LBNL-50681

Improving Transport Fuel Quality in China: Implications for the Refining Sector

Final Report
August 2002

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1. Background

1.1. China's Oil Industry

In the half-century since the establishment of the People's Republic, China has become the fifth largest oil producer in the world. The discovery of numerous large oil fields in succession during the 1960s and 1970s gave rise to expectations in China that reserves, and output, might one day rival those of the Middle East. As a result, oil quickly became a preferred and inexpensive boiler fuel for industry, supplementing or replacing coal in areas where local coal resources were lacking. By 1980, China directly burned five out of every 10 barrels of oil produced.

Contrary to earlier expectations of continued rapid growth in production, in the early 1980s China's oil output peaked and declined for a period while the industry reconsolidated and adopted new production plans consistent with the economic reform program begun in 1979. As the economy began to grow rapidly in the 1980s, the slowdown in oil production growth led to increasing calls to reassess of the use of China's oil resources. Until 1986, the government had limited domestic supply of oil products in favor of crude oil exports, earning as a result substantial foreign exchange income during a period of high prices following the 1979 Iranian Revolution. The collapse of oil prices in 1986, the year after China briefly held the title of largest oil exporter in Asia, accelerated this reassessment. With growing new demand for transport fuels and petrochemical feedstocks, it was felt that the export of this resource at low post-1986 prices could no longer be sustained. At the same time, the widespread direct burning of both crude and fuel oil was viewed as wasteful compared to the higher value-added applications in transport and petrochemicals.

This shift in development strategy had a direct and major impact on the refining sector. For years largely oriented to production of heavy fuel oil, 0-degree pour-point diesel and low octane gasoline, refineries now had to respond both to higher demand and to demand for new types and qualities of products. A new jet fleet required high-quality jet kerosene; new automobiles required higher-octane gasoline; expanded ethylene production required larger volumes of naphtha, while environmental concerns argued for the phase-out of lead in gasoline and reductions in sulfur content.

Growth in demand, however, was not matched by growth in domestic crude oil production. China began limited crude oil imports in 1988, favoring low-sulfur heavy waxy crudes from Indonesia and elsewhere similar to its domestic grades that were suited to China's existing refinery configuration. As demand continued to grow, China itself became a net oil importer in 1993 and a net crude oil importer in 1996. This dramatic shift in external dependency presented China with yet another challenge: as import demand continued to soar, and the import bill for low-sulfur crudes mounted, China needed to develop domestic capacity to process the cheaper higher-sulfur crudes of greater international availability. Acknowledging that its domestic oil industry is no longer capable of self-sufficiency, China has moved to modernize its refineries, expand domestic production of oil products, increase quality, and integrate its oil sector more extensively with the international industry.

1.1.1. Refinery Capacity and Production

At about 270 million tonnes of capacity, China's refining system is now the world's third largest after the United States and Russia. Developed initially in the late 1950s with Soviet assistance, it evolved largely on indigenous efforts after the Sino-Soviet split and China's subsequent self-imposed isolation. The technical foundation of the industry was adapted to handle the quality of Chinese crude, most of which is heavy, low-sulfur and waxy, and to the need to provide substantial quantities of fuel oil to industry. At the time, higher-value products, such as gasoline, diesel, and jet kerosene, were secondary in the output slate, and little upgrading was available to increase production of these fuels. Moreover, the quality of the transport fuels was low: the specification for gasoline octane was 66 (MON [Motor Octane Number]), and the cetane of diesel 35. In comparison, most international gasolines have MON ratings in the 80s, and most automotive diesels have cetane numbers in the 40s or above.

