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EU Petroleum Refining Fitness Check: OURSE Modelling and Results

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Abstract
The OURSE (Oil is Used in Refineries to Supply Energy) model is used to assess ex post the likely impact on the performance and international competitiveness of the EU refineries of the main EU legislation included in the EU Petroleum Refining Fitness Check (REFIT) study. Given the (dis)similar nature of the immediate (i.e. direct) impact mechanisms of the legislation acts on refining industry, the considered directives were grouped into the following three (broader) categories for modelling purposes:

1. Fuel quality specifications change due to the Fuels Quality Directive (FQD) and Marine Fuels Directive (MFD);
2. Demand levels and composition change due to the requirements of the Renewable Energy Directive (RED) and Energy Taxation Directive (ETD); and
3. Sulphur dioxide emissions limits change as implied by the requirements of the Large Combustion Plants Directive (LCPD), Integrated Pollution Prevention and Control Directive (IPPCD) and Air Quality Directive (AQD).

An Analysis of the EU Refining Industry: OURSE Modelling and Results

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Executive summary

We use OURSE (Oil is Used in Refineries to Supply Energy) model to assess *ex post* the likely impact on the performance and international competitiveness of the EU refineries of the main EU legislation included in the EU Petroleum Refining Fitness Check (REFIT) study. Given the (dis)similar nature of the immediate (i.e. direct) impact mechanisms of the legislation acts on refining industry, the considered directives were grouped into the following three (broader) categories for modelling purposes:

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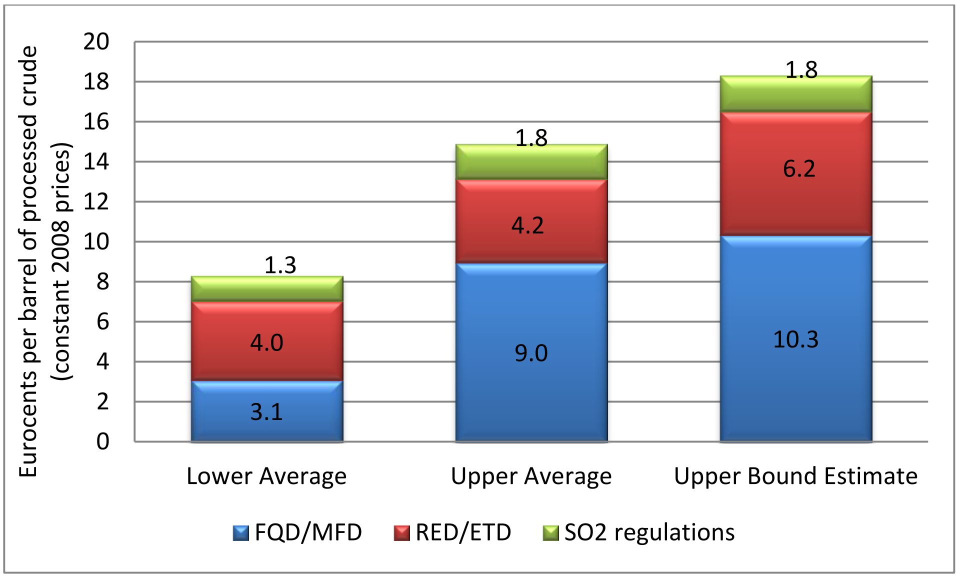
3. Sulphur dioxide emissions limits change as implied by the requirements of the Large Combustion Plants Directive (LCPD), Integrated Pollution Prevention and Control Directive (IPPCD) and Air Quality Directive (AQD).

The summary of the main results in terms of incurred costs by the EU refineries are presented in the following table, where all the cost figures are given in *mln USD per year expressed in constant 2008 prices*:

	Lower average estimate	**Upper average estimate**	**Upper bound estimate**
	Overall costs of the considered directives		
-- Total costs	416.7	753.1	940.3
	Costs due to FQD and MFD		
-- Total costs	154.3	464.0	550.4
---- CAPEX	102.5	408.3	475.2
---- OPEX	51.8	55.6	75.1
	Costs due to RED and ETD		
-- Net forgone earnings	200.1	204.6	297.8
	Costs due to SO2 regulations (LCPD, IPPCD and AQD)		
-- Total costs	62.3	84.5	92.1
---- CAPEX	33.0	33.3	38.7
---- Low-sulphur crude/feedstock switching costs	29.3	51.1	53.4

The details of these results are explained thoroughly in the text. The figure below shows the equivalent *total costs* estimates in terms of *eurocents per barrel of processed crude oil* (again in 2008 prices). If we consider the upper bound estimates, the individual contributions of each group of directives to the estimated *total costs of 18.3 eurocents per barrel of processed crude* have the following distribution: FQD/MFD – 56%, RED/ETD – 34%, and LCPD/IPPCD/AQD (SO2 only) – 10%. The average of these contributions over all the three reported estimates (i.e. lower average, upper average, and upper bound) is similar and gives FQD/MFD – 51%, RED/ETD – 36%, and LCPD/IPPCD/AQD (SO2 only) – 12%. Thus, it can be concluded that for the EU refineries the largest costs implications of the considered directives are due to the FQD/MFD directives.



The RED/ETD-related costs, which quantify the forgone profits due to lower fuel demand caused by these directives, are driven mainly by the RED directive that accounts for about 89% of these costs. In case of SO_2 regulations related costs, however, it should be noted that our estimates of the CAPEX costs are most likely underestimated as the model does not capture all relevant SO_2 emissions abatement measures adopted by refineries in practice.

Using the so-called relative trade balance (RTB) indicator, it is found that the European refining industry would have been somewhat more internationally competitive in a counterfactual situation where tighter fuels quality specifications would have not been imposed in Europe. This result, however, is not exclusively about the external competitive strength of Europe, but in addition also reflects the resulting trade structure of domestic and foreign demand for refined products as implied by the optimal reaction of all refineries world-wide to the new counterfactual European circumstances without the FQD and MFD requirements.

The RED and ETD are assessed to cause a reduction of the EU refineries' crude distillation unit (CDU) utilisation rates, on average, by 0.9% to 1.9% over the entire 2000-2010 period. These reductions are larger in North Europe (NE) than in South Europe (SE) by average factor of 1.8 to 2.2, caused mainly due to higher penetration of biofuels in NE than in SE and also larger demand changes in NE as caused by the ETD directive. The maximum reduction of 3.1% CDU utilisation rate is observed in the second sub-period of 2005-2010 in NE, which is due to larger relevant changes in demand.

Further, it is assessed that in the counterfactual situation without the RED and ETD in place, European imports of diesel oil (from Russia) would have increased, on average over the 2000-2010 period, by 1% to 6.3%, with an upper bound of 8.9% increase. Thus, if one focuses on the trade dependency issues, reduction in diesel imports dependency of the EU (from Russia) can be considered as the most noticeable EU-wide benefit that the RED and ETD directives brought about.

Finally, the overall benefits of legislation acts on SO_2 emissions regulation, notably LCPD, IPPCD and AQD, are assessed to be in the range of 12.7% to 32.5% reductions of SO_2 emissions generated by the EU refineries in North Europe and South Europe over the covered period. The overall European figures show SO_2 emissions reduction of 18.4% to 28.2% over the entire 2000-2010 period. The incurred benefits in South Europe are larger than those in North Europe by factor of 1.3 to 2.3.

Essentially, all models are wrong, but some are useful.
(A quote from Box G.E.P. and Draper N.R. (1987), Empirical Model-Building and Response Surfaces, Wiley, p. 424)

1 Demand for oil products

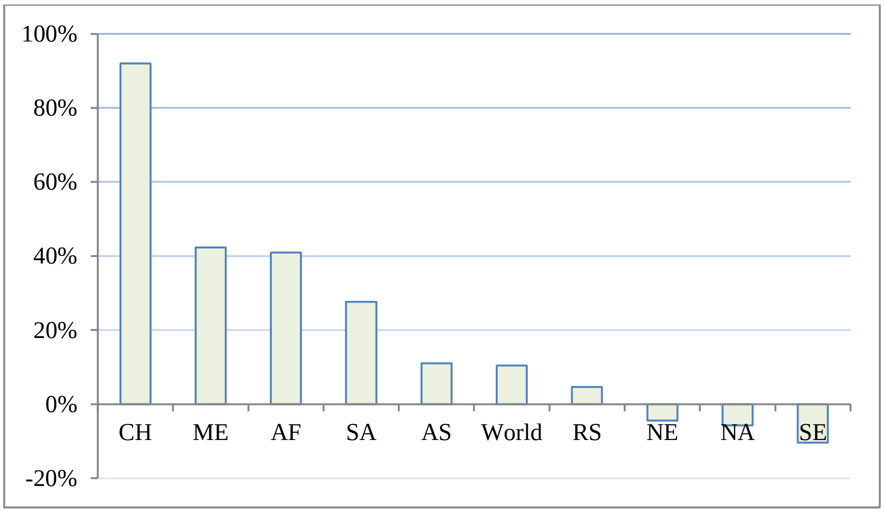
Demand for petroleum products is exogenous in the OURSE model, and has two "nests" or structures. The first nest includes data obtained from available datasets, and distinguishes between 12 types of products. These are liquefied petroleum gases (LPG), naphtha, gasoline, jet fuel, other kerosene, heating oil, diesel oil, residual fuel oil, lubricants, bitumen, petroleum coke and marine bunkers. The main source of these data is the World Energy Statistics database of the International Energy Agency (IEA). These oil products demands include IEA data on final consumption of oil products and oil demand for transformation processes (where mainly demand for electricity generation dominates). Refineries self-consumption is excluded because it is obtained from the model outcomes. It should be noted that the available data are not always consistent with the OURSE product nomenclature. Here we briefly discuss concordances of the two nomenclatures and how the OURSE demand products were derived from the IEA database:

- ✓ LPG: LPG;
- ✓ Naphtha: naphtha;
- ✓ Gasoline: motor gasoline and aviation gasoline (including aviation gasoline for international aviation bunkers);
- ✓ Jet fuel: gasoline type jet fuel, kerosene type jet fuel (including kerosene type jet fuel for international aviation bunkers), other kerosene and white spirit;
- ✓ Other kerosene (for cooking and heating): using other kerosene shares in corresponding heating oil from IFPEN's demand data for 2005, and applying them to the derived heating oil figures for all considered years;
- ✓ Diesel oil: gas/diesel oil used for (road) transport activities;
- ✓ Heating oil: gas/diesel oil, except for road transport;
- ✓ Residual fuel oil: fuel oil;
- ✓ Lubricants: lubricants and paraffin waxes;
- ✓ Bitumen: bitumen;
- ✓ Petroleum coke: petroleum coke; and
- ✓ Marine bunkers: international marine bunkers.

The observed petroleum product demands for the nine OURSE regions, which are used in the baseline scenarios for 2000, 2005 and 2010, are reported in Table 6.1 of the Appendix. This table shows that global demand for all petroleum products increased over time, from roughly 3.3 billion (metric) tonnes in 2000 to more than 3.6 billion tonnes in 2010. The trend of this increase was, however, decreasing, i.e., while in the first considered period of 2000-2005 the world oil demand increased by 8.5%, the corresponding growth for 2005-2010 was only 1.8%.

However, the changes in refined products demand are very heterogeneous across the world regions. Figure 1-1 presents region-specific growth rates of the total oil product demands for the entire period of 2000-2010. Relative to 2000, in 2010 we observe a dramatic 92% increase of demand for petroleum products in China (CH), which is 8.8 times larger than the corresponding global growth rate of 10.4%. Middle East (ME) and Africa (AF) - regions taking, respectively, the second and third positions in the list of top oil consumers - experienced an increase in petroleum products demand that is 4% larger than the relevant world growth rate.

Figure 1-1: Total oil products demand growth rates by region, 2000-2010

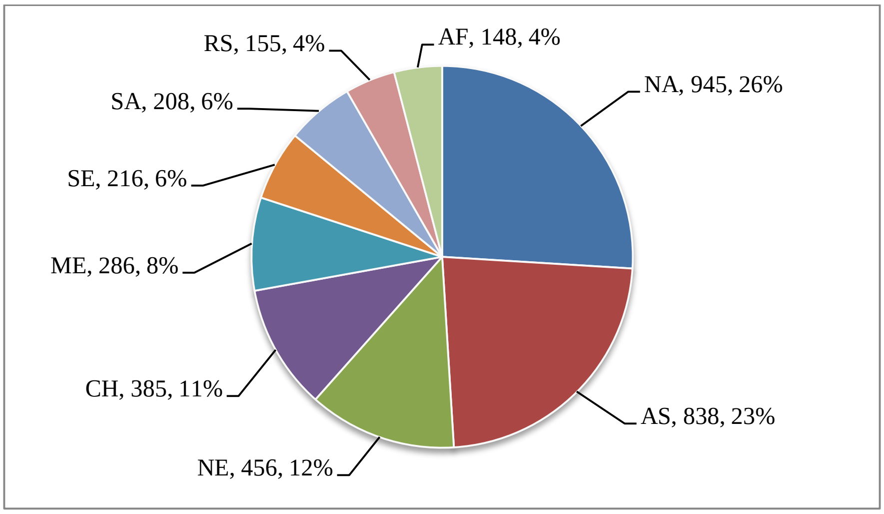


Note: For abbreviations, see the note to Table 6.1.

Figure 1-1 also shows that from 2000 to 2010 in three world regions, namely, North Europe (NE), North America (NA) and South Europe (SE), total refined oil demand has actually decreased with corresponding growth rates of -4.4%, -5.8% and -10.4%. However, looking closer to the data in Table 6.1 we notice that this decrease took place in the second sub-period. That is, during 2000-2005 we observe an increase in total oil demand in NE, NA and SE by 5.4%, 2.3% and 2.3%, respectively, while the corresponding rates of change for the 2005-2010 period were -10.6%, -6.5% and -12.5%.

How come that a huge increase in total oil demand in CH, ME, AF and South America (SA) resulted in comparatively "modest" global change of 10.4%? This can be explained by the fact that the regions with decreasing oil demand make a rather large portion of the global oil consumption. Figure 1-2 shows the regional allocation of world oil demand for the year of 2010, where the overall relevant proportion of NA, NE and SE is indeed quite significant and equals 44.5%. The region Other Asia and Oceania (AS) with the 2000-2010 rate of increase of oil demand of 11.0% also makes a considerable part of the world refined products demand. The corresponding portion of the world oil demand pie was 23.0% in 2010. China is the fourth world largest consumer of petroleum products with the share of 10.6%.

Figure 1-2: Regional oil products demand, 2010



All in all, we observe that in absolute values more than half of the world demand for petroleum products, namely 61.6% in 2010, comes from three regions of NA, AS and NE. European total oil demand in 2010 was equal to 672 million tonnes which makes 18.5% of the global oil consumption. It must be noted that NE and SE include also non-EU countries such as, for example, Iceland, Norway and Switzerland in case of NE, and Macedonia, Serbia and Turkey in case of SE. However, the overwhelming majority of the European demand comes from the EU member states. For example, in 2010 the shares of total oil demand from the EU countries in NE and SE were 94.5% and 82.4%, respectively. All the details of these proportions distinguished by products and years are reported in Table 6.2.

Within the OURSE model demand figures for many of the above-mentioned 12 types of products are further disaggregated in order to represent finer level of different fuel qualities. This makes the second "nest" of (exogenous) demand modelling, which include splitting:

- LPG into propane and butane,

- gasoline into five gasoline grades that differ in their specifications (such as research and motor octane number, vapour pressure, aromatic content),
- diesel oil into four diesel oil qualities,
- heating oil into low and high sulphur content heating oil (0.1% and 0.2%),
- residual fuel oil into low and high sulphur content heavy fuel oil (1% and 3.5%), and
- marine bunkers into low and high sulphur marine bunkers, the specification of which changes over time (i.e., 1.5% vs. 4.5%, 1% vs. 3.5%).

The characteristics of the above-mentioned product qualities are reported in Table 1.1 and Table 6.3. Table 1.1 presents the (observed) specifications of the fuel qualities that change over time, while Table 6.3 includes other characteristics of fuels that remain fixed for the entire period considered in the Fitness Check analysis. One of the main sources for obtaining these figures, particularly on sulphur specifications for non-EU regions, was TransportPolicy.net (http://transportpolicy.net/). Given that the non-EU regions are very heterogeneous in consumption of different qualities of fuels, mainly due to their legislation requirements with respect to fuels maximum sulphur content limits, approximate (or average) and most representative figures for each OURSE region were chosen. For example, in case of sulphur limits of diesel grade predominantly used in North America during the years close to 2005 we chose the relevant requirements in the USA. The US "diesel fuel regulation limited the sulphur content in on-highway diesel fuel to 15 ppm, down from the previous 500 ppm. Refiners were required to start producing the 15 ppm S [sulphur] fuel beginning June 1, 2006. … Refiners could also take advantage of a temporary compliance option that allowed them to continue producing 500 ppm fuel in 20% of the volume of diesel fuel they produce until December 31, 2009".[1] Hence, the relevant sulphur content for 2005 is computed as 15*0.8 + 500*0.2 = 112 ppm. The procedure of computing the relevant figures is more complicated (hence, more approximate) for other regions because, besides the diversity of countries fuel production/consumption structures included in one specific OURSE region, even within one country sulphur limits may be quite different. For example in China there are nation-wide sulphur limits but also city-specific limits, e.g., imposed in Beijing, Shanghai and Guangdong, with the last being stricter. (Or in Brazil there are metropolitan and countryside diesel sulphur specifications.) In such cases, more focus was given to the nation-wide limits. The specifications, reported in Table 1.1 and Table 6.3, are all used in the simulations of the relevant baseline scenarios.

As an example, the correspondence figures (or elements of the concordance matrices) of LPG, gasoline, diesel, heating oil, residual fuel oil and marine bunkers that allocate these

[1] This excerpt comes from http://transportpolicy.net/index.php?title=US:_Heavy-duty:_Emissions (last accessed in May 30, 2014).

fuels into their respective grades/qualities for 2005, are given in Table 6.4. It should be noted that these figures could change over time due to various factors, including regional legislation requirements on the qualities of fuels to be marketed within the specific region. This is exactly the way how we model the changes in sulphur requirements set on the production (and marketing) of heating oil, heavy fuel oil and marine bunkers per region.

Table 1.1: Product specifications used in the baseline scenarios

Specification	Product	2000	2005	2010
Sulphur (ppm)	ReGasol92NAm	300	80	80
Sulphur (ppm)	ReGasol95NAm	300	80	80
Sulphur (ppm)	PremGasol1	1000	1000	500
Sulphur (ppm)	PremGasol2	500	500	150
Sulphur (ppm)	PremGasolEu	150	50	10
Sulphur (ppm)	JetFuel	1000	1000	1000
Sulphur (ppm)	DieselNAm	500	112	15
Sulphur (ppm)	DieselLatAm	3500	2000	1000
Sulphur (ppm)	DieselEu	350	50	10
Sulphur (ppm)	DieselChin	7000	5000	2000
Sulphur (% m/m)	HeatOil1	0.1	0.1	0.1
Sulphur (% m/m)	HeatOil2	0.2	0.2	0.2
Sulphur (% m/m)	HeavyFuelOil1	1	1	1
Sulphur (% m/m)	HeavyFuelOil2	3.5	3.5	3.5
Sulphur (% m/m)	MarineBunk1	4.5	1.5	1
Sulphur (% m/m)	MarineBunk2	5.0	4.5	3.5
PAH (% m/m)	DieselNAm	7	7	7
PAH (% m/m)	DieselLatAm	11	11	11
PAH (% m/m)	DieselEu	11	11	8
PAH (% m/m)	DieselChin	20	20	20
Aromatics (% v/v)	ReGasol92NAm	35	35	35
Aromatics (% v/v)	ReGasol95NAm	35	35	35
Aromatics (% v/v)	PremGasol1	55	55	45
Aromatics (% v/v)	PremGasol2	45	45	42
Aromatics (% v/v)	PremGasolEu	42	42	35
Benzene (% v/v)	ReGasol92NAm	1	1	1
Benzene (% v/v)	ReGasol95NAm	1	1	1
Benzene (% v/v)	PremGasol1	5	5	3
Benzene (% v/v)	PremGasol2	3	3	1
Benzene (% v/v)	PremGasolEu	1	1	1

Within the second nest of demand modelling, besides products splitting there are also two cases where products from first nest are aggregated into one product. These are jet fuel and other kerosene on the one hand, and lubricants and high-sulphur heavy fuel on the other. As a consequence of above-mentioned oil products' splitting and aggregation, the total number of refined products modelled within OURSE is equal to 21.

2 Refining capacities

The flexibility of processing a wide variety of crudes and capability of generating high-value products, hence performance and (domestic and/or international) competitiveness, of any refinery depends on the extent to which the refinery possesses (or invests in) more complex processing units than the so-called atmospheric (or crude/primary) distillation unit. These include various processing units that are used, for example, for catalytic reforming, delayed coking, catalytic (hydro)cracking, alkylation, isomerization and other treatments of the processed crude to increase further the quality and particular characteristics/specifications of the final refined products. In general, OURSE models 47 processing units, and the data for their capacities comes from the IFP Energies nouvelles.

In order to compare the overall processing capabilities of individual refineries usually the so-called Nelson Complexity Index (NCI) is used. This concept was developed by Wilbur L. Nelson in the 1960s and appeared in a series of his papers published in Oil & Gas Journal (see the list of references). There are other complexity indices that extend the NCI by updating some of its unit-specific complexity factors, which are used in the calculation of the refinery overall complexity measure. In general, any complexity indicator is intended to measure not only the investment intensity or cost index of a refinery, but also its value addition potential and flexibility. In this study we make use of the NCI, which generally is defined as follows:

$$\text{NCI} = \frac{\sum_k (\text{Complexity Factor of Unit } k) \times (\text{Capacity of Unit } k)}{\text{Capacity of Distillation Unit}}\,, \qquad (1)$$

where the complexity factors quantify the cost of processing unit k compared to those of crude distillation unit (CDU). Hence, a factor of 1 is assigned to the distillation unit, while all other units are rated in terms of their costs relative to CDU. For example, the fluid catalytic cracking (FCC) unit has a Nelson complexity factor of 6, which means that to build a new FCC unit it would cost roughly six times the costs of constructing new CDU. It should be noted that the numerator in (1) is called *Equivalent Distillation Capacity* (EDC) and is also often used as another indicator for comparisons of refinery costs and/or values.

Using the relevant unit-specific Nelson factors and the processing units capacities used in our modelling, the values for EDC and NCI for the OURSE nine considered world regions have been computed and are reported in Table 2.1. Without going into the details, Table 2.1 shows that, on average, the North American representative (average) refinery is the "most complex" refinery in the world. In 2005, its NCI was equal to 9.1. North and South European refineries take the second and third position, respectively, in this list with the 2005 NCIs of

6.6 and 6.3 that make 70 - 73% of the NCI of the NA refinery. Hence, NA refinery, on average, has roughly 1.4 times more flexibility and/or value addition potential than the European refinery. The other OURSE regions in this list have the following ranking (with their NCIs, in percentage terms, relative to the NA refinery's NCI is reported in the parenthesis): South America (65.2%), Other Asia (59.4%), Middle East (53.0%), Russia (52.6%), Africa (45.7%) and China (45%). It is interesting to note that these NCIs are consistent with Wood Mackenzie average refinery complexities of 9.2 for North America, 6.6 – Europe, 6.2 – Asia Pacific, 4.3 – Middle East, 3.9 – Former Soviet Union, and a world average complexity of 6.4.[2]

Table 2.1: Refining complexity comparison by region

Year	NA	SA	NE	SE	RS	AF	ME	CH	AS	*Total*
	Equivalent Distillation Capacity (EDC, mln tonnes / year)									
2000	9171	1839	3627	1592	1932	545	1599	923	3974	*25201*
2005	9957	1670	3718	1738	1976	681	1732	1205	4534	*27211*
	Nelson Complexity Index (NCI)									
2000	8.6	5.3	6.4	5.8	4.2	3.3	4.5	4.5	4.9	*5.9*
2005	9.1	5.9	6.6	6.3	4.8	4.1	4.8	4.1	5.4	*6.3*

Source: Own calculations based on Nelson factors and process units capacities (source: IFP Energies nouvelles).

In terms of EDC, again North American refinery is, on average, the largest one (or the most expensive refinery) in the globe, which in 2005 had an equivalent distillation capacity of 9.96 billion per year. For the same year, North American refinery is, in terms of EDC, 2.2 times larger than the Asian refinery and 2.9 times bigger than the North European refinery. The EDC differences of the NA refinery with the rest of the regions' refineries are more pronounced. The factors by which the EDC of the NA refinery is larger than that of the remaining regions are: Russia – 5.0, South Europe – 5.7, Middle East – 5.8, South America – 6.0, China – 8.3 and Africa – 14.6.

