Oil Refineries

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS –** In 2012, the global oil refining capacity has reached 93 million barrel per day (b/d): North America (22.8%), Latin America (6.4%), Europe & Eurasia (25.8%), Middle East (8.9%), Africa (3.6%), China (12.5%), India (4.4%), Japan (4.6%), Other Asia Pacific (11.0%). A geographical shift in the refining capacity is reshaping the global downstream industry, namely with refinery closures in developed countries and capacity additions in developing regions [1]. China plans to reach 14 000 thousand b/d of refining capacity by 2015. In addition, there is an increasing need for more *upgrading capacities* in order to accommodate lower quality feedstock on one side, and meet the rising demand for low sulfur diesel on the other side [2]. Global capacity utilization average was 82.4% in 2012 [3] while US average ranged 82.9% to 93.0% in the 2002-2012 period. Configurations for refineries are multiple, but it is possible to distinguish general types of refineries based on their level of complexity: *topping*, *hydro-skimming*, *conversion* and *deep conversion*. Most of the refineries in the US, Asia, Middle East and South America are already conversion or deep conversion refineries (with *upgrading* units): this applies to more than 95% of total crude capacity and 100% of the crude capacity in large refineries (> 50 000 b/d) [6]. Most of the refineries in Europe and Japan are hydro-skimming and conversion refineries. To deal with lower quality input and improve the quality of the output, secondary processes play a vital role in processing raw crude into refined products [1]. They include *upgrading units* (to process heavy oil and oil sands); *hydro-cracking or conversion units* (to get lighter products); *hydro-treating units* (for desulphurization) and *octane units* including catalytic reforming, isomerization and alkylation processes.

■ **PERFORMANCE AND COSTS –** The overall efficiency in US refineries was 90.6% in 2008 (excluding upgrading units): 89.7% for LPG/gasoline/distillate and 93.6% for the remaining products (residual oil/naphtha, etc.) [4]. Energy use increases by 61 MJ/m3 of crude oil feedstock for each additional 1 kg/m3 of sulfur content and 44MJ/m3 for each additional 1kg/m3 in density [5]. Energy use per barrel has increased by 5% after 2006 for compliance with fuel quality standards [6]. The refining sector is a significant source of CO2 emissions: fossil fuel combustion counts for 63.3% of the total emissions [7]. In the US, refineries generated approximately 47.42 kg of CO2-eq per barrel of refined products in 2011. Use of heavy oil and oil sands can double or triple emissions (0.61-1.04 t/m3) compared with the average (0.30 t/m3) [5]. Possible configurations for refineries are multiple, and consequently their economics. New refineries are increasingly capital intensive due to more sophisticated engineering and equipment required to improve efficiency, higher quality fuel standards and environmental legislation. However, on the long term, complex and flexible refineries can generate cost savings by taking advantages of the price differences between heavy and light crude oils and by producing more valuable light products [8]. A review of recent refinery projects provides ranges for investment costs: 20.0-24.2 k$ per b/d for refining capacity expansion; 17.7-26.0 k$ per b/d for refining capacity addition (but 10.3 k$ per b/d for the world largest refinery, 1.24 mb/d); 19.2-90.9 k$ per b/d for upgrading capacity addition; 114.0 k$ per b/d for refining capacity addition with upgraders and CCS. As for total operation costs, they have fluctuated between 5.72 - 9.73 US$ (1999-2009) for the US refiners, including 1.04-2.52 US$ for the energy costs [6]. Another source [23] suggests using the following average operating costs, excluding depreciation and amortization and energy costs: 3.30 US$/barrel for US Gulf Coast & Midcontinent, 4.00 US$/barrel for Northwest and Mediterranean Europe and 3.00 US$/barrel for Asia.

■ **POTENTIAL AND BARRIERS –** The quality of transportation fuels has improved significantly during the past decades and refiners from developed regions (EU, USA, Canada, Japan) have completed the transition to ultra-low sulphur (ULS) fuels. This trend is continuing in developing regions. After the evolution toward high quality refined products, a new trend is a switch in feedstock proportions, i.e. decreasing conventional oil use while increasing non-conventional oil and non-crudes such as biofuels, gas-to-liquids (GTL), coal-to-liquids (CTL) and natural gas liquids (NGL) [1]. Indeed, the rising price of crude oil is a strong incentive to produce transportation fuels from other (cheaper) commodities and to promote advanced refining technology development. Most likely technology advances include alternative processes to the costly and energy-intensive hydro-cracking to produce incremental distillate from crude oil, as well as processes for converting gas and coal into distillates [1]. In addition, the higher availability of shale gas and the related low prices for the gas commodity increase the interest for the natural gas liquids (NGL) and naphtha streams.

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PROCESS AND TECHNOLOGY STATUS

Oil refineries are part of the oil downstream sector and convert crude oil and other feedstock into various refined petroleum products, including transportation fuels. Global demand for refined products amounted to 87.9 million barrels per day (mb/d) in 2011, including light products (ethane/LPG, naphtha, gasoline), middle distillates (diesel/gasoil, jet kerosene) and heavy products (residual fuel, bitumen, lubricants, waxes, still gas, coke, sulphur, direct use of crude oil, etc.). Diesel/gasoil and gasoline alone account for respectively 29.6% and 24.5% of the global demand in 2011; they are expected to represent 33.6% and 24.3% in 2035 [1].