With the initiation of economic reform after 1979, China undertook widespread reform in the oil industry, consolidating crude oil production under the China National Petroleum Corporation (CNPC), refining under the China National Petrochemical Corporation (Sinopec), and offshore exploration and production under the China National Offshore Oil Corporation (CNOOC). Production at oil fields was rationalized and some fields closed; in 1981, crude oil production fell for the first time since the disruptions of the Cultural Revolution in 1967. A national output quota of 100 million tonnes (2 million barrels/day) was established and multiple-tiered pricing implemented. At the same time, the government consolidated the growing refining sector, which heretofore had been administered by numerous government ministries based upon the ultimate use of the oil products; in addition to the Ministry of Petroleum, the Ministry of Textiles, Ministry of Agriculture, and Ministry of Chemical Industries, among others, all operated refineries geared to their own sectors. The establishment of the China Petrochemical Corporation in 1982 consolidated the majority of China's major refining assets into one company, which henceforth would be responsible for optimizing production plans and supplying both oil products and oil-based petrochemicals to the entire economy. The government placed higher value on its oil resources, and invested heavily into a program of substituting coal for oil in industrial uses. Sinopec invested in technologies—primarily fluid catalytic cracking—to support the upgrading of a greater percentage of the crude input to transport fuels. Between 1980 and 1990, the volume of refinery processing went up by 43%, whereas production of gasoline increased nearly 100%, while fuel oil output remained flat. Diesel fuel production rose 38% over this period, hampered by the rapid increase in demand for feedstocks for petrochemical production. In China, ethylene crackers were traditionally designed to run gasoil, and output of such feedstocks rose 170% between 1980 and 1990. Ethylene is the essential "building block" for many basic petrochemicals.

China's oil industry entered a new era in the 1990s as accelerating domestic demand for oil eroded the exportable surpluses of the 1980s. By 1993, China had become a net oil importer. The refining capacity shortages of the 1980s, however, disappeared, as a sustained building program of the late 1980s and early 1990s raised capacity by over 50% and added a substantial volume of secondary upgrading capacity. By 1999, total nominal distillation capacity[1] had reached 276 million tonnes (Table 1). The refining system had also become fairly sophisticated in terms of the variety and volume of equipment—such as catalytic cracking, hydrocracking, and coking—for use in upgrading heavier oil fractions to more valuable lighter fractions. Seen from a simple ratio of total cracking capacity to distillation capacity, China in 1999 ranked second only to the US in terms of refinery sophistication, and it greatly outpaced Japan. The cracking-to-distillation ratio for China in 1999 reached 49% compared to 55% in the US, and only 21% in Japan. This ratio, however, does not address the issue of product quality; in both the US and Japan, where product quality specifications are strict, hydrotreating and hydrofining capacity—used to reduce impurities such as sulfur and improve product quality—greatly exceeds that in China. In 1999, the ratio of hydrotreating and hydrofining capacity to distillation in the US was 65%, 86% in Japan, but just 12% in China.[2]

Table 1. Refining Capacity in China, 1999

	Capacity *(million tonnes)*
Atmospheric/Vacuum Distillation	276.0
Cracking Units	
Fluid Catalytic Cracking (including resid, deep)	92.6
Hydrocracking	12.9
Coking	20.6
Thermal/Visbreaker	8.7
Total Cracking Capacity	134.9

Source: Sinopec

During the 1990s, China experienced a significant improvement in yield patterns, with the production of light products such as gasoline, kerosene, diesel, and petrochemical feedstocks rising significantly as a proportion of the total. In 1990, the output of these four products totaled 54% of throughput in that year; by 1999, the yield of these products rose to 68%. The most dramatic increase over this period has been in the yield of diesel fuel, which rose from 24% of throughput in 1990 to 34% in 1999. The expansion of catalytic cracking in particular (including residual catalytic cracking and deep catalytic cracking) allowed an increasing proportion of heavy feedstocks to be upgraded to lighter fractions. Given the more rapid growth in diesel demand compared to gasoline, refiners significantly expanded the pool of diesel blendstock materials by favoring operating modes of catalytic crackers maximizing diesel blendstock production.

The decline in fuel oil output mirrored the increases in production of light products. In 1990, fuel oil production (including refinery use) totaled 32.2 million tonnes, a 30% yield

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[1] Traditionally, atmospheric distillation capacity and vacuum distillation capacity figures are not separated in Chinese statistics as is the norm internationally.

[2] China statistics from Sinopec; international statistics from the *Oil & Gas Journal*, “Worldwide Refinery Capacities”, December 1999.

on throughput. By 1999, production has dropped to 19.6 million tonnes, or 11% of total throughput. While fuel oil output dropped on average by 5.5% a year over this period, diesel production rose by 10.6% and gasoline by 6.5%. Kerosene output jumped as well, but more dramatic was the shift in composition and use. Lamp kerosene, which accounted for about 75% of kerosene production in the 1980s, fell to only 25% as production of jet kerosene rose to match the rapid expansion of China's domestic and international air routes (Table 2).