Over time the changes of both the EDC and NCI indicators are predominantly positive, and the relevant world average indicators increased by 8.0% and 7.1%, respectively. This clearly shows the trend in the petroleum refining industry world-wide towards building (or upgrading existing refineries with the aim of having) more complex refinery configuration. In particular, note that within the 2000-2005 time period in North and South Europe the NCI indicator increases by 2.5% and 9.2%, respectively.

[2] These figures come from a presentation by Michael Hafner made at the Wood Mackenzie Global Refining Seminar (London, 22 February 2011) that is available from (last accessed in July 2014) https://www.energyinst.org/_uploads/documents/WoodMackenzieGlobalRefiningSeminar-IPWeek2011.pdf .

3 CAPEX, OPEX and transportation costs

The model cost coefficients of capital expenditures (CAPEX) of processing units and of operating expenditures (OPEX) of process-related intermediate products are assumed to be the same for all regions. Because OPEX costs are defined for 403 total intermediate products, we do not report these numbers here. However, for transparency purposes, instead the annualised costs of capital figures, including return on investment (ROI) of 15% and annualised CAPEX on 15 years, are reported in Table 3.1.

Table 3.1: Annual cost of capital (in 2008 USD)

Refining unit	Cost	Refining unit	Cost
Atmospheric distillation	15.54	Isomerization with recycling	44.53
Vacuum distillation unit	7.93	Alkylation (Hydrofluoric Acid - HF)	144.82
Desaslphalting unit C3	30.34	Dimersol	45.62
Desaslphalting unit C5	30.34	Tame unit on LG from FCC & RCC	92.05
DAO HDT	43.26	MTBE unit	137.34
Residue hydroconversion (fixed bed)	67.2	ETBE total unit	137.34
Residue hydroconversion (ebulated bed)	73.92	Visbreaking (vacuum residue)	17.85
Catalytic reformer	18.54	Coking delayed	59.46
Regenerative reformer	31.52	Hydrodesulphurization (HDS) VGO CK	43.26
Reformate splitter	2.79	HDS 90 20bar	17.4
FCC feed HDT (vacuum GO)	28.19	HDS 97-98 30bar	20.47
Mild hydrocracking	33.88	Deep HDS 75 bar	29.53
Catalytic cracking (with feed pre-hydrotreatment)	45.45	FCC gasoline desulphurization (Primeg20)	63.33
Catalytic cracking	45.45	FCC gasoline desulphurization (Primeg10)	63.33
RCC feed HDT (long run residue)	56.14	REF feed HDT	11.74
HDT long run residue catalytic cracking	51.89	Pressure swing absorber	630.23
Long run residue catalytic cracking	51.89	Steam reformer	630.23
Hydrocracking full	64.56	Partial oxydation (vacuum resid. & asph.)	223.93
Hydrocracking jet	53.84	Natural gas cogeneration	136.34
Hydrocracking naphtha	64.56	Natural gas combined cycle (NGCC)	421.39
Hydrocracking 78 conv	64.56	Integrated gas combined cycle (IGCC)	246.13
Deisopentanizer	4.32	MDEA+Claus+hydrosulpreen (SRI)	165.51
Isomerization once through	26.19		

Source: IFP Energies nouvelles. The reported capital costs include a ROI of 15% and annualised CAPEX on 15 years.

The costs of investments in new processing units are thus based on the prices given in Table 3.1, which also enter the objective function of the OURSE model. These are taken into account in the minimization of the overall costs of the world refining industry.

Interregional flows of crude oil and petroleum products incur transportation costs. In OURSE_LP model (to be explained in Section 4.2), estimated crude freight costs are applied to all types of crudes trade, and similarly all refined products have the same transportation costs per trade partner. The relevant values that have been used in by Lantz et al. (2005) and Lantz et al. (2012) are reported in Table 3.2. Note that the crude transportation costs are symmetric, i.e. costs of transporting crude from region *r* to regions *s* is assumed to be equal to the costs of transporting crude from region *s* to region *r*. However, products freight costs are asymmetric. In fact, a closer look at the figures reveals that all pair-wise trade costs are equal except for those between Russia (CIS) on the one hand, and North and South Europe, on the other hand. These costs are lower when a refined product is transported from Russia to North and South Europe by 2.78 USD and 16.27 USD relative to the costs of the reverse product flows. This is (was) part of the calibration process in order to make sure that the model generates European imports of middle distillates, in particular diesel oil, from Russia.

Table 3.2: Transportation costs used in OURSE_LP (in 2008 USD, per tonne)

	NA	SA	NE	SE	RS	AF	ME	CH	AS
	Crude trade transport costs								
NA		11.31	18.32	26.30	36.13	25.59	37.42	15.00	25.00
SA	11.31		21.94	25.79	39.15	27.86	37.42	15.00	25.00
NE	18.32	21.94		16.96	14.56	22.93	34.95	34.00	26.25
SE	26.30	25.79	16.96		20.79	15.31	29.71	34.00	26.25
RS	36.13	39.15	14.56	20.79		30.00	30.00	30.00	30.00
AF	25.59	27.86	22.93	15.31	30.00		17.37	23.00	23.00
ME	37.42	37.42	34.95	29.71	30.00	17.37		11.09	16.89
CH	15.00	15.00	34.00	34.00	30.00	23.00	11.09		7.00
AS	25.00	25.00	26.25	26.25	30.00	23.00	16.89	7.00	
	Products trade transport costs								
NA		18.21	22.16	23.95	26.00	42.53	36.79	13.00	15.00
SA	18.21		42.06	30.39	35.54	23.27	36.76	43.11	41.21
NE	22.16	42.06		18.81	9.78	36.94	41.11	57.52	52.54
SE	23.95	30.39	18.81		23.27	23.39	38.72	49.52	44.54
RS	26.00	35.54	7.00	7.00		23.27	41.11	42.89	42.89
AF	42.53	23.27	36.94	23.39	23.27		18.37	42.45	51.61
ME	36.79	36.76	41.11	38.72	41.11	18.37		23.74	26.13
CH	13.00	43.11	57.52	49.52	42.89	42.45	23.74		15.59
AS	15.00	41.21	52.54	44.54	42.89	51.61	26.13	15.59	

Source: IFP Energies nouvelles.

Although for the crude trade we also use costs data as given in Table 3.2, the approach taken in this study is different in one important respect from earlier studies using OURSE: here we re-estimate trade costs such that the "observed" trade flows of refined products is perfectly calibrated, which is discussed in detail in Section 4.2. This will result in asymmetric trade costs estimates per product and per trade relation due to accounting for such factors as import shares, import-import substitution elasticities, and the share of transport costs in a product's final consumer prices.

4 Model calibration

Calibration of baseline scenarios to the relevant observed data is a very important and, at the same time, the most time-consuming step in any policy-relevant and large-scale modelling. Depending on the nature of a model under consideration, there exist different calibration techniques. In case of OURSE, the following two crucial issues, which are discussed in some more detail in the next two subsections, needed to be addressed first in order to get a properly running model that calibrates the observed data in its baseline scenarios:

- Collection, adjustments and/or estimation of required observed data covering all countries of the world, and
- Calibration of the baseline scenarios.

4.1 Collection and estimation of data that are endogenous in OURSE

The following are the main observed variables that the model has to calibrate properly (after the data is made consistent with the OURSE regional dimensions) in the baseline scenarios for the covered period of 2000-2012 that is represented by "individual" from the modelling perspective years of 2000, 2005 and 2010:

- Production of crude oil by country;
- Production of refined products by country;
- Trade flows of crude oil between countries;
- Trade flows of refined products between countries;
- Refinery throughputs (or total of "conversion in refineries"), which mainly include crude petroleum, feedstocks, natural gas and natural gas liquids.

All the main databases were carefully analysed and the relevant data were compared as a consistency check (only in case when the same variable was available in different datasets). The most important sources used include

- ✓ World Energy Statistics and Oil Information databases of the IEA (www.iea.org);
- ✓ Energy Statistics Database of the United Nations Statistics Division (UNSD), available on-line via the UNdata portal (http://data.un.org);
- ✓ Commodity Trade Statistics Database (Comtrade) of the UNSD, available on-line via the UNdata portal (see above);
- ✓ BP Statistical Review of World Energy[3];
- ✓ Market Observatory and Statistics of the European Commission (http://ec.europa.eu/energy/observatory);
- ✓ JODI Oil World Database (www.jodidata.org);
- ✓ US Energy Information Administration (http://www.eia.gov/petroleum/data.cfm).

[3] See http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html.

Running ahead we note that from the data items listed in the beginning of this section the most complete information include data on production, consumption (also referred to as domestic supply) and international trade of crude oil, while complete and consistent global trade data on petroleum products is largely missing. This leaves us with only one choice of estimating trade matrices of different refined products in our first stage of the model calibration procedure (to be discussed in the next subsection) so that they are consistent with the observed data of total exports, total imports and trade structure. The last include facts and/or knowledge about existence or non-existence of certain interregional trade flows of refined products.

The procedure of obtaining total crude oil trade data consisted of the following steps:

1. The IEA World Energy Statistics data on crude total exports and total imports (in physical units) at country level were aggregated to the regional level of OURSE. Given that rarely trade data are consistent in the sense that at the global level world imports does not equal world exports whereas they should, we make adjustments to the exports data to match the world imports figures. The relevant differences before this adjustment were 4.2%, 3.4% and 8.7% for the 2000, 2005 and 2010 data, respectively. We adjusted exports data and not imports because we think that imports data are more reliable in general than exports figures (a usual assumption taken in similar cases, in particular, in input-output studies).
2. The best source for crude trade data was found to be the UN Comtrade database. The total exports and total imports derived from these obtained trade data showed 3% to 10% discrepancies when compared with the corresponding IEA data. Thus, in the second step we have adjusted the trade matrices such that they became consistent with the IEA total exports and total imports figures from step 1. For this purpose we use the so-called GRAS method, which is a widely used method for balancing/estimation of input-output tables or any other matrix (for details about GRAS, see e.g. Temurshoev et al., 2013).
3. Crude trade variables in OURSE model besides exports and imports also include domestic use of *domestically produced* crude oil. Hence, these must be added to the *intra*-regional (i.e. diagonal) flows of the trade matrix obtained from step 2 (which already had partial information on the intra-regional flows of the aggregate regions coming from the country-level trade data). These are derived using crude oil production and consumption (also referred to as domestic supply) data from the IEA World Energy Statistics. The missing intra-regional flows were computed as the relevant averages of (Production – Exports) and (Consumption – Imports) vectors per region.

4. Finally, the intra- and inter-regional trade matrices from step 3 were again rebalanced (to get rid of insignificant differences after accounting for intra-regional flows) in order to perfectly match the IEA crude total production and consumption (or throughputs) data using the GRAS method. The ultimate "observed" crude oil trade data for 2000, 2005 and 2010, after ignoring small transactions that do not matter for modelling purposes anyhow, are reported in Table 4.1 below.

As will be discussed and justified in Section 4.2, the derived total crude trade figures will not be calibrated per se. However, these data will be very useful in terms of having the right mix (structure) of various types of crudes supplied to each region. That is, for each importing refinery (region), we impose additional constraints in the model ensuring that the total crude imported does not exceed the relevant observed import shares as obtained from Table 4.1. Hence, the main characteristics (i.e. API degree and sulphur content) of total crude processed by each region will be largely consistent with those observed in reality.

Table 4.1: Total crude oil supply/trade used in OURSE baseline scenarios

From\To	**NA**	**SA**	**NE**	**SE**	**RS**	**AF**	**ME**	**CH**	**AS**	***Total***
						2000				
NA	527.7			9.0					6.0	*542.7*
SA	126.7	187.3	6.2							*320.2*
NE	61.3		229.4	8.6						*299.2*
SE				16.3						*16.3*
RS			110.5	43.7	219.1					*373.4*
AF	87.9	7.7	51.9	69.9		78.9		15.5	26.0	*337.9*
ME	114.5	6.1	68.2	72.8		26.9	299.4	30.6	457.0	*1075.6*
CH								150.7	10.6	*161.3*
AS	7.6							8.8	175.6	*191.9*
Total	*925.7*	*201.0*	*466.3*	*220.3*	*219.1*	*105.8*	*299.4*	*205.6*	*675.2*	3318.5
						2005				
NA	537.2			11.7						*548.9*
SA	144.4	187.2	8.6					5.7		*345.9*
NE	40.1		183.9	6.1						*230.1*
SE				14.2						*14.2*
RS	14.3		179.0	73.3	265.2			16.7		*548.6*
AF	123.5	15.6	53.7	65.5		96.6		38.3	23.8	*417.0*
ME	100.2		49.3	65.2		24.8	321.6	55.5	527.9	*1144.5*
CH								174.3	7.3	*181.6*
AS								7.1	176.0	*183.1*
Total	*959.6*	*202.8*	*474.5*	*236.0*	*265.2*	*121.4*	*321.6*	*297.6*	*735.0*	3613.7
						2010				
NA	506.3			6.3						*512.6*
SA	113.9	192.5	7.2					19.9	19.8	*353.3*
NE	17.8		146.4							*164.3*
SE				13.0						*13.0*
RS	27.7		180.2	74.2	291.6			26.4	33.3	*633.4*
AF	117.8	12.4	54.9	48.5		87.8		61.8	49.8	*433.0*
ME	83.8		27.1	54.4		23.3	333.0	94.9	466.0	*1082.5*
CH								200.5		*200.5*
AS								7.2	169.3	*176.4*

Total	*867.3*	*204.9*	*415.8*	*196.4*	*291.6*	*111.1*	*333.0*	*410.7*	*738.2*	*3569.0*

Note: Unit is million metric tonnes.

4.2 Calibration and the OURSE_QP model

The original OURSE model as developed by Lantz et al. (2005) and Lantz et al. (2012) is a linear programming (LP) model. For the reasons soon to become clear, we refer to it as the OURSE_LP model. For transparency purposes, the main equations of OURSE_LP are given in Appendix B, while further details can be obtained from the mentioned reports. However, *sensible* attempts to use the OURSE_LP for the EU Petroleum Refining Fitness Check (REFIT) showed two crucial problems that could not be simply overlooked. These were:

- the natural inability of OURSE_LP to calibrate (at least roughly) the base-year available or estimated observed data, and
- model results of jumpy responses in simulation exercises (for example, constant switching between zero and non-zero values of significant size in interregional trade of refined products in response to smooth changes in exogenous variables, which e.g. does not allow solid analysis of international competitiveness).

This is, of course, not surprising to anyone familiar with linear programming, since in such modelling framework the number of binding constraints determines the number of non-zero endogenous variables in the optimal solution. With large-scale modelling such as that for the REFIT purposes, this causes a big problem because then the number of positive variables observed in real life significantly exceed the number of binding constraints, and that immediately leads to unrealistic case of *overspecialization*.

It turns out that these problems were taken seriously in by now a huge literature in agricultural economics (e.g. on farm-level production modelling). Until the late 80's agricultural economists in policy analyses with LP models introduced additional calibration constraints as a solution to the problem of overspecialization. "However, models that are tightly constrained can only produce that subset of normative results that the calibration constraints dictate" (Howitt, 1995a, p. 330). That is, any kinds of policy conclusions are bounded by the sets of constraints that were additionally imposed in order to make the model's outcomes for the base year more or less reasonable compared to the observed variables, but very often these constraints are inconsistent with the environment under the policy changes. Therefore, a more formal approach called Positive Mathematical Programming (PMP) was developed that perfectly solved the above-mentioned calibration issues in agricultural policy analysis modelling.[4] Applications of PMP date back to Kasnakoglu and Bauer (1988), but a formal method of PMP was developed by Howitt (1995a) that made this approach wide-spread both in empirical applications and further theoretical discussions. Review papers on the theory, applications, criticisms and extensions of the PMP approach include Heckelei and Britz (2005), Henry de Frahan et al. (2007), Heckelei et al. (2012), Langrell (2013), and Mérel and Howitt (2014).[5]

In this study we will borrow ideas from the PMP literature for modelling global refining industry and, in particular, adapt a PMP-like technique of calibration of spatial models of trade proposed by Paris et al. (2011). To the best of our knowledge, PMP ideas have never been applied to the petroleum refining (economic) modelling, thus the current study makes first such attempt as a consequence of paying particular attention to the calibration and jumpy-response issues of the standard LP refining models.

Consider the following two mathematical programming problems:

minimize $\mathbf{c}'\mathbf{x}$ subject to: $\mathbf{Ax} \geq \mathbf{b}$ $\mathbf{x} \geq \mathbf{0}$ **(a) OURSE_LP without calibration constraints**	minimize $\mathbf{d}'\mathbf{x} + 0.5 \cdot \mathbf{x}'\mathbf{Qx}$ subject to: $\mathbf{Ax} \geq \mathbf{b}$ $\mathbf{x} \geq \mathbf{0}$ **(b) OURSE_QP problem**	(2)

In (2.a) we have the general LP problem formulation, in our case it would be OURSE_LP problem, where $\mathbf{c}$ is the vector of *accounting* costs per unit of decision (endogenous) variables $\mathbf{x}$, which are restricted to be non-negative as given by the last set of constraints. Any linear (i.e. equality, less-than-or-equal, greater-than-or-equal) constraints can be written in the form of the linear constraints $\mathbf{Ax} \geq \mathbf{b}$ which are the same for both problems in (2). It is important to note that these in (2.a) do not include artificial calibrating constraints, thus the OURSE_LP presentation in (2.a), while content-wise is complete, is still incomplete for empirical simulations purposes. The only, but crucial, difference between the OURSE_LP and OURSE_QP problems given in (2) is that the second problem in (2.b) has a quadratic (i.e. non-linear) objective function, where the nonlinearity is captured by the quadratic term $0.5 \cdot \mathbf{x}'\mathbf{Qx}$ (hence, the term QP – quadratic programming). The significance

[4] Technically, this was done by introducing *non-linear* terms in the objective function of the model used for policy analyses such that its optimality conditions are satisfied at the observed levels of endogenous (or decision) variables without introducing artificial constraints.

[5] Other recent related studies worthwhile to mention include Heckelei and Wolff (2003), Mérel and Bucaram (2010), Jansson and Heckelei (2011), Merél et al. (2011), Howitt et al. (2012), Louhichi et al. (2013), and Maneta and Howitt (2014).

of introducing non-linear terms in the objective function lies in the fact that they: (i) allow for perfect calibration without introducing artificial constraints, (ii) allow for interior solutions and thus overcome the LP overspecialization problem, and (iii) results in smooth (hence, more realistic) reactions of the outcomes to exogenous shocks.

In OURSE_QP, $\mathbf{d}$ and $\mathbf{Q}$ are parameters of the "implicit cost function" (Howitt, 1995b) that need to be estimated such that the base year observations are exactly calibrated.[6] It is called implicit cost function, because such quadratic function "is a *behavioural function* … that is intended to capture the aggregated influence of economic factors that are not explicitly included in the model" (Jansson and Heckelei, 2011, p. 140). Without having any additional information on cross-cost (hence, cross-price) effects and following the logic of Occam's razor, we assume that $\mathbf{Q} = \widehat{\mathbf{q}}$ is a diagonal matrix.[7] Factors that could be potentially captured by the implicit parameters include, for example, aggregation bias, data errors, costs/price expectations, risk behaviour, or any type of model misspecification. The optimality conditions for our QP problem in (2.b) are given by the following system of equations (for details, see e.g. Murty, 1988):

$$\mathbf{u} = \widehat{\mathbf{q}}\mathbf{x} - \mathbf{A}'\mathbf{y} + \mathbf{d}\,, \tag{3}$$

where $\mathbf{y}$ and $\mathbf{u}$ are the Lagrange multipliers associated with the linear and non-negativity constraints, respectively. Let $\mathbf{s} = \mathbf{A}\mathbf{x} - \mathbf{b}$ denote slack variables in the linear constraints, which in conjunction with (3) imply the optimal levels of the decision variables as

$$\mathbf{x} = -\widehat{\mathbf{q}}^{-1}(\mathbf{d} - \mathbf{u}) + \widehat{\mathbf{q}}^{-1}\mathbf{A}'(\mathbf{A}\widehat{\mathbf{q}}^{-1}\mathbf{A}')^{-1}\{\mathbf{A}\widehat{\mathbf{q}}^{-1}(\mathbf{d} - \mathbf{u}) + \mathbf{b} + \mathbf{s}\}\,. \tag{4}$$

Take the derivative of $\mathbf{x}$ with respect to costs coefficients $\mathbf{d}$, and neglecting the second term in (3), gives $\partial x_i/\partial d_i = -1/q_{ii}$, which yields the own-cost supply (or demand, depending on the modelling framework) elasticity of $\tilde{\varepsilon}_{ii} = (-1/q_{ii})(d_i/x_i)$.[8] Define this elasticity in absolute terms as $\varepsilon_{ii} = -\tilde{\varepsilon}_{ii}$. Then with *exogenous* values of the cost elasticities, observed

[6] This procedure is, in a sense, exactly similar to CGE modelling, where first exogenous parameters are estimated in the base year calibration process.
[7] Obviously, having a full positive (semi)definite matrix $\mathbf{Q}$ results is a more flexible cost specification, but it makes the problem too complex. In particular, for the refining model, if calibration is performed via trade flows as in this paper, $\mathbf{Q}$ will have six dimensions, indicating trade flows' sources and destinations and products traded, for example, its entry could show the direct cost impact of diesel trade between North Europe and Russia on gasoline trade between Africa and North America. However, "in the absence of information on cross-price effects, the benefit of a more flexible specification may be debatable" (Mérel and Howitt, 2014).
[8] In the agriculture policy analysis literature, these are supply elasticities with respect to (own) price, given that their model formulation is different from that of OURSE. They consider profit maximization with given prices, while in OURSE the objective is cost minimization without explicit consideration of price effects.

base year values of endogenous variables $\bar{x}_i$ and the estimated values of the direct implicit costs d_i (to be explained below), one can readily obtain the estimate of q_{ii} from

$$q_{ii} = \frac{1}{\varepsilon_{ii}} \frac{d_i}{\bar{x}_i} \ . \tag{5}$$

In the agriculture literature, calibrations using exogenous elasticities as in (5) are referred to as "myopic calibration methods", because in deriving the expression for elasticity the second complicated expression in (4) is ignored, which is, however, a widely used calibration method (see e.g. the survey of Heckelei et al., 2012). The ignorance of this term is equivalent to not accounting for the effects of changes in shadow values of the linear constraints **y**. However, if the estimates are not *ad hoc* but come from rigorous estimation procedures, then using myopic calibration method is reasonable since then the estimates will already implicitly account for the impact of, for example, resource limitations.

In OURSE we calibrate only trade flows of petroleum products, which automatically also imply calibration of production, total exports and total imports of refined products. This holds because the demand-supply balance of (production + imports = exports + consumption) has to be satisfied per product, where consumption (or demand) is exogenous. We also tried to simultaneously exactly calibrate total crude trade flows as given in Table 4.1, but this did not work well, for example, one gets excess supply. We think this is the direct consequence of material balances of inputs and outputs at each stage of intermediate production within a refinery, because the model is an aggregate model and cannot exactly replicate the appropriate real inputs-outputs interrelations (otherwise, calibration of only one side of the model, either products side or crude side, would calibrate the explicitly non-calibrated part as well). Also in view of the material balances, there are inconsistencies in world totals of exogenous demand for products and of crude oil supply. In addition, given that crude data in Table 4.1 do not distinquish between its nine types as used in the model, it has been decided to use these "observed" crude trade data for the purposes of allowing or not allowing interregional crude flows and for getting the right mix of crude oil use by each purchasing region.

However, as mentioned earlier there is a problem of availability of global trade flows of petroleum products, hence these had to be estimated first using the total exports and total imports data from the IEA World Energy Statistics. These trade totals are given in Table 4.2. Note that we restricted our focus on four aggregate refined products because the trade data for the other products seemed to be unrealistic.[9] The exports data are proportionally adjusted such that these figures sum up to total imports per product (as in crude case, here also the global balances of imports and exports did not hold, though the differences were generally small). Table 4.2 clearly shows the continuously strengthening position of Europe over time as net exporter of gasoline and net importer of jet fuel, diesel/gasoil and fuel oil (except the residual fuel oil trade position of South Europe). Exactly calibrating these figures in the three base-year scenarios thus would be very crucial for the entire analysis, because these data fully capture the main problem facing the EU refining industry in general, which is the growing supply-demand mismatch for gasoline and diesel. Thus, the European excess supply of gasoline in the EU market is reflected in the EU taking a net exporter position in the world gasoline market, while excess demand for middle distillates (in particular, diesel oil) at home resulted in the EU becoming a net importer of these fuels. Note, however, since we summed up exports and imports at country-level per region, these are *not* region-specific exports and imports as they include trade between countries included within the same region. The intra-regional trade will be estimated by the model, given that these are not readily available data either for all regions.