■ **Capacity** – In 2012, the global oil refining capacity has reached 93 million b/d (Table 1). In the recent years, the growth in the global capacity appears modest as the large additions in Asia Pacific were largely offset by significant reductions in the Atlantic Basin in Europe and Latin America. In Europe, about 1.5 mb/d of capacity has been shut down since the economic recession of 2008, including facilities such as the Coryton refinery in the UK (220 kb/d) and the Wilhelmshaven (260 kb/d) and Hamburg refineries (110 kb/d) in Germany [9]. In the OECD countries a total 3.5 mb/d of capacity has been shut down in the same period. Similar trends are observed for refinery throughputs: the net increase that occurred in non-OECD countries and the US has been somewhat balanced by the decline in Europe and Latin America (Table 2). There is a clear geographical shift of refining capacity from developed countries (Europe especially) to developing regions, namely Asia (China, India) and the Middle East due to an increasing domestic demand and the trend towards domestic refining. China has already more than doubled its refining capacity in the last 10 years in order to meet its fast-growing demand (Table 3), and this trend is expected to continue to reach a 14 mb/d refining capacity by 2015 for either light crude oil and, increasingly, heavier crude oils imported from Latin America and Middle East. [10]. Driven by two major players, i.e. China Petroleum and Chemical Corporation (Sinopec 46%) and China National Petroleum Corporation (CNPC, 31%), the Chinese refining industry is also increasing the export.

In addition to regional changes, the refining industry is also evolving globally in terms of feedstock and quality of the refined products. There is an increasing need to process lower quality feedstock (e.g. heavy oil, oil sands) as well as to meet rising demand for cleaner products (e.g. low-sulphur diesel) all over the world [2]. However, the US has consolidated its position as a net exporter of refinery products. Most refineries of the Gulf Coast region are already highly complex and flexible facilities to produce high-quality products from diversified feedstock, and benefit from a competitive

Table 1 - Global Refining Capacity, 2008-2012 [3]

(kb/d)*	2008	2009	2010	2011	2012
North America	21,086	21,023	21,151	20,974	21,057
- United States	17,672	17,584	17,736	17,322	17,388
Lat. America	6,658	6,678	6,651	6,483	5,912
Europe/Eurasia	24,612	24,538	24,372	24,259	23,865
- West Europe	13,104	13,010	12,621	12,539	12,251
- Russian Fed.	5,422	5,401	5,508	5,569	5,754
Middle East	7,672	7,925	8,051	8,167	8,255
Africa	3,121	2,982	3,175	3,123	3,323
Asia Pacific	26,111	27,671	28,383	29,170	30,119
- China	8,722	9,479	10,302	10,834	11,547
- India	2,992	3,574	3,703	3,795	4,099
- Japan	4,650	4,630	4,291	4,274	4,254
World	89,259	90,817	91,782	92,176	92,531

*Atmospheric distillation capacity on a calendar-day basis (refining process at atmospheric pressure and temperatures of about 300º to 350º C).

Table 2 - Global Refinery Throughputs, 2008-12 [3]

(kb/d*)	2008	2009	2010	2011	2012
United States	14,648	14,336	14,724	14,806	15,006
Other N. America	3,231	3,165	3,016	2,900	2,995
Lat. America	5,363	4,889	4,834	5,047	4,624
Europe/Eurasia	20,635	19,509	19,595	19,507	19,459
Middle East	6,396	6,297	6,396	6,519	6,444
Africa	2,456	2,293	2,449	2,149	2,201
China	6,953	7,488	8,571	9,059	9,371
India	3,213	3,641	3,899	4,085	4,302
Japan	3,946	3,627	3,619	3,410	3,400
Other Asia Pacific	8,107	7,991	8,190	8,275	8,431
World	74,949	73,234	75,293	75,757	76,233

*Atmospheric distillation capacity on a calendar-day basis (refining process at atmospheric pressure and temperatures of about 300º to 350º C).

advantage. The need for upgrading and desulphurisation is expected to increase everywhere to meet more stringent quality standards.

■ **Utilization Rate** – The utilization rate of the refining capacity depends basically on the demand for refined products, feedstock availability and existing capacities. It is therefore a good indicator of refinery margins and profitability [1].

The average utilisation rate has been declining during the last decade particularly in Europe where the decreasing domestic demand, the extra capacity in developing countries, the rising use of natural gas, NGL, biofuels and gas-to liquids have driven structural changes in the refining market and lower utilisation rates [9]. A global view of the utilization rate of the refining capacity between 2002 and 2012 is given in Figure 1. The global average in 2012 was 82.4%.

■ **Configuration and Processes** – Atmospheric distillation is the first main refining step where the crude oil is heated to 300°C-350°C to distillate the more volatile components (diesel and kerosene). The atmospheric residue is then further distilled under vacuum (500°C-560°C) to yield further volatile products and leave a high viscosity vacuum residue as a by-product [3]. The vacuum residue required additional processing. See Figure 2 for an example of a complex refinery.

Configurations for refineries are indeed multiple: there is about as much configurations as there are refineries. Similarly, there are numerous types of processes; as many as fifty distinct processes can be used in large and complex refineries [6]. However, it is possible to distinguish general types of refineries based on their level of complexity. See Table 4 for an overview of the main processes included in each type of configurations [6] [7]:

Topping refineries: They are limited to the basic crude oil distillation and support operations. They can separate the crude oils into refined products, but cannot modify the natural yield patterns of the crude oils. Consequently, they are producing a limited range of intermediate distillates, but not gasoline. In addition they do not have process unit to reduce the sulphur levels.

Hydro-skimming refineries**:** These are refineries with hydrotreating, blending and/or reforming units in addition to the main distillation unit that allow producing a full range of refined products but from a limited range of feedstock, and not heavy oil. Reforming units allow upgrading naphtha to produce gasoline that meets octane specifications. They produce hydrogen as by-product for the hydrotreating units, which allow reducing the sulphur levels from light fuels such as gasoline and diesel to meet sulphur specifications. However, they cannot modify the natural yield patterns of the crude oils.