Table 2. Output and Yields of Petroleum Products in China

(million tonnes)

	1990	1995	1996	1997	1998	1999
Throughput	107,235	135,011	142,318	153,727	152,392	183,566
Gasoline	21,161	28,408	30,532	32,548	31,977	37,413
Kerosene	3,848	5,280	5,126	5,548	5,750	7,195
Diesel	25,374	36,843	41,087	45,940	45,445	63,027
Fuel Oil	32,173	27,202	23,107	20,795	18,338	19,594
Petrochemical Feedstock	7,847	11,854	13,333	14,995	16,558	16,463
Yields						
Gasoline	20%	21%	21%	21%	21%	20%
Kerosene	4%	4%	4%	4%	4%	4%
Diesel	24%	27%	29%	30%	30%	34%
Fuel Oil	30%	20%	16%	14%	12%	11%
Petrochemical Feedstock	7%	9%	9%	10%	11%	9%
Yield of Light Products:	54%	61%	63%	64%	65%	68%

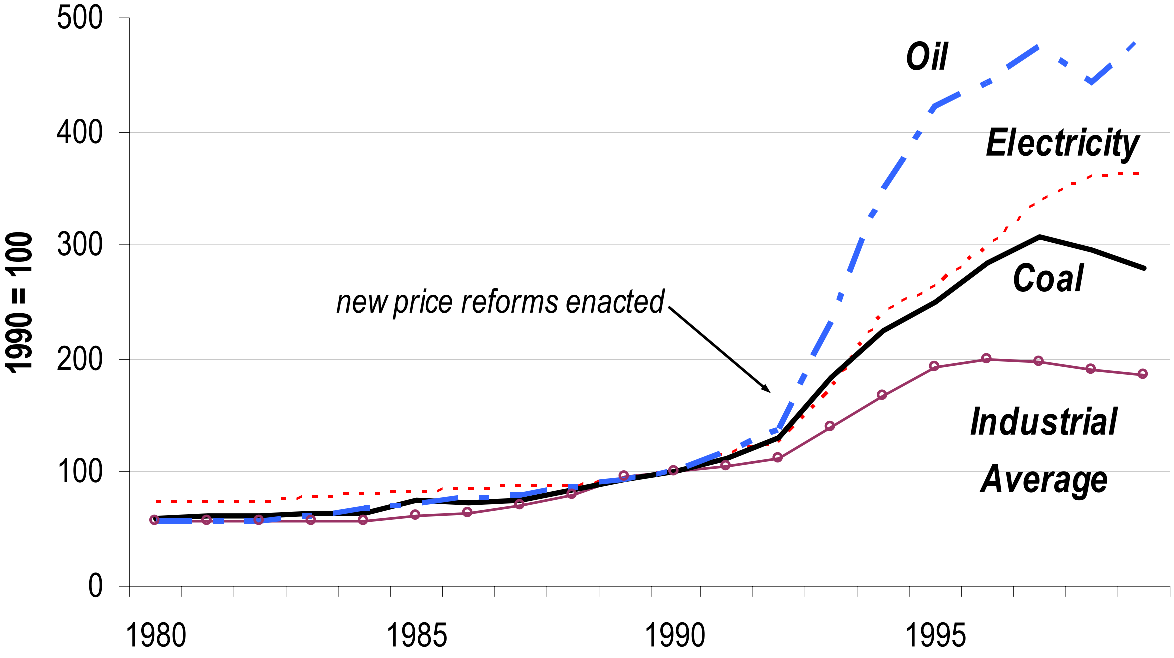
Source: *Sinopec Annual*, 1994, 2000

1.1.2. Pricing

For much of modern China's history, the government has directly controlled the price of crude oil and petroleum products. Until price reforms proceeded in earnest in the early 1990s, oil prices were generally below international prices in order to restrain input costs to industry, which consumed the majority of oil products. Severe financial losses at CNPC in the late 1980s and early 1990s and a growing volume of imported oil led the government to reform the pricing mechanism in 1994, substantially boosting crude and product prices. This reform returned CNPC to profitability, but in order to maintain profitability at Sinopec in the face of higher crude input prices, the margin between retail and refinery gate prices was narrowed to allow higher ex-refinery prices without passing the full increase on to consumers.