Table 4.2: Total exports and imports data calibrated in OURSE_QP baseline scenarios

	2000			2005			2010		
	Imports	Exports	Net Exports	Imports	Exports	Net Exports	Imports	Exports	Net Exports
				Gasoline					
NA	33.3	14.5	-18.8	61.0	16.8	-44.2	59.1	24.4	-34.7
SA	0.9	11.3	10.4	1.8	13.2	11.5	3.4	4.2	0.9
NE	34.4	41.1	6.7	29.2	53.3	24.0	25.7	53.2	27.6
SE	4.6	9.7	5.1	5.2	18.1	12.9	3.3	20.6	17.3
RS	3.9	5.8	1.9	2.4	10.2	7.8	4.6	7.1	2.5
AF	7.7	2.0	-5.6	10.6	2.7	-7.9	17.3	1.5	-15.8
ME	4.0	3.2	-0.8	12.0	4.6	-7.3	15.3	4.6	-10.7
CH	0.4	4.4	4.0	0.4	5.5	5.1	0.4	5.3	4.9
AS	15.3	12.5	-2.8	26.2	24.3	-1.9	28.8	36.8	8.0
				Jet Fuel					
NA	9.1	4.1	-5.0	12.1	5.7	-6.5	7.8	6.8	-1.0
SA	1.0	3.9	2.9	0.4	3.9	3.6	1.9	2.9	1.0
NE	17.6	9.4	-8.2	27.9	11.7	-16.2	31.4	12.6	-18.7
SE	2.0	2.0	0.1	3.6	1.9	-1.7	7.2	3.0	-4.2
RS	0.5	0.6	0.1	0.6	0.7	0.1	1.0	1.8	0.8
AF	3.8	3.9	0.0	3.6	3.6	-0.1	5.1	3.0	-2.2
ME	0.9	14.3	13.4	1.1	19.2	18.1	1.5	17.7	16.1
CH	5.7	2.0	-3.8	7.8	2.6	-5.2	10.2	5.3	-4.9
AS	14.5	15.1	0.6	13.8	21.8	7.9	10.1	23.2	13.1
				Gas/Diesel Oil					
NA	21.0	14.8	-6.2	22.2	15.7	-6.5	22.2	39.7	17.6
SA	9.1	10.1	1.0	8.3	9.2	0.9	23.3	4.6	-18.7

[9] For example, the derived total exports and imports data for naphtha showed that North Europe was largely dependent on imports from Other Asia & Oceania, while Russia had zero exports of naphtha. In case of LPG, the product balance for Middle East results in a huge value of negative consumption.

NE	63.7	47.1	-16.6	86.7	60.7	-26.0	97.4	69.4	-27.9
SE	17.0	10.9	-6.1	28.8	15.1	-13.7	35.0	17.0	-18.0
RS	3.9	25.2	21.3	2.3	39.1	36.8	5.9	48.3	42.4
AF	10.8	5.7	-5.2	10.4	4.4	-6.0	21.0	1.5	-19.5
ME	3.2	22.2	19.0	12.4	25.2	12.8	21.4	20.4	-0.9
CH	6.3	0.6	-5.7	4.1	1.4	-2.7	7.0	4.5	-2.5
AS	30.5	29.0	-1.5	40.8	45.2	4.4	52.3	79.9	27.5
					Fuel Oil				
NA	40.2	17.1	-23.2	48.0	22.3	-25.7	36.0	33.0	-3.0
SA	0.6	17.9	17.3	1.2	19.3	18.1	2.4	16.8	14.3
NE	34.0	37.5	3.5	49.3	45.7	-3.6	62.8	51.8	-10.9
SE	20.7	7.4	-13.3	14.7	10.0	-4.8	11.7	11.8	0.1
RS	1.4	24.9	23.5	1.4	43.9	42.5	2.8	60.4	57.6
AF	1.8	14.1	12.3	2.4	12.2	9.8	3.7	10.5	6.8
ME	13.5	35.1	21.7	15.7	25.8	10.0	19.4	23.1	3.6
CH	18.4	1.6	-16.8	32.3	3.5	-28.8	33.0	8.3	-24.7
AS	53.0	28.1	-24.9	50.9	33.4	-17.5	76.2	32.4	-43.8

Note: Unit is million metric tonnes; Source: IEA World Energy Statistics.

Hence, within the model product trade flows (including intra-regional flows) of jet fuel and various qualities/grades of gasoline, diesel oil, heating oil and heavy fuels are estimates such that the margins of the obtained and relevant aggregate trade matrices are consistent with the data given in Table 4.2, while trade matrices of the remaining seven (out of 21) products were estimated by the model itself in the view of the absence of reliable/realistic relevant total exports and total imports data.

In what follows, we give the technical details of the calibration steps. The first step as already discussed above include estimating trade matrices of refined products whose margins exactly calibrate the observed data presented in Table 4.2. For this purpose we need the estimates of exogenous elasticities and direct costs in order to be able to compute the implicit costs of the non-linear terms using equation (4). Since, we are calibrating trade flows only and given the OURSE model formulation, we need estimates of the *trade elasticities with respect to transport costs* per product and trade partners. Since these are exogenous parameters, it is important to use the best available relevant estimates. Going through numerous studies on the effect of transportation costs on trade flows, we ended up using the results of Hummels (1999) and Balistreri et al. (2010).[10] The estimated substitution elasticities from these two studies are reported in Table 4.3.

Table 4.3: Estimates of substitution elasticities for refining sector

	Balistreri et al. (2010)	Hummels (1999)	This study
LPG	17	---	2.615

[10] Some of other useful related studies, which however do not consider refining industry as such, include Limão and Venables (2001), Hummels (2007), Helliwell (1997), Martínez-Zarzoso et al. (2008), Bussiére et al. (2013), and Bensassi et al. (2014).

Naphtha	25	---	3.846
Gasoline	39	---	6.000
Jet fuel, kerosene	15	---	2.308
Diesel, fuel oil	33	---	5.077
Residual fuel oil	21	---	3.231
Other	27	---	4.154
Total petroleum products	---	5.75	---

Using fixed-effects gravity regressions, Balistreri et al. (2010) estimate import-import substitution elasticities for seven refined products, which are reported in the second column of Table 4.3.[11] On the other hand, Hummels (1999) estimate substitution elasticities for 89 sectors, where the estimation technique is motivated by his multi-sector model of trade. The author reports the values of elasticity of substitution for the entire petroleum refining industry of 5.61 and 5.75 in, respectively, his OLS and non-linear least squares estimates of imports demands, and the last value is presented in Table 4.3. We use the results of *both* these studies due to the following reasons. The product-specific estimates of Balistreri et al. (2010) provide (potentially) very useful information in terms of heterogeneity of substitution elasticities across different types of refined products. However, we think the values themselves are rather large, especially in view of their comparisons to the usual values of substitution elasticities used in various CGE models and related results for other industries (e.g. results reported in the studies mentioned in footnote 10). From this perspective, we find the result of Hummels (1999) more reasonable. Hence, we have decided to choose the value of 6, essentially that reported in Hummels (1999), as an estimate of the elasticity of substitution for gasoline, which has the largest elasticity according to Balistreri et al. (2010) study, while keeping the heterogeneity of these elasticities across different products as estimated by the last study. Thus, the values of the substitution elasticities used in this study were computed from (6/39)×(Balestreri et al.'s estimate of substitution elasticity) and are reported in the last column of Table 4.3.

However, elasticity of substitution is *not* trade elasticity with respect to transportation costs. Given that the estimation of substitution elasticities are based on the use of CES expenditure system, it can be shown that the absolute value of the elasticity of trade flows of product p from region k to region i with respect to transport cost, ε_{ki}^{p} , is equal to (for the proof, see Temurshoev and Lantz, 2015):

$$\varepsilon_{ki}^{p} = \sigma^{p}(1 - s_{ki}^{p})\tau_{ki}^{p} , \qquad (6)$$

[11] They also estimate substitution elasticities for six crude grades, which however are not used here as crude oil trade is not explicitly calibrated.

where σ^p, s_{ki}^p and τ_{ki}^p are, respectively, the substitution elasticity of refined product p, the share of imports from region k in total trade flows to region i, and the proportion of transport costs in the consumer (CIF) price of product p of the considered trade flow. Thus, all other things being equal, equation (6) states that the trade elasticity with respect to transport costs is higher, the (a) higher the substitution elasticity of the product in question, (b) smaller the relevant import (or export) share, and (c) larger the contribution of transport costs to the final price of the product. Therefore, as expected, if a region is largely dependent on imports of, say, gasoline from another region, then changes in the relevant transport costs would have rather little impact on the affected gasoline trade flow, at least, in the short-run. The qualitative impacts of the other two factors captured in (6) on the trade elasticity are also consistent with a common-sense reasoning.

To use (6), besides the estimates of σ^p, we need the values of s_{ki}^p and τ_{ki}^p. Given that the observed global trade flows of refined products are missing, we use instead the 2005 total exports data from Table 4.2 as these would give us the trade shares which vary across the source regions. Hence, as an approximation of s_{ki}^p the exports shares are used, which are the same for each purchasing region i, but different across products. What will make the estimates of trade elasticities also dependent on the importing region i, is the use of the values of τ_{ki}^p's. The last are obtained by dividing direct products' freight costs for 2008, as estimated by IFPEN and assumed be the same for all refined products (see Table 3.2), by 2008 products' CIF prices which are available for LPG, naphtha, gasoline (regular and super), jet fuel, diesel oil, gasoil, fuel oil with 1% sulphur content and fuel oil with 3.5% sulphur content, and for 13 regions of the world (for our purposes, the product and region classifications were made consistent with the relevant OURSE classifications). These price data come from the IHS database, purchased and used specifically for the REFIT study purposes. The final estimated according to (6) trade elasticities per product ant trade partners are reported in Table 4.4.

Table 4.4: Trade elasticities with respect to transport costs used in OURSE_QP

Product		NA	SA	NE	SE	RS	AF	ME	CH	AS
PropTot, ButanTot	NA		0.05	0.06	0.07	0.07	0.12	0.11	0.03	0.04
	SA	0.05		0.12	0.09	0.11	0.07	0.11	0.12	0.12
	NE	0.04	0.08		0.04	0.02	0.08	0.08	0.11	0.10
	SE	0.06	0.09	0.05		0.07	0.07	0.11	0.13	0.12
	RS	0.07	0.11	0.02	0.02		0.07	0.12	0.12	0.13
	AF	0.13	0.07	0.12	0.08	0.07		0.06	0.12	0.16
	ME	0.11	0.12	0.13	0.12	0.13	0.06		0.07	0.08
	CH	0.04	0.13	0.18	0.16	0.13	0.13	0.07		0.05
	AS	0.04	0.11	0.13	0.12	0.12	0.14	0.07	0.04	
Naphtha	NA		0.07	0.09	0.10	0.11	0.18	0.15	0.05	0.06
	SA	0.07		0.17	0.13	0.16	0.10	0.15	0.16	0.17
	NE	0.05	0.11		0.05	0.03	0.11	0.12	0.15	0.13

	SE	0.08	0.11	0.07		0.10	0.10	0.16	0.18	0.17
	RS	0.10	0.14	0.03	0.03		0.10	0.18	0.16	0.18
	AF	0.17	0.10	0.17	0.11	0.11		0.08	0.17	0.23
	ME	0.14	0.15	0.18	0.18	0.19	0.08		0.09	0.11
	CH	0.05	0.17	0.25	0.23	0.20	0.19	0.11		0.07
	AS	0.05	0.14	0.18	0.18	0.17	0.20	0.10	0.05	
	NA		0.11	0.13	0.14	0.16	0.26	0.22	0.07	0.08
	SA	0.10		0.25	0.19	0.23	0.14	0.23	0.24	0.24
	NE	0.08	0.17		0.08	0.04	0.16	0.18	0.22	0.19
ReGasol92NAm, PremGasol1	SE	0.13	0.17	0.11		0.14	0.14	0.23	0.27	0.25
	RS	0.15	0.22	0.04	0.04		0.15	0.26	0.25	0.26
	AF	0.26	0.15	0.25	0.16	0.16		0.12	0.26	0.33
	ME	0.22	0.23	0.27	0.26	0.28	0.12		0.14	0.16
	CH	0.08	0.27	0.37	0.33	0.29	0.28	0.16		0.10
	AS	0.08	0.22	0.27	0.25	0.25	0.29	0.15	0.08	
	NA		0.11	0.13	0.15	0.16	0.27	0.24	0.07	0.09
	SA	0.10		0.26	0.20	0.23	0.15	0.24	0.25	0.25
	NE	0.08	0.17		0.08	0.04	0.17	0.19	0.24	0.21
ReGasol95NAm, PremGasol2, PremGasolEu	SE	0.13	0.18	0.11		0.15	0.14	0.25	0.28	0.26
	RS	0.15	0.22	0.05	0.05		0.15	0.28	0.26	0.27
	AF	0.26	0.15	0.26	0.17	0.16		0.13	0.27	0.35
	ME	0.23	0.24	0.28	0.27	0.29	0.13		0.15	0.17
	CH	0.08	0.28	0.39	0.34	0.30	0.29	0.17		0.10
	AS	0.08	0.23	0.28	0.26	0.26	0.30	0.16	0.08	
	NA		0.03	0.04	0.05	0.05	0.08	0.07	0.02	0.03
	SA	0.04		0.09	0.06	0.07	0.05	0.08	0.08	0.08
	NE	0.04	0.07		0.03	0.02	0.07	0.07	0.10	0.09
	SE	0.05	0.06	0.04		0.05	0.05	0.08	0.10	0.09
JetFuel	RS	0.05	0.07	0.02	0.02		0.05	0.09	0.09	0.09
	AF	0.08	0.05	0.08	0.05	0.05		0.04	0.08	0.10
	ME	0.05	0.05	0.06	0.06	0.07	0.03		0.04	0.03
	CH	0.03	0.08	0.12	0.10	0.09	0.09	0.05		0.03
	AS	0.02	0.06	0.07	0.07	0.06	0.08	0.03	0.02	
	NA		0.09	0.11	0.12	0.13	0.21	0.18	0.06	0.07
	SA	0.09		0.21	0.16	0.18	0.12	0.19	0.20	0.20
DieselNAm, DieselLatAm, DieselEu, DieselChin, HeatOil, HeatOilHq	NE	0.08	0.16		0.07	0.03	0.14	0.15	0.20	0.18
	SE	0.11	0.15	0.09		0.11	0.11	0.19	0.23	0.21
	RS	0.11	0.15	0.03	0.03		0.10	0.18	0.17	0.17
	AF	0.21	0.12	0.19	0.12	0.12		0.10	0.21	0.26
	ME	0.17	0.17	0.18	0.18	0.19	0.09		0.10	0.12
	CH	0.07	0.22	0.30	0.26	0.23	0.22	0.13		0.08
	AS	0.06	0.17	0.20	0.18	0.17	0.21	0.11	0.06	
	NA		0.17	0.19	0.21	0.22	0.35	0.31	0.10	0.12
	SA	0.15		0.37	0.27	0.31	0.20	0.31	0.32	0.32
	NE	0.16	0.34		0.14	0.07	0.27	0.30	0.37	0.35
	SE	0.21	0.31	0.18		0.21	0.21	0.35	0.39	0.37
HevFOilLowSulf	RS	0.18	0.29	0.05	0.05		0.17	0.30	0.28	0.29
	AF	0.37	0.23	0.34	0.22	0.21		0.16	0.33	0.42
	ME	0.29	0.34	0.35	0.33	0.34	0.15		0.17	0.20
	CH	0.12	0.45	0.56	0.48	0.41	0.39	0.22		0.13
	AS	0.11	0.36	0.42	0.36	0.34	0.40	0.20	0.11	
	NA		0.11	0.14	0.15	0.16	0.24	0.20	0.06	0.08
	SA	0.10		0.27	0.19	0.22	0.13	0.20	0.21	0.21
	NE	0.10	0.22		0.10	0.05	0.18	0.19	0.24	0.23
HevFOilHiSulf	SE	0.14	0.20	0.13		0.15	0.14	0.23	0.25	0.24
	RS	0.12	0.19	0.04	0.04		0.12	0.20	0.18	0.19
	AF	0.25	0.15	0.25	0.15	0.15		0.11	0.21	0.28
	ME	0.20	0.22	0.25	0.24	0.24	0.10		0.11	0.13

	CH	0.08	0.29	0.41	0.34	0.29	0.26	0.14		0.09
	AS	0.08	0.23	0.30	0.26	0.24	0.27	0.13	0.07	
BituMed, PetCoke	NA		0.14	0.18	0.19	0.20	0.31	0.26	0.08	0.10
	SA	0.13		0.35	0.25	0.28	0.17	0.26	0.27	0.27
	NE	0.13	0.28		0.13	0.06	0.23	0.25	0.31	0.29
	SE	0.18	0.25	0.16		0.20	0.18	0.29	0.32	0.31
	RS	0.16	0.24	0.05	0.05		0.15	0.25	0.23	0.24
	AF	0.32	0.19	0.32	0.20	0.19		0.14	0.27	0.35
	ME	0.25	0.28	0.32	0.30	0.31	0.13		0.14	0.16
	CH	0.10	0.37	0.52	0.44	0.38	0.34	0.19		0.11
	AS	0.10	0.30	0.39	0.34	0.31	0.35	0.17	0.09	

Note: All the figures are in fact negative, but instead their absolute values are given. This is consistent with the notation introduced in the text. Trade flows from row region to column region.

Note that all the trade elasticities' estimates are less than unity, as expected. Just for illustration purposes, consider for example the elasticity for diesel oil that is supplied by CIS (notably by Russia) to Europe. From Table 4.4 it follows that this figure is equal to 0.03, implying that a 1% increase in the costs of transporting diesel oil from CIS region to Europe would decrease the corresponding trade flow (in physical term) only by 0.03%. This is a reasonable estimate, given that Europe is largely dependent on imports of diesel from CIS, particularly from Russia.

Next, in order to estimate the implicit cost terms q_{ij}^{p} associated with product p and trade flows between regions i and j from an equation similar to (5), we need to define the *initial* estimate of the direct cost term $d_{ij}^{0,p}$, while d_{ij}^{p} will be estimated in the last step of our calibration process so that the model's endogenous trade flows will be exactly calibrated to their "observed" values. In order to take into account model uncertainty, the following two rules (or calibration approaches) are used[12]:

Standard rule: $d_{ij}^{0,p} = c_{ij}^{p}$, i.e. the uncalibrated direct implicit trade costs are equal to the direct accounting costs. That is, in the OURSE_QP framework these are set to direct freight costs, which are mostly symmetric in terms of bilateral flows and assumed to be the same for all products.

Average cost rule: $d_{ij}^{0,p} + 0.5 q_{ij}^{p} \bar{x}_{ij}^{p} = c_{ij}^{p}$, i.e. it is assumed that average costs (using the uncalibrated direct cost coefficients) are equal to their respective direct accounting costs. Using (5), the average cost rule can be written as

[12] The expressions *standard rule* and *average cost rule* are borrowed from the PMP literature, which represent additional assumptions used to estimate the unknown parameters of the non-linear terms in the cost (profit) function. However, the two approaches in the PMP literature and here are not equivalent.

$$d_{ij}^{0,p} = \frac{2\varepsilon_{ij}^{p}}{2\varepsilon_{ij}^{p}+1} \times c_{ij}^{p} \,. \tag{7}$$

From (7) it follows that average cost rule results in direct costs which, unlike in standard rule option, are *asymmetric in bilateral flows* and are *product-specific*. Now, we are ready to explicitly give the mathematical formulation of the calibration procedure, which consists of the following three steps.

Step 1: Estimate interregional trade flows such that they are consistent with the observed total exports and imports data presented in Table 4.2. This is implemented with the following LP program:

$$\text{minimize } \mathbf{c}'\mathbf{x} + \sum_{p,i,j} \left(d_{ij}^{0,p} + \frac{d_{ij}^{0,p}}{\varepsilon_{ij}^{p}} \right) \times T_{ij}^{p}$$

subject to:

$$\mathbf{A}\mathbf{x} \geq \mathbf{b} \,,$$
$$\textstyle\sum_{i,p\in ap} T_{ij}^{p} \geq im_j^{ap} \text{ for all } j,$$
$$\textstyle\sum_{j,p\in ap} T_{ij}^{p} \leq ex_i^{ap} \text{ for all } i,$$
$$\mathbf{x} \geq \mathbf{0}, \text{ and } T_{ij}^{p} \geq 0,$$

where ap denotes aggregate product, im_j^{ap} and ex_i^{ap} are, respectively, the exogenous total imports and exports data from Table 4.2, and T_{ij}^{p} is trade flow of product p between regions i and j. $\mathbf{x}$ includes all other variables in the OURSE refining model, each of them having different dimensions, which for simplicity of presentation are all suppressed. The first set of constraints in the LP program above includes all constrains that are presented in Appendix B, while the second and third constraints make our calibration constraints. To clarify the difference between the sets ap and p, as an example consider ap being gasoline, then the earlier mentioned five grades of gasoline constitute products p making up this aggregate product. Ideally, of course, one would like to have the total exports and imports data at each disaggregate product level p (in the absence of trade matrices), but the data availability problem forces us to use calibration constraints at the more aggregate product level. The motivation for the choice of the specific form of the objective function used in Step 1 will become clear shortly. The trade flows obtained from Step 1 optimization are then denoted as $\hat{T}_{ij}^{p}$ and considered to be "observed" interregional trade flows.

Step 2: Run the following auxiliary non-linear (NLP) program:

$$\text{minimize } \mathbf{c}'\mathbf{x} + \sum_{p,i,j}\left(d_{ij}^{0,p} \times T_{ij}^{p} + 0.5 \times q_{ij}^{p} \times \left\{T_{ij}^{p}\right\}^{2}\right)$$

subject to:

$$\mathbf{Ax} \geq \mathbf{b}\,,$$
$$T_{ij}^{p} = \hat{T}_{ij}^{p} \quad \text{for all } i \text{ and } j,$$
$$\mathbf{x} \geq \mathbf{0}, \text{ and } T_{ij}^{p} \geq 0,$$

with the purpose of obtaining dual values λ_{ij}^{p} of the calibrating constraints $T_{ij}^{p} = \hat{T}_{ij}^{p}$. Note that unlike the PMP procedure (see e.g. Howitt, 1995a, 1995b), here calibrating equations are defined as a set of equations, rather than inequalities. This approach is adopted from Paris et al. (2011), who also focuses on calibrating spatial models of trade. Given that the calibration constraints are stated as a set of equations, λ_{ij}^{p} will be a free variable. This "specification is based on the consideration that, if accounting transaction costs are measured incorrectly, then they may be either over or under estimated. Thus, the magnitude and sign of the estimated [λ_{ij}^{p}] will determine the effective unit transaction costs that will produce a calibrated solution of the quantities produced and consumed in each country" (Paris et al., 2011, p. 2511). Using the solution of Step 1 LP model as initial values for all the variables, Step 2 NLP program gives an immediate solution that is exactly the same as Step 1 solution. This is the reason for using the specific form of the objective function used in Step 1, whose formal proof is not presented here further due to space consideration. Thus, the extra information obtained from Step 2 includes quantification of the shadow values of trade flows calibrating constraints.

Step 3: The final calibrating model has the form given in (2.b), specifically

$$\text{minimize } \mathbf{c}'\mathbf{x} + \sum_{p,i,j}\left(\left\{d_{ij}^{0,p} - \lambda_{ij}^{p}\right\} \times T_{ij}^{p} + 0.5 \times q_{ij}^{p} \times \left\{T_{ij}^{p}\right\}^{2}\right)$$

subject to:

$$\mathbf{Ax} \geq \mathbf{b}\,,$$
$$\mathbf{x} \geq \mathbf{0}, \text{ and } T_{ij}^{p} \geq 0.$$

Note that the *effective* unit transaction cost in the linear cost term d_{ij}^{p} adjusts the earlier uncalibrated direct costs $d_{ij}^{0,p}$ with the shadow values of the trade flows calibrating constraints λ_{ij}^{p}, i.e., $d_{ij}^{p} = d_{ij}^{0,p} - \lambda_{ij}^{p}$. Running this final OURSE_QP model, using the solution of Step 2 NLP program as initial values for all the variables, will immediately produce exactly the same solution. Thus, it endogenously calibrate perfectly observed trade flows $\hat{T}_{ij}^{p}$'s, production of products, production and consumption of crudes and *all* other variables used in the refining model that are consistent with the relevant base-year "observed" trade flows implied by the products' supply-demand balances and all material balances included in the model. As a consequence, the final OURSE_QP model can now be reasonably used, without including any artificial calibrating constraints, to evaluate the likely effects of and world refineries' reactions to various policy instruments captured by the model.

Finally, note that in case of availability of trade flows data, Step 1 in our calibrating procedure would be redundant. Hence, if one has a luxury of having access to detailed interregional trade data of refined products that are observed in reality, the above-presented calibrating procedure reduces to two steps in order to arrive at the final QP (or NLP) model that perfectly calibrates the observed data in its baseline scenario(s).

5 Baselines, simulation scenarios and results

Given that it is impractical to present all the details of the OURSE_QP modelling outcome, in this section we discuss and report the main inputs and/or outputs related to the construction and/or implementing the necessary baselines, simulation (counterfactual) scenarios and the underlying main results.