Conversion refineries: Also called cracking refineries as they include catalytic cracking and/or hydrocracking process units in addition to all processes common to hydro-skimming refineries. With those processes, conversion refineries can modify and improve the natural yield patterns of the crude oils. Contrary to the most simpler configurations described above, these processes indeed allow converting heavy oil (gas oils) into lighter products (gasoline, jet fuel, diesel fuel, and petrochemical feedstocks). However, they cannot produce some heavy products, as residual fuel and asphalt.

Table 3. Major New/Upgrade Refineries in China [10]

Location	kb/d	y	Notes
Sinopec			
Maoming	200	2012	Upgrade
Nanjing/Jinling	110	2012	Construction
Caofeidian/Tianjin	200	2013	Construction
Guangdong/Zhanjian	300	2015	Constr;Q8/Total
Zhenhai/Zhejiang	300	2015	Expansion
Lianyungang/Jiangsu	240	2016	Expansion
Fujian	240	2018	Exxon/Aramco
CNPC/PetroChina			
Pengzhou	200	2012	Construction
Huabei	100	2013	Approval
Anning/Yunnan	260	2014	JV/Aramco
Guangdong/Jieyang	400	2014	Approval;
Huludao	200	2014	Construction
Qinzhou	200	2015	Expansion
Tianjin	260	2015	Feasibility,JV/Rosnet
Changzhou	200	2015	Feasibility
Chongqing	200	2016	Myanmar pipeline
Jiangsu/ Taizhou	400	2017	Approval;Qatar/Shell
CNOOC			
Huizhou	200	2017	Expansion
Sinochem			
Quanzhou	240	2014	Approval
Ningbo	240	2020	Approval

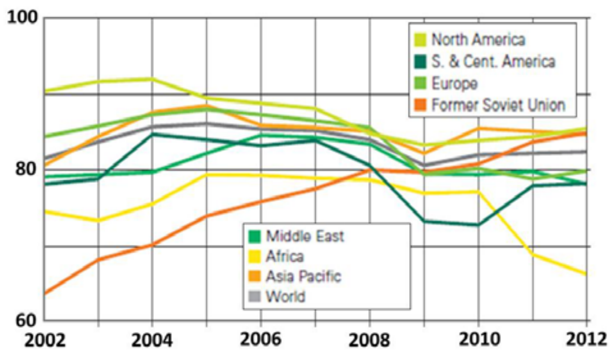

Figure 1 - Refinery Utilization Rates, 2002-2012 [3]

Deep conversion refineries: These refineries also have catalytic cracking and/or hydrocracking process units to covert heavy oils into light products, but coking units as well. Coking processes allow treating the heaviest crude oil fractions (residual oil) and convert them to lighter products. These products can then serve as feedstocks into other conversion processes (catalytic cracking) or upgrading processes (catalytic reforming) to produce the most high quality products. For instance, these refineries have upgrading units to process bitumen from oil sands.

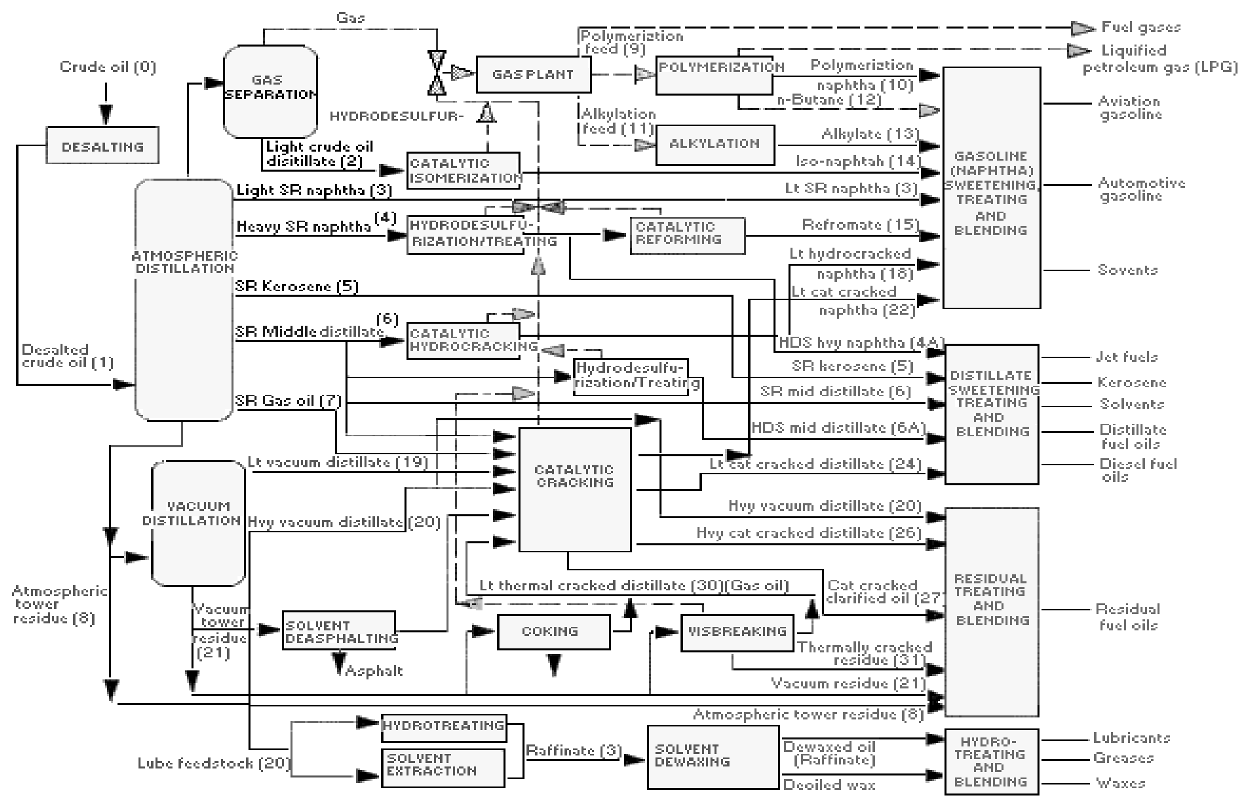

Figure 2. Representation of a complex refinery [21]

The refinery configuration is influenced by its location, year of construction, level of capital investments, feedstock type and availability, refined product demand (domestic and international), quality standard requirements and environmental regulations. For example, while the majority of North American refineries are configured in order to maximize gasoline production (Table 5), refineries in the rest of the world are configured in order to maximize distillate production and sometimes petrochemical feedstock. Table 6 shows minimum and maximum refinery yields in other world regions based on different refinery combinations [23].

