rate of development of road haulage that represents a large proportion of total diesel demand and the rate of growth of air transport. The WM figures are considered optimistic by some i.e. forecasting too low diesel to gasoline ratios towards the end of the period. It also has to be recognised that these figures were elaborated before the current economic crisis and the resulting total demand may turn out to be higher than reality.

Figure 1 EU petroleum product demand evolution 2000-2020
("Petrochemicals" includes light olefins and aromatics)



Source: Wood Mackenzie

Evaluation of the impact of marine fuel legislation requires estimating demand volumes at a more detailed level than available from WM. This includes demand in SECAs as well as additional demand for "ferries" (as per Directive 2005/33/EC see *section 4.1* above).

Demand in the North and Baltic seas SECAs was originally estimated on the basis of internal information. The figures were found to be in reasonable agreement with those used by IIASA for their integrated air quality assessment model RAINS. Estimation of the additional demand represented by "ferries" that operate within European waters but outside SECAs proved more difficult not least because there does not appear to be full agreement as to what vessels are covered by the definition given in the Directive. The BMT report [3] indicates that "RoRo" (Roll-on/Roll-off) and cruise ships represent about 30% of total fuel consumption in Europe. Based on a recent study of shipping in the Mediterranean by ENTEC for CONCAWE, "passenger" ships represent roughly 50% of the available engine power in the overall RoRo segment, which include both cargo only and passenger ships. We therefore assumed that the vessels meant to be covered by the Directive account for 15% (50%*30%) of total EU demand. In order to avoid double counting this percentage was only taken into account for areas not affected by the SECA regulation. The resulting demand for the various segments is shown in **Table 3**.

Table 3 Residual marine fuel demand for various segments

Mt/a	2000	2005	2010	2015	2020
Total	36.3	46.5	56.0	60.3	62.1
SECAs	9.6	12.5	15.9	17.2	17.8
% of total	*26%*	*27%*	*28%*	*29%*	*29%*
non SECA ferries			5.9	6.3	6.5
SECAs + Ferries	9.6	12.5	21.8	23.5	24.3
% of total	*26%*	*27%*	*39%*	*39%*	*39%*

Having established the European market demand, one has to estimate the actual call on EU refineries i.e. make an assumption on the amount of trade (import/export) that is likely to take place. We have deliberately kept these figures constant in order to keep consistency between cases i.e. compare cases where EU refineries have to bear the cost of adaptation to changes. As shown in **Appendix 4** we have assumed 22 Mt/a of gasoline exports, 20 Mt/a of gasoil and 15 Mt/a of jet fuel imports. These distillate figures are consistent with actual figures from the last few years. Gasoline exports have been higher in the last 2-3 years but there are many signs that this market is shrinking and we thought it to be prudent to use a somewhat lower figure.

If data on marine fuel consumption is rather scarce, information on the origin of these fuels is even more difficult to obtain. In this study, we have assumed that bunkering outside the EU by EU-bound ships is roughly balanced with ships doing the reverse i.e. that EU refineries are supplying the equivalent of the whole of the EU demand in both quantitative and qualitative terms.

3.4. CRUDE OIL SUPPLY

Crude oil is a worldwide commodity. Although most grades are traded on a wide geographical basis, consuming regions tend, for logistic and geopolitical reasons, to have preferred supply sources. The favourable geographic location of Europe in relation to light and sweet crude producing regions (North Sea, North and West Africa) has resulted in a fairly light crude diet in the past two to three decades.

North Sea: This is indigenous production for which Western Europe has a clear logistic advantage. Although some North Sea crude finds its way to the US, the bulk is consumed in Europe.

Africa: North African crudes (Algeria, Libya, Egypt) are naturally part of Southern Europe's "captive" production. West African crudes can profitably go either to North America or to Europe and the market is divided between these two destinations.

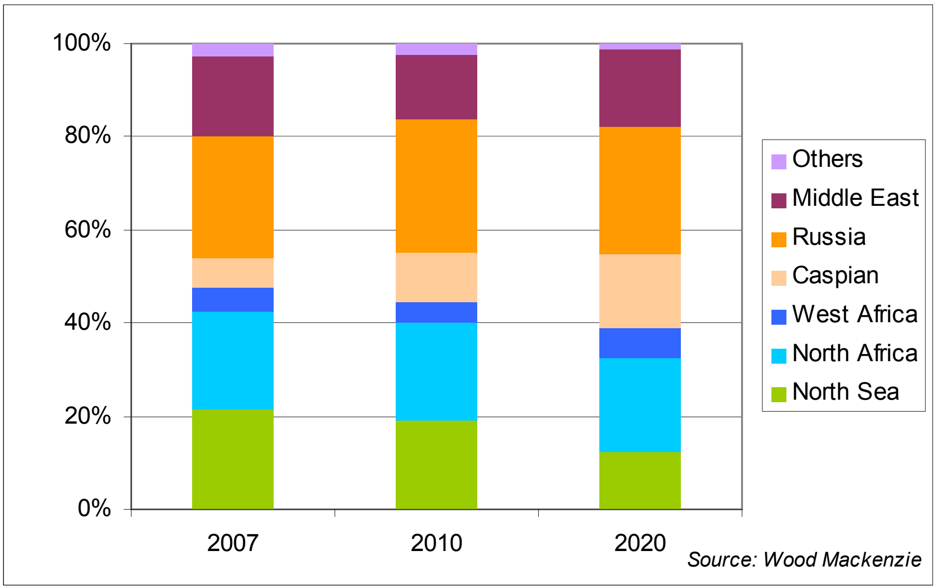
Middle East: The region is an important supplier, mainly of heavy, high-sulphur grades, typically used for the manufacture of bitumen or base oils for lubricant production and by refineries with appropriate desulphurisation and residue conversion facilities.

FSU: Russia is a steady and growing supplier to Europe, partly through an extensive inland pipeline system extending to most former East European block countries. The Caspian basin is poised to become a major producer with Europe as a preferred customer because of favourable logistics.

EU-27+2 consumed about 715 Mt of crude oil and feedstocks in 2005 (695 Mt in 2000). This is set to grow to 765 Mt in 2020. Although it is considered that supply should be adequate within this timeframe, the sources of supply for Europe will change. North Sea production will decline but other regions such as West Africa and the Caspian basin will take over. These changes in the origin of the crude oil will not significantly affect the average quality and it should be possible to maintain the current proportion of around 45% of sweet (i.e. low sulphur) crudes over the next decade. In the long term though, the quality of world reserves heralds an inevitable trend towards heavier and more sulphurous crudes.

The current and projected European crude supply is shown **Figure 2**.

Figure 2 Current and projected crude slate in Europe



Source: Wood Mackenzie

Using our model crudes this diet was modelled as shown in **Table 4**. During the model calibration exercise it appeared that matching the average sulphur content of the combined crude diet with actual figures resulted in too low a proportion of residual material. This was corrected by “heavying” the diet through addition of 20 Mt/a of Brent vacuum residue.

Table 4 Model crude diet

Mt/a	2000	2005	2010	2015	2020
Brent*	228.1	238.2	254.7	265.4	265.7
Nigerian	58.7	58.7	58.7	58.7	58.7
Algerian condensate	1.7	1.7	1.7	1.7	1.7
Iranian light	143.0	143.0	143.0	143.0	143.0
Urals	139.0	128.9	112.4	101.7	101.4
Kuwait	71.3	94.7	Balance as required		

* Plus 20 Mt/a vacuum residue of same origin

4. KEY IMPACTS OF MARINE FUELS QUALITY CHANGES ON EU REFINERIES

In this first section of the study we sought to illustrate the effect of marine fuel quality changes at the 2020 time horizon. To this end we developed a number of scenarios, all based on 2020 supply/demand and quality constraints on other products, with different assumptions on marine fuels quality from the pre-2006 situation through to enforcement of the IMO decision and further, gradually converting all marine fuels to distillates. **Table 5** summarises the cases.

Table 5 Summary of study cases (all 2020 basis)

Residual fuel cases	
Cap 4.5%	Reference case. Global sulphur cap at 4.5%, no SECAs *Representative of pre 2006 legislation*
Cap 3.5% S+F 1.5%	Global sulphur cap at 3.5%. SECAs sulphur limit at 1.5% (North and Baltic seas, as per MARPOL Annex VI), same limit applicable to “passenger ships on regular service to or from an EU port” (Ferries, as per Directive 2005/33/EC). *Representative of current situation*
Cap 0.5% SECA 0.1%	Global sulphur cap at 0.5%. SECAs sulphur limit at 0.1% (North and Baltic seas, as per MARPOL Annex VI). No specific limit for “Ferries”. *Representative of situation in 2020 under IMO proposal*
Cap 0.5% S+F 0.1%	As previous with “Ferries” subject to SECA sulphur limit *Not formally proposed*
Distillate fuel (DMB) cases	
XX% DMB 0.1/0.5%	Substitution of XX% of each residual marine fuel grade by distillate (DMB grade) at 0.5% sulphur (0.1% in SECAs and for Ferries) (1) 3 steps at XX = 25, 50, 75 and 100%

(1) This was simulated as a single distillate grade with specifications as per DMB (**Appendix 3**) and 0.3% sulphur content

The results of the simulations are summarised in **Table 6a** for the residual fuel cases and **6b** for the distillate fuel cases. Next to the “100% DMB” scenario the table also shows two extra cases which will be further discussed below. **Figure 2 through 6** illustrate the impact of changes on the most relevant parameters.