5.1 Benchmark (baseline) scenarios

We start with the crude prices, which are exogenous, but quite important, variables in the OURSE model. These were derived using the relevant data from IEA and IHS. IEA data are crude oil spot prices in current dollars (USD) per barrel, while IHS crude price data are FOB prices in constant 2013 USD per barrel. Hence, the two data were used together in order to derive Brent (which is a reference crude in OURSE) prices in constant 2008 USD per tonne of processed crude, for the three sub-periods covered in the modelling exercises. We translate the prices into constant 2008 year prices, because all the costs coefficients, including those of operating and capital expenditures, are expressed in 2008 USD. These crude oil prices are reported in Table 5.1.

Table 5.1: Crude oil and feedstock prices (in 2008 USD per tonne)

Period	Brent	Arabian Light	Arabian Heavy	Forcados	Condensate	Feedstock
2000	194.78	171.76	116.32	186.56	222.79	82.40
2005	381.53	347.46	292.53	374.74	436.09	210.65
2010	691.95	639.52	585.45	687.53	790.66	423.85

The reference crude price averages over 2000-2002, 2003-2007 and 2008-2012 are taken as Brent prices for the three modelling time periods of 2000, 2005 and 2010, respectively. The prices of the other four crude types and feedstock (mainly representing atmospheric residue) are derived using the long-term equilibrium (i.e. cointegration) relationships between these crudes and Brent, as estimated and reported in Lantz et al. (2012).

Table 5.2: Crude oil supply to regional refineries in the OURSE_QP baselines

	Quantity	API	S (%)	Quantity	API	S (%)	Quantity	API	S (%)
	2000, standard rule			**2005, standard rule**			**2010, standard rule**		
NA	793.9	34.9	1.30	817.7	33.2	1.30	787.6	33.3	1.21
SA	174.2	31.5	1.28	181.5	32.1	1.27	163.8	32.5	1.37
NE	432.2	34.3	1.15	448.7	33.2	1.27	422.0	33.5	1.23
SE	208.0	32.7	1.40	226.7	31.6	1.41	208.8	31.6	1.56
RS	205.1	31.8	1.81	243.7	32.6	1.64	266.7	32.3	1.57
AF	106.3	32.0	0.83	118.5	32.7	0.70	123.6	35.9	0.70
ME	298.5	27.0	2.69	347.3	27.0	2.69	372.5	27.0	2.69
CH	156.1	34.8	1.70	230.5	33.6	1.68	314.7	32.8	1.61
AS	579.7	34.1	1.57	628.4	33.6	1.73	641.4	33.2	1.69
World Total	*2953.9*	*33.2*	*1.52*	*3243.0*	*32.4*	*1.56*	*3301.1*	*32.4*	*1.55*
	2000, average cost rule			**2005, average cost rule**			**2010, average cost rule**		
NA	774.8	33.2	1.35	805.1	32.9	1.29	765.1	33.4	1.30
SA	171.5	32.3	1.31	171.7	32.5	1.29	177.3	32.0	1.25
NE	419.0	32.7	1.22	431.9	32.7	1.28	406.4	33.1	1.12
SE	202.4	31.0	1.43	221.4	31.2	1.43	203.9	31.3	1.49
RS	213.0	34.6	1.70	248.5	33.5	1.68	268.7	32.2	1.71
AF	104.4	33.7	0.82	120.0	36.0	0.69	116.6	35.9	0.70
ME	329.9	27.0	2.69	361.1	27.0	2.69	377.5	27.0	2.69
CH	153.1	34.8	1.71	237.2	33.8	1.58	332.3	32.8	1.61
AS	580.8	33.3	1.78	627.7	33.0	1.88	640.1	33.2	1.69
World Total	*2948.8*	*32.5*	*1.59*	*3224.6*	*32.3*	*1.60*	*3287.8*	*32.3*	*1.57*

Note: Quantities are in million tonnes, API is the API degree, and S denotes the sulphur content. For 2005 and 2010 baselines, respectively, the capacities in processing units of 2000 and 2005 are used in the estimation procedure. Standard rule and average cost rule indicate the specific calibration approach used (for details, see Section 4.2).

The total quantities and characteristics of crude oil (excluding feedstock), supplied to regional refineries as produced by the model for the baseline scenarios, are presented in Table 5.2. As an example, however, in Table 6.5 in Appendix A we present the detailed trade flows of the six crude types and feedstock for the 2005 baseline scenario.

The characteristics of the crudes reported in Table 5.2 in terms of API degree and sulphur content are close to the relevant observed average figures by consuming regions. If we compare the crude input quantities with those presented in Table 4.1, we find, for example, that at the global level the "observed" crude inputs in Table 4.1 are larger than those endogenously derived by the model and ranges from 8.1% to 12.5% depending on year and/or calibration approach used. At the regional level these discrepancies are higher, and range from -11.8% to 34.3%. Total throughputs (i.e. inputs of crude and feedstock) for the three baselines and the two calibration approaches used, which we do not report here for space consideration, show lower discrepancies. Thus, at the global level, the "observed" total throughputs are again larger compared to the model outcomes, ranging from 7.0% to 8.9%, while the corresponding range for the regional level differences are -1.7% and 17.8%. However, these discrepancies should *not* be taken (too) seriously, because: (a) the "observed" crude and feedstock trade matrices are (best) estimates themselves as explained in Section 4.1, and (b) calibration was implemented on the output-side of the refinery, hence from an input-output material balance perspective the lower amount of global refined products vs. world crude (which seem to be in place, given that at least our demand data do not include the unspecified products category from the IEA dataset) would result in the model throughputs that are somewhat lower at the global level than the "observed" ones. The last is exactly what we find, and this may also partly explain the larger deviations at the regional levels of crude and total throughput supply. Nonetheless, the obtained crude and feedstock outputs are considered sufficiently reasonable, at least, for modelling purposes. We remind that the data from Table 4.1 were used as constraints at total crude level in terms of maximum allowed import shares from various regions for each consuming refinery (region), which ensures that the API degree and sulphur content qualities of the model's crude supply per region, as reported in Table 5.2, match well with those characteristics observed in reality.

Next we turn to reporting some of the OURSE_QP outputs for arbitrary selected baseline scenarios. In Table 5.3 the products' balances at a somewhat more aggregated levels for all regions are presented. The results show that North and South Europe are net exporters of gasoline, and net importers of the majority of other reported products, in particular, diesel, heating oil, jet fuel and residual fuel oil. These results, of course, reflect the calibration step as discussed in detail in the previous section. The bottom right part of Table 5.3 shows products balances at the world level. From these figures we can infer that in 2005 out of the estimated 387.2 mln tonnes of oil products traded world-wide, residual fuel oil trade accounts for

Table 5.3: Product balances for all regions, 2005 baseline (average cost rule)

	Production	Imports	Exports	Consumption	Production	Imports	Exports	Consumption
	North America				*Africa*			
LPG	67.4		4.8	62.6	4.5	4.5		9.0
Naphta	0.7	19.3		20.0	5.3		4.5	0.7
Gasoline	403.2	44.2		447.4	19.6	7.9		27.5
JetFuel	92.6	6.5		99.1	15.4	0.1		15.5
HeatingOil	93.6	6.5		100.1	10.3	4.8		15.1
DieselOil	148.0			148.0	26.8	1.3		28.1
ResFuelOil	56.7	43.3	17.5	82.5	29.1		9.8	19.3
Bitumen	38.3			38.3		2.6		2.6
PetCoke	13.4	8.7	2.9	19.2	0.3	1.2		1.5
MarinBunk	33.4			33.4	6.1			6.1
	South America				*Middle East*			
LPG	9.4	4.8		14.2	16.9	4.1	9.6	11.4
Naphta	12.3		2.0	10.3	36.8		33.9	2.9
Gasoline	47.4		11.5	35.9	41.8	7.3		49.1

JetFuel	12.6		3.6	9.0	46.5		18.1	28.4
HeatingOil	22.9		0.9	22.0	48.5		11.6	36.9
DieselOil	45.5			45.5	42.6		1.3	41.3
ResFuelOil	33.9		18.1	15.8	61.9		10.0	51.8
Bitumen	3.6			3.6	27.3		19.1	8.1
PetCoke	6.8	0.2		7.0	8.0		7.4	0.6
MarinBunk	7.3			7.3	17.8			17.8
	North Europe				*China*			
LPG	28.5		10.1	18.4	22.6		4.3	18.2
Naphta	28.8	13.1		41.9	38.5		9.4	29.0
Gasoline	109.0		24.0	85.0	54.2		5.1	49.1
JetFuel	34.9	16.2		51.2	12.9	5.2		18.0
HeatingOil	72.9	10.2		83.1	62.1	2.7		64.8
DieselOil	104.5	15.8		120.3	42.9			42.9
ResFuelOil	24.6	5.9	2.3	28.2	13.9	28.8		42.7
Bitumen	14.2			14.2	6.6	0.6		7.2
PetCoke	4.7	2.1		6.8	7.6	1.0		8.6
MarinBunk	39.3			39.3	10.7			10.7
	South Europe				*Other Asia & Oceania*			
LPG	11.3	5.6	4.1	12.8	32.6	14.3		46.9
Naphta	5.2	4.5		9.7	79.8	26.0		105.8
Gasoline	48.4		12.9	35.5	119.5	1.9		121.4
JetFuel	13.7	1.7		15.4	150.1		7.9	142.1
HeatingOil	30.2	2.9		33.1	102.5	1.2	5.6	98.1
DieselOil	55.5	10.8		66.3	115.6			115.6
ResFuelOil	32.3	4.8		37.1	74.2	17.5		91.8
Bitumen	9.2			9.2		14.5		14.5
PetCoke	2.3	8.9		11.2	22.0		9.7	12.3
MarinBunk	16.2			16.2	47.9			47.9
	CIS (Russia)				*World Total*			
LPG	10.9		0.3	10.6	204.2	33.3	33.3	204.2
Naphta	24.6		13.1	11.5	231.9	63.0	63.0	231.9
Gasoline	46.2	2.4	10.2	38.4	889.4	63.7	63.7	889.4
JetFuel	12.9		0.1	12.8	391.5	29.7	29.7	391.5
HeatingOil	33.9		10.2	23.7	476.9	28.3	28.3	476.9
DieselOil	41.5		26.6	14.9	622.9	27.8	27.8	622.9
ResFuelOil	71.7		42.5	29.1	398.3	100.2	100.2	398.3
Bitumen	5.3	1.4		6.7	104.6	19.1	19.1	104.6
PetCoke	3.3		2.1	1.2	68.4	22.0	22.0	68.4
MarinBunk					178.7			178.7

Note: Quantities are in million tonnes. Source: OURSE_QP results. 2000 capacities are used in the model estimation.

25.9%, gasoline – 16.5%, naphtha – 16.3%, jet fuel – 7.7%, heating oil – 7.3% and diesel oil – 7.2%.

Given that the regions of North Europe and South Europe also include non-EU countries as discussed in Section 1, the product balances of the EU regions are reported separately in Table 5.4. These figures were estimated using the relevant data from

Table 5.3 and the demand shares reported in Table 6.2. Given that these shares are found to be quite high, ranging from 74.4% to 100%, except for the LPG demand proportion of the EU countries in South Europe being 65.1%, the qualitative and, to a large extent, the quantitative outcomes remain similar to those presented in

Table 5.3 and discussed above.

Table 5.4: Products balances for the EU regions, 2005 baseline (average cost rule)

	Production	Imports	Exports	Consumption	Production	Imports	Exports	Consumption
	North Europe: EU countries				*South Europe: EU countries*			
LPG	26.7		9.5	17.2	7.4	3.7	2.7	8.4
Naphta	28.8	13.1		41.9	4.6	4.0		8.6
Gasoline	102.2		22.5	79.6	42.4		11.3	31.1
JetFuel	32.6	15.1		47.7	11.6	1.4		13.1
HeatingOil	66.4	9.3		75.6	26.3	2.5		28.8
DieselOil	101.6	15.3		116.9	48.1	9.3		57.4
ResFuelOil	24.0	5.7	2.2	27.5	24.1	3.5		27.6
Bitumen	13.6			13.6	7.2			7.2
PetCoke	4.3	1.9		6.2	2.3	8.7		11.1
MarinBunk	36.9			36.9	15.1			15.1

Note: These figures were obtained using the observed demand shares reported in Table 6.2 and the corresponding figures presented in Table 5.3.

From this point onwards, most of the results of refined products will be presented in terms of three widely-used broad oil product groupings. These are *light* products (LPG, naphtha and gasoline), *medium* products (jet fuel, heating oil and diesel oil), and *heavy* products (residual fuel oil, marine bunkers and bitumen).

The product trade flows for 2005 baseline (average cost calibration approach) are presented in Table 5.5. Focusing on the products trade of Europe with the other regions of the world, one can observe from Table 5.5 large dependence of Europe on imports of medium products from CIS/Russia and Middle East. On the other hand, as exporter Europe's largest market destinations for its gasoline are North America and Africa. In terms of imports of heavy products, Europe again is largely dependent on CIS/Russia region. It should be noted that the model captures the most important trade flows, and not all small transactions that maybe observed in reality. On the other hand, not each and every flow reported in Table 5.5 should be taken for granted as absolutely accurately representing the real flows, as these are only the model's outcomes and thus may not give the exact size of the real trade flows. This possibility is unavoidable in the current study given that the observed global refined products trade data are unavailable, otherwise the calibration step of the OURSE_QP would have ensured exactly identical observed and model's trade flows per product. Nonetheless, the results are encouraging as they capture the main features of *interregional* trade interdependencies and structure in global petroleum products market, which is more than sufficient for modelling purposes. In any case, OURSE_QP improves significantly upon the OURSE_LP results in this respect.

Table 5.5: Products trade flows, 2005 baseline (average cost calibration approach)

	NA	SA	NE	SE	RS	AF	ME	CH	AS

	Light products								
NA	16.79	4.82							
SA	13.46	1.78							
NE	21.68		29.22	5.62	2.37	4.49			
SE	0.91			5.24		7.89	8.22		
RS	10.17		13.11						0.35
AF				4.54		2.68			
ME	17.32						4.64		26.15
CH							3.23		15.67
AS									24.28
	Medium products								
NA	21.33								
SA	4.48	8.61							
NE			72.43						
SE				17.03					
RS			25.97	10.90	2.93				
AF						7.93			
ME			16.24	4.51		6.04	13.51	2.88	1.22
CH									
AS	8.52					0.07		4.96	53.42
	Heavy products								
NA	4.77								17.53
SA	18.11	1.21							
NE	2.28		43.40						
SE				9.97					
RS	13.12		5.87	4.76	1.36			18.79	
AF	9.76					2.42			
ME					1.43	2.64	15.75	10.59	14.50
CH									
AS									33.37

Note: Unit is in million tonnes. Source: OURSE_QP results. Observed 2000 capacities in processing units are used in the model estimation procedure. Intra-regional flows estimate the flows between countries of the same region.

5.2 Counterfactual scenarios and results

To assess the likely impacts of the legislation acts included in the EU Petroleum Refining Fitness Check (REFIT) on the performance and international competitiveness of the EU refining industry, the following three types of scenarios are defined:

4. Fuel quality specifications change scenario: this includes changing fuel specifications as dictated by the Fuels Quality Directive (FQD) and Marine Fuels Directive (MFD).
5. Demand level and composition change scenario: this assesses the impact of the Renewable Energy Directive (RED) and Energy Taxation Directive (ETD).
6. Pollution limits change scenario: this deals mainly with the assessment of the Large Combustion Plants Directive (LCPD), Integrated Pollution Prevention and Control Directive (IPPCD) and Air Quality Directive (AQD).

The likely impacts of the remaining directives included within the REFIT scope will not be assessed with the OURSE model because of: (a) the model's unsuitability of evaluation, at least at the current stage of the OURSE development, of a specific directive's impact (such as

Strategic Oil Stocks Directive), (b) the prior knowledge of the irrelevance of a directive (such as the Directive on Clean and Energy Efficient Vehicles), or (c) the availability of the *exact* costs and/or benefits incurred by the individual EU refineries due to the requirements of a directive (such as EU ETS).

5.2.1 Impact assessment of changes in fuels quality specifications

Several sets of scenarios have been considered in order to take into account modelling uncertainties and economic environment uncertainties. This is an *ex post* impact assessment study, thus the main point of departure should be building counterfactual scenarios for the periods considered such that they exclude the changes in fuels quality specifications exogenously and then the model outcomes need to be compared with those of the corresponding baselines. But given that refining processing units capacities and products demands as model inputs play crucial role in the OURSE model (or any other refining mathematical programming model), the general structure of the three sets of the baseline and counterfactual scenarios are "visualized" in Table 5.6. It can be easily seen from this table that the differences in outcomes between the relevant baseline and counterfactual scenarios quantify the impact of fuels' qualities changes.

Table 5.6: Baseline and counterfactual scenarios main structure

Scenario	Refining capacities	Product demands	Fuel qualities
2000-2010 baseline	2000	2010	2010
2000-2010 counterfactual	2000	2010	2000
2000-2005 baseline	2000	2005	2005
2000-2005 counterfactual	2000	2005	2000
2005-2010 baseline	2005	2010	2010
2005-2010 counterfactual	2005	2010	2005

Since the REFIT covers 2000-2012 time period, which in OURSE language is translated into three periods 2000-2005-2010, there are two possibilities of assessing the cumulative impact over the entire period. First, consider the entire 2000-2010 period, without using the information on the intermediate period of 2005: this case is represented as the first set of baseline and counterfactual scenarios in Table 5.6. However, ignoring the intermediate year data could give biased results due to likely significant changes in economic environment. In particular, as already discussed in Section 1, in Europe total fuel demand increased during 2000-2005 period (by 5.4% and 2.3% in NE and SE regions, respectively), but then decreased largely in the second sub-period of 2005-2010 (the respective figures were -10.6%

and -12.5%). To take this change in demand into account, it is important to consider the two sub-periods separately. The main inputs structures of the relevant scenarios are given in the last two sets of scenarios presented in Table 5.6.

To account for different economic environments (as sensitivity analysis), two cases in the modelling exercises will be considered. In *Case 1* counterfactual scenarios (time-wise as depicted in Table 5.6) were constructed, such that:

- *only* for North Europe and South Europe the relevant fuels quality specifications were set to their initial-year (2000 or 2005) levels in the counterfactual envirionment, which include maximum limits of sulphur for gasoline (PremGasolEu) and diesel oil (DieselEu), of polyaromatic hydrocarbons (PAH for DieselEu) and of aromatic fraction (for PremGasolEu); the exact figures of these limits are given in Table 1.1;
- *only* for European regions the respective initial-year shares that split exogenous aggregate demand of heating oil, residual fuel oil and marine bunkers into higher- and lower-sulphur content fuels are used instead of their final-year levels (2005 or 2010, depending on the scenario); the relevant splitting shares for 2005 are given in Table 6.4, and in general for European regions the consumption shares of low-sulphur fuels increase over time; and
- for the remaining OURSE regions, the relevant fuels specifications and the above-mentioned three fuels disaggregation consumption shares were *not* changed, where the last were set at the end-year values of the counterfactual scenarios.

A different economic environment for the counterfactual scenarios is assumed under *Case 2* simulations, where non-EU regions are assumed *not* to tighten their fuels quality specifications that are instead made more stringent in the European regions, and vice versa. That is, under *Case 2* is the mirror image of *Case 1* environment and mimics the hypothetical environment where non-EU regions tighten *all* their fuel quality specifications, while North Europe and South Europe do not.

In what follows we present some of our main findings related to the assessments of implied costs, benefits, and impact on trade and international competitiveness. At this point it is important to note that in order to assess the costs and/or benefits implications of the mentioned directives, it is crucial to keep trade flows of petroleum products fixed at their baseline level. The reason is that we need the refineries to have the same production as in the baseline scenario, but under a different environment related to the assessment goal, for example, under less stringent regulations on fuels quality limits. Given that demand is exogenously fixed, keeping trade flows unchanged also automatically imply unchanged production levels (due to products' balances). However, when the focus shifts towards the assessment of likely impacts on international competitiveness, trade flows should be kept endogenous during the simulation runs. On the practical note, this might increase the simulation-time considerably.

5.2.1.1 Costs

We first present somewhat detailed results for an arbitrary selected scenario of 2005-2000 (using the average cost calibration approach and *Case 1* environment) to shed some light on the outcomes, and then provide the costs estimates from all the simulations without further detailed explanations. The costs of investments in new processing units - capital expenditures (CAPEX) - and the operating costs (OPEX) from the 2005-2000 baseline and counterfactual scenarios are reported in Table 5.7.

Table 5.7: CAPEX and OPEX costs, 2005-2000 scenarios, Case 1 (in 2008 mln USD)

	NA	SA	NE	SE	RS	AF	ME	CH	AS	NE&SE	Total
						CAPEX					
Baseline	10709.7	778.0	4573.0	373.6	1702.3	2067.8	17791.2	27902.5	106766.9	4946.6	172664.9
Counterfactual	10988.7	744.4	4328.4	57.6	1715.4	2067.8	17791.2	27902.5	106751.4	4386.0	172347.3
Difference	279.1	-33.6	-244.6	-316.0	13.1	0.0	0.0	0.0	-15.5	-560.7	-317.6
						OPEX					
Baseline	11307.1	1725.1	5068.0	1959.2	1787.2	655.9	3751.2	3319.1	10027.5	7027.2	39600.2
Counterfactual	11251.5	1738.5	4822.3	1876.0	1751.5	655.9	3751.2	3319.1	10002.2	6698.2	39168.1
Difference	-55.6	13.4	-245.7	-83.2	-35.6	0.0	0.0	0.0	-25.4	-328.9	-432.0

Note: Difference = Counterfactual – Baseline. Calibration is based on the average cost specification rule.

As expected with weaker fuels quality specifications in place, Europe would have had less need for capital investments in new processing units. Also note that some other non-EU regions (refineries), closely linked with the European petroleum product market, are affected by the European legislation as well, though the size of this impact (in absolute value) is generally much less than that on the EU refineries. This is a crucial advantage of global refinery modelling, as in open economies there are always *inter-regional spillover and feedback effects* present. The extent of these inter-regional effects depend, of course, on the size of the relevant trade flows of crude oil and refined products, among other factors.

According to the considered scenario, the total estimated CAPEX costs for all European refineries due to the FQD and MFD directives over the 2005-2000 period amounted to 560.7 mln USD, or 112.13 mln USD (=560.7/5 years) in annualised term. Some details of these results in terms of differences in new investments (in mln *tonnes* per year) of the counterfactual and baseline scenarios at somewhat aggregated unit group levels are also presented in Table 5.8. The list of these aggregate units grouping and the associated individual processing units is given in Table 6.6. Thus, from Table 5.8 one observes that with tighter fuels specifications for gasoline, diesel, heating oil, residual fuel oil and marine bunkers, Europe had to invest (more) in gasoil hydrodesulphurisation units (HDS gasoil), naphtha processing units, residue catalytic cracking, hydrotreatment (HDT) of vacuum gas oil, and hydrogen units.

Table 5.8: Differences in new investments, 2005-2000 scenarios (mln tonnes/year)

	NA	SA	NE	SE	RS	AF	ME	CH	AS	NE& SE	Total
Topping unit & VDU							0.0		0.3		0.3
Naphtha processing units			-5.5	-1.7	0.6	0.0	0.0		0.0	-7.2	-6.6
FCC							0.0	0.0			0.0
RCC		-0.1	-0.6				0.0		-0.1	-0.6	-0.9
HDS gas oil			-43.8	-29.5	-4.3	0.0	0.0	0.0		-73.4	-77.6
FCC gasoline desulphur.											
HDT vacuum gas oil			-0.2				0.0			-0.2	-0.2
HDT naphtha											
Hydrocraking units						0.0	0.0	0.0	-0.1		-0.1
Residue hydroconversion											
Etherification units	0.4	0.0						0.0			0.4
Visbreaking unit									-0.2		-0.2
Coking unit								0.0	0.1		0.1
Hydrogen units				-0.1	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1
Total difference	0.4	-0.1	-50.1	-31.3	-3.7	0.0	0.0	0.0	0.0	-81.4	-112.3

Note: CAPEX difference = Counterfactual CAPEX – Baseline CAPEX.

Further impact on processing units *use* can be traced by looking at the capacities endowments as of 2000 and their use afterwards. These can be seen from capacities utilization rates in the 2005-2000 baseline and counterfactual scenarios, which are reported in Table 5.9. These rates per each processing unit are computed as:

$$\text{Capacity utilisation rate} = \frac{\text{Capacity used}}{\text{Old capacity} + \text{New investments}} \times 100. \qquad (8)$$

Thus, given that new investments in gasoil HDS units decrease without FQD/MFD, it should not be surprising to observe an *increase* in their utilisation rates in the counterfactual with weaker European fuel quality specification as reported in Table 5.9. On the other hand, for underutilized units with zero new investments, like FCC gasoline desulphurization units, a *decrease* of utilisation rate in the counterfactual scenario implies lower need for desulphurisation. This trend is observed for North Europe, where the average utilisation rate of the FCC desulphurisation units goes down from 61.1% to 17.1%. Finally, part of the costs of more desulphurisation need will be reflected in higher operating costs, for example, through the increase in operating variable costs, such as costs of catalysts use.