Most of the US refineries as well as the most recent refineries elsewhere (Asia, Middle East, South America) are conversion or deep conversion refineries: more than 95% of total crude capacity and 100% of the crude capacity in large refineries (>50 kb/d). These complex refineries can performed cracking or coking operations that allow converting heavy crude oil (with high molecular weight hydrocarbons) into lighter products (with smaller hydrocarbons). However, most of the refineries in Europe and Japan are hydroskimming and conversion refineries. Higher is the level of complexity, greater is the capital investment intensity and ability to add value to crude oil by using low quality inputs and producing high quality outputs.

Table 4 – Level of complexity of refineries and typical yield patterns [6]

Refinery Type Key Processes	Yield Profile (vol %) gsl	Yield Profile (vol %) dst	Notes
Topping Distillation	31	30	• Sulfur levels same as crude fraction sulfur level • Product yield/quality dominated by crude type; low-octane gas.
Hydro-skimming Distillation; Reforming; Hydro-treating	28	30	• Sulfur levels control by hydro-treating • Capability to improve yields and quality • Reforming-improved octane
Conversion Distillation, FCC Hydro-cracking, Reforming, Alkylation Upgrading, Hydro-treating	44	32	• Sulfur level control by hydro-treating • Capability for yield and quality improvement
Deep Conversion Distillation, Coking, FCC, Hydro-cracking, Reforming, Alkylation Upgrading Hydro-treating	47	42	• Sulfur levels control by hydro-treating • Max. yield of high-value refined products • Max. capability for quality improvement

Most relevant processes used for treating lower input quality (bitumen) while improving output quality (low sulphur fuels) are further described in the following section.

■ Processes and product quality specifications – Important investments have been made in developed countries to improve refined product quality specifications and to comply with increasingly more stringent regulation regarding in particular fuels for transport (unleaded gasoline and low-sulfur fuels). Complex refineries can produce ultra-low sulphur fuel (ULSF) up to <5 ppm [6]. In the coming years, improvements will also focus on reducing benzene and aromatics in gasoline, while improving the octane number, and on reducing poly-aromatics of diesel while improving the cetane number [1].

In order to improve the quality of their finished products, refiners can play with the composition of their feedstock, play with the operation mode of their existing process units (hydro-cracking and hydro-treating units) or add new process units such as upgraders and octane units. While adding primary distillation units is necessary to meet the increasing demand for refined products, adding secondary process units is equally important to meet the increasing demand for high quality refined products and to improve the refinery's 'value added'.

Indeed, these units play a more vital role in processing raw crude into refined products while complying with stricter quality specifications and increasingly advanced products [1]:

- **Hydro-cracking units:** These process units are used to crack heavier hydrocarbons into lighter hydrocarbons for further processing using hydrogen and a catalyst. In other words, it upgrades low quality heavy gas oils into high quality fuels (jet fuel, diesel and gasoline). Some refineries still do not have such hydrocrackers, but their number is increasing with the global demand for middle distillates. The increasing demand for lighter products leads to more important capacity additions for conversion units rather than for distillation units. The proportion of conversion units is actually in the range of 40–50% but is expected to grow over time with the increase in the refining complexity.

- **Hydro-treating units:** These process units are commonly used to reduce the sulphur content of crude oil and used in most refineries. The increasingly tighter limits on sulphur content are leading to an expansion of the desulphurization capacity faster than the expansion of the general refining capacity.

- **Octane units:** These process units are used to rearrange molecule structures to get higher octane gasoline. New capacity additions through octane units are driven by the increasing demand for high quality gasoline and such processes include catalytic reforming (convert low octane naphthas into high octane reformates), isomerization (convert linear molecules to higher octane molecules) and alkylation (produce high octane component for gasoline blending).

Table 5 - US Refinery Yield, 2002-2012 (%) [12]

	Motor gasol.	Distill. fuel oil	Jet fuel	Fuel oil resid	Petrol coke	Still gas	LPG	Other*
2002	47.3	23.3	9.8	3.9	5.1	4.3	4.3	8.2
2004	46.8	23.9	9.7	4.1	5.2	4.4	4.0	8.5
2006	45.8	25.4	9.3	4.0	5.3	4.5	3.9	8.0
2008	44.3	27.8	9.7	4.0	5.3	4.3	4.1	7.0
2010	45.7	27.5	9.3	3.8	5.3	4.4	4.3	6.8
2012	45.2	29.2	9.5	3.1	5.5	4.4	4.0	6.3

* Includes asphalt, road oil, petrochemical naphtha/oils, waxes, lubricants, naphtha, kerosene, aviation gasoline, other products; ** Refinery processing gain 4.8 -7.5%.