The price reform of 1994, however, maintained fixed prices—albeit higher—under government control, depriving producers and refiners of price signals from the market. One consequence of the distortion was a massive rise in "unofficial imports", particularly of diesel fuel, during 1997 and 1998 when international prices fell substantially below Chinese domestic prices. In response, the government enacted further reform, for the first time tying domestic crude oil and product prices to international markets. Under this scheme, domestic product prices were adjusted retroactively according to the average FOB price in Singapore the previous month. Additionally, Sinopec and CNPC (later PetroChina) were given authority to adjust the retail price within a 10% band in their marketing areas. In August 2001, the link between domestic product prices and Singapore FOB prices was extended, but the adjustment band was abolished. Sinopec, however, concerned about the impact of volatile Singapore FOB prices on the Chinese market, subsequently investigated an alternative mechanisms referencing prices in other world markets such as New York and Rotterdam. This reform of the pricing mechanism for products was introduced in late 2001. Crude prices, however, now are freely set by the market, and for the most part are internationally priced. As shown in Figure 1, the prices of all energy products have risen considerably since 1994 and currently are at international levels or above.

Figure 1. Price Indices of Energy Products in China, 1980-1999



Source: China Statistical Yearbook, various years

1.1.3. Trade

In the 17 years since 1985, when China became Asia's largest oil exporter, surpassing Indonesia, it has since become Asia's second largest oil importer. Oil import policy has shifted dramatically over the years, and promises to see substantial further liberalization when agreed WTO reforms are enacted over the next three to five years. The entire period, however, has been characterized by the maintenance of state control over the volume and type of oil imports. State control is implemented through quota and licensing arrangements issued by the State Development Planning Commission and carried out for the most part by China's national oil trading firms, Unipec, China Oil, and Sinochem.

Table 3 indicates the trends of Chinese oil exports and imports since 1990. In 1990, China remained a major exporter, with total oil exports nearly five times higher than total imports. In 2000, the situation had reversed nearly completely, with imports over four times higher than total exports.

Table 3. China Oil Trade

(thousand tonnes)

Product Exports by Product

	LPG	**Mogas**	**Naphtha**	**Kerosene**	**Diesel**	**Fuel Oil**	**Other Prods***	**Total Products**	**Crude**	**Total Oil**
1990		1,789.1	549.4	438.1	1,601.4	576.5	455.2	**5,409.7**	23,986	**29,395.9**
1991		2,112.3	387.8	320.5	1,209.7	475.4	499.3	**5,005.0**	22,598	**27,603.4**
1992		2,697.6	325.6	179.6	1,479.3	631.1	653.6	**5,966.8**	21,507	**27,474.0**
1993		1,845.5	68.8	74.7	1,289.4	323.5	945.7	**4,547.6**	19,435	**23,982.1**
1994	13.8	2,100.9	43.1	106.9	1,215.8	155.2	974.2	**4,609.9**	18,491	**23,100.8**
1995	72.9	1,855.3	12.4	374.4	1,306.3	277.9	1,238.2	**5,137.4**	18,844	**23,981.7**
1996	340.3	1,314.0	4.5	659.2	1,567.6	279.0	1,159.1	**5,323.7**	20,329	**25,653.0**
1997	399.0	1,782.4	49.8	723.0	2,321.3	384.3	1,463.7	**7,123.5**	19,829	**26,952.4**
1998	508.5	1,820.0	0.0	891.9	985.2	409.9	1,981.5	**6,597.0**	15,601	**22,197.7**
1999	75.9	4,138.3	98.4	1,249.6	604.7	209.5	1,905.4	**8,281.8**	7,167	**15,448.4**
2000	2,290	4,551.0	687.4	1,772.2	554.8	308.5	2,161.1	**12,325.2**	10,438	**22,762.9**
90-00 AAI %	n/a	10%	2%	15%	-10%	-6%	17%	9%	-8%	-3%