Table 6a Key impacts of marine fuels quality changes on EU refineries
Residual fuel cases

Case (all 2020)		*Cap 4.5%*	*Cap 3.5%* *S+F 1.5%*	*Cap 0.5%* *Seca 0.1%*	*Cap 0.5%* *S+F 0.1%*
Marine fuel production (Mt/a)					
(Residual) Marine fuel 4.5%		63.0	38.6		
(Residual) Marine fuel 1.5%			24.2		
(Residual) Marine fuel 0.5%				43.7	37.3
Marine fuel 0.1%				16.7	23.2
DMB 0.1/0.5%					
Middle distillates/ gasoline production ratio		3.2	3.2	3.2	3.2
Sulphur removed	Mt/a	4.2	4.4	5.9	5.9
	% of total	51%	54%	70%	71%
Existing and new process plant capacity throughput (Mt/a)					
Crude atmospheric distillation		712.7	713.1	716.1	716.2
Vacuum distillation		281.6	275.8	209.2	206.7
Visbreaking		90.8	87.7	62.6	60.8
Coking		12.0	11.6	11.4	11.4
FCC		97.8	101.8	107.8	106.8
Hydrocracking		116.1	110.1	83.1	84.8
Resid desulphurisation/conversion		17.4	21.4	81.2	84.1
Reformate / FCC gasoline splitting		26.2	28.6	24.0	22.8
Aromatics extraction		11.7	11.8	12.0	11.9
Isomerisation / Alkylation		14.4	14.2	12.8	13.0
PP splitting		4.1	4.3	4.5	4.5
Middle distillate hydrotreating		201.0	204.2	218.9	218.0
Hydrogen (in kt/a of H_2)		980.0	985.0	1348.7	1373.6
Steam cracker		76.3	75.6	74.6	74.6
New process plants capacity (Mt/a)		*Relative to base 2005*			
Crude atmospheric distillation		46.5	49.6	48.9	49.0
Vacuum distillation		23.6	18.0	-1.9	-2.2
Visbreaking		12.7	9.3	-3.8	-3.8
Coking		0.2	-0.1	-0.1	-0.1
FCC		-0.7	-0.6	-0.1	-0.1
Hydrocracking		73.6	65.2	25.0	27.3
Resid desulphurisation/conversion		7.4	11.4	71.3	74.1
Reformate / FCC gasoline splitting		-20.3	-18.3	-18.6	-19.5
Aromatics extraction		3.5	3.6	3.7	3.7
Isomerisation / Alkylation		-0.9	-1.1	-1.5	-1.5
PP splitting		0.9	1.0	0.6	0.7
Middle distillate hydrotreating		49.2	52.5	69.4	68.5
Hydrogen (in kt/a of H_2)		633	638	1002	1027
Steam cracker		8.3	7.6	6.7	6.7
Capital expenditure	G$	47.4	46.8	62.8	65.2
Total annual additional cost(	G$/a	9.2	9.1	13.8	14.3
Energy consumption	Mtoe/a	48.0	48.1	50.3	50.2
	% of tot. feed	6.7%	6.7%	7.0%	7.0%
CO_2 emissions					
From refineries	Mt/a	145.5	146.4	160.0	160.2
	t/t of tot. feed	0.20	0.20	0.21	0.22
From fuel products	Mt/a	1996	1996	1992	1992
Total	Mt/a	2140	2141	2150	2150
(including burning of fuel products)					
From refineries	% of total	6.8%	6.8%	7.4%	7.4%

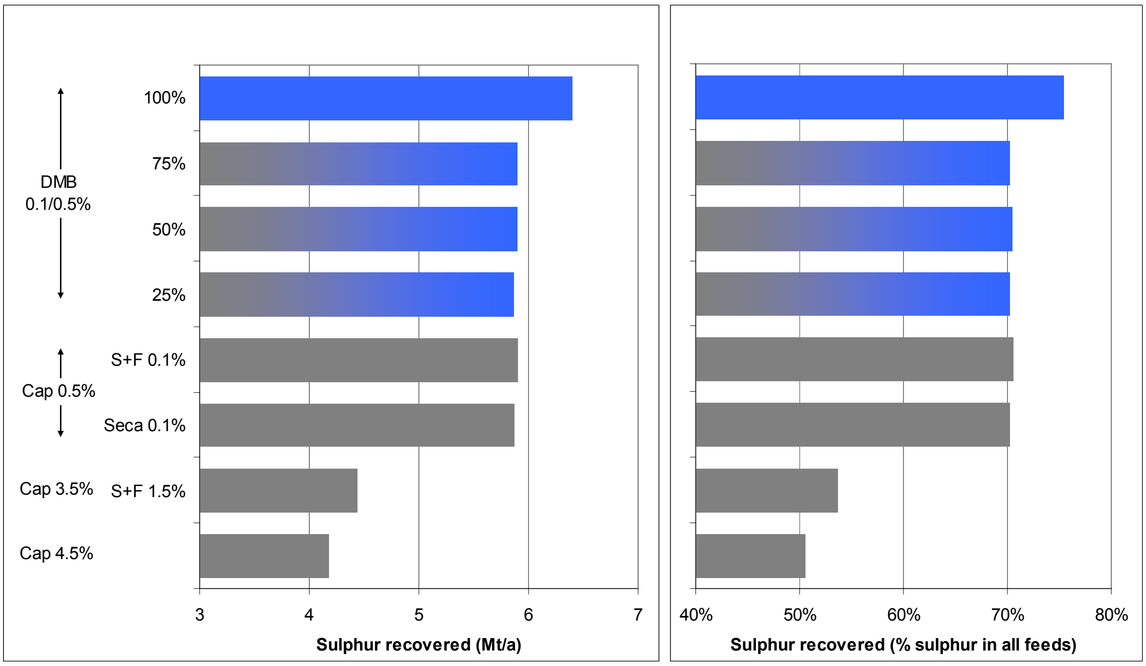
(1) Including capital charge, excluding margin effects

Table 6b Key impacts of marine fuels quality changes on EU refineries
Distillate fuel (DMB) cases