Table 5.9: Capacities average utilisation rates, 2005-2000 scenarios, Case 1

	NA	SA	NE	SE	RS	AF	ME	CH	AS	NE&SE
					Baseline					
Topping unit & VDU	76.4	57.3	70.6	76.4	44.2	47.4	100.0	100.0	88.8	73.5
Naphtha processing units	68.3	65.2	75.1	84.7	73.0	91.7	74.4	100.0	82.2	79.9
FCC	84.8	74.7	100.0	95.9	98.3	100.0	100.0	100.0		98.0
RCC	100.0	100.0	98.8			100.0	100.0	95.8	73.9	98.8
HDS gas oil	68.5	44.5	73.3	55.9	65.2	100.0	100.0	100.0	76.8	64.6
FCC gasoline desulph.	17.0		61.1							61.1
HDT vacuum gas oil	100.0	100.0	100.0	94.4	100.0		100.0	100.0	62.4	97.2
HDT naphtha	1.7	3.8	1.3	1.0	1.0	0.5	5.0	31.3	3.6	1.1
Hydrocraking units	87.1		60.7			100.0	70.6	100.0	100.0	60.7
Residue hydroconversion			100.0				36.7	93.0	35.9	100.0
Etherification units	100.0	100.0	50.6					100.0		50.6
Visbreaking unit	90.4		53.6	18.7	20.3		100.0	100.0	100.0	36.1
Coking unit	25.5	69.3	100.0	100.0	60.7	69.0	100.0	100.0	100.0	100.0
Hydrogen units	83.0	71.5	82.5	100.0	100.0	100.0	100.0	100.0	100.0	91.2
					Counterfactual					
Topping unit & VDU	76.3	57.2	71.0	76.6	44.0	47.4	100.0	100.0	88.8	73.8
Naphtha processing units	68.3	47.3	75.3	84.6	49.6	91.7	74.4	100.0	85.5	80.0
FCC	86.3	74.3	100.0	99.2	98.3	100.0	100.0	100.0		99.6
RCC	100.0	100.0	98.8			100.0	100.0	95.8	74.1	98.8
HDS gas oil	71.3	41.5	82.9	84.3	68.0	100.0	100.0	100.0	80.1	83.6
FCC gasoline desulph.	48.4		17.4							17.4
HDT vacuum gas oil	100.0	100.0	100.0	100.0	100.0		100.0	100.0	62.8	100.0
HDT naphtha	1.6	4.2	1.3	1.5	1.0	0.5	5.0	31.3	3.6	1.4
Hydrocraking units	81.6		56.7			100.0	70.6	100.0	100.0	56.7
Residue hydroconversion			100.0				36.7	93.0	37.4	100.0
Etherification units	100.0	100.0	71.8					100.0		71.8
Visbreaking unit	100.0		43.9	17.5	13.3		100.0	100.0	100.0	30.7
Coking unit	25.1	76.4	100.0	100.0	61.6	69.0	100.0	100.0	100.0	100.0
Hydrogen units	62.0	69.9	65.5	88.2	100.0	100.0	100.0	100.0	100.0	76.9

Source: OURSE_QP results.

In Table 5.7 above also the operating costs (OPEX) are reported, which in particular include operating variable costs (such as costs of catalysts, solvents and chemicals) and operating (but not capital) maintenance costs. The annualised OPEX of the impact of the FQD and MFD, according to the scenario discussed, are assessed to be 65.8 mln USD per year. A closer examination of the OPEX numbers would give the details of potentially each and every intermediate production contributions, the details of which we do not provide further here.

More simulations were carried out. In particular, separate simulations for the 2000-2005 and 2005-2010 sub-periods using both calibration approaches were implemented. Besides, also simulations taking the entire 2000-2010 period at once were run as further sensitivity analysis. However, as discussed earlier it is likely that running the entire 2000-2010 simulations might not account for larger demands in 2005 and bigger change in fuels qualities over the 2000-2005 period than in the 2005-2010 period. Further, all the two hypothetical economic environments discussed earlier were imposed/considered in all the simulations in order to single out the likely impact of the FQD and MFD directives. The final annualised total CAPEX and OPEX figures of all these counterfactual simulations as compared to the results of the relevant baseline scenarios are summarized in Table 5.10.

Table 5.10: Summary of the total annualised CAPEX and OPEX costs (mln 2008 USD)

	2000-2005 (1)	2005-2010 (2)	Average of (1) and (2)	2000-2010
	Annualised CAPEX			
	Case 1: Old specs in Europe, new specs elsewhere			
Standard rule	475.23	341.47	408.35	143.99
Average cost rule	112.13	92.82	102.48	72.62
	Case 2: New specs in Europe , old specs elsewhere			
Standard rule	341.81	41.63	191.72	31.13
Average cost rule	38.40	24.48	31.44	32.16
	Annualised OPEX			
	Case 1: Old specs in Europe, new specs elsewhere			
Standard rule	75.13	36.11	55.62	45.70
Average cost rule	65.78	37.81	51.80	46.55
	Case 2: New specs in Europe , old specs elsewhere			
Standard rule	26.79	4.86	15.82	5.66
Average cost rule	12.51	3.83	8.17	2.58
	Total annualised CAPEX and OPEX			
	Case 1: Old specs in Europe, new specs elsewhere			
Standard rule	550.36	377.58	463.97	189.68
Average cost rule	177.92	130.63	154.27	119.17
	Case 2: New specs in Europe , old specs elsewhere			
Standard rule	368.60	46.49	207.54	36.78
Average cost rule	50.91	28.31	39.61	34.74

Source: OURSE_QP results; "specs" stands for "fuels quality specifications".

The results of the two reverse environments are similar in terms of trends of the costs to the EU refineries. *Case 2* environment is in itself interesting to consider as this gives the costs estimates for European refineries without fuel quality improvement in all non-EU regions. However, given that *Case 1* is most relevant for our quantification of the likely costs due to the FQD/MFD legislation, we focus on the output of *Case 1* only. Using the average costs figures for the 2000-2005 and 2005-2010 sub-periods (reported in column 4 of Table 5.10) as our final estimates, we can conclude that tighter fuels qualities specifications over the 2000-2012 period for all European refineries cost, on average, from 154.27 to 463.97 mln USD per year of both CAPEX and OPEX expenditures. The corresponding upper bound could be considered the largest observed figure of 550.36 mln USD per year, obtained for the 2000-2005 sub-period using the standard rule calibration method. Average CAPEX costs are assessed to range from 102.48 to 408.35 mln USD per year, with an upper bound of 475.23

mln USD. Finally, the average OPEX are estimated to be in the range of 51.80 to 55.62 mln USD per year, and the corresponding upper bound is 75.13 mln USD.

The question is now how realistic are these numbers, given that this study is an *ex post* impact assessment study. In particular, we possess the relevant refinery data from Solomon Associates (2014) and CONCAWE, and thus it is interesting to compare our estimates with the observed data. Of course, given that any model is a simplification of the reality, i.e. there are way too many factors that influence business decisions, and these for obvious reasons cannot be taken into account in any type of modelling, ideal match cannot be obtained. Nevertheless, it is instructive to compare figures referring to more or less the same costs items and explain the differences.

The observed total costs of investments in new processing units and of their modifications for clean fuels of the EU-28 countries are reported in the first part of Table 5.11. In Solomon Associates' surveys taking place every even year, refineries are also asked about their capital expenditures for the study year, one-, two- and three-years prior to the survey date. One item of the refineries' capital investments include "investments in new process unit/modifications for clean fuels", distinguished by its three components related to investments needed to meet gasoline, diesel/gasoil and other specifications (we do not consider here these components separately). In each study year (bolded in Table 5.11) refineries report investment figures for each of the three previous years, and some discrepancies in reported figures occur in overlapping years due to variation in the participating refineries in any given study year, as can be seen in Table 5.11. We take here a pragmatic approach of considering both the maximum and minimum values of the two matching figures reported, which are presented in the second block of Table 5.11. If we take the average over 1999-2012 period, the observed costs of investments become 656 mln EUR per year when using minimum values of the matching figures, and 689 mln EUR per year if the maximum values are considered. The upper bound estimate of CAPEX in our modelling assessment was 475.23 mln USD per year, which would be roughly 399.3 mln EUR per year (using the average of 2000-2012 official exchange rates from Eurostat, which equals 0.8402 EUR per USD). Hence, Solomon Associates (2014) data report 1999-2012 average figures on European refineries' investments costs that are larger than our CAPEX upper bound estimate by factors of 1.6 to 1.7. These differences can be explained as follows.

Table 5.11: Investments in new process unit/modifications for clean fuels in the EU-28 (mln EUR)

	2012	2011	**2010**	2009	**2008**	2007	**2006**	2005	**2004**	2003	**2002**	2001	2000	1999
Total investments according to	134	385	549	673										
			537	699	883	668								

average values (actual investments)					942	790	699	779						
							683	846	1481	874				
									1428	888	686	652		
											648	605	377	514
Investments (min)	134	385	537	673	883	668	683	779	1428	874	648	605	377	514
Investments (max)	134	385	549	699	942	790	699	846	1481	888	686	652	377	514

Notes: Figures on EU-28 actual investments are obtained from Solomon Associates (2014), by multiplying the number of refineries participating in Solomon Associates' surveys and the reported average investments values. All figures are rounded to the nearest integer.

First, we should note that our modelling exercises assessed the impact of fuels qualities changes that took place within the 2000-2010 period. In particular, the most important ones were related to the changes in gasoline and diesel sulphur maximum limits that were implemented in 2005 and 2009. For heating oil the relevant limits changes occurred in 2008, while sulphur limit change of heavy fuel oil happened much earlier in 2003. Finally, for marine fuels the sulphur limits changes, taken into account by our modelling evaluation, were implemented in 2006 (4.5% and 1% sulphur limits) and in 2010 (the change to 3.5% and 1%, respectively). Taking into account this latest date captured in our modelling assessment, it makes sense for fair comparison purposes to consider the reported investments costs only for the period of 1999-2009 and annualise it over the entire 1999-2012 period. *This results in the observed annual investments costs comparable to OURSE outcomes of 581 mln EUR/year if minimum values of the matching cost numbers are chosen and 612 mln EUR/year if instead maximum values of the matching figures are used.* Comparing these to our upper bound CAPEX estimate of 399.3 mln EUR/year reduces the factor differences by 11% which now become 1.45 – 1.53.

Second, there are items and/or real refinery characteristics that are captured in the observed data but not in the OURSE model. These may include the following.

- There are items included in the observed investment costs figures that are not captured by the CAPEX coefficients of the OURSE model. For example, our personal communication with Solomon Associates' team revealed that "investments in the new units/modifications for clean fuels may well include OSBL [Outside Battery Limits] investments if they were needed as part of the project, such as a new tankage and any pipework, but will not include items such as control rooms, laboratories, or administrative facilities". Costs of *new tankage* and *pipework* is not captured by OURSE CAPEX figures, and there could be more factors that are not accounted for in our modelling framework, but still are important in the real-life refinery functioning and decision making.[13]

[13] A colleague from IFP Energies nouvelles (Paris, France) with an extensive expertise in both refining industry and OURSE modelling indicated that these extra real costs not accounted for by the model, if indeed taken place, could amount up to but not more than 20% of the obtained CAPEX estimates.

- Similar to the previous observation, yearly capital maintenance costs are not included in the model's CAPEX figures.[14] On the other hand, the observed investments costs include costs of replacement or modification of a unit that are not accounted for in OURSE.[15]
- Finally, OURSE has one representative refinery per region, implying that all the heterogeneities of individual refineries (in terms of complexity, location advantage, size, etc.) that we observe in real life within one region are not fully accounted for (which is an unfeasible task anyways). Thus, the model mainly accounts for common characteristics of refineries in each covered region.

Hence, a very conservative way to account for the discussed items missing in OURSE modelling assessment (see footnotes 13 and 14) could be to multiply the estimated CAPEX figure of 399.3 mln EUR/year by 1.35. This would have yielded a CAPEX estimate of 539 mln EUR/year that would have decreased the difference factor gap by additional 26% and the difference factor would have been only 1.1. We, however, do not do such upward adjustments in our final estimates mainly because of the lack of the relevant information but at the same time caution the reader about the mentioned underestimation possibility. Another explanation of this remaining gap is that OURSE costs estimates are expressed in *constant 2008 prices*, while those based on Solomon Associates (2014) data are given in *current prices*. All in all, given our discussions above and the fact that a modelling world cannot account for all factors, we may conclude that our OURSE_QP outcomes reasonably evaluate the likely impact of the FQD/MFD directives on the EU refineries in terms of incurred costs.

Finally, we present the costs estimates in terms of total crude processed. This normalisation is useful also for comparison of the modelling outcome and the observed figures, given that the processed crude figures will also vary in these cases. More importantly, the normalised costs estimates are easier to understand in many contexts. As a normalising factor we chose processed crude oil, but not total throughputs given that the last does not include exactly the same components in the model and the observed figures (for example, refined products used as intermediates are not modelled in OURSE). The figures of Case 1 in Table 5.10 are first normalised by processed crude oil. Given that the NE and SE regions include non-EU countries as well, the obtained processed crude had to be slightly adjusted downwards. Using the IEA data we found that the shares of the EU countries in the NE and SE crude consumption were 0.93 and 0.87, respectively, in both years of 2005 and 2010. Consequently,

[14] Related to the previous footnote, the rough bias from ignoring capital maintenance costs could be around 10%-15% of the estimated CAPEX figures (source: personal communication with a colleague from IFP Energies nouvelles). We note that these are extra possible differences in addition to the bias just indicated.

[15] In Solomon Associate's (2014) Input Form and Instructions describing the data it is written that the item of investments costs in new units also "includes any applicable replacement or modification of a unit if the cost exceeds 50% of the total replacement costs or the project increases capacity greater than 40% of that unit".

these numbers were used to obtain crude oil processed in NE and SE solely by EU countries. The figures then were converted to EUR using the average of EUROSTAT official exchange rates over the covered period of 2000 to 2012 (which is equal to 0.8402 EUR per USD), and then divided by 7.33 (a conversion factor that is based on worldwide average gravity) to get costs per *barrel* of processed crude oil. These results are reported in Table 5.12.

Table 5.12: CAPEX and OPEX in eurocents per barrel of processed crude oil (at constant 2008 prices)

	2000-2005 (1)	2005-2010 (2)	Average of (1) and (2)	2000-2010
		Annualised CAPEX		
Standard rule	8.9	6.9	7.9	2.9
Average cost rule	2.2	1.9	2.1	1.5
		Annualised OPEX		
Standard rule	1.4	0.7	1.1	0.9
Average cost rule	1.3	0.8	1.0	1.0
		Total annualised CAPEX and OPEX		
Standard rule	10.3	7.6	9.0	3.8
Average cost rule	3.5	2.7	3.1	2.5

Source: OURSE_QP results.

It turns out that all the discussions on comparing OURSE costs results in absolute terms with the observed CAPEX figures that we made extensively above, hold *exactly* also for the normalised costs. Thus we do not repeat this discussion here again. We conclude that *tighter fuels qualities specifications over the 2000-2012 period for all European refineries, according to the OURSE estimates, cost on average from 3 to 9 eurocents (at constant 2008 prices) per barrel of processed crude per year of both CAPEX and OPEX expenditures*. *The corresponding upper bound is 10.3 eurocents per barrel of processed crude per year*. *Average annual CAPEX costs are assessed to range from 2 to 8 eurocents per barrel of processed crude, with an upper bound of 9 eurocents. Finally, the average annual OPEX are estimated to be 1 eurocent per barrel of processed crude oil, with an upper bound of 1.4 eurocents*. Of course, the possibility of CAPEX costs underestimation due to the reasons discussed earlier in detail is still valid, but generally as mentioned earlier the modelling results are considered to be reasonable.

5.2.1.2 Benefits

The benefits of the FQD and MFD directives in terms of minimizing human influence on environment are straightforward and are studied extensively elsewhere (see e.g. the impact assessment documents of the FQD, or Le Tertre et al., 2014). These are also discussed in more detail in the relevant overview chapters of the REFIT study. Quantification of such environmental benefits (e.g. reduction in GHG emissions due to the use of cleaner fuels by consumers and/or producers) is, however, outside the scope of the OURSE modelling framework and rather needs a different type of modelling framework (e.g. models used in transport economics, economy-wide simulation models, econometric input-output models, or computable general equilibrium framework). Therefore, the issue of incurred benefits due to the implementation of the FQD and MFD requirements will not be further considered in this study.

5.2.1.3 Trade and competitiveness

The simulations results discussed in this section do not fix the baselines' trade flows of refined products as was required before. Instead now we focus on the likely impact of fuels specifications change on interregional trade flows, hence also on international competitiveness of the EU refineries. From the outset we note that considering competitiveness within a trade setting only is a rather narrow definition of competitiveness in general, as other factors may well influence a refinery's competitive position both in domestic and global markets.

Table 5.13: Production of the refineries (standard calibration rule)

	NA	SA	NE	SE	RS	AF	ME	CH	AS
	Counterfactual production (mln tonnes, 2005)								
Light	486.8	72.4	174.8	70.2	69.4	25.0	82.2	104.5	240.2
Medium	333.9	81.1	211.8	101.0	89.3	52.5	135.7	117.9	368.3
Heavy	126.2	47.4	79.8	57.3	78.4	36.7	102.5	31.8	121.5
	Counterfactual - Baseline (mln tonnes, 2005)								
Light	1.0	0.5	0.7	-0.7	-0.8	0.5	-2.0	0.3	0.6
Medium	-0.3	0.1	-0.5	1.6	0.9	-0.1	-1.8	0.0	0.1
Heavy	-2.3	2.6	1.7	-0.5	0.0	-1.2	0.2	0.0	-0.7
	Counterfactual production (mln tonnes, 2010)								
Light	469.8	70.2	161.8	67.3	75.2	37.8	105.8	147.4	263.2
Medium	326.6	79.9	213.3	91.9	99.9	51.2	147.8	171.0	394.7
Heavy	107.0	45.7	61.5	44.8	76.2	27.0	98.7	34.1	96.4
	Counterfactual - Baseline (mln tonnes, 2010)								
Light	-0.4	-0.1	0.6	0.6	-0.1	0.6	1.6	-0.1	-2.7
Medium	-8.4	0.9	8.0	0.0	0.8	-0.2	2.3	-0.5	-2.8
Heavy	4.1	-0.2	2.7	2.0	-6.2	-3.7	-3.8	-1.0	5.6

Source: OURSE_QP results

In Table 5.13 production figures and the difference between those of the counterfactual and baseline scenarios are reported. The counterfactual represents *Case 1* hypothetical environment (trade calibration is based on standard rule). What we observe is that Europe as a whole in both periods *increases* its production of light, medium and heavy products, except for no change in light products production in the first period. This is primarily caused by the fact that in response to the relaxed sulphur specifications on all fuels, in the counterfactual scenario EU refineries are able to process more throughputs, including heavier crude. For example, in the 2010 scenario the total throughputs in North Europe and South Europe increase by 2.6% and 1.3%, respectively.

Table 5.14: Changes in trade (counterfactual - baseline, mln tonnes), 2010

	NA	SA	NE	SE	RS	AF	ME	CH	AS	*Total*
					Light products					
NA	0.00	0.16								*0.16*
SA	0.09	0.00								*0.09*
NE	0.77				0.22	-0.28	-0.14			*0.58*
SE	0.45					0.19	0.00			*0.64*
RS	0.06								0.02	*0.08*
AF						0.00			0.47	*0.47*
ME							0.00		1.44	*1.44*
CH									-0.17	*-0.17*
AS	-0.79				0.00			-0.10		*-0.89*
Total	*0.58*	*0.16*			*0.22*	*-0.09*	*-0.14*	*-0.10*	*1.76*	*2.39*
					Medium products					
NA	0.00	-1.94	-9.25					0.44		*-10.76*
SA	-1.02									*-1.02*
NE										
SE						-0.12				*-0.12*
RS			0.91	-0.16						*0.75*
AF						0.00				*0.00*
ME			0.36	0.06		0.26	0.00			*0.68*
CH										
AS	-1.34					0.08	-1.61	0.02		*-2.85*
Total	*-2.36*	*-1.94*	*-7.98*	*-0.10*		*0.22*	*-1.61*	*0.46*		*-13.32*
					Heavy					
NA									1.12	*1.12*
SA	-2.63									*-2.63*
NE	0.86									*0.86*
SE								0.13	-3.36	*-3.24*
RS			-1.85	-5.25				0.95	-0.04	*-6.19*
AF	-1.22	-2.44				0.00				*-3.66*
ME						-0.48		-0.09	-3.27	*-3.84*
CH										
AS										
Total	*-3.00*	*-2.44*	*-1.85*	*-5.25*		*-0.48*		*0.99*	*-5.56*	*-17.58*

Source: OURSE_QP results. Trade calibration is based on the standard specification rule.

An increase in European fuel production has straightforward implication in terms of EU import dependency. The product balances tell us that per product we have the following accounting identity: production + imports = exports + consumption. Given that consumption figures are fixed in our counterfactual scenarios, in terms of changes the last identity boils down to (change in production) = (change in net exports). Thus, our finding of higher production implies also that the EU net exports position for light, medium and heavy products would have improved with the relaxed fuel quality specifications in place. This also largely explains the resulting trade flows. As an example, the differences between the counterfactual and baseline trade flows for 2010 are given in Table 5.14. One can observe from Table 5.14 that indeed with relaxed sulphur regulation Europe increases its gasoline exports to the US. This is possible because even if Europe would have had its 2005 gasoline maximum sulphur limit of 50 ppm (instead of 10 ppm), that would be still stricter than the corresponding 2010 US limit of 80 ppm. Similarly, in general, the EU decreases its *overall* imports dependency of middle and heavy products. The decrease in middle products imports comes mainly by reducing EU imports from the US, because of higher transportation costs, if compared to imports from Russia. A relatively small increase of middle products imports from Middle East reflects EU imports of jet fuel.

One of the indicators of industry performance or industry competitiveness is the so-called *relative trade balance* (RTB), which measures the trade balance relative to total trade in a sector and for product i is defined as (see e.g. European Commission, 2009):

$$RTB_i = \frac{X_i - M_i}{X_i + M_i}, \tag{9}$$

where X_i and M_i are, respectively, exports and imports of product i. Of course, it should be noted that negative RTB reflecting negative trade balance is not necessarily a bad thing, since imports also contribute to the domestic economy and stimulate production in (usually) more than one sector. In addition, trade balances reflect domestic and foreign demand. Thus, "this indicator does not exclusively reflect external competitive strength; it also indicates a difference between domestic and international demand" (EC, 2009, p. 136).

Table 5.15: Europe's relative trade balance (RTB) for all refined products

	2000	2005	2010	2000	2005	2010
	Standard rule			Average cost rule		
Baseline	-0.391	-0.208	-0.190	-0.436	-0.314	-0.242
Counterfactual	-0.391	-0.194	-0.125	-0.436	-0.300	-0.228
Counterfactual – Baseline	0.000	0.014	0.065	0.000	0.014	0.015

Source: OURSE_QP results. Counterfactual scenario corresponds to *Case 1* environment.

For Europe as a whole the RTB index for all petroleum products were computed both for the baseline and counterfactual scenarios. The corresponding results are reported in Table 5.15. In both scenarios for all years the European refinery RTB's are negative, indicating that more petroleum products were imported to Europe than exported by Europe to the rest of the world. However, in both scenarios the negative values of the RTB's are decreasing (in absolute value), indicating improvement of the refining industry performance over time. This period-to-period improvement is somewhat better in the counterfactual scenario. Next if we compare the counterfactual with the baseline scenario, we find that, in general, the external competitive strength of Europe is higher in the counterfactual scenario, and this difference is increasing over time. Hence, *according to the RTB indicator, the European refining industry would have been somewhat more internationally competitive in a counterfactual situation where tighter fuels quality specifications would have not been imposed in Europe.* Again we remind that this result is not exclusively about the external competitive strength of Europe only, but also reflects the optimal reaction of all (representative) refineries world-wide to the assumed counterfactual changes in Europe.

5.2.2 Impact assessment of changes in products demand

The most relevant consequence of the Renewable Energy Directive (RED) and Energy Taxation Directive (ETD) for the EU refineries is lower demand for refined products due to, respectively, (a) substitution of the traditional fuels by biofuels, and (b) reduced fuels demand because of higher fuel prices caused by an increase in minimum energy tax levels in those Member States where such a change in minimum taxation was binding in comparison to their actual national taxation levels. Therefore, in both cases one may argue that without the RED and ETD in place, one would expect higher demand for refined products. Since both of the mentioned directives have an immediate impact of demand, their likely impact will be jointly assessed in this modelling study. In what follows we first quantify the changes in fuels demand caused by the RED and ETD, and then evaluate the impact of the counterfactual increased demand on the EU refining business.