Product Imports by Product

	LPG	**Mogas**	**Naphtha**	**Kerosene**	**Diesel**	**Fuel Oil**	**Other Prods***	**Total Products**	**Crude**	**Total Oil**
1990	150.5	154.7	14.2	0.5	2,250.8	636.9	142.8	**3,350.4**	2,923	**6,273.1**
1991	269.0	108.0	0.0	26.2	3,196.3	1,163.6	88.4	**4,851.5**	5,972	**10,823.9**
1992	330.8	330.9	13.6	156.3	5,012.2	2,020.7	258.9	**8,123.4**	11,360	**19,483.4**
1993	647.5	2,184.6	270.9	536.7	9,401.0	4,564.0	534.9	**18,139.6**	15,640	**33,779.6**
1994	1,407.7	1,053.2	426.8	275.8	6,238.7	4,624.7	334.1	**14,361.0**	12,346	**26,707.0**
1995	2,358.1	158.7	416.6	761.3	6,122.6	6,591.4	572.8	**16,981.5**	17,090	**34,071.4**
1996	3,692.0	79.1	521.6	743.6	4,625.0	8,540.1	723.3	**18,924.7**	22,617	**41,541.6**
1997	3,586.8	84.3	810.6	1,380.7	7,429.5	12,671.8	961.7	**26,925.4**	35,470	**62,395.4**
1998	4,784.7	14.9	738.6	1,261.6	3,032.9	15,304.8	1,181.7	**26,319.2**	26,802	**53,120.9**
1999	5,542.6	0.0	372.3	2,111.9	310.6	14,062.3	1,691.8	**24,091.5**	36,613	**60,704.5**
2000	4,817.5	0.3	122.5	2,254.8	259.4	14,227.7	1,592.7	**23,275.0**	70,134	**93,409.3**
90-00 AAI %	41%	-46%	24%	> 53%	-19%	36%	27%	21%	37%	31%

*includes lubes, paraffin, asphalt, petroleum coke, liquid paraffin

Source: Sinopec, citing China Customs Statistics

The nature of China's oil trade has shifted over the last decade. In the early 1990s, China continued to maximize export earnings through the export of crude oil and products, particularly gasoline and diesel. As demand continued to rise and domestic refinery capacity expanded, increasing amounts of crude oil were shifted from the export market to domestic use in China's own refineries. Similarly, exports of gasoline and diesel began a downward trend. At the same time, however, exports of "other" products, particularly paraffin, liquid paraffin, and petroleum coke expanded, offsetting some of the revenue decline from lower crude, gasoline, and diesel exports.

In the late 1990s, however, as refinery runs grew and the supply of petroleum products increased, China once again was able to increase the export of products, while crude oil exports continued to decline sharply. Currently, China's output of gasoline exceeds domestic consumption by nearly 5 million tonnes, and even exports of naphtha have rebounded from the zero level prompted by shortfalls in the product in 1998. Overall, exports of products grew during the 1990s, but total oil exports declined as cut-backs in crude exports more than offset the increase in product exports.

There occurred an important shift in the nature of crude oil imports during the 1990s. As China's refineries were designed and built to process China's domestic low-sulfur waxy crude, early crude imports were of crude types that were similar in sulfur content and quality to those available domestically. The import of higher-sulfur crudes were quite limited, as few refineries had the appropriate equipment needed to process higher-sulfur grades. As seen in Table 4, of the 15.7 million tonnes of crude imported in 1993, only 2% fell into a higher-sulfur category. The primary suppliers were Indonesia, producer of a low-sulfur waxy crude similar to Daqing, and Oman, producer of a low-sulfur light grade in the Middle East.

Table 4. Crude Imports by Source, 1993, 1999
(tonnes)

	1993	1999	1993 share	1999 share
North Sea	188,618	4,205,958	1%	11%
North Africa	708,352	535,479	5%	1%
West Africa	1,421,430	6,347,476	9%	17%
Middle East	6,598,696	16,903,865	42%	46%
Middle East Higher Sulfur	*282,654*	*7,750,857*	*2%*	*21%*
SE/Australasia	6,511,115	6,821,213	42%	19%
N/S America/Others	229,071	736,613	1%	2%
Former Soviet Union	13,923	1,063,084	0%	3%
Total	15,671,205	36,613,688	100%	100%

Source: *China Customs Statistics Yearbook, 1994 and 2000*

Through a program of revamping and expansion of existing refineries, particularly the coastal refineries of Maoming, Guangzhou, Fujian, Zhenhai, Gaoqiao and Qilu, China, by 1999, had significantly expanded capacity to process and treat higher sulfur crude oil. In that year, 21% of the import slate was higher-sulfur crudes such as Saudi and Iranian Light, Iraqi, and Kuwaiti crudes. Nonetheless, this represented just 4% of total crude runs in that year.