Case (all 2020)		*25%DMB 0.1/0.5%*	*50%DMB 0.1/0.5%*	*75%DMB 0.1/0.5%*	*100% DMB 0.1/0.5%*	*100% DMB 0.1/0.5% Cokers*	*100% DMB 0.1/0.5% Cokers no RHDS*
Marine fuel production (Mt/a)							
(Residual) Marine fuel 4.5%							
(Residual) Marine fuel 1.5%							
(Residual) Marine fuel 0.5%		33.0	22.1	11.1			
Marine fuel 0.1%		12.5	8.5	4.4			
DMB 0.1/0.5%		14.7	29.4	44.0	58.5	58.5	58.6
Middle distillates/ gasoline production ratio					3.7	3.7	3.7
Sulphur removed	Mt/a	5.9	5.9	5.9	6.4	6.2	6.2
	% of total	70%	70%	70%	75%	73%	72%
Existing and new process plant capacity throughput (Mt/a)							
Crude atmospheric distillation		716.1	716.3	717.4	720.9	722.0	725.2
Vacuum distillation		217.7	224.3	228.5	242.8	243.6	304.2
Visbreaking		63.8	64.0	62.0	61.8	51.8	76.2
Coking		11.5	11.6	14.9	19.9	30.8	37.1
FCC		105.2	100.2	94.6	94.6	93.4	83.7
Hydrocracking		95.6	110.8	125.8	134.0	137.8	147.2
Resid desulphurisation / conversion		80.8	82.5	87.5	97.9	88.3	49.6
Reformate / FCC gasoline splitting		18.5	11.4	7.7	9.8	9.4	16.6
Aromatics extraction		11.9	11.9	11.7	12.3	12.2	12.2
Isomerisation / Alkylation		13.0	13.2	15.0	15.5	15.7	16.6
PP splitting		4.4	4.4	4.1	4.1	4.0	4.0
Middle distillate hydrotreating		211.2	201.9	197.6	194.3	194.5	193.8
Hydrogen (in kt/a of H_2)		1397.6	1475.5	1749.3	2187.7	2031.8	2419.5
Steam cracker		74.9	75.1	76.3	76.8	77.0	78.5
New process plants capacity (Mt/a)		*Relative to base 2005*					
Crude atmospheric distillation		49.0	50.4	52.7	58.2	60.0	60.8
Vacuum distillation		-1.4	-1.8	2.6	4.3	5.1	45.6
Visbreaking		-3.7	-3.1	-1.8	-2.0	-4.7	-5.6
Coking		-0.1	-0.1	3.1	8.2	19.0	25.3
FCC		-0.1	-0.3	1.2	-1.2	-0.3	-1.2
Hydrocracking		43.3	67.1	87.8	96.4	100.6	111.8
Resid desulphurisation/conversion		70.9	72.5	77.5	87.9	78.4	39.7
Reformate / FCC gasoline splitting		-21.9	-26.5	-27.4	-27.4	-27.2	-25.2
Aromatics extraction		3.6	3.7	3.5	3.4	3.3	3.3
Isomerisation / Alkylation		-1.5	-1.4	-0.5	0.0	0.3	2.6
PP splitting		0.9	1.2	1.1	1.2	1.2	1.1
Middle distillate hydrotreating		61.8	51.4	46.0	43.2	43.2	41.6
Hydrogen (in kt/a of H_2)		1051	1129	1328	1765	1609	1997
Steam cracker		6.9	7.2	8.2	8.7	8.9	10.4
Capital expenditure	G$	67.7	75.1	91.0	210.4	108.4	111.2
Total annual additional cost(	G$/a	15.0	16.8	20.6	49.3	25.0	26.8
Energy consumption	Mtoe/a	50.5	50.9	52.0	54.9	53.0	55.6
	% of tot. feed	7.1%	7.1%	7.2%	7.6%	7.3%	7.7%
CO_2 emissions							
From refineries	Mt/a	161.7	164.4	172.7	188.3	178.1	186.8
	t/t of tot. feed	0.22	0.22	0.23	0.25	0.24	0.25
From fuel products	Mt/a	1990	1988	1983	1978	1992	1993
Total (including burning of fuel products)	Mt/a	2150	2151	2154	2165	2168	2179
From refineries	% of total	7.5%	7.6%	8.0%	8.7%	8.2%	8.6%

(1) Including capital charge, excluding margin effects

Figure 3 Key impacts of marine fuels quality changes on EU refineries: Sulphur removal from crude and feedstocks

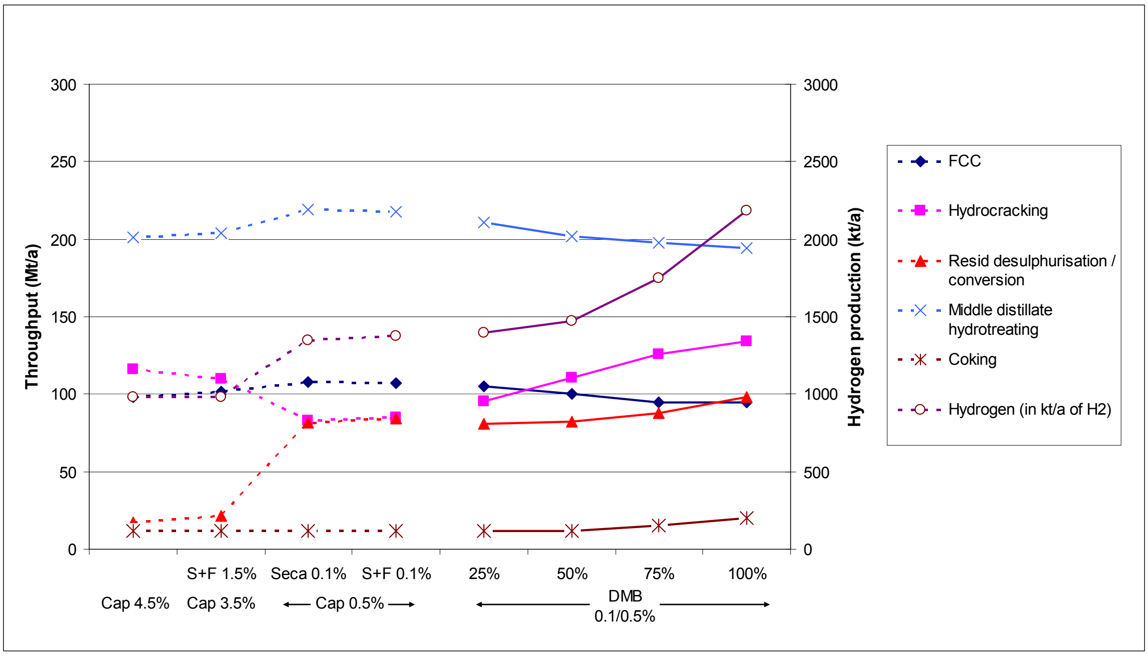


It should come as no surprise that the dramatic marine fuels sulphur reduction implied by the IMO measures results in an increase of the refinery sulphur production by about 50% or 2.2 Mt/a (**Figure 3**). Also accounting for desulphurisation of other products sulphur removal from refinery feedstocks will reach about 70% in 2020 compared to only 50% if pre 2006 marine fuels legislation still prevailed.

One would expect the switch to distillate fuels to have little or no impact on this inasmuch as the level of sulphur in the marine fuel pool would remain the same. This is indeed what we observe for the first 3 DMB cases (up to 75% switch). The 100% DMB case seems to show a discontinuity in this respect with more sulphur being removed. The reason for this appears to be that, at that point, the model needs to install so much conversion that it ends up having mostly low sulphur components to blend in what is left of the residual fuel oil pool i.e. some 30 Mt/a of inland fuel with a resulting significant sulphur giveaway in these grades. In other words, at that point, sulphur is not an economic constraint anymore.

Such deep desulphurisation imposes a major adaptation of the refining tool. **Figure 4** shows the capacity of the most relevant groups of process units that need to be utilised in order to meet the new quality constraints. As desulphurisation depth increases, more residue desulphurisation and partial conversion capacity is required (mostly atmospheric residue desulphurisers), partially reducing the call on distillate hydrocracking capacity. Distillate hydrotreating capacity increases somewhat while FCC utilisation remains broadly constant. The total hydroprocessing capacity is on the increase and so is hydrogen production as a result.

Figure 4 Key impacts of marine fuels quality changes on EU refineries: Main process plant utilisation



Even after deep desulphurisation of residual fuels, converting marine fuels to distillates (DMB) presents a much bigger challenge, requiring substantial further increases of hydrocracking, residue desulphurisation only very partially compensated by a reduction of distillate hydrotreating and FCC capacity. One can already see from **Figure 4** that the changes are not linear with the fraction of marine fuels being converted to distillates. The underlying reason for this reaction of the model is the already very high demand for middle distillates compared to gasoline that is further exacerbated when marine distillates (albeit of a fairly heavy variety) need to be produced.

Hydrogen production capacity needs to increase by about 40% for the 0.5% sulphur cases and more than double for the DMB cases. This has a particularly large impact on refinery CO_2 emissions.

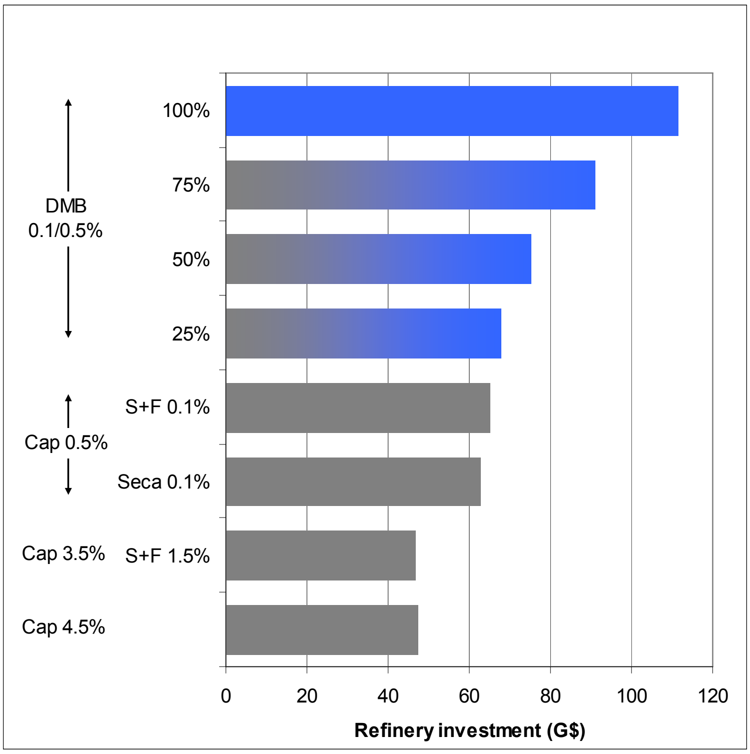
Coking requires a special mention. The constant demand that we impose on all runs within a time period extends to petroleum coke. This is in order to keep the same demand envelope for all runs and maintain consistency and comparability. The differences in coker utilisation observed in the main series of cases relate to the use of different feedstocks with different coke yields (e.g. the higher utilisation in the "All DMB" case points out to lighter feeds being selected). Freeing up coke demand gives the model the opportunity to use more cokers at the expense of other conversion units. The choice is, however, strongly influenced by the arbitrary assumption made regarding the price of coke relative to other products, rather than the indication of a structural requirement. We have tested this on the "100% DMB" case, purposely assigning a high value to coke in order to entice the model to use more cokers (see **Table 6**, "100% DMB/Cokers" case). Indeed coker utilisation nearly doubled as a result. As can be seen from **Figure 4** though, the impact on utilisation of other conversion plants is modest. In a further sensitivity case we barred the model from building additional atmospheric residue desulphurisers, which is significant option in order to maximise utilisation of existing FCCs