5.2.2.1 Demand change due to the RED and ETD

Quantifying fuels demand without biofuels is rather straightforward: rather than using the various biofuels targets indicated in the so-called National Renewable Action Plans, which in the majority of cases were not met by Member States in time, we collect real data on biofuels consumption and assume it to be instead *extra demand* for traditional relevant fuel in a counterfactual scenario without biofuels. Hence, using the IEA World Renewable and Waste Energy Statistics database we obtained the consumption (i.e. domestic supply) figures of *biogasoline* and *biodiesels* for all OURSE regions, including EU countries separately.[16] The

[16] The IEA definitions of the two biofuels are as follows. Biogasoline includes bioethanol (ethanol produced from biomass and/or the biodegradable fraction of waste), biomethanol (methanol produced from biomass and/or the biodegradable fraction of waste), bioETBE (ethyl-tertio-butyl-ether produced on the basis of bioethanol: the percentage by volume of bioETBE that is calculated as biofuel is 47%) and bioMTBE (methyl-tertio-butyl-ether produced on the basis of biomethanol: the percentage by volume of bioMTBE that is calculated as biofuel is 36%). Biodiesels consist of biodiesel (a methyl-ester produced from vegetable or animal oil, of diesel quality), biodimethylether (dimethylether produced from biomass), Fischer Tropsch (Fischer

relevant data that was first made consistent with the OURSE classification is shown in Table 5.16. For our three modelling periods the obtained 1998-2012 IEA data was transformed as follows: for 2000 we chose the average of 1998-2002 IEA data, for 2005 – average of 2003-2007 IEA data, and for 2010 – average of 2008-2012 IEA data. Note that we have first converted the relevant IEA data expressed in kt to energy units (i.e. in ktoe). [17]

In Table 5.16 we also give the percentages of biogasoline and biodiesels consumption in, respectively, the relevant baseline demand for gasoline and diesel oil. For this purpose the demand data were also expressed in energy terms using the relevant data reported in Table 6.1. What we observe is that the "share" of biogasoline in gasoline demand for North Europe was 0.6% in 2005 and increased to 3.1% in 2010, while the respective figures for South Europe were 0.3% and 1.0%. The "penetration rates" of biodiesels were higher than those of biogasoline. That is, in NE in 2005 the size of biodiesels consumption relative to diesel demand was 2.2% which further increased to 5.4% by 2010. The respective figures for SE are 0.6% and 4.1%.

Table 5.16: Biogasoline and biodiesels consumption (ktoe)

	Biogasoline (ktoe)			Biodiesels (ktoe)		
	2000	2005	2010	2000	2005	2010
NA	3939	9585	23463	16	434	1619
SA	3070	3433	3856		70	2004
NE	67	518	2193	552	2616	7133
SE	14	103	300	40	375	2814
RS						23
AF			3			
CH		335	1060		52	130
AS	48	176	652	0	66	1119
	Biogasoline/(Baseline gasoline demand)			Biodiesels/(Baseline diesel demand)		
NA	0.9%	2.0%	5.2%	0.0%	0.3%	1.1%
SA	8.3%	9.1%	8.3%		0.2%	3.6%
NE	0.1%	0.6%	3.1%	0.5%	2.2%	5.4%
SE	0.0%	0.3%	1.0%	0.1%	0.6%	4.1%
RS						0.1%
AF			0.0%			
CH		0.7%	1.4%		0.1%	0.2%
AS	0.0%	0.1%	0.5%	0.0%	0.1%	0.9%

Source: IEA World Renewable and Waste Energy Statistics.

Table 5.16 also shows that, if compared to other regions, NE and SE were top consumers of biodiesels (relative to the corresponding demand for diesel oil), while in terms of biogasoline

Tropsch produced from biomass), cold pressed biooil (oil produced from oil seed through mechanical processing only) used straight as road diesel or for electricity and heat generation.

[17] The relevant conversion factors were obtained from European Commission (2006).

South America is the top consumer with a very large (compared to other regions) and stable "share" of 8% to 9% in SA's gasoline demand. This is, of course, not surprising as Brazil is known to be one of the largest world producers of biogasoline and in fact is the sole main contributor to biogasoline consumption in the SA region.

Quantification of reductions in fuels demands due to the ETD is more complicated. There are potentially many options on the table, including using various large-scale complicated models. Given that there will never be *real* fuel consumption figures on the impact of the ETD available and there will always be uncertainties in their estimates, we adopted a rather straightforward and conservative (in the sense of giving maximum possible demand impact) approach, which is discussed in detail and implemented in the ETD overview chapter. Thus, these discussions are not repeated here. It is just worth mentioning that in translating the assessed price changes of gasoline and diesel into the corresponding quantity demand changes, the estimates of gasoline and diesel price elasticities of transport fuel demand reported in an extensive study of Dahl (2012) were used. Dahl (2012) presents two estimates of gasoline demand price elasticities, one set of which takes into account the impact of introduction of turbo-charged fuel injection diesel engines in Europe causing a switch from gasoline use to diesel consumption. In particular, the author "increased gasoline demand price elasticities by 50% for all those countries that have seen a strong switch towards diesel fuel with gasoline consumption decreasing" (Dahl, 2012, p. 7). We used the higher reported gasoline demand price elasticities that tries to explicitly account for European fuel consumption switch from gasoline to diesel.

Of course, not all Member States were affected by the ETD requirements, as one of the main objectives of changing minimum taxation levels was harmonizing taxation of energy products across Member States. The ETD overview chapter analyses the relevant price and demand impacts on Member-States level, but here we investigate the impact at the more aggregate level of North Europe and South Europe. The OURSE-relevant final estimates of demand reductions obtained in the ETD analysis are reported in Table 5.17.

Table 5.17: Estimated demand reductions in NE and SE due to ETD (in kt)

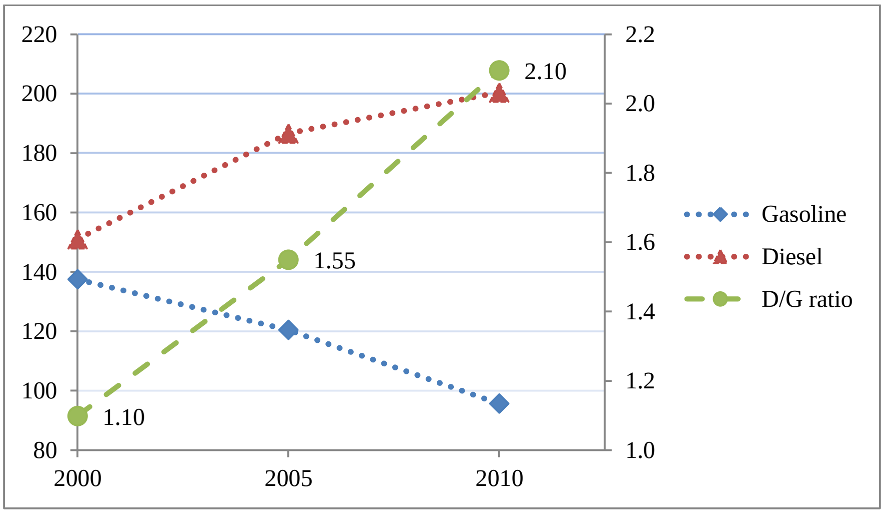
	Demand change (kt)		**Share in baseline demand**	
	2005	2010	2005	2010
	North European EU countries (EU1)			
Gasoline	102.15	114.61	0.12%	0.17%
DieselOil	72.51	175.65	0.06%	0.13%
	South European EU countries (EU2)			
Gasoline	84.14	122.24	0.24%	0.45%
DieselOil	99.08	408.93	0.15%	0.60%
	D/G ratios with ETD		**D/G ratios without ETD**	

EU1	1.468	1.994	1.467	1.993
EU2	1.858	2.384	1.856	2.389
EU1 & EU2	1.576	2.099	1.575	2.100

Source: Own calculations. D/G stands for the ratio of diesel demand to gasoline demand.

The first observation to be made from demand reduction figures in Table 5.17 and Table 5.16 is that the ETD had much lower impact on demands compared to the RED, in particular, at the entire European level. This is to be expected since the Member States directly affected by the ETD newly set minimum taxation levels were mostly small economies compared to the other EU national economies (see the ETD overview chapter). The demand reductions relative to the corresponding baseline demands shows a maximum percentage change of only 0.17% in North Europe for gasoline in the modelling period of 2010. For South Europe the maximum change of 0.60% was estimated for diesel oil demand during the same modelling period of 2010. Note that the demand impacts (relative to baseline observed demand levels) in SE were always larger than those is NE by factors ranging roughly from 2.0 to 4.5.

Figure 5-1: The trends of European demands for gasoline and diesel (baselines data)



Note: "D/G ratio" refers to the ratio of European diesel demand to European gasoline demand, whose scale is given in the right-hand side vertical axis. The unit for the left-hand side vertical axis is mln tonnes.

In the bottom of Table 5.17 also the ratios of diesel demand to gasoline demand (D/G ratio) as observed with the ETD in place, and D/G ratios in the counterfactual environment without the ETD are given. The same figures for the observed demand are illustrated in Figure 5-1. In particular, it shows that the ratio of observed (i.e. baseline) European demand for diesel to that for gasoline was 1.10 in 2000, 1.55 in 2005, and further increased to 2.10 by 2010. The respective ratios for all EU countries only are very similar and were equal to 1.12, 1.57 and 2.10 for the mentioned periods, respectively. This mismatch of the EU diesel-gasoline demand with the relevant supply of the gasoline-oriented EU refineries is by now a widely known issue that has implication for European refining industry (e.g. overcapacity problem). However, comparing the observed and counterfactual D/G ratios in Table 5.17 we observe very negligible changes in these ratios from -0.07% to 0.21%. This implies that we do not find any discernable impact of the ETD in terms of the European consumption switch from gasoline to diesel at this level of aggregation. Further details of this impact at the Member State level is discussed in detail the ETD overview chapter.

Similar to the RED modelling, in the counterfactual scenario without the EDT the fuels demand would be higher by the amounts shown in Table 5.17. To conclude, the European demand change figures due to both the ETD and RED are for easier comparison purposes presented together in Table 5.18. The last two rows in this table show that the overall European gasoline and diesel demand changes are mainly driven by biofuels substitution of these products, implying that any aggregated European results related to gasoline and diesel demand changes are to the large extent caused by biofuels consumption impact on the refining industry rather than that of the EU minimum energy taxation changes. The only exception is for gasoline demand change in the first period in SE, where the impact of the ETD and RED is roughly the same (i.e. the respective contributions to the overall 2005 demand change are 46% and 54%). While in NE biofuels policy has dominating effect responsible for at least 82.9% of the demand changes, in SE this impact is somewhat smaller, where the ETD accounts for 12.1% to 46.1% of the demand changes for gasoline and/or diesel.

Table 5.18: Summary of demand changes due to ETD and RED (mln tonnes)

		Demand change due to ETD		**Demand change due to RED**		**Demand change due to both ETD and RED**	
		2005	2010	2005	2010	2005	2010
NE	Gasoline	0.10	0.11	0.49	2.09	0.60	2.20
NE	DieselOil	0.07	0.18	2.59	7.06	2.66	7.24
SE	Gasoline	0.08	0.12	0.10	0.29	0.18	0.41
SE	DieselOil	0.10	0.41	0.37	2.79	0.47	3.20
		Contributions of the ETD and RED to total demand change					
NE	Gasoline	17.1%	5.2%	82.9%	94.8%	100%	100%
NE	DieselOil	2.7%	2.4%	97.3%	97.6%	100%	100%
SE	Gasoline	46.1%	29.9%	53.9%	70.1%	100%	100%
SE	DieselOil	21.1%	12.8%	78.9%	87.2%	100%	100%
NE&SE	Gasoline	23.9%	9.1%	76.1%	90.9%	100%	100%
NE&SE	DieselOil	5.5%	5.6%	94.5%	94.4%	100%	100%

Source: Own calculations.

The proportions of total demand changes due to both the ETD and RED relative to the relevant baseline demand levels for gasoline and diesel oil are also given in Table 5.19. These figures are used in increasing (giving shock to) the exogenous gasoline and diesel demands in

OURSE assessment exercises. One can readily see from the table that larger demand impacts are estimated for the second period for both fuels, with corresponding factor differences ranging from 2.5 to 6.6. On the other hand, larger changes are obtained for diesel demand compared to gasoline demand changes for both European regions and both periods, where the relevant factor differences range between 1.4 and 3.2.

Table 5.19: Total demand increase relative to the baseline demand (%)

		2005	2010
NE	Gasoline	0.70%	3.23%
SE	Gasoline	0.51%	1.49%
NE	DieselOil	2.21%	5.49%
SE	DieselOil	0.71%	4.66%

Source: Own calculations.

5.2.2.2 Costs

Given that we have two sub-period demand changes due to the relevant fuel price increase, we run two sets of counterfactual scenarios of 2000-2005 and 2005-2010. Here we do not consider the counterfactual covering the entire period 2000-2010, as it makes more sense to implement demand changes for the two of its sub-periods separately due to higher demand levels in 2005. Not accounting for this trend in demand would be particularly inappropriate in analysing demand shocks scenarios.

It is clear that higher exogenous demand within the model will always result in higher CAPEX and OPEX expenditures. By simply running the model with higher demands, it was found that capital investments similar to those in our earlier assessment of the FQD/MFD directives are required. This in essence means that even though demand for fuels are higher without the RED and ETD, refineries still have to obey by the European fuel specifications which require additional investments. As a result this would imply that refineries "benefitted" from lower demand, otherwise they would have had to make additional investments. However, one can argue that this makes little sense since those costs are already taken into account in the FQD/MFD assessment. We solve this problem by changing the original capacities in the counterfactual scenario in such a way that the new solution does not require any new (endogenous) investments in processing units. Technically, such evaluation procedure consists of two steps. In the first step the new counterfactual scenarios are run with corresponding original capacities that results in additional investments. Then in the second step the same counterfactual are implemented but with adjusted capacities, where we add the new investments from the first step outcome to the original capacities. This results in zero investments in processing units, and also lower OPEX compared to the first-step results.

The question now is what are refineries' costs related to the RED and ETD directives? We consider *forgone earning* due to lower demand as "costs" incurred by the EU refineries. That is, in the counterfactual scenario without the RED and ETD, the EU refineries would have made more (gross and net) revenues due to higher demand for gasoline and diesel. To estimate these *net forgone revenues* (i.e. profits), the baseline and counterfactual (from the mentioned second step estimation) results for all refined products are valued at their corresponding *shadow prices* as provided endogenously by the model. Then, per region (refinery), by subtracting from these revenues the costs of:

- crude and feedstock (atmospheric residue) purchases, including transportation costs,
- other inputs, such as natural gas, ethanol, methanol, etc., and
- OPEX costs,

we obtain the estimates of the forgone net earnings. Thus, the (opportunity) costs of the refineries due to the RED/ETD is calculated as

$$\begin{aligned}&\text{Net forgone earnings due to RED/ETD}\\&\qquad = (\text{Total revenues without RED/ETD } - \text{Total costs without RED/ETD})\\&\qquad - (\text{Total revenues with RED/ETD } - \text{Total costs with RED/ETD}).\end{aligned}$$

To give a full picture of our derivations, we provide the estimation details on an arbitrary chosen scenario of the second period (average 2010) demand change when the standard calibration approach is used. These are reported in Table 5.20.

Table 5.20: Details of forgone net earnings derivations (2010, standard calibration rule)

	Production (mln tonnes)				Shadow prices (USD per tonne)				Revenue (mln USD)			
	with RED/ETD		without RED/ETD		with RED/ETD		without RED/ETD		with RED/ETD		without RED/ETD	
	NE	SE	NE	SE	NE	SE	NE	SE	NE	SE	NE	SE
LPG	22.9	11.8	22.9	11.8	814	1197	817	1119	18635	14065	18717	13151
Naphta	42.4	10.2	42.4	10.2	763	712	763	720	32373	7286	32381	7374
Gasoline	95.9	44.6	98.1	45.0	787	717	788	732	75455	32015	77328	32964
JetFuel	31.7	12.2	31.7	12.2	763	711	763	720	24166	8695	24172	8801
HeatingOil	60.6	29.1	60.6	29.1	754	707	755	715	45656	20589	45707	20827
DieselOil	113.1	50.5	120.3	53.7	764	717	765	726	86364	36221	92018	38983
ResFuelOil	9.5	16.2	9.5	16.2	636	682	633	673	6065	11049	6040	10903
Bitumen	12.8	9.4	12.8	9.4	544	610	540	596	6963	5723	6908	5598
PetCoke	5.2	5.3	5.2	5.3	619	609	609	589	3237	3239	3185	3131
MarinBunk	36.4	17.2	36.4	17.2	636	682	633	673	23157	11745	23059	11590

	with RED/ETD		without RED/ETD	
Total revenues	*322071*	*150627*	*329516*	*153321*
Costs (mln USD)				
Crude & feedstock	285445	135319	292298	137728
Crude transportation	5093	4336	5208	4410
Other inputs costs	9335	3674	9546	3748

CAPEX costs	6379	800	6379	800
OPEX costs	4904	2012	4985	2048
Total costs	*311156*	*146141*	*318415*	*148734*
Net revenues	*10915*	*4487*	*11101*	*4587*
Forgone net earnings due to RED/ETD (mln USD)			*186*	*101*

Source: OURSE_QP results.

Baseline (with RED/ETD) and counterfactual (without RED/ETD) production levels for North and South Europe are given in the second to fifth columns in Table 5.20. Then shadow prices of the corresponding fuels are reported. We do not use exogenous prices (i.e. prices excluding duties and taxes) because this would be inconsistent with the model outcomes (e.g. the shadow prices of the same fuel are different between the baseline and counterfactual scenarios reflecting different economic environments of the two cases). These two sets of outcomes are used to compute the gross revenues of the two regions, which are presented in the last four columns of the top part of Table 5.20. The bottom part of the table provides the details of the associated costs. Subtracting the counterfactual net revenue from that of the baseline scenarios gives us finally the estimate of net forgone earnings of *287 mln USD per year* for all European refineries. These are estimates per year, because the estimated demand changes due to both RED and ETD are average changes over the two periods of 2003-2008 and 2009-2012/13. Note that the net forgone earnings in NE are larger than thos in SE mainly because the positive changes in gasoline and diesel demands are larger in NE than in SE.

The aggregate European outcomes of the net forgone earnings (or costs) due to the RED/ETD are summarized in Table 5.21. Taking the averages of the two periods, *the estimates of the RED and ETD-related costs, incurred by the EU refineries in the form of net forgone earnings, are assessed to range from 200 to 205 mln USD per year. The corresponding upper bound estimate is 298 mln USD per year*, which corresponds to the EU refineries' forgone earnings in the second period. The first period estimates are lower than their corresponding second-period costs because in the second period the size of demand reductions is higher (see Table 5.19). Recall also our earlier discussions that these changes are to the large extent driven by the RED rather than ETD impact.

Table 5.21: Forgone earnings and net margins of the EU refineries due to RED and ETD

	2000-2005 (1)	**2005-2010 (2)**	**Average of (1) and (2)**
	Net forgone earnings due to RED/ETD (mln USD per year)		
Standard calibration rule	113	287	200
Average cost rule	111	298	205
	Forgone net margins due to RED/ETD (USD/bbl)		
Standard calibration rule	3.8	3.0	3.4

Average cost rule	3.9	3.1	3.5

Source: OURSE_QP results. Net margins are computed as *extra* net earnings per *extra* crude and feedstock processed by European refineries (i.e. extra = counterfactual – baseline).

The question is now how realistic are the derived costs estimates due to the RED/ETD directives. To answer this question we compute the underlying net margins of these estimates, that is the obtained net earnings are divided by the extra European throughput needed to satisfy the changes in demand. These are reported in the bottom part of Table 5.21. The implied net margins thus range on average from 3.4 to 3.5 USD per barrel of throughput, with a maximum net margin of 3.9 USD/barrel of throughput. These are entirely realistic figures, if not somewhat overestimated, and are in general consistent with the HIS margins data. This means that our results do make sense, given that one could simply calculate the EU refineries' forgone net earnings (costs) by multiplying the average observed net margins by the extra required throughput for the relevant period, and the results would be have been close to what is reported in Table 5.21.

As in case with the FDQ/MFD directives, we provide the final results presented in Table 5.21 in EUR and per processed crude. These are reported in Table 5.22. Thus, the *net forgone earnings of the EU refineries due to the RED and ETD directives are assessed to be, on average, roughly 4 eurocents per barrel of processed crude oil per year, with an upper bound of 6.2 eurocents per barrel of processed crude.*

Table 5.22: Net forgone earnings due to the RED and ETD directives, in eurocents per processed crude oil (constant 2008 prices)

	2000-2005 (1)	2005-2010 (2)	Average of (1) and (2)
Standard calibration rule	2.1	5.8	4.0
Average cost rule	2.2	6.2	4.2

Source: OURSE_QP results.

If one is interested in the separate contribution of the ETD and RED directives, then from the bottom part of Table 5.18 one can find that the *overall average* contributions of the ETD and RED impact on the entire EU demand changes over 2000-2012 period are 11% and 89%, respectively. These numbers can be used to correspondingly allocate the total EU-wide estimated costs to ETD and RED. Hence, *the annual net forgone earnings of the EU refineries due to the RED directive are estimated to be, on average, 3.65 eurocents per barrel of processed crude oil. The remaining 0.45 eurocents per barrel of crude are thus the average annual net forgone earnings of the EU refineries due to the ETD directive.*

5.2.2.3 Capacity utilisation rates and the EU trade dependency

Higher demand with fixed exports and imports automatically implies higher production levels in the EU regions. This also means higher capacity utilisation rates of the EU refineries. The percentage changes in utilisation rates of *crude distillation unit* (CDU) in North Europe and South Europe due to lower demands related to the RED and ETD directives relative to those in the counterfactual scenarios are reported in Table 5.23. It shows that compared to the counterfactual CDU utilisation rates without the RED and ETD in place, on average the baselines CDU utilisation rates decreased from 0.9% and 1.9%. Thus, *the RED and ETD are found to cause a reduction of the EU refineries' utilisation rates, on average, by 0.9% to 1.9% over the entire 2000-2010 period*. These figures are higher (in absolute value) in NE than in SE by average factor of 1.8 to 2.2, which as discussed earlier is caused mainly due to higher penetration of biofuels in NE than in SE (see Table 5.18) and also due to larger demand changes in NE as caused by the ETD directive. The maximum reduction of 3.1% utilisation rate is observed in the second sub-period of 2005-2010 in NE, which is due to larger relevant changes in demand. On average, the reduction in utilisation rates in the second sub-period is assessed to be larger than those in the first sub-period by factor of 2.2 to 4.2.

Table 5.23: Reduction in utilisation rates of CDU due to RED and ETD (%)

	2000-2005 (1)	**2005-2010 (2)**	**Average of (1) and (2)**
		Standard calibration rule	
NE	-1.4	-2.1	*-1.7*
SE	-0.3	-1.7	*-1.0*
Average	*-0.8*	*-1.9*	*-1.4*
		Average cost calibration rule	
NE	-0.6	-3.1	*-1.9*
SE	-0.4	-1.3	*-0.9*
Average	*-0.5*	*-2.2*	*-1.4*

Source: OURSE_QP results. CDU stands for crude distillation unit.

In terms of trade the RED and ETD theoretically have two opposite effects. On the one hand, larger European conventional diesel demand has to be satisfied, and given that European refineries are mainly gasoline-oriented, Europe dependence on diesel imports (notably, from Russia) is expected to increase. On the other hand, more European conventional gasoline demand can reduce Europe dependence on gasoline exports markets (notably, to the US). However, it should be noted that these are not two separate effects. If European refineries increase their production of gasoline in response to higher gasoline demand, this will also allow them to increase their diesel production. Thus, there is no straightforward one-to-one link of the mentioned imports and exports effects to the exogenous changes in diesel and gasoline demands, respectively. This calls for modelling assessment.

The relevant OURSE results with free trade are reported in Table 5.24. In terms of gasoline exports there seems to be a rather small impact. For example, *in the environment without the RED and ETD, on average over the 2000-2012 period, European gasoline exports are estimated to decrease only by 1%* (according to the average cost calibration method; the standard rule essentially does not show any discernable average impact). However, the impact is somewhat larger in terms of the EU diesel imports dependency. It is assessed that *in the counterfactual situation without the RED and ETD in place, European imports of diesel oil would have increased, on average over the 2000-2010 period, by 1% to 6.3%, with an upper bound of 8.9% increase in imports* corresponding the 2005-2010 period (average cost calibration rule). These flows are all related to Russian exports of diesel oil. *Thus, if one focuses on trade dependency issues, reduction in diesel imports dependency of the EU (from Russia) can be considered as the most noticeable (obvious) EU-wide benefit that the RED and ETD directives brought about*.

