



Refining Crude Oil – Part 2

Refining is a capital-intensive industry in a market driven by divergent forces—cleaner fuels to address local air pollution; greater fuel efficiency against the backdrop of record oil prices; and steadily rising consumption of transportation fuels due to rising income, especially in developing countries. Part 2 of the briefing notes on refining discusses these topics and other global trends.

Profits boom on strong demand,” read the title of an article on refining in the September 2006 issue of *Petroleum Economist*. “Time to prepare for the downstream downturn,” read the title of an article on refining that appeared exactly a year later in the same industry journal. “People are beginning to reconsider investments, because they are seeing cost overruns, delays, and quality impairment,” the second article reported [1,2]. The refining industry has been subject to booms and busts, and the titles of these articles encapsulate the swings in the industry cycle.

Challenges facing the refining industry are many. It is not enough that crude oil be refined. The outputs—relative amounts of gasoline, kerosene, diesel, residual fuel oil—must match demand, or else there will be a shortage of some fuels and a surplus of others. The fuel mix of demand is not static but has been changing over time. For example, concerns about rising transportation fuel prices and a desire for higher fuel economy are driving European car owners to turn increasingly to diesel vehicles (which have better fuel economy than gasoline vehicles), increasing demand for diesel at the expense of gasoline and causing an imbalance between demand and supply. The fuels must also meet the specifications set by governments. Fuel specifications are tightening progressively, making refining more costly.

Satisfying the above criteria and remaining commercially competitive requires that the refinery configuration and crude mix be optimized for the market the refinery is serving. This briefing note discusses these and other issues facing the global refining industry today.

Location

The location of a refinery influences its economics, mainly on account of associated transportation costs.

First, refineries serving domestic markets are gen-

erally more profitable than those serving the export market. This is because exported fuels are sold at export-parity prices: the prices in the destination market minus the cost of shipping. A refinery serving the domestic market in a net importing country, in contrast, may be able to charge import-parity prices, which include freight costs which the domestic refinery is not incurring. This gives a natural advantage to a refinery serving the domestic market over export-oriented refineries. If domestic demand for oil is much less than the capacity of an economic scale refinery—which would be 100,000 barrels per day (bpd) or larger, against oil demand in Cambodia in 2005 of 28,000 bpd [3]—then a refiner is faced with two options: build a small refinery to serve primarily the domestic market, or build an economic scale refinery and export some or even the bulk of the products. A small refinery may not be able to compete with product imports from large, efficiently-run refineries in the neighboring countries. A world-scale export refinery can take advantage of economies of scale, but will face full international competition.

Second, refining domestic crude is generally more economic than refining imported crude. This is because importing crude incurs the cost of shipping crude to the refinery, possibly even a long distance, whereas the cost of transporting domestic crude to a domestic refinery is generally lower.

Third, some locations offer natural protection. A landlocked refinery receiving crude by pipeline might be well-positioned to compete with trucked refined products, but the same refinery located near a large harbor capable of receiving oil products from around the world might struggle to remain competitive.

Declining Demand for Fuel Oil

As suggested in the previous briefing note [4], ar-

guably the most significant reason for the restructuring of the global refining sector is increasingly stringent fuel specifications, and in particular the move for large cuts in the fuel sulfur content. The most commonly adopted fuel specifications are those needed to meet the so-called Euro vehicle emission standards, known as Euro 1, 2, and so on. The sulfur limits on gasoline and diesel corresponding to the Euro standards are shown in Table 1. Developing countries follow similar specifications, but with a time lag. In Asia, the sulfur content of automotive fuels in Thailand is at the Euro 3 level, and in China Euro 2.

Year	1993	1996	2000	2005	2009
Euro	2	2	3	4	5
Gasoline	0.05	0.05	0.015	0.005	0.001
Diesel	0.2	0.05	0.035	0.005	0.001

Note: Euro 2 was in effect from 1993 to 2000, but in October 1996 the diesel sulfur limit was lowered.