("100% DMB/Cokers/no RHDS" case). This indeed resulted in a reduction of FCC utilisation and rebalancing of hydroconversion units to the benefit of hydrocrackers while vacuum distillation capacity also increased. As will be further pointed out below, neither of these two side cases resulted in a significant change in investment, energy consumption or CO_2 emissions suggesting that the outcome is robust.

The additional capacity requirements translate in investments in new plants (**Figure 5**). Starting from the situation in 2005, migration to the 2020 demand and product quality requires just under 50 G$ investment assuming no change in marine fuels legislation. The 2006 legislation (SECAs and Ferries at 1.5% sulphur) requires different investments but for about the same amount as a large part of the new low sulphur grade is made through segregation rather than additional desulphurisation. Achieving the 2020 IMO targets of 0.1% in SECAs and a global cap of 0.5% requires 15 G$ of additional investments and another 2.5 G$ should ferries be included.

Going all the way to distillates would be much more onerous though, mostly due to the steep increase of residue conversion and hydrocracking needs to produce the additional middle distillates out of an already stretched system. Increased reliance on cokers would not change the picture significantly. It is clear from **Figure 5** that the requirements are strongly not linear with the proportion of distillate being introduced. As the required fraction of DMB increases the system is increasingly stretched.

Figure 5 Key impacts of marine fuels quality changes on EU refineries: Capital expenditure (relative to base 2005)



It must be realised that such investments would require a massive effort for the industry, especially when they are considered within the context of other calls for new installations. **Figure 5** shows that nearly 50 G$ investment is needed to meet the 2020 demand even without changes in marine fuels specifications. In addition there are other regulatory constraints that will imply additional investments such as implementation of the IPPC and Large Combustion Plant Directive. Beyond the all important financial and economic aspects, the feasibility of such massive investment requirements is sure to be a major issue in terms of the ability of the industry to mobilise sufficient material and human resources.

Refinery energy consumption and CO_2 emissions follow roughly the same trends (**Figure 6**). 2020 marine fuels legislation increases energy consumption by about 2 Mtoe/a and adds 15 Mt/a CO_2 emissions. Some of this is recovered through the fact that marine fuels have now a higher hydrogen/carbon ratio but the net effect is still an increase of CO_2 emissions by about 10 Mt/a (see **Table 6a**).

Going over to distillates here also introduces major changes, further increasing emissions by 30 Mt/a if all marine fuels are to be converted. As was the case for investment the energy and CO_2 impact is strongly non-linear.

Allowing more coking capacity reduces energy consumption somewhat, reducing the extra emissions by about one third (**Table 6a**). It has to be kept in mind though that this option is not fully comparable with the others because it produces a different product slate. The additional coke produced would be burned somewhere, substituting other, possibly lighter, fuels and potentially creating additional emissions.

Figure 6 Key impacts of marine fuels quality changes on EU refineries: Energy consumption and CO_2 emissions

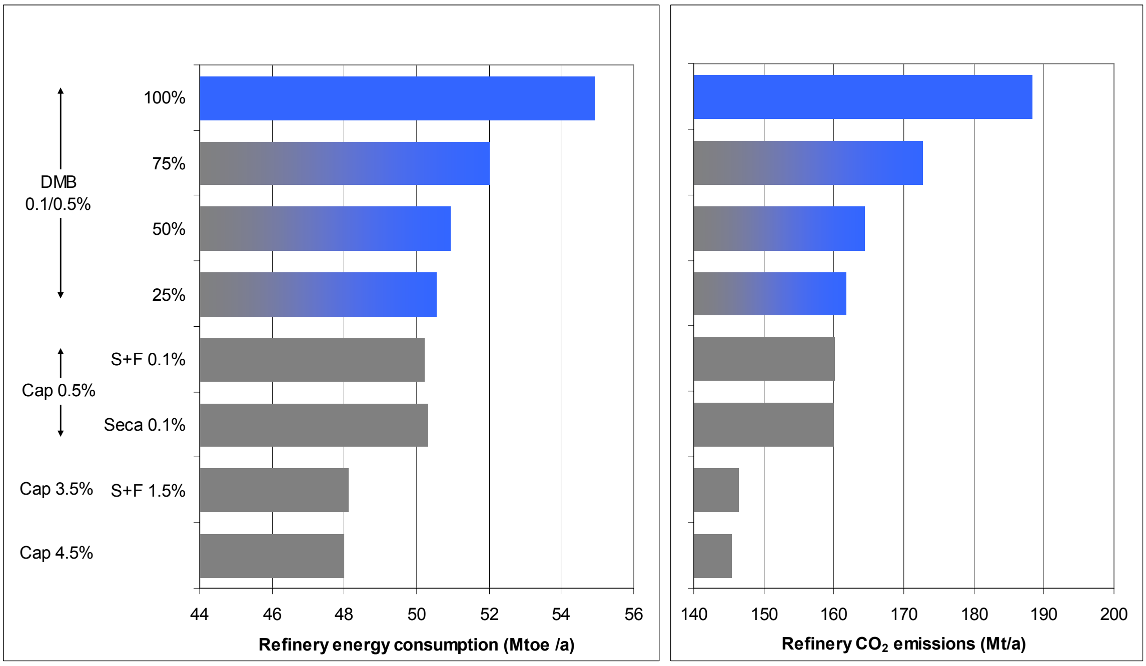


Figure 7a/b shows the composition of the different marine fuel grades. The changes brought about by sulphur reductions are striking. Current fuels, including the current "low sulphur" grades (1.5%) are typically blended from visbroken residues diluted with a variety of distillates either cracked or straight run. At 0.5% sulphur, visbroken residue is cut by two thirds and replaced by a combination of virgin and desulphurised residues and some hydrocracker bottoms. At 0.1% sulphur, visbroken residue has all but disappeared essentially replaced by mostly hydrocracker bottoms and some virgin and desulphurised residue.

Clearly this 0.1% sulphur "residual" fuel is a very different product from what ships are currently burning. Although the model blends fulfil all stipulated quality requirements in terms of density, viscosity, carbon residue etc, such exotic grades may exhibit different behaviours in terms of a/o ignition properties of compatibility and their introduction would need careful consideration by both fuel suppliers and ship owners. This analysis is, in this sense, preliminary and could be overoptimistic in terms of the feasibility of producing fit for purpose residual fuels with such very low sulphur content. Referring to the analysis in *section 6*, it can also be questioned whether such fuel would in practice be produced, rather than going all the way to a distillate grade, a likely more economically attractive alternative.

The "distillate" grade is essentially a blend of vacuum distillate and virgin and (desulphurised) cracked gasoils with increasing amounts of hydrocracker bottoms as the proportion of distillate in the marine fuel pool increases. About two thirds of the components used to blend this grade are drawn directly from the middle distillate pool compared to 10% or less for the low sulphur marine fuel cases, i.e. accounting a genuine large increase of the distillate demand.