Table 5.24: Changes in European gasoline exports and diesel imports without the ETD and RED

	2000-2005 (1)	**2005-2010 (2)**	**Average of (1) and (2)**
	Change in European gasoline exports (%)		
Standard calibration rule	-0.3%	0.5%	0.1%
Average cost calibration rule	-0.6%	-1.5%	-1.0%
	Change in European diesel imports (%)		
Standard calibration rule	0.4%	1.6%	1.0%
Average cost calibration rule	3.7%	8.9%	6.3%

Source: OURSE_QP results.

5.2.3 Impact assessment of changes in pollution limits

The detailed discussion of the Large Combustion Plants Directive (LCPD), Integrated Pollution Prevention and Control Directive (IPPCD), and Air Quality Directive (AQD) are given in the relevant overview chapters of the REFIT study. The main message taken from these discussions relevant for OURSE modelling is that during the time period analysed here there were no strict and definitive legal obligations imposed on industrial activities (including refining of mineral oil and gas) with regard to their emissions reduction. In addition, the long-term objectives of the directives were implemented very differently across Member States during the time period analysed here. Hence, there do *not* exist objective and well-defined policy instruments (measures) that could be used in our OURSE evaluation of the likely impact of the LCDP, IPPCD and AQD. Therefore, instead we use a pragmatic approach of applying the *observed emission intensities* (i.e. emissions generation per processed crude) in the modelling exercises, the details of which is given below. From the list of emissions that are targeted by the mentioned directives, in OURSE only sulphur dioxide (SO_2) emissions are modelled, hence only the impact of SO_2 emissions regulations will be considered here.

In all the baseline scenarios, used also earlier for the evaluation of the FQD/MFD impact, we imposed exogenously on the EU refineries SO_2 emissions intensities per processed crude oil. These are derived using Solomon Associates (2014) data on SO_x emissions per net input figures. The last were multiplied by the appropriate ratio (Net raw material input)/(Total crude processed) in order to obtain SO_2 emissions intensities per processed crude. These are reported in Table 5.25 below.

Table 5.25: Sulphur emissions intensities per processed crude (gram per tonne)

Year	SO_x emissions intensities using Solomon Associates (2014) data	Chosen SO_2 emissions intensity limits for the European refineries
2000		1490.0
2004	784.3	
2005		784.3
2006	855.0	
2008	721.3	
2010	558.7	450.1
2012	450.1	

Note: The second column gives SOx in gram per tonne processed crude, computed on the base of Solomon Associates (2014). The third column reports SO_2 intensity limits for the NE and SE refineries used in OURSE_QP modelling. No other SO_2 intensity limits were applied to other regions, except for North America, where in the absence of further information it was assumed to be 1490 g per tonne of processed crude in all periods of 2000, 2005 and 2010.

The choice of the values of SO_2 intensities for the three modelling period were based on the corresponding intensities of SO_x emissions. We adopt a conservative approach here in the sense of choosing the smallest (relevant in terms of time) intensity value. For 2005 we choose the intensity value of 784.3 g SO_2 per tonne processed crude, which is the SO_x intensity of 2004 as obtained from Solomon Associates (2014). Note that we do not use the higher intensity of 855.0 reported for 2006 (hence, our approach is conservative as we choose the *stricter* intensity value). Similarly, for 2010 period's SO_2 intensity we choose the obtained SO_x intensity of 450.1 reported for 2012. For the modelling years close to 2000 for which Solomon Associates (2014) data were missing, we used the relevant information from CONCAWE (2010) survey for 1998. In particular, CONCAWE's survey of 77 refineries shows that in 1998 the total crude intake was 502 mln tonnes and total sulphur emitted at refinery (from all sources) was 374 kt. These result in SO_2 emission intensity of 1490 g per tonne of processed crude. This value was also imposed on the North American refinery for all three periods in the absence of further relevant information, while no such restrictions were imposed on the refineries of the remaining regions.

5.2.3.1 Costs

In constructing the counterfactual scenarios, we relax SO_2 emission intensity limits. These are set to the initial year values, and the choice of year depends on the scenario considered. The structure of such choices is exactly similar to that reported in Table 5.6 for the FQD/MFD impact assessment case. That is, substituting "Fuels qualities" in this table to "SO_2 emissions intensities" will provide the full overview of the way the intensities have been relaxed in each of the six considered counterfactual scenarios.

As before in all simulation runs we keep the trade flows of refined products fixed at their appropriate baseline levels. However, if we run the counterfactuals without any other constraints, OURSE results in more investments costs than in the environment with stricter observed SO_2 emissions intensities imposed. This result might be at first glance counterintuitive, but makes sense if we recall that in OURSE world-wide refining costs are minimized and not only those of the European regions. Thus what happens then is that it becomes optimal for NE and SE with relaxed SO_2 emissions limits to switch to cheaper crudes with higher sulphur content, which however require additional capital investments to be refined to petroleum products. For example, in various simulations scenarios European regions are found to replace 10% to 25% of Brent crude with higher sulphur content crudes such as Arabian Light and Arabian Heavy. We, however, find such extent of crude substitution effect unrealistic (in particular, due to the short-run nature of the analysis), hence impose constraints on residue catalytic cracking (RCC) and naphtha-processing capacities of the NE and SE regions only that do not allow new investments in these units above their corresponding baseline levels. Another set of scenarios are run fixing additionally crude mix supply to the NE and SE regions, while similar restriction is not imposed on other regions.

Before providing the costs estimates, it is interesting to look in which scenarios the sulphur emissions limits will be binding. To give a more policy-relevant flavour to the relevant issue, it is interesting to consider the appropriate emission limit values as advocated in the LCPD and IPPCD (currently, Industrial Emissions Directive). According to the LCPD that came into force in November 2002, for example, Member States had to take appropriate measures in order to ensure that operation permits given to the EU refineries (with thermal input size between 50 to 300 MW) contain certain conditions that are (more or less) consistent with the adopted sulphur *emission limit value* (ELV) of 1700 mg SO_2 per Nm^3 (O_2 content of 3%) of liquid fuels use/burnt. In OURSE model there is SMOKE variable (measured in Nm^3) which is generated from the use of liquid and refinery fuels, gas and coke along all the relevant intermediate inputs processes within the refinery.[18] Using this variable output together with the appropriate SO_2 emissions estimates of the model, for all baseline scenarios the observed counterpart of the sulphur ELVs referred to as *refinery combustion bubble concentrations for* SO_2 as produced by the OURSE_QP model were computed, which are reported in Table 5.26.

All the "observed" SO_2 concentrations show the expected tendency of decreasing over time, with the exception of the intermediate period (for both calibration options) for NE, where in 2000 the SO_2 bubble concentrations are lower than those in 2005. As can be seen from Table 5.26, this will also imply that from 2000 to 2005 sulphur emissions in NE increase. Given our conservative approach, we will ignore the results related to 2000-2005 counterfactual. Otherwise, one could state that relaxing SO_2 emissions intensities is equivalent to relaxing SO_2 ELVs to the values which, depending on the scenarios chosen, will be rather close to the relevant SO_2 concentration values reported in Table 5.26.

Table 5.26: Baselines' refinery combustion bubble concentrations for SO_2 (mg/Nm^3) and SO_2 emissions (kt)

	Standard rule				**Average cost rule**			
	2000	2005	2010	2000-2010	2000	2005	2010	2000-2010
	SO_2 mg per Nm^3				SO_2 mg per Nm^3			
NE	1007	1010	796	797	1037	1301	729	738
SE	1696	1663	938	918	1694	1652	913	954
NE&SE	1200	1200	838	833	1217	1398	781	798
	SO_2 emissions (kt)				SO_2 emissions (kt)			
NE	247.4	261.5	189.9	190.2	265.7	338.7	182.9	183.7
SE	162.4	106.9	94.0	92.7	162.9	163.3	91.8	92.3
NE&SE	409.8	368.4	283.9	282.9	428.6	502.0	274.8	276.0

Source: OURSE_QP results. "NE&SE" gives the overall results for both North Europe and South Europe.

It is interesting to compare OURSE-based SO_2 concentrations estimates reported in Table 5.26 with the observed ones estimated by CONCAWE (2010) based on their sulphur surveys of the European refineries for the years of 1998, 2002 and 2006. In particular, CONCAWE (2010, p. 11) reports the weighted average (using refinery production as weights) combustion bubble SO_2 concentrations of 1116 mg/Nm^3, 791-816 mg/Nm^3 and 594 mg/Nm^3, respectively, for the years of 1998, 2002 and 2006.[19] Further, the presented cumulative distributions of the SO_2 concentrations (Figure 5) show that 35%, 25% and 22% of the

[18] In its calculation it is assumed, for example, that the flue gas volume of FCC coke is equal to 11000 Nm^3 per tonne, or of liquid fuel is 11500 Nm^3 per tonne, etc. Somewhat detailed explanation of the calculation methodology of the refinery combustion bubble SO_2 concentration is discussed in CONCAWE (2010, p.10 and Appendix 1).

[19] CONCAWE (2010), however, caution about citing the 2006 value as "this was based on only 80% of the overall refinery oxidised sulphur emission due to missing stack and fuel information in some responses" (p.11).

surveyed refineries in 1998, 2002 and 2006 had the bubble concentration values, respectively, in the ranges of 1000-5200 mg/Nm^3, 1000-4200 mg/Nm^3 and 1000-3180 mg/Nm^3. Thus, our estimates of the European refineries' SO_2 concentrations are not unrealistic and are largely consistent with those reported in CONCAWE (2010).

We start with the quantitative estimates of the *crude mix substitution effects* lying behind the SO_2 restrictions relaxation policies and the relevant costs estimates to be presented soon. These are percentage changes of crude type (and feedstock) purchases in the counterfactual scenarios relative to the relevant baselines in NE and SE, and are presented in Table 5.27. As an example, consider the 2005-2010 simulation results from the average cost calibration approach, where we observe a decrease in Brent purchase by -2.5% and a simultaneous increase in purchase of Arabian Light by 2.9% in North Europe. This is essentially crude mix substitution effect taking place because of the relaxed SO_2 emissions regulations, i.e. it now becomes optimal for the EU refineries to purchase somewhat larger quantities of cheaper sourer crude than continue using more expensive sweeter crude. In general, all the reported estimates of crude mix substitution effects are reasonable (which range from -2.5% to 2.9%), since large changes are likely to be unrealistic, at least, for relatively short-run analysis covered in this study.

Table 5.27: Crude mix substitution effect in NE and SE (percentage changes)

	Brent (0.32% S)	ArLght (1.86% S)	ArHeav (2.69% S)	Forcad (0.18% S)	Conden (0.01% S)	FeedStock	*Total throughput*
	2005-2010, Standard calibration rule (%)						
NorthEurope	-1.2	0.7	-0.1	0.1	0.1	0.6	0.01
SouthEurope	0.0	-1.1	1.2	-0.6	-0.9	-0.4	-0.07
	2005-2010, Average cost calibration rule (%)						
NorthEurope	-2.5	2.9	-0.2	0.0	-0.3	-0.2	-0.03
SouthEurope	2.8	-1.6	0.0	-0.1	0.1	0.1	-0.06
	2000-2010, Standard calibration rule (%)						
NorthEurope	-1.1	0.6	-0.1	0.1	0.0	0.7	0.03
SouthEurope	0.0	0.1	-0.1	0.0	-1.9	-0.6	-0.07
	2000-2010, Average cost calibration rule (%)						
NorthEurope	-1.7	1.4	-0.3	0.2	-1.0	0.9	-0.04
SouthEurope	0.0	-0.1	0.0	0.0	-0.1	0.0	-0.02

Source: OURSE_QP results.

The summary of the incurred CAPEX costs, and crude and feedstock switching costs due to stricter SO_2 emissions regulations, as assessed by the OURSE_QP model, is reported in Table 5.28. It shows that *the impact of the EU and Member State-level SO_2-related regulations is assessed to cost EU refineries in terms capital investments, as captured by the OURSE model, on average over the entire 2000-2012 period, 33 mln USD annually, with an upper bound estimate of 38.7 mln USD*. The crude and switching costs account for the burden of switching to low-sulphur crude and fuels (as feedstock) to be taken by EU refineries in order to limit their sulphur emissions. These essentially quantify the costs of crude mix substitution effects discussed above. *Low-sulphur switching costs are assessed to be, on average over the entire 2000-2012 period, 29.3 to 51.1 mln USD per year, with an upper bound estimate of 53.4 mln USD.* Hence, even though the degree of crude mix substitution effects reported in Table 5.27 might have seemed small at the first glance, their underlying costs are not small at all. *All in all, the annual total costs associated with the EU and Member State-level SO_2-related regulations are assessed, on average over the 2000-2010 period, to range between 62.3 and 84.5 mln USD, with an upper bound estimate of 92.1 mln USD.*

Table 5.28: CAPEX and crude/feedstock switching costs due to SO_2 emissions regulations (mln 2008 USD per year)

	2005-2010 (1)	2000-2010 (2)	Average of (1) and (2)
	CAPEX costs(mln USD per year)		
Standard calibration rule	38.67	27.31	32.99
Average cost calibration rule	37.43	29.26	33.34
	Crude and feedstock switching costs (mln USD per year)		
Standard calibration rule	39.56	19.07	29.32
Average cost calibration rule	48.84	53.44	51.14
	Total costs (mln USD per year)		
Standard calibration rule	78.23	46.38	62.31
Average cost calibration rule	86.27	82.70	84.48

Source: OURSE_QP results.

Typical investments that make up the above mentioned CAPEX include investments in vacuum gasoil hydrotreatment (HDT) and naphtha processing units. As an example, additional savings in new units expressed in mln tonnes per year due to relaxed SO_2 emission limits for 2010-2000 simulation are reported in Table 5.29.

Table 5.29: Differences in new investments, 2010-2000 scenarios (mln tonnes/year)

	NA	SA	NE	SE	RS	AF	ME	CH	AS	NE& SE	Total
Topping unit & VDU							0.0	0.0	0.0		0.0
Naphtha processing units			-0.7	-1.7	0.0	0.0	0.0	0.0	0.0	-2.4	-2.4
FCC					0.0		0.0	0.0			0.0
RCC		0.0			0.0		0.0	0.0	0.0		0.0

HDS gas oil	0.0	0.0			0.0			0.0	0.0		0.0
FCC gasoline desulphur.							0.0	0.0			0.0
HDT vacuum gas oil			-1.0				0.0	0.0		-1.0	-1.0
HDT naphtha											
Hydrocraking units						0.0		0.0	0.0		0.0
Residue hydroconversion											
Etherification units	0.0	0.0	0.0					0.0		0.0	0.0
Visbreaking unit								0.0	0.0		0.0
Coking unit								0.0	0.0		0.0
Claus											
Hydrogen units				0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
Total difference	0.0	0.0	-1.7	-1.7	0.0	0.0	0.0	0.0	0.0	-3.4	-3.5

Note: CAPEX difference = Counterfactual CAPEX – Baseline CAPEX. Trade calibration is based on the average cost rule.

Now we return to the discussion of to what extent our CAPEX estimates are realistic. We have Solomon Associates (2014) data on capital investments on "Refinery emissions and effluent" which include "costs related to fuels refinery-based environmental items, such as wastewater treating and atmospheric emissions, and related to the handling and treatment of solid and hazardous wastes". Similarly, we have data from recent CONCAWE survey related to the REFIT study on "Total air emissions abatement capital investments", which include costs related to diverse abatement measures adopted/installed by the EU refineries in order to reduce emissions of SO_x, NO_x, carbon monoxide (CO), dust and metal emissions, and volatile and organic compound (VOC) emissions. The last data includes also costs on waste water treatment, which if compared to costs on air emissions abatement shows that the share of air emissions abatement capital investments in total air emissions and wastewater treatment for EU refineries is, on average, 83%. However, Solomon Associates (2014) include also costs related to handling and treatment of solid and hazardous wastes, hence the share of air emissions related costs in their data must be lower than 83%. However, we do not have information on the exact costs contribution related to SO_2 emissions reduction only. A personal communication with a CONCAWE member suggested to use a figure of 50% "as a rough estimate of the share of CAPEX for SOx emissions abatement measures in "Total air emissions abatement capital investments", basing this estimate on the relevant data for Repsol Cartagena emissions abatement capital investments figures. Using this figure *CONCAWE data shows an estimate of annual SOx emissions abatement CAPEX of 124 mln EUR/year obtained as an average of 1998-2012 investments*. Applying 30% and 40% shares (these share are less than 50% figure used above, because of extra cost due to "related to the handling and treatment of solid and hazardous wastes") to 1998-2012 *Solomon Associates (2014) figures on "Refinery emissions and effluent" investments costs netted of wastewater treatment costs, gives SO_2 emissions abatement CAPEX estimates ranging between 97 to 129 mln EUR/year* according to the observed data. Therefore, our upper estimate of SO_2 emissions abatement CAPEX of roughly 35 mln EUR/year is *lower* than the relevant values discussed above by factors ranging from 2.8 to 3.7. *Hence, it is likely that our estimates of*

SO_2 emissions abatement costs are underestimated. The reason for such underestimation lies in the fact that the OURSE model does not capture all the relevant measures adopted/installed by refineries in real life in order to reduce SO_2 emissions.

Finally, for easier readability/comparability purposes as with other directives, the total costs figures from Table 5.28 were translated to normalized figures expressed in eurocents per processed crude. These are reported in Table 5.30, and show that *the annual total costs of EU refineries due to SO_2 emissions regulations, as captured by OURSE, are assessed to be roughly 2 eurocents per processed crude*.

Table 5.30: Total costs due to SO_2 emissions regulations in eurocents per processed crude oil

	2005-2010 (1)	2000-2010 (2)	Average of (1) and (2)
Standard calibration rule	1.6	0.9	1.3
Average cost calibration rule	1.8	1.7	1.8

Source: OURSE_QP results.

5.2.3.2 Benefits

The benefits of abiding by various air emissions regulations are obvious: air emissions should be reduced by the industrial activities and/or final consumers. Since SO_2 emissions are modelled in OURSE, such benefits in terms of SO_2 emissions reduction by refineries can be assessed. For all the above considered scenarios the relevant results are presented in Table 5.31. It reports the total percentage decrease in SO_2 emissions in the baseline environment compared to those in the counterfactual scenarios with weaker environmental regulations.

Table 5.31: Decrease in SO_2 emissions with regulations (% change per period)

Simulation	Calibration approach	NE	SE	NE&SE
2005-2010	Standard calibration rule	-13.8	-31.3	-20.5
	Average cost calibration rule	-25.8	-32.4	-28.2
2000-2010	Standard calibration rule	-12.7	-28.0	-18.4
	Average cost calibration rule	-25.7	-32.5	-28.1

Source: OURSE_QP results.

From Table 5.31 the following conclusions can be made:

- ✓ The overall benefits of legislation acts on SO_2 emissions regulation, notably LCPD, IPPCD and AQD, are assessed to be in the range of 12.7% to 32.5% reductions of

SO_2 emissions generated by the EU refineries in North and South Europe over the covered period. The overall European figures show SO_2 emissions reduction of 18.4% to 28.2% over the entire 2000-2010 period.

- ✓ The incurred benefits in South Europe are larger than those in North Europe by factor of 1.3 to 2.3. This finding most probably has to do with the fact that there was more room in reduction of sulphur dioxide emissions for South European refineries than for refineries located in North Europe.

Finally, the estimates of the size of SO_2 emissions reduction can be computed easily by combining the relevant OURSE_QP results reported in Table 5.26 and Table 5.31, which we will not discuss further here.

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6 Appendix A: Tables

Table 6.1: Observed demand for refined products used in OURSE baseline scenarios

Product	NA	SA	NE	SE	RS	AF	ME	CH	AS	Total
					2000					
LPG	67.1	14.0	15.7	13.5	7.7	6.9	9.2	12.0	43.9	*189.9*
Naphta	18.6	11.9	41.0	12.6	9.1	1.5	2.6	22.0	82.3	*201.6*
Gasoline	418.4	35.4	97.9	39.6	33.9	23.0	36.6	35.6	108.8	*829.1*
JetFuel	96.7	8.9	42.0	13.0	10.7	11.7	19.8	11.6	91.8	*306.1*
Kerosene	5.0	0.6	5.7	0.4	0.4	2.9	7.5	1.3	49.2	*73.0*
HeatingOil	98.1	16.9	87.5	32.2	23.1	11.9	29.0	43.2	92.6	*434.5*
DieselOil	127.0	40.3	102.0	49.0	14.1	22.7	31.6	25.3	110.5	*522.5*
ResFuelOil	74.1	18.5	28.3	48.9	38.2	14.0	43.3	30.7	108.1	*404.1*
Lubricant	10.9	1.3	5.6	2.7	3.5	1.1	1.4	4.3	6.5	*37.3*
Bitumen	36.5	3.7	13.9	7.3	5.9	1.8	5.2	3.9	14.5	*92.7*
PetCoke	13.8	5.9	5.4	8.3	1.4	0.2	0.3	4.6	6.9	*46.9*
MarinBunk	36.5	5.6	32.5	13.6	0.0	7.0	14.6	6.1	39.8	*155.7*
Total	*1002.5*	*163.2*	*477.5*	*241.0*	*147.9*	*104.8*	*201.1*	*200.5*	*755.1*	*3293.5*
					2005					
LPG	62.6	14.2	18.4	12.8	10.6	9.0	11.4	18.2	46.9	*204.2*
Naphta	20.0	10.3	41.9	9.7	11.5	0.7	2.9	29.0	105.8	*231.9*
Gasoline	447.4	35.9	85.0	35.5	38.4	27.5	49.1	49.1	121.4	*889.4*
JetFuel	94.0	8.2	45.8	14.9	12.4	11.8	18.9	16.1	90.0	*312.0*
Kerosene	5.1	0.8	5.4	0.4	0.4	3.7	9.5	2.0	52.2	*79.5*

HeatingOil	100.1	22.0	83.1	33.1	23.7	15.1	36.9	64.8	98.1	*476.9*
DieselOil	148.0	45.5	120.3	66.3	14.9	28.1	41.3	42.9	115.6	*622.9*
ResFuelOil	73.2	14.4	23.2	34.4	25.2	17.6	50.3	34.7	85.2	*358.2*
Lubricant	9.3	1.4	5.0	2.7	3.9	1.7	1.6	8.0	6.5	*40.1*
Bitumen	38.3	3.6	14.2	9.2	6.7	2.6	8.1	7.2	14.5	*104.6*
PetCoke	25.1	7.0	6.8	11.2	1.2	1.5	0.6	8.6	12.3	*74.4*
MarinBunk	33.4	7.3	39.3	16.2	0.0	6.1	17.8	10.7	47.9	*178.7*
Total	*1056.5*	*170.6*	*488.3*	*246.6*	*149.0*	*125.5*	*248.5*	*291.2*	*796.5*	*3572.7*
					2010					
LPG	56.6	16.0	18.8	11.7	12.2	11.2	11.6	20.6	58.4	*217.1*
Naphta	15.6	10.8	42.4	10.2	12.7	1.0	5.0	41.2	124.1	*263.1*
Gasoline	431.0	44.3	68.3	27.3	47.5	34.6	58.6	72.2	134.5	*918.3*
JetFuel	77.0	10.2	45.9	16.1	14.0	12.4	19.9	23.5	79.8	*298.7*
Kerosene	4.6	1.2	4.5	0.4	0.4	4.6	12.3	2.4	52.5	*82.8*
HeatingOil	90.4	30.7	69.7	29.1	22.3	18.8	47.6	80.4	98.6	*487.7*
DieselOil	146.5	54.7	131.9	68.5	19.3	37.3	50.5	72.5	126.0	*707.2*
ResFuelOil	34.9	16.7	16.1	13.9	14.6	15.8	51.3	16.9	68.1	*248.2*
Lubricant	8.6	1.6	4.4	2.2	2.3	1.8	0.7	11.5	6.9	*40.1*
Bitumen	28.1	4.6	12.8	9.4	6.2	2.2	6.6	10.4	16.5	*96.7*
PetCoke	17.2	9.0	5.2	9.8	1.7	2.2	0.4	12.3	13.1	*70.9*
MarinBunk	34.3	8.7	36.4	17.2	1.6	5.7	21.7	21.1	59.8	*206.5*
Total	*944.8*	*208.4*	*456.5*	*215.9*	*154.7*	*147.6*	*286.2*	*384.9*	*838.1*	*3637.1*

Note: Unit is expressed in million metric tonnes. NA – North and Central America, SA – South/Latin America, NE – North Europe, SE – South Europe, RS – Russia and other CIS countries, AF – Africa, ME – Middle East, CH – China, and AS – other Asia and Oceania.