Table 6 – World region Refinery Yield, 2012 (%) [23]

	Northwest Europe		Medditeranean Region		Singapore region	
	Min	Max	Min	Max	Min	Max
LPG	4	6	2	6	2	4
Gasoline	13	35	13	24	10	26
Naphtha	0	0	0	0	6	7
Kerosene	7	13	7	14	12	23
Diesel	30	37	30	43	23	37
HSFO	0	42	0	42	0	42
LSFO	0	32	0	36	0	37

- **Upgrading units:** These process units are used to upgrade bitumen into synthetic oil using fractional distillation and/or chemical treatment so that it can be used in refineries. Upgrading means reducing the viscosity of bitumen (which is up to 1000 times higher than for light crude oil). Not all refineries have upgrading units, although their number is increasing with the production of unconventional oil. Consequently, a portion of the refining capacity addition comes from upgrading projects in existing refineries to process heavy oil and oil sands, which is less costly than building new facilities.

As illustrated in Table 7, the major motivations for investments in existing refineries in the past were the ability to process heavier crude oil and the compliance with new environmental regulations. The trend will continue in the developing world. The global refining system is projected to expand by 7,200 kb/d between 2011 and 2016 and these projects will add more than 6,000 kb/d of desulphurization capacity (hydro-treating units), 4,700 kb/d of conversion capacity (hydro-cracking) and around 1,700 kb/d of combined reforming, alkylation and isomerization capacity (octane units) [1].

Performance and Costs

■ **Energy Use and Efficiencies –** The energy efficiency of the refinery industry in increasing everywhere, particularly in new or renewed installations. In the US the average oil refining efficiency has improved from 90.1% in 2006 to 90.6% in 2008 [4]. On the other hand, the energy use in the refining industry is increasing because of the need for processing non-conventional oil resources (heavy oil, oil sands) and to produce high-quality final products. A detailed methodology to allocate the energy efficiencies by type of refined product outputs was developed by [4]. The methodology looks at two groups of refined products: LPG/gasoline/distillate on one side and the remaining products (residual oil/naphtha, etc.) on the other side. The first group accounts for 84.6% of the total energy content from refinery outputs, while the second group accounts for 15.4%. Using this methodology, the energy efficiency was established at 89.7% for the first group (-1% below the total average efficiency of 90.6% when including all products) and 95.9% for the second group. These estimates correspond to an energy intensity of 1.11 and 0.42 respectively (Table 8).

These results exclude the energy use for upgrading; it is assumed that heavy oil crude and oil sand are treated prior to the refining process and converted to synthetic fuel at the upstream level. In fact, heavy crude oil feedstock required more energy and hydrogen consumption for processing as they have a larger portion of vacuum residue (see Figure 2) that needs to be upgraded to produce commercially viable refined products. However, hydrocracking residue can be gasified to produce hydrogen for use in hydrotreating and upgrading.

Table 9 shows the types and quantities of fuels that are consumed by the US refineries, i.e the energy that is used as fuels (and not that main feedstocks that are processed into refined products). These numbers show that refineries use a variety of other fuels in order to process crude oil into refined products (the total of refined produced by US refineries is indicated in the first row in order to derive the fuel consumption for each barrel of outout). In relation with the refined product quality, reducing the sulfur content of a refined product requires more energy consumption and consequently leads to an increase in GHG emissions. “Refinery energy must be expended to 1) produce the additional hydrogen required for the necessary desulfurization; 2) increase refinery and process throughput as needed to replace the product yield losses due to desulfurization; and 3) increase the severity of reforming and upgrading operations as needed to replace the octane losses due to desulfurization.” [1]. Although it is difficult to determine with precision, rough estimates can be made from the recent trends in terms of energy consumption by US refineries in association with their production of low-sulfur fuels: while the total energy use to produce

Table 7 - US Refinery Configurations (% Downstream Capacity) [8]

	2002	2004	2006	2008	2009
Coking	15.8	15.7	15.4	16.0	16.3
Catalytic cracking	33.0	33.7	33.9	34.3	33.6
Catalytic reforming	21.8	21.8	21.7	21.0	21.5
Hydro cracking	10.7	10.7	11.0	11.1	12.1
Catalytic hydro-treating	n.a	79.5	85.8	87.7	87.0
Alkylation	7.1	7.3	7.5	7.2	7.0

Table 8 - Refining Energy Efficiency for Petroleum Products [4]

	% of the Energy Content included in the Total Refinery Output	Energy Intensity	Refinery Efficiency
	%	In/Out	%
LPG, Gasol., Distillate	84.6	1.11	89.7
Others	15.4	0.42	95.9
Total aver. efficiency (all products)			90.6

Table 9 - Energy and fuel consumption in the US refineries (kb, except where noted) [12]

	2008	2010	2012
Total production of refined products (mb)	5,347	5,374	5,477
Crude Oil	-	-	-
LPG	2,930	2,404	1,521
Distillate Fuel Oil	472	440	539
Residual Fuel Oil	1,390	980	540
Still Gas	237,161	219,890	220,094
Marketable Petroleum Coke	81,811	82,971	85,190
Catalyst Petroleum Coke	364	897	694
Natural Gas, m cubic meters	109	67	56
Coal, k metric tons	644	686	765
Purchased Electricity, GWh	43	29	30
Purchased Steam, Mt	9.4	21.0	20.2
Other Products*	81,447	82,074	84,496

*Includes pentanes plus, other hydrocarbons, oxygenates, hydrogen, unfinished oils, gasoline, special naphthas, jet fuel, lubricants, asphalt and road oil, and miscellaneous products.

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each barrel of refined products in US refineries declined by 10% in average between 1985-2005, the trend was opposite between 2006-2010 where the energy use per barrel increased by 5% probably due to the compliance with the new federal standards that entered into force in 2006 [6].