Figure 7a Key impacts of marine fuels quality changes on EU refineries: Residual marine fuel grades composition

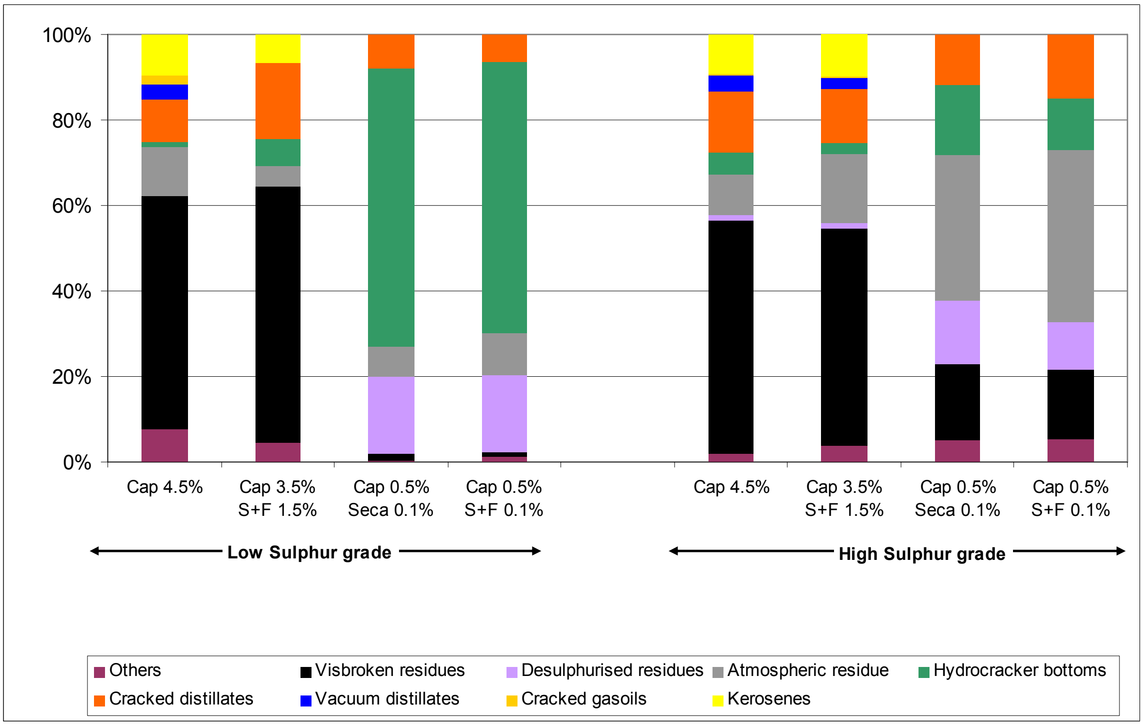
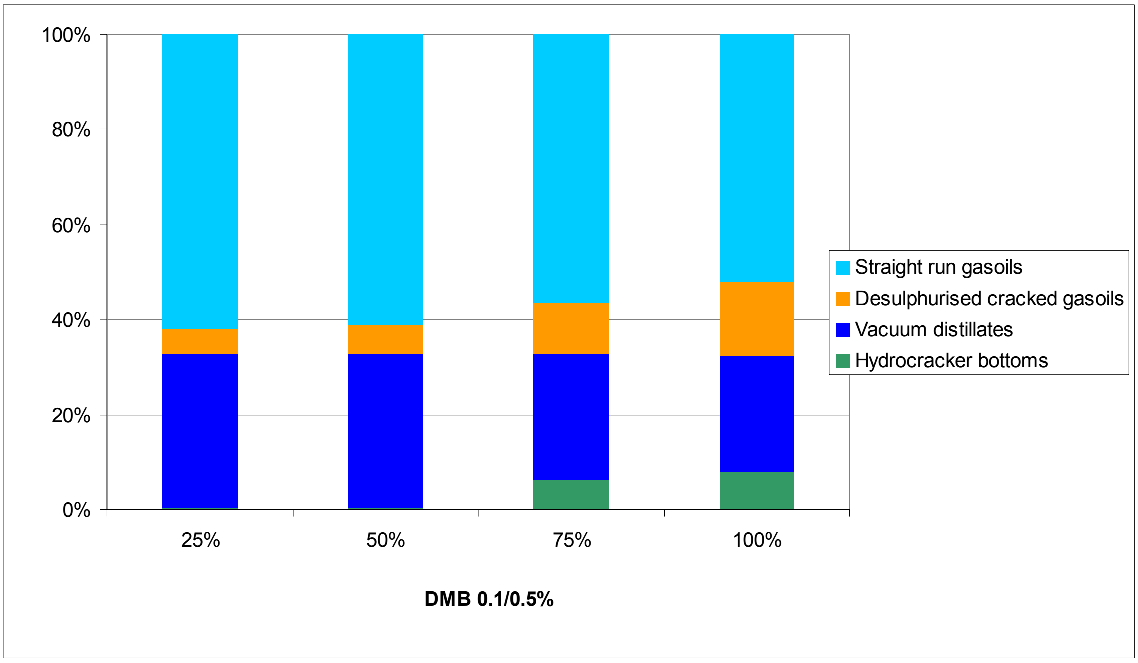


Figure 7b Key impacts of marine fuels quality changes on EU refineries: Distillate marine fuel grade composition



5. COMPARISON WITH OTHER STUDIES

A number of other studies have been published in recent months on this subject particularly a study by EnSys [4] for the American Petroleum Institute and a study by ECN [5] for the Dutch government. Comparisons between such studies are always difficult. Although the linear programming modelling technique is normally used, the representation of the refining system, the granularity, the constraints and flexibilities imposed are all different. Each study has its own set of base assumptions in terms of a/o future crude oil supply and product demand and the geographic envelope considered. The interrelationships allowed between regions are not always the same and the actual scenarios considered are also different. Cost evaluation brings another level of uncertainty related to the general level of plant construction cost considered. In the foregoing we have nevertheless attempted to rationalise differences in results between the two studies mentioned above and ours although we limited the comparison to the impact on CO_2 emissions from refineries.

EnSys looked at the worldwide impact of lowering marine fuels sulphur (down to 1.5%) and of migrating to distillates (at 1.0 and 0.5% sulphur). EnSys estimated a worldwide refinery CO_2 emissions increase of some 12 Mt/a for lowering the sulphur of 310 Mt/a of residual marine fuels to 1.5%. This is equivalent to 0.04 t CO_2/t of fuel which is fairly close to the figure we found for producing 1.5% sulphur fuels for SECAs (0.05 t/t).

For the switch to distillate, the EnSys numbers point out to 0.4 t CO_2/t fuel. From **Table 6b** we can calculate a range of figures depending on the proportion of distillates converted. Converting all residual marine fuels into DMB corresponds to nearly 0.7 t CO_2/t fuel. This difference should, however, not come as a surprise. EnSys models the world and, while recognising logistics constraints and transport costs, assumes flexibility to produce demand wherever it appears most economic in effect assuming perfect worldwide economic optimisation. In contrast our analysis is restricted to Europe where we force production to match demand, leading to less degrees of freedom and therefore higher impacts. Both views are defendable and informative but they will always lead to different results. The shortage of middle distillates is much more acute in Europe than in the rest of the world. Indeed the middle distillate to gasoline ratio is about 1.5 in EnSys compared to 3.2 for our European envelope. Another difference between the two approaches is related to cokers. EnSys's model is free to use and does use additional coking capacity. Coking is in effect a partial conversion process and its direct impact is less than that of full conversion options. The problem is that different cases produce different amounts of coke and a full comparison requires agreement on a common fate for that coke. If one includes combustion of the extra coke the total CO_2 impact in the EnSys study becomes 0.72 t/t, which is very close to our number.

EnSys subsequently ran further cases on request of a Scientific Group of Experts appointed by IMO to support the MARPOL Annex VI discussions.

Another point to realise is that the impact of switching to DMB is highly dependent on the proportion to be converted. Starting from the 2020 end point without DMB, one can compute from **Table 6b** an impact from 0.11 t CO_2/t DMB in the 25% case to 0.48 in the 100% case. This illustrates again how scenario-dependent the impact is.

The ECN study focussed on the "all distillate" case in the Dutch context and found CO_2 impacts similar to EnSys. Here again a direct comparison is difficult. The same arguments are valid though regarding the middle distillate to gasoline ratio and the changes in coke make. In addition ECN allowed the crude diet to change making it possible for refineries to use lighter crudes which of course reduces the direct impact. This, however, ignores the fact that crude availability is a “zero-sum” game where the gains of some are the loss of others. More light crude in Europe would necessarily mean less light crude somewhere else in the world. ECN subsequently issued an addendum where they fixed the crude slate [6]. Their conclusions then aligned a lot better with our work.

Another study was done in Japan by the Japan Petroleum Energy Centre (JPEC, unpublished report). This study looked at the Japanese refining sector only. Interestingly JPEC ran their model in a 2020 scenario predicting a drop in total petroleum product demand. The model showed however, that even under those circumstances significant investments would be required to adjust refinery balances in the case of a complete switch of marine fuels to distillate.

Overall it is clear that, although results differ at a detailed level, all four studies point out to a serious impact of desulphurisation of marine fuels and particularly of a migration to distillate fuels.