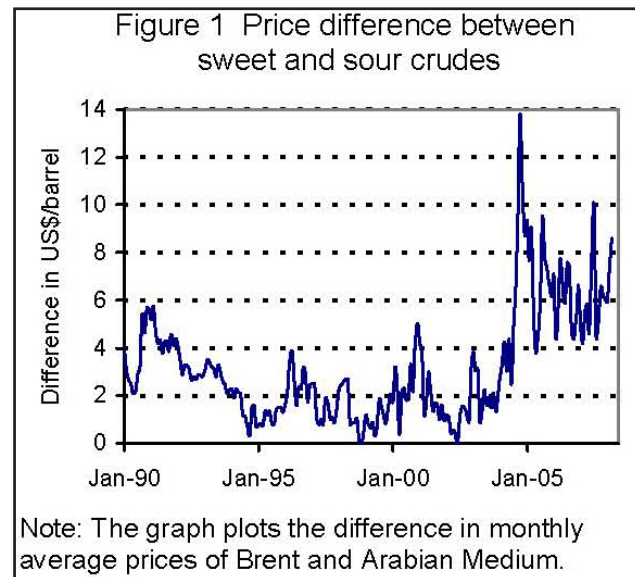
The sulfur content of straight-run fuels depends on the crude oil from which the fuels are made. Sulfur levels will be much higher when the crude is sour (containing high sulfur levels; see Note 1 [5] for definitions of sweet and sour). The sulfur content of straight-run fuels increases the “heavier” the fraction (that is, the higher the density): naphtha (feedstock for gasoline) is “lighter” than kerosene, which is lighter than diesel, which in turn is lighter than residual fuel oil, and the sulfur content increases when moving from kerosene to residual fuel oil.

Table 2 compares the sulfur content of straight-run naphtha, kerosene and diesel from two types of crude oil with different sulfur contents: Arabian Medium and Brent. Brent is a sweet crude and has a sulfur content of 0.4 percent, while Arabian Medium has a sulfur content of 2.5 percent. As can be seen from Table 2, the sulfur content of straight-run fuels derived from these two crudes differs markedly, and diesel from Arabian Medium contains 250 times as much sulfur as the limit in effect in Europe today.

Crude	Arabian Medium	Brent
Naphtha	0.046	0.0015
Kerosene	0.14	0.043
Diesel	1.24	0.14

Table 2 explains why hydroskimming refineries cannot produce products that meet fuel specifications in effect in Asia and elsewhere. A hydroskimming refinery has just enough sulfur-removal capacity to pretreat the feedstock for its reformer, which makes gasoline. It does not usually have additional capacity to reduce sulfur in heavier fractions, nor does it have a hydrogen production unit to generate additional hydrogen.

Because of the rapidly increasing demand for sweet crudes, the price difference between sweet and sour crudes has widened in recent years, as shown in Figure 1. Global crude oil production is becoming increasingly sour—that is, the sulfur content is rising. This means that those refineries that have invested in processing high-sulfur (cheaper) crudes have benefited from the extra investment made—for hydrotreating and hydrogen production—to reduce sulfur.