Table 6.2: Observed demand shares of the EU countries in OURSE regions of Europe

	2000		**2005**		**2010**	
Product	**EU in NE**	**EU in SE**	**EU in NE**	**EU in SE**	**EU in NE**	**EU in SE**
LPG	93.0%	65.4%	93.5%	65.1%	93.8%	63.0%
Naphta	99.9%	87.7%	100.0%	88.4%	100.0%	78.6%
Gasoline	94.1%	88.4%	93.7%	87.7%	93.4%	88.4%
JetFuel	94.1%	88.1%	95.4%	83.2%	94.7%	77.6%
Kerosene	91.9%	87.1%	91.1%	87.0%	90.2%	76.4%
HeatingOil	91.9%	87.1%	91.1%	87.0%	90.2%	76.4%
DieselOil	97.4%	86.7%	97.2%	86.6%	96.4%	83.4%
ResFuelOil	98.4%	83.7%	98.0%	80.7%	97.8%	87.0%
Lubricant	96.7%	79.7%	97.2%	68.1%	97.7%	60.1%
Bitumen	95.3%	81.2%	95.6%	78.3%	94.8%	69.4%
PetCoke	88.6%	97.5%	91.1%	98.6%	81.4%	95.8%
MarinBunk	94.0%	97.0%	94.0%	93.4%	91.8%	97.8%
Total	*95.1%*	*86.1%*	*95.0%*	*85.2%*	*94.5%*	*82.4%*

Table 6.3: Other (constant) characteristics of gasoline and diesel oil used in OURSE

Specification	**Gasoline grades**

	ReGasol92NAm	ReGasol95NAm	PremGasol1	PremGasol2	PremGasolEu
MON	82	85	80	84	85
RON	92	95	90	94	95
Density min	0.72	0.72	0.72	0.72	0.72
Density max	0.775	0.775	0.775	0.775	0.775
Oxygenate max	2.7	2.7	2.7	2.7	2.7
Olefine max	18	18	20	18	18
Vapour pressure	0.75	0.75	0.8	0.8	0.6

Specification	**Diesel oil grades**			
	DieselNAm	**DieselLatAm**	**DieselEu**	**DieselChin**
Density min	0.82	0.82	0.82	0.82
Density max	0.86	0.88	0.845	0.88
Cetane	46	46	49	46
Cloud point	-31.8	-31.8	-31.8	-31.8

Table 6.4: Further grades/quality split of fuels within OURSE, 2005

	NA	SA	NE	SE	RS	AF	ME	CH	AS
					LPG split				
Propane	40%	40%	40%	40%	40%	40%	40%	40%	40%
Butane	60%	60%	60%	60%	60%	60%	60%	60%	60%
					Gasoline split				
ReGasol92NAm	70%								
ReGasol95NAm	30%								
PremGasol1		80%			80%	90%		70%	30%
PremGasol2		20%			20%	10%	100%	30%	60%
PremGasolEu			100%	100%					10%
					Diesel oil split				
DieselNAm	100%								30%
DieselLatAm		50%			50%		30%	60%	30%
DieselEu			100%	100%					20%
DieselChin		50%			50%	100%	70%	40%	20%
					Heating oil split				
HeatingOil1	80%		85%	85%					5%
HeatingOil2	20%	100%	15%	15%	100%	100%	100%	100%	95%
					Residual fuel oil split				
HeavyFuelOil1	80%	10%	90%	90%	10%	10%	10%	10%	40%

HeavyFuelOil2	20%	90%	10%	10%	90%	90%	90%	90%	60%
					Marine bunker split				
MarineBunk1	60%		70%	70%					
MarineBunk2	40%	100%	30%	30%	100%	100%	100%	100%	100%

Note: For the specifications of the above-listed fuels, see Table 1.1 in the main document.

Table 6.5: Crude oil types and feedstock trade, 2005 baseline (standard rule)

		NA	**SA**	**NE**	**SE**	**RS**	**AF**	**ME**	**CH**	**AS**
	NA	51.20			9.66					
	SA	7.75	16.43							
	NE	20.38		60.46						
	SE				4.96					
Brent	RS					29.18				
	AF	20.77	2.23	8.13	10.07		15.62		4.74	1.49
	ME									22.61
	CH								22.33	
	AS								0.55	82.11
	NA	136.14								
	SA									
	NE			20.07						
	SE				1.10					
ArLght	RS	8.23		100.18	47.36	133.99			9.44	
	AF									
	ME									80.01
	CH								4.09	
	AS									1.02
ArHeav	NA	130.99								
	SA	42.81	78.57	3.44					1.86	

	NE	4.64		31.59						
	SE				2.43					
	RS	2.08		31.57	12.93	51.14			2.07	
	AF									
	ME	85.39		46.59	62.61		24.23	347.30	42.99	326.10
	CH								81.87	5.27
	AS									
Forcad	NA	101.76			1.35					
	SA	64.42	59.96	4.62					2.50	
	NE	9.13		61.42	5.90					
	SE				5.12					
	RS	1.24		15.10	6.92	24.27			1.42	
	AF	64.42	10.88	39.65	49.09		71.06		23.12	18.32
	ME									17.59
	CH								4.60	0.96
	AS									5.99
Conden	NA	37.65			0.22					
	SA	8.03	12.61	0.10					0.05	
	NE			0.33						
	SE									
	RS	0.64		22.43	3.25	5.11				
	AF	20.06	0.84	3.05	3.78		7.55		1.78	0.56
	ME									5.02
	CH								22.11	
	AS								4.97	61.32
FeedStock	NA	25.71								
	SA	75.54	29.62	1.67					0.90	
	NE	9.33		27.26	5.90					
	SE				2.85					
	RS	0.10		3.56	0.52	4.77				
	AF									10.15
	ME									41.46
	CH								43.53	10.77
	AS									65.56

Note: Unit is million tonnes. Source: OURSE_QP results.

Table 6.6: Unit groupings for reporting purposes

Unit group	Unit
Topping unit & VDU	Atmospheric distillation
Topping unit & VDU	Vacuum distillation unit
HDT vacuum gas oil	DAO HDT
Residue hydroconversion	Residue hydroconversion (fixed bed)
Residue hydroconversion	Residue hydroconversion (ebulated bed)
Naphtha processing units	Catalytic reformer
Naphtha processing units	Regenerative reformer
Naphtha processing units	Reformate splitter
HDT vacuum gas oil	FCC feed HDT (vacuum GO)
HDT vacuum gas oil	Mild hydrocracking
FCC	Catalytic cracking (EC)
FCC	Catalytic cracking (CC)
Residue hydroconversion	RCC feed HDT (long run residue)
RCC	HDT long run residue catalytic cracking
RCC	Long run residue catalytic cracking
Hydrocraking units	Hydrocracking full
Hydrocraking units	Hydrocracking jet

Hydrocraking units	Hydrocracking naphtha
Hydrocraking units	Hydrocracking 78 conv
Naphtha processing units	Deisopentanizer
Naphtha processing units	Isomerization once through
Naphtha processing units	Isomerization with recycling
Naphtha processing units	Alkylation (Hydrofluoric Acid - HF)
Etherification units	Tame unit on LG from FCC & RCC
Etherification units	MTBE unit
Etherification units	ETBE total unit
Visbreaking unit	Visbreaking (vacuum residue)
Coking unit	Coking delayed
HDT vacuum gas oil	Hydrodesulphurization (HDS) VGO CK
HDS gas oil	HDS 90 20bar
HDS gas oil	HDS 97-98 30bar
HDS gas oil	REVAMP HX 50bar
HDS gas oil	Deep HDS 75 bar
FCC gasoline desulphurization	FCC gasoline desulphurization (Primeg20)
FCC gasoline desulphurization	FCC gasoline desulphurization (Primeg10)
HDT naphtha	REF feed HDT
Hydrogen Units	Pressure swing absorber
Hydrogen Units	Steam reformer
Claus	MDEA+Claus+hydrosulpreen (SRI)

Note: In eight units not listed in this table new investments were not allowed due to the short-term nature of our assessment.

7 Appendix B: OURSE_LP equations

Here we present the mathematical formulation and relevant interpretations of the main (but not all the) equations of the OURSE_LP model. For easy readability purposes, all the exogenous (resp. endogenous) variables are written in red and with lower-case letters (resp. in black and with upper-case letters), while the description excerpt of each individual set of equations is separated by lines from its top and bottom parts.

(1) Balance of raw crude:

sum{reg_to, RAW_CRUDE_TRADE(raw_crude, reg, reg_to)} $\leq$ crude_supply_limit(raw_crude, reg);

where RAW_CRUDE_TRADE(raw_crude, reg_from, reg_to) = interregional trade (supply) of crude oil, crude_supply_limit(raw_crude, reg) = crude supply limits by region (reg).

Interpretation: Total crude oil supplied from the source region to all destination regions is limited (constrained) by the source region's crude oil availability at the point in time considered.

(2) Balance of crude trade:

sum{raw_crude, RAW_CRUDE_TRADE(raw_crude, reg_from, reg_to)* trans_crude(raw_crude, reg_from, crude)} = CRUDE_TRADE(crude, reg_from, reg_to) ;

where trans_crude(raw_crude, reg, crude) = crude yields from (raw) crude types (a matrix transforming raw_crude to crude) with the property that sum{crude, trans_crude(raw_crude, reg, crude)} = 1 for each raw_crude and reg.

Interpretation: Translating the endogenous interregional supply of the more disaggregated crude oil types to the corresponding interregional trade (supply) flows of the more aggregated crude types used in the model.

(3) Balance of crude consumption in regions:

sum{reg_from, CRUDE_TRADE(crude, reg_from, reg)} - INTER_PROD(crude, reg) = 0;

where CRUDE_TRADE(crude, reg_from, reg_to) = interregional supply of crude oil (positive *variable* in the model), INTER_PROD(crude, reg) = intermediate production/use of crude by the representative refinery of a region.

Interpretation: Total crude coming to a destination region from all possible source regions is entirely used by the destination region's refinery as intermediate product (which is equivalent to the intermediate production of that refinery).

(4) Balance of crudes and their cuts:

INTER_PROD(crude, reg) – sum{cut$(crude_cut(crude, cut)), INTER_PROD(cut, reg)} = 0;

where crude_cut is a set showing a crude and its corresponding cuts, e.g. crude_cut(Brent, cut) = {Brent.BrentAcut, Brent.BrentBcut}.

Interpretation: This equation guarantees that the total quantity of the processed crude in each region (or representative refinery) is equal to the sum of the different relevant processed cuts of the crude.

(5) Balances of intermediate products:

sum{intp, INTER_PROD(intp, reg)*INTER_PROD_FACTORS(intp_eq, intp)} = 0;

where INTER_PROD_FACTORS(intp_eq, intp) = factors for intermediate products, intp_eq = interim products names for production equations, INTER_PROD(intp, reg) = production of intermediate product intp in regin reg.

Interpretation: This is the material balance of intermediate products for each refinery that states that production is equal to the internal use. That is, the sum of intermediate use by a refinery equals its intermediate production. Depending on whether the intermediate products at the production "stage", indicated by intp_eq, are inputs or outputs, the corresponding interim-production factors INTER_PROD_FACTORS(intp_eq, intp) are positive or negative, respectively.

---

(6) Balances of final products:

FIN_PROD(fp, reg) = sum{intp, INTER_PROD(intp, reg)*PROD_FACTORS(fp, intp)} ;

Where PROD_FACTORS(fp, intp) = production factors/coefficients of final products per unit of intermediate product (whenever non-zero, for all "market" final petroleum products these are set to unity; for such products as sulphur, refining gas, isobutene, propane, etc. these are all in the (0, 1) interval, being much closer to the lower zero bound).

Interpretation: Whenever an intermediate production contributes to the production of a certain type of final product, the corresponding production factor reflects this. Hence, multiplying production factors by the volume of intermediate production and summed over all possible intermediate products gives the total of a particular final product.

---

(7) Balances of regional production, demand and trade of final products (excluding marine bunker):

FIN_PROD(fp_not_marine_bunker, reg)
** Use for other products
+ sum{intp, INTER_PROD(intp, reg)*USE_FACTOR(fp_not_marine_bunker, intp)}
** Import
+ sum{reg_from, EXIMPORT(fp_not_marine_bunker, reg_from, reg)}
** Export
- sum{reg_to, EXIMPORT(fp_not_marine_bunker, reg, reg_to)}
** Supplies of final products
= FIN_SUPPLY(fp_not_marine_bunker, reg);

where USE_FACTOR(fp, intp) = factors for blending components (if nonzero, these are all negative) and are defined for the following final products (fp): LiquidFuel, Feedstock, Natural Gas, Sulphur, RefinGas, PropaneC3, ButaneC4, ButaneN4, IsoBUTAn, IsoBUTEn, NormBUTEn, MTBEbio, METHANOLbio, ETBEbio, EMHvBio, HydrogPure, Hydrogen, ChemHPsteam, and SulfGas;
FIN_SUPPLY(fp, reg) = Supplies of final products by region.

Interpretation: For each region the balance of product which is not a marine bunker is given. That is, the total supply of final product of region is equal to the production of final product in the region (refinery), plus the internal use of the product by the refinery, plus imports from and minus exports to other regions. In other words, this balancing equation guarantees that supply (i.e., domestic production and imports) equals demand (i.e., domestic consumption and exports).

---

(8) Balance of global production, demand and trade of marine bunkers:

sum[reg, FIN_PROD(marine_bunker, reg)
** Use for other products
+ sum{intp, INTER_PROD(intp, reg)*USE_FACTOR(marine_bunker, intp)}]
** Supplies of final products
= sum{reg, FIN_SUPPLY(marine_bunker, reg)};

Interpretation: This is similar to (7) an equality of demand and supply balancing equation for marine bunkers. In contrast to (7), however, now there is no separate regional dimension and no exports and imports. This is due to the fact that the demand and supply corresponding for marine bunkers are satisfied only at the world level; hence, for marine bunkers OURSE has a separate, global balance.

---

(9) Demand of market products balance:

FIN_SUPPLY(fp, reg) ≥
sum{prodem, DEMPROD(prodem, reg)*COM_PROD(prodem, reg, fp)
** From original GRANDOURSE modification of demand for Petroleum Coke
- (0.1*sum[reg_from, RAW_CRUDE_TRADE("BXHC", reg_from, reg)])$(prodem ="PetCoke"))};

where DEMPROD(prodem, reg) = demand for petroleum product prodem (12 types) by consumers in region reg, COM_PROD(prodem, reg, fp) = composition of demanded products from final products: these are shares that transform the 12 types of demanded products into the 24 final products of the OURSE model, thus sum{fp, COM_PROD(prodem, reg, fp)} = 1 for each demanded product prodem and region reg.

Interpretation: The exogenous demand has to be satisfied; hence, the endogenous supply of a final product is equal to the corresponding exogenously given demand. [Not sure why modification to the demand for petroleum coke is necessary, ask IFPNE. It seems that 10% of the total use of Bitumen and Extra-Heavy Oil of a region [in the data it is only North America] also satisfies the demand for petroleum coke.]

---

(10) Balance of final products in terms of volume:

VOLUME(fp, reg) = sum{intp, INTER_PROD(intp, reg)*VOLUME_FACTORS(fp, intp)};

where VOLUME_FACTORS(fp, intp) = volume factors of final products (if nonzero, they are positive and often larger than unity).

Interpretation: It is similar to the balance of final product given in (6), with the only difference that this balance is given in terms of volume (while in equation (6) above it is expressed in terms of weight). The volume equations are defined only for the following final products: different grades of gasoline (ReGasol92Nam, ReGasol95NAm, PremGasol1, PremGasol2, PremGasolEu), jet fuel, diesel (DieselNAm, DieselLatAm, DieselEu, DieselChin), heating oil (HeatOil, HeatOilHq), heavy fuel oil (HevFOilLowSulf, HevFOilHiSulf, HevFOilULowSulf), marine bunkers, bitumen, and liquid fuel.

---

(11) Product quality specification equations for MIN conditions:

sum{fp1, FIN_PROD(fp, reg)*Spec_Min_Prod_Factor(spec, fp, fp1)}
+ sum{intp, INTER_PROD(intp, reg)*SPEC_MIN_FACTORS(spec, fp, intp) }

+ sum{intp, VOLUME(fp, reg)*Spec_Min_Vol_Factor(spec, fp, intp)} $\geq$ 0;

where Spec_Min_Prod_Factor = final products' quality minimum specification coefficient/factor for production variables and are defined only for density (=1) and viscosity (<0) specifications; SPEC_MIN_FACTORS = minimum specifications for final products in tons per unit of intermediate product (>0) and are defined for RON, MON, vescosity, and cetan index); Spec_Min_Vol_Factor = final products' minimum specification factors for volume variables (<0) and are defined for density, RON, MON and cetan index.

However, given that in the data Spec_Min_Prod_Factor and Spec_Min_Vol_Factor have only one dimension of final product, the above specification equation can simply be re-written as follows:

FIN_PROD(fp, reg)*Spec_Min_Prod_Factor(spec, fp) + VOLUME(fp, reg)*Spec_Min_Vol_Factor(spec, fp)
+ sum{intp, INTER_PROD(intp, reg)*SPEC_MIN_FACTORS(spec, fp, intp)} $\geq$ 0;

Interpretation: This equation specifies that final products must meet a number of legal and technical quality minimum specifications. Each intermediate product quantity (in volume or in weight term) generates certain specification quality as captured by the SPEC_MIN_FACTORS coefficients. The final products' quality minimum specifications are given and controlled by Spec_Min_Prod_Factor and Spec_Min_Vol_Factor coefficients. The last should reflect, for example, existing (or earlier) legal requirements on final products.

---

(12) Product quality specification equations for MAX conditions:

sum{fp1, FIN_PROD(fp, reg)*Spec_Max_Prod_Factor(spec, fp, fp1)}
+ sum{intp, INTER_PROD(intp, reg)*SPEC_MAX_FACTORS(spec, fp, intp)}
+ sum{intp, VOLUME(fp, reg)*Spec_MAX_Vol_Factor(spec, fp, intp)} $\leq$ 0;

where Spec_Max_Prod_Factor = final products' quality maximum specification coefficients/factors for production variables and are defined for density (=1), CO2 emissions, oxygen content, sulphur content, cloud point, viscosity and poly-aromatics fraction (all <0); SPEC_MAX_FACTORS = maximum specifications for final products in tons per unit of intermediate product (>) and are defined for CO2, AromaticFrac, BenzenFrac, CloudPoint, FracOlefin, PolyArmo, SulphurFrac, VaPress, and viscosity; Spec_Max_Vol_Factor = final products' maximum specification factors for volume variables (<0) and are defined for AromaticFrac, BenzeneFrac, Density, FracOlefin, and VaPress.

Similar to (11), in the data Spec_Max_Prod_Factor and Spec_Max_Vol_Factor have only one dimension of final product, hence the above specification equation can be simply re-written as follows:

FIN_PROD(fp, reg)*Spec_Max_Prod_Factor(spec, fp) + VOLUME(fp, reg)*Spec_Max_Vol_Factor(spec, fp)
+ sum{intp, INTER_PROD(intp, reg)*SPEC_MAX_FACTORS(spec, fp, intp)} $\leq$ 0;

Interpretation: This equation specifies that final products must meet certain number of legal and technical quality maximum specifications. Each intermediate product quantity (in volume or in weight term) generates certain specification quality as captured by the SPEC_MAX_FACTORS coefficients. The final products' quality maximum specification are given and controlled by the Spec_Max_Prod_Factor and Spec_Max_Vol_Factor coefficients. The last should reflect, for example, current (or earlier) legal maximum specification requirements on final products.

---

(13) Capacity equation:

CAPA_OLD(unit, reg) + CAPA_NEW(unit, reg) $\geq$
sum{intp, INTER_PROD(intp, reg)*CAPACITY_FACTORS(unit, intp)};

where CAPACITY_FACTORS(unit, intp) = indicate the use of certain unit in the production/processing of intermediate products (if non-zero, all are set to unity), CAPA_OLD(unit, reg) = installed capacity at the beginning of the year; CAPA_NEW(unit, reg) = new investments in capacities (positive variable in the model).

Interpretation: This capacity constraint states that the input flows of a processing unit are limited by the capacity installed in the past and new capacity (investments). Capacity is the only "dynamic" variable in the model. The usual stock-flow formula is used to derive capacity of a processing unit at the end of time *t* that is used as the beginning capacities of year *t+1*as follows:

CAPA_END(unit, reg) = CAPA_OLD(unit, reg)*{1-1/lifetime(unit)} + CAPA_NEW(unit, reg),

where lifetime(unit) = 30 years.

---

(14) Equation for combusted fuels:

TOT_COMBUS(reg) = sum{intp, INTER_PROD(intp, reg)*Ref_Fuel_Weight_Factor(intp)};

where TOT_COMBUS(reg) = total fuel combusted, Ref_Fuel_Weight_Factor(intp) = factors for refinery fuel balance in weight terms (if nonzero, all are unity).

Interpretation: Total combusted fuels, on the demand side of the refinery fuel requirements, is proportional to the inputs of the processing units. The refinery fuel demand is satisfied by either the intermediate or final products, which have different calorific values.

---

(15) Net consumption of utilities in energy terms:

UTIL_NET_USE(util, reg) + sum{intp, INTER_PROD(intp, reg)*UTIL_NET_USE_FACTOR(util, intp)}
+ UTIL_NET_USE(util, reg)*UTIL_USE_UTIL(util, util) = 0;

where util denotes 'utility' that include electricity, low pressure steam, high pressure steam and refinery fuel, UTIL_NET_USE_FACTOR(util, reg) = factors of net use/production of utility in utilities (energy) terms (can be negative or positive), and UTIL_USE_UTIL(util, util) = factors of utilities use for the refinery fuel. The last coefficients are as follows: UTIL_USE_UTIL('RefFuel', 'Electr') = -0.00022, UTIL_USE_UTIL ('RefFuel', 'HighPreSteam') = -0.071, and UTIL_USE_UTIL('RefFuel', 'LowPreSteam') = -0.059.

Interpretation: This equation states that the net use of utilities (in utilities terms) should equal the production and consumption of utilities during all stages of the intermediate production within the refinery.
Note: There are two other options of this equation, 'greater than' and 'less than' equations, denoted as EQ_UTIL_NET_USE_G(util, reg) and EQ_UTIL_NET_USE_L(util, reg), respectively. The last are exactly similar to the above equations, except the equality sign, which becomes $\geq$ or $\leq$, respectively.

---

(16) Emissions balance equation:

TOTAL_EMISSIONS(reg, polutant) =
    *** Thermal emissions*
    sum{intp, INTER_PROD(intp, reg)*EMISSION_FACTOR(polutant, intp)}
    *** CO2 emissions from upgraders*
    +[sum{reg_from, RAW_CRUDE_TRADE("BXHC", reg_from, reg)}*0.2588]$(if pollutant="CO2")
    $ontext
    *** CO2 emissions from hydrogen production*
    +[1.01*INTER_PROD("TOTinfeedHydrogUnit", reg) +
    sum{reg_from,(EXIMPORT("HYDROGEN",reg_from, reg))}/0.30]$(if pollutant="CO2")
    $offtext
    *** CO2 emissions from chemical processing*
    +[sum{intp, EMIS_FACT_CHEM(intp, reg)*INTER_PROD(intp, reg)}]$(if pollutant="CO2");

where EMISSION_FACTOR(polutant, intp) = emissions factors for SO2 and CO2 per unit of intermediate product, EMIS_FACT_CHEM(intp, reg) = CO2 emission factors from chemical processing.

Interpretation: Atmospheric pollution of SO2 and CO2 emissions include total thermal emissions, which are computed assuming that pollution content of the refinery fuels are proportional to the quantities of fuels burnt (as captured by the values of emission coefficients), and, in case of CO2 emissions, also direct emissions from the processing units. The last include CO2 emissions from upgraders, hydrogen production and chemical processing.

---

(17) Equations for calculation of emissions:

TOTAL_EMISSIONS(reg, polutant) $\leq$ EMISSIONS_LIMIT(reg, polutant);

where EMISSIONS_LIMIT(reg, polutant) = limit on emissions (in kt).

Interpretation: The pollutant emission in the stack emission can be restricted using this constraint.

---

(18) Objective function - costs minimization:

TOTAL_COSTS =
    *** Crude oil costs*
    + sum{(crude, reg_from, reg_to), CRUDE_TRADE(crude, reg_from,
reg_to)*CRUDE_PRICE(crude)}

    *** Crude oil freight costs*
    + sum{(crude, reg_from, reg_to),
        CRUDE_TRADE(crude, reg_from, reg_to)*FREIGHT_CRUDE(crude, reg_from, reg_to)}

    *** Products freight costs*
    + sum{(fp, reg_from, reg_to),
        EXIMPORT(fp, reg_from, reg_to)*FREIGHT_PROD(reg_from, reg_to)}

    *** Investement costs*

```
+ sum{(unit, reg), CAPA_NEW(unit, reg)*CAPEX(unit)}

** Operational costs
+ sum{(intp, reg), OPEX(intp)*INTER_PRODUCTION(intp, reg)}

**  Carbon cost
+ sum{reg, TOTAL_EMISSIONS(reg, "CO2")*CARBON_PRICE(reg)};
```

Interpretation: All the above-mentioned components of total costs are self-explanatory. Note that pollution permits can be introduced in the objective function via positive carbon pricing.

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