6. LOW SULPHUR RESIDUAL FUELS: MAKE OR CONVERT?

In CONCAWE report 2/06 [2] we showed that, given the choice, refiners were more likely to invest in deep residue conversion than in residue desulphurisation, unless the price differential between residual fuels and distillates was considerably reduced.

The present study is based on revised future demand scenarios, a more comprehensive account of changes in quality of all products, 2020 rather than 2015 as end point and a different price set. We therefore briefly repeated the previous analysis (**Table 7**). Starting from the 2020 “IMO” scenario (0.5% global cap and 0.1% in SECAs, first column), we removed the fixed demand constraint on marine fuels in effect simulating a case where refiners have the option to stop production of residual bunker fuels and convert them into higher value products, primarily diesel and motor gasoline. We did this first with constant prices i.e. assuming that better quality would not translate into higher prices (second column).

Table 7 confirms previous findings. If prices remain unchanged the model, when given the option) produces very little marine fuels, preferring the more economically attractive conversion option which allows reduction of crude intake. In order for the model to produce the originally fixed demand for marine fuels prices have to be increased by a considerable amount (third column). For the 0.5% sulphur grade the differential with gasoil has to be slashed by a factor three and a factor of nearly 5 for the 0.1% sulphur grade. Note that, when taking into account the difference of calorific value (still around 5%), the price of residual fuels is even closer than that of gasoil on an energy basis.

Table 7 Marine fuel price changes required to economically produce demand

Case		2020 Cap 0.5%, Seca 0.1%		
Marine fuel prices		Base		Adjusted
Marine fuels demand		Fixed	Open	
Prices	$/t			
Gasoil		630		
Marine fuel 0.5% S		327		517
Marine fuel 0.1% S		344		569
Differentials to gasoil	$/t			
Marine fuel 0.5%		304		113
Marine fuel 0.1%		287		61
Marine fuel production	Mt/a			
0.5% S		43.7	0.7	41.5
0.1% S		16.7	2.4	16.8
Crude and feedstocks intake		745	692	743
Capital expenditure	G$	62.8	74.1	62.9
Total annual additional cost(1)	G$/a	13.8	16.5	13.8
Energy consumption	Mtoe/a	50.3	50.7	50.3
	% of tot. feed	7.0%	7.6%	7.0%
CO_2 emissions from refineries	Mt/a	160.0	167.0	159.7
	t/t of tot. feed	0.21	0.24	0.21

(1) Including capital charge, excluding margin effects

The increased processing intensity in the conversion case is reflected in higher CO_2 emissions per tonne of feedstock. Even though less crude is processed, CO_2 emissions are also higher in absolute terms. As a result a high CO_2 price would somewhat dampen the above trend. At the commonly foreseen medium term CO_2 prices, the impact would be minimal though: at 40 $/t CO_2 the extra cost would only be equivalent to 5 $/t marine fuel.

A consequence worth considering of this analysis is that the introduction of 0.5 and 0.1% sulphur marine fuels may have a higher impact on refinery configuration and CO_2 emissions than could be anticipated simply based on the desulphurisation needs. Indeed a number of refiners may prefer the conversion alternative and either exit the marine fuel market or sell distillates as premium fuels. The desulphurisation case should therefore be seen as a minimum, reality settling somewhere between this and the “all DMB” case.

7. ENERGY AND CO_2 FOOTPRINT OF MARINE FUELS

As part of the debate on the rationale and justification for reducing sulphur in marine fuels, attempts have been made to establish the “life cycle” emissions associated with a particular type of fuel in so-called “well-to-hull” studies. One crucial element of such analyses is the energy and carbon footprint attributed to the production of the fuel.

Estimating this footprint raises a specific problem in the case of petroleum products. Indeed oil refining, through which they are produced, is a co-production process whereby a number of different products are obtained simultaneously through a complex combination of interrelated physical and chemical processes.

Whereas the total resources required to run an oil refinery in terms of feedstocks, costs, energy and the resulting emissions can be established in a straightforward manner, there is no scientifically sound way of apportioning any of these between the different products of the refinery. Several attempts have been made to devise pseudo-scientific methods to allocate the resources used by each individual process unit to a particular final product on the basis of the destination of the main product of that unit. Simpler methods distribute the resources according to some arbitrary key such as mass, energy content, economic value etc. All these methods are fundamentally flawed as they have no rational basis or justification. They ignore the complex interactions, constraints, synergies within a refinery and, where the scope is wider, also between the different refineries in a certain region. Importantly they also make the implied assumption that the refining system under scrutiny is static and cannot/will not evolve and change.

A refinery product does not have “a” value but a range of values depending on circumstances and each tonne of product made by the refinery may well have a different value. The same holds for the energy and carbon footprint. The tool that allows a glimpse into this complex reality is usually called marginal or differential analysis. Its fundamental principle is to compare a base or “business-as-usual” case with an alternative case where the production of a certain product is changed, all other parameters being kept the same. The changes in cost, energy, emissions etc between the base and alternative case can then justifiably be “charged” to the amount of the specific product that was changed.

The present study gives us an opportunity to estimate the marginal footprint of marine fuels, at least as far as the refining step is concerned. To this end we have used the same 2020 “IMO” scenario as starting point. We have then changed the marine fuel demand upwards and downwards by a fixed amount, one grade at a time, keeping all other demands and model constraints the same. For the 0.5% sulphur residual grade we used a 10% step change corresponding to about 4 Mt/a. For the 0.1% sulphur residual grade the volumes involved are smaller so we used a 20% step change in order to have sufficient resolution. The results are shown in **Table 8**.

Table 8 Marginal changes in energy and CO_2 emissions associated with low sulphur residual marine fuel production

Case		2020 Cap 0.5%, Seca 0.1%				
		Reference	0.5% S grade		0.1% S grade	
			-10%	10%	-20%	20%
Marine fuels demand	Mt/a					
Marine fuel 4.5% S						
Marine fuel 0.5% S		*43.7*	-4.3	4.3	0.0	-0.1
Marine fuel 0.1% S		*16.7*	0.0	0.0	-3.4	3.4
DMB 0.1/0.5% S						
Energy consumption						
Total	ktoe/a	*50337*				
Change			-6	20	-10	-48
Average for all products	koe/t	*69*				
Average for changed demand			1	5	3	-14
CO_2 emissions from refineries						
Total	Mt/a	*159.6*				
Change			-0.1	0.2	-0.2	0.1
Average for all products		*0.22*				
Average for changed demand	t CO_2/t		0.03	0.04	0.05	0.04

Clearly marginally reducing or increasing demand for either grade of marine fuel results in very small changes in the total energy consumption and CO_2 emissions of EU refineries. When expressed relative to one tonne of changed demand, they represent only a small fraction of what applies to the average product from the refinery. In other words producing more or less residual fuel does not increase or decrease energy consumption or CO_2 emissions significantly.

Note that the differential figures do not appear entirely consistent particularly in the 0.1% sulphur, +20% case where energy consumption decreases when production increases, whereas CO_2 emissions increase. The reason for this is that the differential are so small that we are reaching the limits of the model capability to depict such changes, particularly when considering the fact that the model optimises profits rather than either energy consumption or CO_2 emissions.

The situation can be expected to be different when the quality requirements placed in marine fuels are changed. In order to illustrate this, we have made similar simulations starting from different notional cases where the marine fuels sulphur limit remains at 4.5%, 50% of marine fuels is converted to DMB while the balance is desulphurised (as per 2020 reference case) and finally where all marine fuels are converted to DMB (all based on 2020 demand). Results are summarised in **Table 9** and **10**.

Decreasing the demand of high sulphur marine fuel actually *increases* both energy consumption and CO_2 emissions (**Table 9**). In other words this type of marine fuel has a negative footprint. This is understandable inasmuch as demand for undesulphurised heavy material provides a sink for the naturally occurring heavy crude fractions.

The opposite trends are observed in the “DMB” case. **Table 10** indeed shows that marginal DMB has a positive footprint i.e. energy consumption and CO_2 emissions increase with increasing demand. However, the actual magnitude of the increase strongly depends on the reference point i.e. what proportion of the marine fuel demand is being supplied as DMB. In the 50% DMB case the marginal DMB footprint is less than the average for all refinery products. In the 100% DMB case it is nearly twice as much. This is because the product that now needs to be made is a distillate, of which there already is a shortage and the higher the demand, the more demanding the marginal tonne becomes. Not surprisingly, the numbers found here are consistent with what was observed in previous work for diesel fuel [7]. In actual fact the figures for the 100% DMB case are even higher illustrating the increasing difficulty of producing an ever larger proportion of middle distillates.