■ **Emissions –** Since fossil fuels account for a large part of the energy consumed by refineries, the refining sector is a significant source of CO2 emissions. For example, the GHG emissions resulting from the energy use in the US refining sector amounted to 261.87 Mt of CO2-eq in 2010 and 256.26 Mt in 2011, corresponding to 17.5% of the total emissions from the industrial sector [13]. Based on the information provided in Table 2, these estimates are equivalent to 48.73 kg of CO2-eq per barrel of refined products in 2010 and 47.42 in 2011. In addition to the fossil fuel combustion emissions (63.3% in average), some processes are important source of CO2 emissions such as fluid catalytic cracking units (FCCU), hydrogen production plants and sulfur recovery plants [7]. As for CH4 emissions, they come from equipment leaks, storage tanks, asphalt blowing, delayed coking units, and blow down systems. Flaring of waste gas is also a significant source of CO2 and CH4 emissions. Figure 3 provides a breakdown of GHG emissions in the US refineries [7].

The emission intensity of processing different quality feedstock has been evaluated from the energy used in refinery facilities in four US regions accounting for 97% of the total refining capacity from 1999 to 2008 [5]. The density and the sulphur content of the various types of crudes could predict 90% of the energy intensity as well as 85% of the emission intensity differences between regions and years. The results showed that the GHG emissions could be increased by up to 39% when using low quality crudes as feedstock. Energy consumption by refineries increases by about 61 MJ/m3 of crude oil feedstock for each additional 1 kg/m3 of sulfur content and 44MJ/m3 for each additional 1kg/m3 in density. Consequently, the use of heavy oil and oil sands in refineries can double or triple emissions (0.61-1.04 t/m3) compared with the US average (0.30 t/m3) [5].

■ **Refinery Costs –** Refineries may have a number of different configurations, with different economic performance. In general, new refineries are increasingly capital intensive due to more sophisticated engineering and equipment required to improve efficiency, meet higher quality fuel standards and environmental legislation. However, on the long term, complex and flexible refineries can generate cost savings by taking advantages of the price differences between heavy and light crude oils and more valuable light products [8].

Investment costs. In the refining industry, there are three types of investment costs: investment in new capacity (building new refineries); capacity additions in existing facilities (adding units at existing refineries); gradual existing stock replacement and annual maintenance. Globally, construction costs for new refineries are rising due to the increasing costs of raw materials, labor and construction equipment. For example, the increase in the total construction costs was between 5% and 10% for the period 2010-2011 [1]. For the same reasons, the investments cost of capacity additions in existing facilities is also increasing. As for the gradual stock replacement and annual maintenance, the industry practice and norms set the maintenance capital replacement rate at 2% of the installed base each year. Additional costs need to be taken into account for investment in the related infrastructure, i.e. beyond the refinery gate (port facilities, loading and receiving facilities, tankers, storage tanks, pipelines, distribution network).

According to [1], the global refining capacity is projected to expand by 7,200 kb/d between 2011 and 2016 and the cost of constructing this capacity is estimated at 230,000 M$. These figures give a rough average of 31.9 k$ per unit of capacity (b/d). The investment required to upgrade an existing refinery depends on many factors. The largest increases come from the investment in additional hydrogen supply and use [6]. In all cases, upgrading techniques require increasing hydrogen production capacity, sulfur recovery, storage and other support facilities, as well as new catalysts, and new processes. In the US National Energy Modeling System (NEMS), the capital cost of refurbishing is assumed to be 50% of the cost of adding a new unit [14]. In Canada, the typical replacement value of old refineries is estimated to exceed 7,000 M$, excluding the cost of land-acquisition [9]. If we consider that the average capacity of Canadian refineries is about 106,500 b/d as an indication, the average investment costs for building a new refinery in Canada would be 65.7 k$ per b/d. The cost of building a new refinery in Canada is also estimated between 7,000 M$ and 10,000 M$ by [22]. In fact, the financial issues have been the most important barrier in expanding the refining capacity, with initial investment amounting to more than 10,000 M$ [16] or 93.9 k$ per b/d.

A review of recent announcement on refinery projects provides some order of magnitude regarding the investment costs for different types of projects: new refinery construction, capacity additions, upgrader construction, etc. (Table 10).

■ **Operating costs –** Operating costs depend on multiple factors such as the size and the complexity of refineries, utilisation rates, wages of workers and environmental regulations. Consequently, these costs vary widely across countries and regions. Some components of the operating costs vary are fixed (labour, insurance, etc.), others vary with the refinery throughput (catalysts, chemicals, etc.) [23]. It is difficult to report and even more to compare operationg costs

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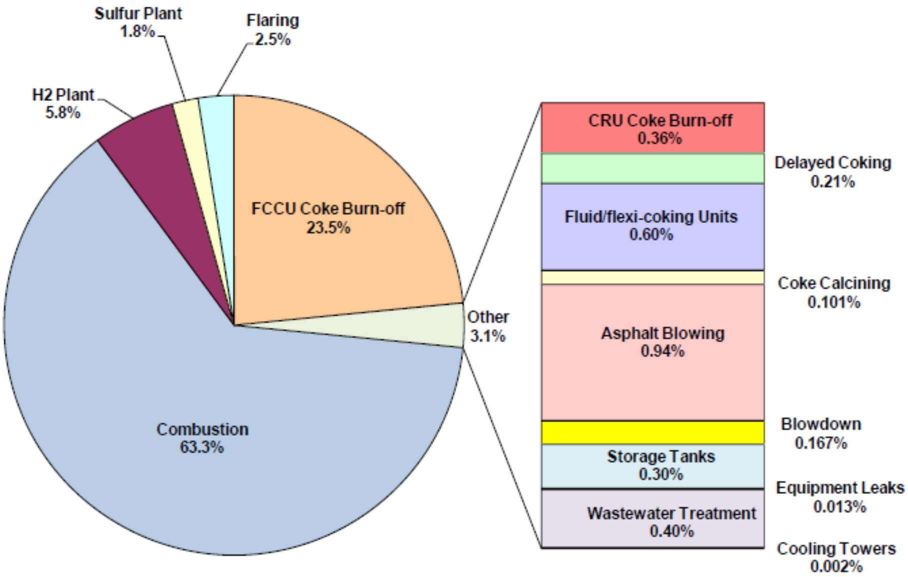

Figure 3 - Relative contribution of GHG emission sources from oil refineries [7]

from different refiners as they are not reported regularly and on a common basis (e.g. including or excluding energy costs, depreciation, maintenance, etc.). However, some indications are provided below.