Declining Demand for Fuel Oil

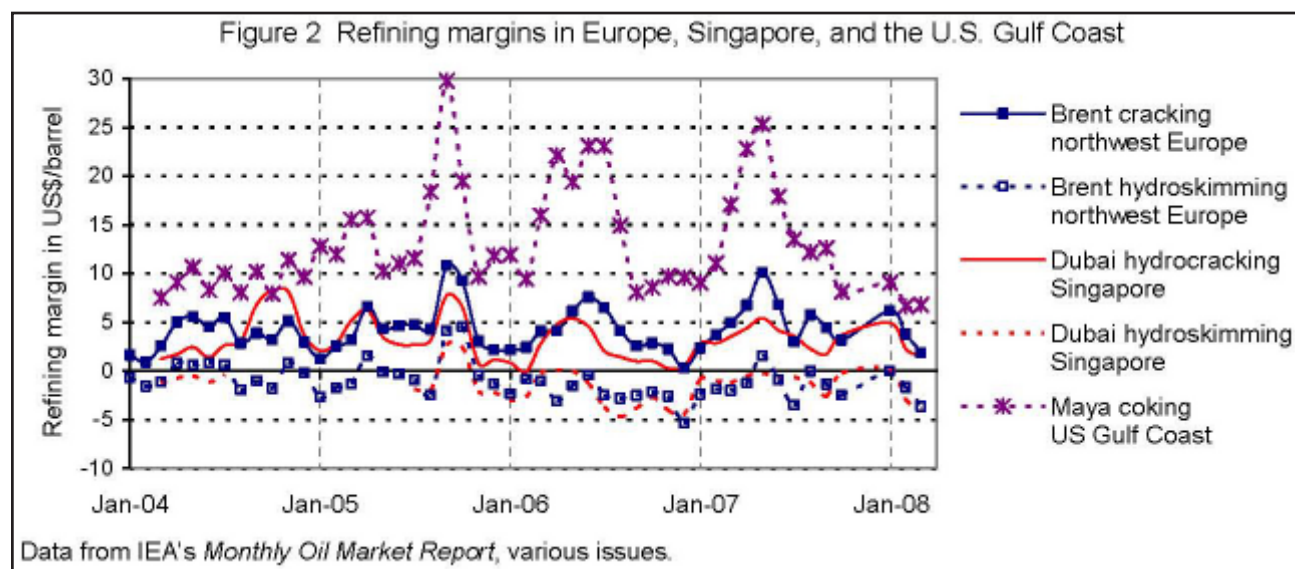
Another factor affecting the refining industry is the worldwide trend away from burning residual fuel oil, accompanied by solid growth of demand for transportation fuels. Residual fuel oil is being replaced by natural gas (for environmental and efficiency reasons) or coal (for reasons of cost and, in coal-rich countries, local availability) in power plants, and the steep rises in oil prices since early 2004 have added to this fuel switching. Meanwhile, there are not yet readily suitable substitutes for gasoline and diesel as automotive fuels on a wide scale, this when many countries are reaching the threshold income level above which vehicle ownership increases sharply. The International Energy Agency (IEA) predicts that, globally, transport’s share of oil demand will rise from 47 percent in 2005 to 52 percent

in 2030. More than 1 billion additional vehicles will be on the road by 2030, and most of the extra vehicles will be in Asia. As a result, demand for gasoline and diesel will continue to grow steadily [6].

The increasing share of gasoline and diesel in total oil demand has meant that simple refineries without catalytic cracking or hydrocracking facilities are making too much residual fuel oil which they may have to sell at a discount, adversely affecting refinery economics. Table 3 compares the yield of Arabian Medium and Brent crudes. Without facilities to crack residual fuel oil, Arabian Medium yields about 35 percent gasoline (naphtha in the table) and diesel. Compared to global demand for gasoline and diesel of 47 percent in 2005, the yield is not adequate to meet demand. Brent, in contrast, yields 58 percent gasoline and diesel. This also explains why “light” crudes—which contain a larger proportion of (straight-run) naphtha, kerosene, and diesel—are more sought after and fetch higher prices than “heavy” crudes. Typically, light crudes also have a lower sulfur content. The combined effect is to widen the price gap between sweet and light versus sour and heavy crudes.

cracking, and hydrocracking. Hydroskimming is the simplest refinery configuration and does not convert residual fuel oil to lighter products. A cracking refinery has a catalytic cracking unit; it may also have alkylation and other processing units that do not involve cracking heavier fractions into lighter fractions. A hydrocracking refinery is similar to a cracking refinery except catalytic cracking is replaced by hydrocracking. Refining margins in the figure are from the IEA and represent the monetary gain or loss associated with processing specific crudes. The margins take into account refinery construction costs, wages and other associated costs incurred in refinery operation, and variable costs of buying and processing crude oil. The refinery margins give an indication of the net return to a refinery, and thus possible investment trends.