Table 9 Marginal changes in energy and CO_2 emissions associated with high sulphur marine fuel production

Case		2020 Cap 4.5%, No Seca		
		Reference	-10%	10%
Marine fuels demand	Mt/a			
Marine fuel 4.5% S		*63.0*	-6.3	6.2
Marine fuel 0.5% S				
Marine fuel 0.1% S				
DMB 0.1/0.5% S				
Energy consumption				
Total	ktoe/a	*48894*		
Change			69	-49
Average for all products	koe/t	*67*		
Average for changed demand			-11	-8
CO_2 emissions from refineries				
Total	Mt/a	*148.5*		
Change			1.2	-0.9
Average for all products		*0.20*		
Average for changed demand	t CO_2/t		-0.19	-0.15

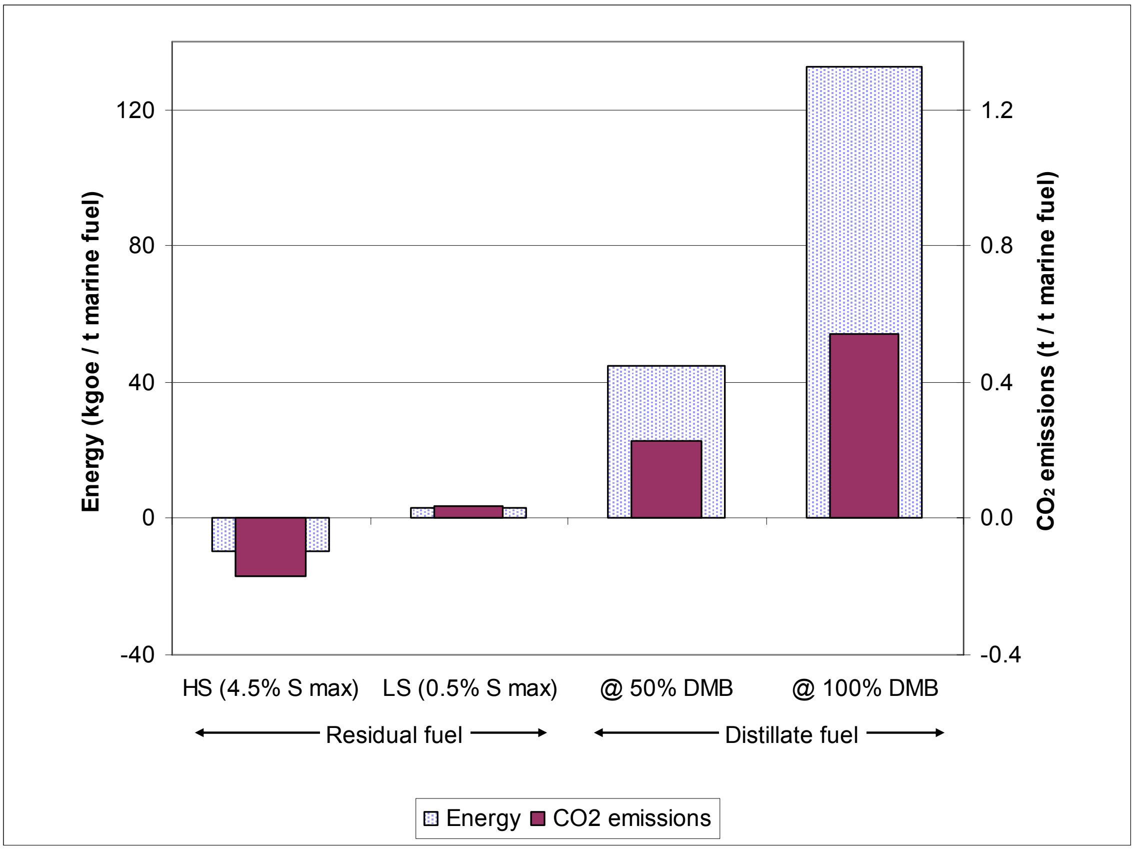
Table 10 Marginal changes in energy and CO_2 emissions associated with distillate marine fuel production

Case		2020 50% DMB 0.1/0.5%			2020 100% DMB 0.1/0.5%		
		Reference	-10%	10%	*Reference*	-10%	10%
Marine fuels demand	Mt/a						
Marine fuel 4.5% S							
Marine fuel 0.5% S		*22.1*	0.0	0.0			
Marine fuel 0.1% S		*8.5*	0.0	0.0			
DMB 0.1/0.5% S		*29.4*	-9.1	7.5	*58.5*	-6.7	6.6
Energy consumption							
Total	ktoe/a	*50921*			*55669*		
Change			-218	499		-860	899
Average for all products	kgoe/t	*70*			*77*		
Average for changed demand			24	66		129	136
CO_2 emissions from refineries							
Total	Mt/a	*164.4*			*190.3*		
Change			-1.5	2.2		-3.2	4.0
Average for all products		*0.23*			*0.26*		
Average for changed demand	t CO_2/t		0.16	0.30		0.48	0.60

The striking outcome of the four cases discussed above is further illustrated in **Figure 8**. As is the case for all refinery products, the energy and CO_2 footprint of marine fuels is very much a function of their desired quality and of the relative demand for the different grades. Indeed the same grade can have a different footprint depending how much of it is required.

In addition it must also be realised that the numbers found above are only valid for the European scenario under which they have been generated. A different demand scenario would result in different numbers.

Figure 8 Marginal changes in energy and CO_2 emissions associated with marine fuel production (± 10% change)



8. CONCLUSIONS

Deep desulphurisation of marine fuels as implied by the recent IMO decision will have a profound impact on refineries worldwide and particularly in Europe.

It will require large investments in addition to what is already required to meet other quality and demand changes. This would require a massive effort for the industry, especially when seen within the context of other calls for new installations for meeting quality specifications of other products, adapting to changes in supply/demand and complying with other regulatory constraints such as implementation of the IPPC and Large Combustion Plant Directive and possibly the gradual introduction of CO_2 capture to control CO_2 emissions to atmosphere. Beyond the all important financial and economic aspects, the feasibility of such massive investments must be considered in terms of the ability of the industry to mobilise sufficient material and human resources.

The complexity of EU refineries will increase leading to extra energy consumption, increase need for hydrogen and therefore extra CO_2 emissions.

A complete switch to distillate fuels, as tabled during the IMO legislative process, would be much more demanding, particularly so in Europe where middle distillates are already in serious short supply.

Because of the relentless increase in demand for light products and particularly middle distillates in Europe, residue conversion is likely to be more attractive to EU refiners than residue desulphurisation, unless the price of desulphurised marine fuels approaches that of gasoil. This suggest that the real life impact of imposing very low sulphur marine fuels may be higher than what could be anticipated purely on the basis of the desulphurisation needs. It also highlights the fact that there is likely to be a cost trade-off for ship operators between using low sulphur fuel and installing on-board flue gas scrubbing facilities.

The contribution of marine fuels to the total energy consumption and CO_2 emissions of refineries is a strong function of their desired quality and of the relative demand for the different grades. For Europe we have shown that decreasing marine fuel demand can either increase or decrease energy consumption and CO_2 emissions depending on whether the required grades are high sulphur residual fuels or low sulphur distillate fuels.

9. REFERENCES

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APPENDIX 1 REFERENCE PRICE SET

North West Europe, 2007 average

All figures in $/t except when otherwise stated

Feedstocks and components

North Sea/Low Sulphur	552
West African	539
Russian	486
Middle East medium sour	517
Middle East sour	502
Condensate	641
Crude input average	524
$/bbl	*71.8*
Chemical Naphtha	665
Natural Gas	512
Atm Residue (North Sea)	402
Ethanol	500
Other Feed average	487
ETBE	824
Jet fuel	692
Middle distillate low sulphur	657
Middle distillate high sulphur	626
Blendstock Import average	671
All Input	530

Products

LPG	628
Ethylene	902
Propylene	859
Butylenes	710
Benzene	1047
Toluene	812
Xylenes	829
Chemical Products average	895
Gasoline EU Premium	687
Gasoline East Europe	687
Gasoline EU Super	696
Gasoline Export (US)	680
Gasoline EU Regular	678
Gasoline average	686
Jet fuel	697
Non Road Diesel	656
Road Diesel North	656
Road Diesel Middle	656
Road Diesel South	660
Road Diesel	657
Heating Oil North	626
Heating Oil Middle	627
Heating Oil South	637
Heating Oil	630
Marine Diesel	631
Diesel & Heating Oil average	648
Fuel Oil 0.6% Sulphur	354
Fuel Oil 1.0% Sulphur	354
Fuel Oil 2.5% Sulphur	347
Fuel Oil 3.5% Sulphur	329
Bunker Low sulphur	347
Bunker High Sulphur	326
Fuel Oil average	338
Bitumen	322
Lubricant base oils	626