1.1.4. Consumption

In the 1990s, oil consumption in China nearly doubled, rising from 109 million tonnes in 1990 to 203 million tonnes in 1999 (Table 5). The average 7.1%-per-year average growth over this period masks substantial differences in the demand trends for various products. Highest among these was LPG, which recorded an average 19% per year growth in the 1990s as it became a favored fuel in urban households to replace coal used for cooking and heating water. As the heavy nature of Chinese crude results in only low refinery yields of LPG (around 2%), expansion of the use of this fuel required substantial imports. By 1999, 46% of China's LPG consumption came from import sources, the highest external dependency for any oil product.

Table 5. Total Oil Consumption

(million tonnes)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	AAI
LPG	2.53	3.01	3.57	5.00	5.70	7.49	9.30	10.10	11.86	12.07	19.0%
Gasoline	19.00	22.10	25.10	28.78	26.97	29.10	31.82	33.12	33.29	33.81	6.6%
Kerosene	3.51	3.85	4.18	4.26	4.52	5.12	5.56	6.82	6.71	8.24	10.0%
Diesel	26.92	29.75	33.73	39.48	38.03	43.21	46.91	52.91	52.83	62.32	9.8%
Fuel Oil	33.68	35.09	34.22	38.03	35.95	36.94	35.64	36.72	37.93	39.02	1.6%
Crude Oil*	5.48	4.61	4.27	4.89	5.05	3.76	5.71	5.72	6.18	6.11	1.2%
Other Prods**	18.25	19.96	20.74	20.87	26.52	29.25	35.09	42.52	43.97	41.30	9.5%
Total Oil	109.35	118.36	125.80	141.31	142.74	154.87	170.03	187.90	192.76	202.87	7.1%

*excluding refining throughput

**includes lubes, asphalt, petroleum coke, and petrochemical feedstocks (naphtha and gasoil)

Note: Total Oil figures exclude losses.

Recording the second highest growth rate was kerosene, at 10% per year over the last decade. Even this high rate of growth subsumed two widely varying developments: the relative decline of lamp kerosene consumption and the explosive growth of jet fuel consumption. In 1990, about 21% of kerosene consumption was jet fuel; by 1999, 61% was jet fuel—a 20% per year rate of increase. In contrast, lamp kerosene consumption remained fairly stable, growing at only 2.4% per year between 1990 and 1999 as a result of increased industrial use, while residential use continued its decline and further displacement by other fuels.

The third fastest growing product was diesel, averaging nearly 10% a year growth during the 1990s. Diesel has four key applications in China as an industrial fuel, for transport, in agriculture, and for power generation. Although shortcomings in China's energy statistical system do prevent an accurate breakdown of diesel use by sector (see "Transport Fuels" below for additional discussion), even official statistics show that "transport" use of diesel has expanded at over 13% a year during the decade, compared to just 4% per year growth in agricultural use. Consumption for industrial use has remained strong as well, at 9% per year in the 1990s, and use in power plants has steadily grown at over 6% a year.

Much of the diesel used for power generation is in small fairly inefficient units, but they play an important role in maintaining steady power supply in some areas.

Another fast growing product in the 1990s was “other products”, or the aggregate volume of lubes, asphalt, petroleum coke, and petrochemical feedstock (called “light oil for the chemical industry” in China). Nearly half of this volume is petrochemical feedstocks, which grew at a very rapid pace as China’s domestic ethylene production capacity grew through expansion of existing units and construction of new ethylene crackers. From 2.23 million tonnes in 1993, total capacity nationwide grew to 4.42 million tonnes in 2000, requiring some 18 million tonnes of feedstock. In contrast, demand for ethylene is expected to reach 15 million tonnes by 2005, tying China in the near term to large scale imports of plastics from the international market.

Historically, China used primarily the gasoil fraction from distillation as ethylene feedstock, but as cracker scales were small (generally around 200,000 tonnes/year) and the feedstock fairly heavy, yields were low, often in the 20-23% range. With modernization, China has steadily increased the scale of its crackers to 450,000 and 600,000 tonnes/year and has increasingly shifted to lighter naphtha as a feedstock to increase ethylene yields. In the future, China expects ethylene crackers to be primarily naphtha-based, implying continued high rates of demand growth for this product.