Profitability of the refiners is mostly affected by two main components: price changes of refined product relative to price changes of crude oil, and operating costs. In the US refineries, the total operation costs in the 1999-2009 period have fluctuated between US$ 5.72 and 9.73 per barrel (see operating costs for selected years in Table 11). This range is a good indicator of possible changes in operation costs as it remains similar in a two decade period, from 1989 to 2009. In particular, 2009 energy costs were at one of their lowest levels reported in the refiner's history due among other reasons to the increased availability of natural gas at low prices and the completion of cogeneration projects [6]. The remaining part of the operating cost reduction between 2008 and 2009 was due to operation cost cutting, as well as better negotiated costs for materials and labor, lower waste water-treatment costs based on advanced technologies, lower turnaround costs, and no charge for hurricane-related events. As for the associated costs of compliance with the Clean Air Act Amendments of 1990, they were different from a refiner to another: it increased the operation costs for some while it decreased for other [6]. Finally, the lowest marketing cost of the last decade was possible for refiners in 2009 by refocusing the marketing operations, but mainly by exiting motor gasoline retailing: direct refiner-operated motor gasoline outlets were reduced by 6% from 2008 to 2009 to the benefit of third-party channels of distribution.

Table 10 - Sample of Planned/Proposed Refinery Projects and Investment Costs [15, 16, 17]

Country	Project	Capac. (kb/d)	Inv. M$	Inv. k$/ b/d
Indonesia	Expans. Cilacap, Planned 2013	62	1500	24.2
Indonesia	Expans. Dumai, Planned 2014	50	1000	20.0
Indonesia	Constr. Banten., Planned 2015	150	3000	20.0
Indonesia	Constr. Pare-Pare, Constr. 2015	300	3500	11.7
Indonesia	Constr. Situbondo,	150	3000	20.0
Canada	Constr. oil sands upgrader, Project	55	5000	90.9
Canada	Bitumen upgrade and diesel (50 kb/d). CCS 1.2 Mt CO2/y EOR,	50	5700	114.0
Canada	Oil sands upgrader, Postponed	260	5000	19.2
Canada	Oil sands upgrader, Postponed	240	14,400	60.0
Kuwait	ME Largest Oil Ref., Project 2018	615	14,500	23.6
Canada	Kitimat Ref. for DilBit process, Project 2020	550	13,000	26.0
India	World's biggest fuel supplier, Plan	1,240	6,000	10.3

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Another source of information [23] reports operation costs for different refiners based on their annual reports, with indications on what is included or excluded when available (Table 12). Independent US refiners are the most transparent sources of data for operating cost. This table shows the large range of variation in operating costs. Operating costs of european refiners tends to be alittle higher than those of refiners in other markets. The reports [23] suggests using the following average operating costs, excluding depreciation and amortization and exclusing energy costs: 3.30 US$/barrel for US Gulf Coast & Midcontinent, 4.00 US$/barrel for Northwest and Mediterranean Europe and 3.00 US$/barrel for Asia.

POTENTIAL AND BARRIERS

The evolution in the refining sector is mainly determined by supply and demand trends for refined products. The transportation sector is expected to require an additional 19.5 mb/d by 2035 compared with 2011 [1], with 60% of middle distillates (gasoil/diesel and jet/kerosene). The share for middle distillates is expected to increase their share from 37% in 2011 to 41% by 2035. The quality of transportation fuels has improved significantly during the past decades and refiners from developed regions (EU, USA, Canada, Japan) have completed a transition to Ultra Low Sulphur (ULS) fuels. The trend will continue in developing regions.

After a strong evolution toward high-quality refined products (outputs), a new trend in the refinery industry is the switch in feedstock proportions (inputs): a decrease of conventional oil versus an increase of non conventional oils (extra heavy oil, oil sands, shale oil). Refineries will need to adapt to these changes in crude oil qualities, i.e. by getting more hydro-treating and upgrading process units for instance. Consequently, capacity additions for these secondary process units are expected to growth faster than capacity additions of basic distillation units. An important portion of these capacity additions from these secondary process units relate to small hydrotreating and upgrading projects into existing refineries. Moreover, most newly built refineries are complex refineries, including upgrading units, to process lower quality feedstocks into refined products that meet the most stringent specifications such as Euro standard [1]. The global capacity addition for distillation is estimated to increase by 14.9 mb/d between 2011-2035 [1]. For secondary processes, the estimated additions are: 11.6 mb/d for conversion units (hydro-cracking, upgrading, coking, etc.), 22.0 mb/d for hydro-treating units and 5.4 mb/d for octane units.

In addition, there is a increasingly higher proportions of non-crude feedstocks such as biofuels, gas-to-liquids (GTL), coal-to-liquids (CTL) and natural gas liquids (NGL) [1]. Indeed, the rising price of crude oil is a strong incentive to produce transportation fuels from cheaper commodities and to promote advanced refining technology development. Some developments could have a significant impact on the refining industry in the near future, as well as on refined product consumption and trade patterns. Among the most likely technologyl advances, there are the alternatives to hydro-cracking processes (costly and energy intensive) that are producing incremental distillates from crude oil. Refineries are modified in order to allow for processing higher proportions of non-crude feedstock as well as converting gas, coal and naphtha into distillates [1]. The high availability of shale gas and the related low prices increase the interest in natural gas liquids (NGL) and streams. Other developments relates to carbon capture and storage option at refineries and upgrading complex in order to reduce CO_2 emissions.