In the first two cases, Brent, which is produced in the North Sea in the European continental shelf, is refined in northwest Europe. The next two cases consider refining Dubai crude, produced in the United Arab Emirates, in Singapore. The last case considers a coking refinery on the U.S. Gulf Coast refining Maya crude



Installing a catalytic cracking or hydrocracking unit would convert residual fuel oil into gasoline and diesel, but these units are expensive and benefit from large economies of scale. As a result, large, complex refineries are increasingly common, meaning that small simple refineries struggle to compete.

Refining Margins

Figure 2 compares the monthly refining margins of five representative refineries in northwest Europe, Singapore, and the U.S. Gulf Coast. Three types of refineries are considered: hydroskimming, catalytic

oil from Mexico. A coking refinery is more complex than a cracking refinery. The average U.S. Gulf Coast refinery configuration has shifted in recent years increasingly to the complex coking refinery, which takes advantage of the growing price gap between heavy sour and light sweet crudes by processing heavy sour crude to produce a high proportional yield of valuable products. Since the early 1990s, Maya crude has been the benchmark heavy sour crude on the U.S. Gulf Coast.

For a given crude oil refined at the same location, hydroskimming refineries consistently have lower profitability than more complex refineries with cracking or

hydrocracking capability. The margins for hydroskimming refineries have in fact been mostly negative. This explains why most new refineries are not hydroskimming. The figure also illustrates high volatility of refining margins. The margin at the representative hydrocracking refinery in Singapore ranges from the high of US\$8.26 a barrel to a low of -\$0.02. Since January 2004, there have been six months when the refining margin was less than \$1 a barrel, and about twice as many months when the margin was less than \$2 a barrel, both low margins. In contrast, the coking refinery on the U.S. Gulf Coast is shown to be highly profitable: the refining margin ranged from the high of nearly \$30 a barrel to a low of \$6.62, averaging \$13.12. That average is higher than the maximum monthly margins of the cracking refineries in northwest Europe and Singapore. The refining margin peaked in September 2005, on account of the shortage of refined products caused by hurricane Katrina. That price spike was transmitted to the rest of the world, as evident from similar, although less pronounced, spikes in Singapore and northwest Europe.

Rising Costs

Rapidly rising demand in emerging economies has resulted in a global shortage of equipment, labor, and materials in recent years, and, as a result, world prices of steel, other materials, engineering design, and engineering labor costs have risen sharply, affecting the petroleum, power, and other industries. A number of refinery projects have been delayed or even canceled. For example, government-owned Kuwait National Petroleum Company (KNPC) tendered a 615,000 bpd refinery with a budget of US\$6.3 billion in 2005. KNPC, however, was forced to withdraw the tender in February 2006 after the lowest bid came in at US\$15 billion due to cost escalation. In October 2007, KNPC's board more than doubled the budget and allocated US\$14.6 billion for the refinery [7].

Global Trends

As an illustration of the trend towards larger refineries, the average refinery size in the United States in 1969 was 42,000 bpd. In 1982, the *Oil and Gas Journal's* "Worldwide Refining Survey" found 301 refineries in the United States; by January 2008, the number had declined to 131, with an average size of 133,000 bpd. In the intervening years, 170 refineries—more than half of the refineries that existed in 1982—had been shut down and replaced by fewer, much larger refineries through expansion of existing refineries [8].

It is therefore not surprising that new refineries

being planned around the world are larger than even the average existing U.S. refinery today. A worldwide survey of new refinery construction, published by the *Oil and Gas Journal* in April 2007, found 24 refineries under construction or being planned. Of the 24, 21 were larger than 100,000 bpd, and 15 were larger than 200,000 bpd. The minimum size was 70,000 bpd, and the maximum 615,000 bpd. The average size was 260,000 bpd.

Refining is capital intensive with built-in large economies of scale. The industry has not been known historically for high profitability. The poor margins experienced by Asian refineries in 1998–2002 led to the closure of many small and inefficient plants. High margins in recent years have encouraged many new project proposals: as of mid-2007, there were 38 new refinery projects with an average capacity exceeding 260,000 bpd [9]. Some analysts have suggested that there is a risk of over-expansion, especially if the economic growth of emerging markets falters. Rising construction costs in recent years have meant that even oil-rich countries are having difficulties moving forward with new projects.

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