On average, gasoline demand increased rapidly in the 1990s but slowed in 1998 and 1999, reaching about 34 million tonnes in 1999. Owing to the slower growth in gasoline demand, the gasoline/diesel ratio of production began to decline in the late 1990s after steadily increasing for 15 years. Sinopec targeted an output ratio close to 1:1, hoping to keep refinery production in balance and use its extensive catalytic cracking capacity for gasoline production, as the cycle oil from these units run in diesel maximizing mode is fairly low quality. In 1993, the ratio reached its peak at 0.89:1. By 1999, however, it had dropped to 0.59:1, the same as in 1980. In 2000, diesel output surged even further, dropping the ratio to 0.58:1.

Least growth in the last decade was seen in fuel oil and crude oil direct use, with both growing at less than 2% a year during this period. Direct burning of fuel oil and crude oil has been constrained by government policy encouraging the use of coal as a boiler fuel wherever feasible. As a result, the proportion of fuel oil and crude oil burned directly in boilers has declined from 36% of total oil consumption in 1990 to 22% in 1999. Some applications, such as glassmaking and ceramics, cannot easily use coal and continue to prefer fuel oil, while in the South, where coal transport costs are high, use of fuel oil in power plants is still permitted, and many of these fuel-oil fired power plants provide valuable peak-load service. Currently, about 25% of fuel oil is used in power plants.

1.1.5. Transport Fuels: Gasoline and Diesel

The structure of China’s energy statistics makes it difficult to ascertain the actual volume of fuels used for transport purposes. Continuing a classification scheme developed during the Soviet-influenced period of emphasizing material balances in the economy, statisticians classify gasoline and diesel consumption into the sectors responsible for their consumption, not the nature of the consumption. As a result, for example, gasoline consumption, which normally would be nearly completely for transportation purposes, is divided among agricultural, industrial, commercial, transport, construction, and residential sectors for the purposes of reporting. In this classification scheme, "transport" consumption includes only that volume used by transportation companies assigned to the transport sector of the economy. Transport consumption by factory delivery trucks, for example, remains in the industrial sector.

Without adjusting the numbers to account for "true" transportation usage, transport fuel demand in China appears fairly low compared to other countries at a similar stage of development. On an unadjusted basis, transport demand for gasoline and diesel accounted for just 12% of total oil demand in 1990, rising to 17% in 1999. Adjusting the figures involves certain assumptions owing to a lack of appropriate survey data to base the adjustment on. For gasoline, it is safe to assume that nearly all gasoline is used in vehicle in transportation uses, although a small amount may be used for solvents and other non-energy purposes. In 1999, China recorded 86,000 tonnes of gasoline used for such purposes out of a total 33.8 million tonnes of gasoline consumption, or just 0.3% of the total. Basically, all gasoline consumption can be assumed to be for transportation.

For diesel fuel, the situation is more complex as diesel serves a number of transformation and end-use purposes. In agriculture, for example, diesel use in "walking tractors" used to transport goods and people (often the most common rural form of transportation) should be counted as transportation use. In industry and commerce as well, a certain proportion of recorded diesel use is likely used in trucks and other conveyances and should be classified as transportation use. Only in power generation is it unlikely that the diesel fuel is used for other purposes. Although no hard data exists to calculate these proportions, some surveys taken in the early 1990s, and subsequent surveys by Sinopec can help estimate what a "true" transportation number should be. These adjustments include: 20% of agricultural diesel, 10% of industrial diesel, and 12% of commercial diesel to derive a new transportation diesel figure. Table 6 summarizes these adjustments for gasoline and diesel, and provides a rebased volume of gasoline and diesel fuel for transport usage.

Table 6. Gasoline and Diesel Transportation Use

(million tonnes)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Gasoline										
Official Transport	6.20	7.04	8.08	8.37	9.00	9.82	9.91	11.83	12.17	12.66
Adjusted Transport	18.99	22.09	25.09	28.78	26.96	29.09	31.82	33.11	33.29	33.80
Adj % of Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Diesel										
Official Transport	7.09	7.60	8.28	10.02	9.98	12.47	12.61	13.80	19.02	22.22
Adjusted Transport	9.75	10.40	11.28	13.57	13.47	16.32	16.84	18.08	23.31	27.28
Adj. % of Total	38%	38%	37%	38%	38%	40%	38%	40%	46%	45%
Total										
Official Transport	13.30	14.64	16.35	18.40	18.98	22.29	22.52	25.63	31.19	34.87