Table 11 - Operation costs of US refineries [6]

US$2009/barrel	2004	2006	2008	2009
Marketing costs	1.75	1.50	1.76	1.47
Energy costs	1.63	1.85	2.52	1.32
Other costs	2.84	3.89	5.45	4.52
Total operating costs	6.22	7.25	9.73	7.31

Table 12 – Operation costs for different refiners [23]

Refiners/Refineries	Units	Costs
USA		
Valero Energy, US Gulf Coast (1)	US$/bbl, 2012	$3.53
Valero Energy, US West Coast (1)	US$/bbl, 2012	$5.59
Valero Energy, US Midcontinent (1)	US$/bbl, 2012	$4.64
Valero Energy, North Atlantic (1)	US$/bbl, 2012	$3.37
Valero Energy, Total refining (1)	US$/bbl, 2012	$3.87
Marathon Petroleum (2)	US$/bbl, 2012	$5.46
Western Refining (3)	US$/bbl, 2012	$3.91
Tesoro Midcontinent (3)	US$/bbl, 2012	$3.95
Phillips 66 Atlantic Basin (3)	US$/bbl, 2012	$4.00
Phillips 66 Midcontinent (3)	US$/bbl, 2012	$2.20
Phillips 66 Gulf Coast (3)	US$/bbl, 2012	$3.77
Europe		
Petroplus, Coryton	US$/bbl, 2011	$3.80
Petroplus, Antwerp	US$/bbl, 2011	$3.31
Petroplus, Petit Couronne	US$/bbl, 2011	$4.24
Petroplus, Ingolstadt	US$/bbl, 2011	$3.29
Petroplus, Cressier	US$/bbl, 2011	$4.13
Neste Oil	US$/bbl, 2011	$4.35
Neste Oil	US$/bbl, 2012	$4.60
Asia		
Thai Oil	US$/bbl, 2012	$1.50

(1) Excluding depreciation and amortisation
(2) Maintenance and Turnarounds (0.96$), Depreciation and Amortisation (1.39$), Other Direct Opex (3.11$)
(3) Excluding depreciation and amortisation and maintenance

Table 12– Summary Table: Key Data and Figures for Oil Refining Technologies

Technical Performance	Typical current international values and ranges
Energy input (feedstocks)	Crude oil (light, heavy, oil sands, etc.) and other feedstock (natural gas, NGLs).
Output	Light products (ethane/LPG, naphtha, gasoline); Middle distillates (diesel/gasoil, jet kerosene); Heavy products (residual fuel, bitumen, lubricants, waxes, still gas, coke, sulphur, direct use of crude oil, etc.). Globally: gasoline (24.5%), diesel/gasoil (29.6%). US: gasoline (42.2%), diesel/gasoil (27.2%). Topping: gasoline (31%), diesel/gasoil (30%); Hydro-skimming gasoline (28%), diesel/gasoil (30%); Conversion gasoline (44%), diesel/gasoil (32%); Deep Conversion gasoline (47%), diesel/gasoil (42%);
Efficiency, %	Overall efficiency in US refineries is 90.6% in 2008 (exc. upgrading units): 89.7% for LPG/gasoline/distillate and 93.6% for the remaining products (residual oil/naphtha, etc.). Input: Energy use increases by 61 MJ/m3 of crude oil feedstock for each additional 1 kg/m3 of sulfur content and 44MJ/m3 for each additional 1kg/m3 in density. Output: Energy use per barrel has increased by 5% after 2006 for compliance with fuel quality standards.
Total cumulative capacity,	Global oil refining capacity has reached 93 mb/d in 2012: North America (22.8%), S. & Cent. America (6.4%), Europe & Eurasia (25.8%), Middle East (8.9%), Africa (3.6%), China (12.5%), India (4.4%), Japan (4.6%), Other Asia Pacific (11.0%).
Utilization rates	Globally: average of 82.4% in 2012. In the US: 82.9% - 93.0% annual averages on the 2002-2012 period.
CO2 emissions, gCO_{2eq}/kWh	In general: fossil fuel combustion count for 63.3% of the emissions. In the US: 48.73 kg of CO2-eq per barrel of refined products in 2010 and 47.42 in 2011. Use of heavy oil and oil sands can double or triple emissions (0.61-1.04 t/m3) compared with the average (0.30 t/m3). GHG can increased by up to 39% when using low quality crudes as feedstock

Costs	Typical current international values and ranges (2012 US$, 1€ = 1.3 US$)
Invest cost (US$)	Average of 31.9 k$ per b/d for new projects based on future projects. • 20.0-24.2 k$ per b/d for refining capacity expansion. • 17.7-26.0 k$ per b/d for refining capacity addition (but 10.3 k$ per b/d for the world largest refinery, 1.24 mb/d). • 19.2-90.9 k$ per b/d for upgrading capacity addition. • 114.0 k$ per b/d for refining capacity addition with upgraders and CCS.
O&M cost (US$ 2012)	Average operating costs, excluding depreciation and amortization and energy costs: 3.30 US$/barrel for US Gulf Coast & Midcontinent, 4.00 US$/barrel for Northwest and Mediterranean Europe and 3.00 US$/barrel for Asia. In US: 5.72 and 9.73 US$ (1999-2009), including energy costs (1.04-2.52 US$).
Fuel cost (US$ 2012)	1.04-2.52 US$

Data Projections	Typical current international values and ranges
Capacity additions 2011-2035 (mb/d)	Global capacity addition for distillation: + 14.9 mb/d. For secondary processes: +11.6 mb/d for conversion units (hydro-cracking, upgrading, coking, etc.), +22.0 mb/d for hydro-treating units and +5.4 mb/d for octane units.
Inv.cost, $/kW 2010-2020	See investment costs for new projects above.

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