APPENDIX 2 PRODUCT QUALITY LEGISLATION AND QUALITY LIMIT TARGETS FOR MODELLING

				Incremental Changes													
			1999	FQD: Auto Oil 1-2000 2000	SLFD: Heating oil 0.2% S 2000	SLFD: Inland HFO 1% S 2003	FQD: Auto Oil 1-2005 2005	SLFD: 1.5% S SECA & Ferries 2006	SLFD: Heating oil 0.1% S 2008	FQD: Auto Oil-2 2009	FQD: AGO PAH 8%, NRD 10 ppm S 2009	SLFD: 1.0% S SECA 2010	FQD: Inland waterways GO 10 ppm S 2011	SLFD: 0.1% S SECA 2015	SLFD: 0.5% S all marine fuels 2020	*Marine Fuel to 0.5% S distillate*
Gasoline																
	Sulphur	ppm	500	**150**	150	150	**50**	50	50	**10**	10	10	10	10	10	10
	Vap. Pres.	kPa	70	**60**	60	60	60	60	60	60	60	60	60	60	60	60
	Benzene	% v/v	5	**1**	1	1	1	1	1	1	1	1	1	1	1	1
	Aromatics	% v/v		**42**	42	42	**35**	35	35	35	35	35	35	35	35	35
	Olefins	% v/v		**18**	18	18	18	18	18	18	18	18	18	18	18	18
Diesel																
	Density	kg/m^3	860	**845**	845	845	845	845	845	845	845	845	845	845	845	845
	Sulphur	ppm	500	**350**	350	350	**50**	50	50	**10**	10	10	10	10	10	10
	Cetane		46	**51**	51	51	51	51	51	51	51	51	51	51	51	51
	PAH	% m/m		**11**	11	11	11	11	11	11	**8**	8	8	8	8	8
Heating Oil																
	Sulphur	% m/m	0.5	0.5	**0.2**	0.2	0.2	0.2	**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Marine Gasoil																
Inland	Sulphur	% m/m	0.5	0.5	**0.2**	0.2	0.2	0.2	**0.1**	0.1	0.1	0.1	**0.001**	0.001	0.001	0.001
Other	Sulphur	% m/m	0.5	0.5	**0.2**	0.2	0.2	0.2	**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**
Inland HFO																
	Sulphur	% m/m	3.5	3.5	3.5	**1.0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Marine fuels																
Global cap	Sulphur	% m/m					**4.5**	4.5	4.5	4.5	4.5	**3.5**	3.5	3.5	**0.5**	
SECAs	Sulphur	% m/m					**4.5**	**1.5**	1.5	1.5	1.5	**1.0**	1.0	**0.1**	0.1	
Ferries	Sulphur	% m/m					**4.5**	**1.5**	1.5	1.5	1.5	**1.0**	1.0	**0.1**	0.1	
Model constraints																
Gasoline																
	Sulphur	ppm		**140**	140	140	**40**	40	40	**7**	7	7	7	7	7	7
	Vap. Pres.	kPa		**60**	60	60	60	60	60	60	60	60	60	60	60	60
	Benzene	% v/v		**0.9**	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Aromatics	% v/v		40	40	40	**33**	33	33	33	33	33	33	33	33	33
	Olefins	% v/v		17	17	17	17	17	17	17	17	17	17	17	17	17
Diesel																
	Density	kg/m^3		**840**	840	840	840	840	840	840	840	840	840	840	840	840
	Sulphur	ppm		**340**	340	340	**40**	40	40	**7**	7	7	7	7	7	7
	Cetane			**49**	49	49	49	49	49	49	49	49	49	49	49	49
	PAH	% m/m		**11**	11	11	11	11	11	11	**7**	7	7	7	7	7
Heating Oil																
	Sulphur	% m/m		0.48	**0.18**	0.18	0.18	0.18	**0.09**	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Marine Gasoil																
Inland	Sulphur	% m/m		0.48	**0.18**	0.18	0.18	0.18	**0.09**	0.09	0.09	0.09	**0.0007**	0.0007	0.0007	0.0007
Other	Sulphur	% m/m		0.48	**0.18**	0.18	0.18	0.18	**0.09**	0.09	0.09	0.09	0.09	0.09	0.09	**0.09**
Inland HFO																
	Sulphur	% m/m		3.2	3.2	**0.9**	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Marine fuels																
Global cap	Sulphur	% m/m					**4.2**	4.2	4.2	4.2	4.2	**3.2**	3.2	3.2	**0.4**	
SECA	Sulphur	% m/m					**4.2**	**1.4**	1.4	1.4	1.4	**0.9**	**0.9**	**0.09**	0.09	
Ferries	Sulphur	% m/m					**4.2**	**1.4**	1.4	1.4	1.4	**0.9**	0.9	**0.09**	0.1	

APPENDIX 3 MARINE DISTILLATE “DMB” SPECIFICATION

The values listed below were used as model constraints.

Property	Units	Minimum	Maximum
Density	kg/m^3	800	900
Sulphur	%m/m		0.3(1)
Viscosity	Cst @40°C		11
Pour Point	°C		0
Cetane		40	
Carbon residue	%m/m		0.3(2)

(1) Average taking into account general 0.5% cap and 0.1% limit in SECAs

(2) Modelled indirectly through individual component limits

APPENDIX 4 EU-27 DEMAND, TRADE AND CALL-ON-REFINERIES

EU-27 Demand

Year =>	2000	2005	2010	2015	2020
LPG	18.8	20.0	20.4	19.8	18.7
Ethylene	21.2	23.7	24.2	24.2	25.4
Propylene	14.1	15.2	15.4	15.9	16.7
Butylenes	2.2	2.7	3.0	3.4	3.9
Benzene	7.9	8.5	9.2	10.0	10.8
Toluene	2.2	2.3	2.3	2.4	2.4
Xylenes	2.6	3.3	4.1	5.1	6.4
Chemical Products total	50.3	55.7	58.2	60.9	65.6
Gasoline EU Premium	108.1	104.4	94.2	88.0	86.6
Gasoline East Europe	6.6	0.0	0.0	0.0	0.0
Gasoline EU Super	6.2	4.6	3.1	2.9	3.1
Gasoline Export (US)	0.0	0.0	0.0	0.0	0.0
Gasoline EU Regular	10.4	6.3	2.9	2.7	2.6
Gasoline total	131.3	115.3	100.2	93.6	92.2
Jet fuel & kerosene	51.9	56.5	65.7	73.0	76.8
Non Road Diesel(1)	1.4	1.2	0.0	0.0	0.0
Road Diesel	152.7	186.7	229.8	243.0	236.6
Heating Oil	95.2	92.9	78.8	78.6	78.2
Marine Diesel	13.7	12.3	12.5	8.2	8.3
Diesel & Heating Oil total	263.0	293.1	321.1	329.8	323.1
Fuel Oil 0.6% Sulphur	0.5	0.5	0.4	0.4	0.3
Fuel Oil 1.0% Sulphur	40.7	39.8	31.7	27.8	26.7
Fuel Oil 2.5% Sulphur	6.0	0.0	0.0	0.0	0.0
Fuel Oil 3.5% Sulphur	16.1	4.7	4.2	3.8	3.5
Marine fuel (SECA)	0.0	0.0	21.6	23.4	24.2
Marine fuel (non SECA)	36.3	46.5	34.3	36.9	38.0
Fuel Oil total	99.7	91.5	92.3	92.3	92.6
Bitumen	19.7	20.2	21.1	22.0	22.2
Lubricant base oils	6.9	6.1	6.3	6.3	6.3

(1) As separate grade

Trade

Year =>	2000	2005	2010	2015	2020
Gasoline Export	22.1	22.1	22.1	22.1	22.1
ETBE Import	1.7	1.7	1.7	1.7	1.7
Kerosine Import	15.0	15.0	15.0	15.0	15.0
Distillate Import LS	10.0	10.0	10.0	10.0	10.0
Distillate Import MS	10.0	10.0	10.0	10.0	10.0

Call on Refineries

Year =>	2000	2005	2010	2015	2020
LPG	18.8	20.0	20.4	19.8	18.7
Chemical Products total	50.3	55.7	58.2	60.9	65.6
Gasoline total	153.4	137.4	122.3	115.7	114.3
Jet fuel & kerosene	51.9	56.5	65.7	73.0	76.8
Diesel & Heating Oil total	263.0	293.1	321.1	329.8	323.1
Fuel Oil total	36.3	46.5	34.3	36.9	38.0
Bitumen	19.7	20.2	21.1	22.0	22.2
Lubricant base oils	6.9	6.1	6.3	6.3	6.3