Adjusted Transport	28.74	32.49	36.38	42.34	40.43	45.41	48.65	51.19	56.60	61.08
Total Oil Consumption*	109.35	118.36	125.80	141.31	142.74	154.87	170.03	187.90	192.76	202.87
Official Transport as % of Total Oil	12%	12%	13%	13%	13%	14%	13%	14%	16%	17%
Adjusted Transport as % of Total Oil	26%	27%	29%	30%	28%	29%	29%	27%	29%	30%

Although the assumptions used to recalculate transport diesel demand do not likely hold true over the entire decade, the result of the calculation 1999 accords closely with the result of Sinopec's own investigation, which estimates diesel transport use as 45% of total diesel in 2000, rising to 48% in 2005 and 52% by 2010.

1.1.6. Product Specifications

Growing concern over the environmental impact of rising oil consumption underlay in part the investment in new refining technologies and supported the revision of product specifications over the last decade. During the 1990s, focus has been on increasing octane, eliminating lead, and reducing allowable sulfur content. For diesel fuel, focus has been on improving cetane and reducing allowable sulfur.

Table 7 provides a simplified summary of the evolution of Chinese product specifications during the last decade. National specifications for petroleum products are issued by the State Bureau of Quality and Technical Supervision (SBQTS, now State Administration for Quality, Supervision, Inspection, and Quarantine, or AQSIQ). Mandatory standards issued by AQSIQ carry the designation of GB (*guo biao* 国标), indicating a national standard. Other parallel standards do exist, including standards developed by the refining sector itself that carry the prefix designation of SH (*shi hua* 石化), indicating a standard developed by and for the petrochemical industrial, or a QB (*qi biao* 企标), indicating a standard developed by industry for specific enterprises, often in conjunction with major customers. The standards listed in Table 7 include only the major GB standards; the old 70 MON gasoline standard, for example, was an SH standard, and has been largely phased out of use and production.

Table 7. Recent Developments in Chinese Gasoline and Diesel Specifications

Leaded Gasoline

		1993			2000		
Octane RON	min	90	93	97	90	93	97
Lead g/l	max	0.35	0.45	0.45			
Sulfur ppm	max	1500	1500	1500		*(abolished)*	
Olefins %		ns	ns	Ns			
Benzene %		ns	ns	Ns			
Oxygenates %		ns	ns	Ns			
Standard No.			GB484-93				

Unleaded Gasoline

		1993			2000/2003		

Octane RON	min	90	93	95	90	93	95
Lead g/l	max	0.013	0.013	0.013	0.005	0.005	0.005
Sulfur ppm	max	1500	1500	1500	800	800	800
Olefins %	max	ns	ns	Ns	35	35	35
Aromatics %	max	ns	ns	Ns	40	40	40
Benzene %	max	ns	ns	Ns	2.5	2.5	2.5
Oxygenates %	min	ns	ns	Ns	2.7	2.7	2.7
Standard No.			SH0041-93			GB 17930-99	

Diesel (zero-degree pour only)

		1994			2002		
Grade		Premium	First	Qualified	Premium	First	Qualified
Cetane		45	45	45	45		
Sulfur ppm	max	2000	5000	10,000	2000	*(abolished)*	
T95 °C	max	365	365	365	365		
Standard No.			GB252-94		GB252-00		

Note: Grades of light diesel fuel produced from intermediate base crudes or containing FCC fractions can have a cetane number of no less than 40.
ns=no specification

The old specifications for leaded gasoline were abolished in 2000. Unleaded gasoline specifications were revised in 1999 for implementation in the major cities of Beijing, Shanghai and Guangzhou in July 2000. The number of grades covered remained the same, but the 97 RON grade from the 1993 standard was replaced by 95 RON grade. This standard is to be implemented nationwide at the beginning of 2003. Compared to the 1993 standard, allowable sulfur has been reduced by 47% and new controls were placed on allowable content of olefins, benzene and aromatics. Given the high degree of reliance on FCC and RCC units for gasoline production and the relatively low volume of reformate blended into gasoline, it is likely that the olefin constraint became the most binding on refiners.

For diesel fuel, the table shows the specifications for only the zero-degree-Celsius pour-point grade of light diesel fuel, which is the most common of the various grades produced in China. Following the old Soviet classification system, diesel fuel is graded by pour point, or the minimum temperature at which the fuel will flow easily and ignite. Others include -50, -35, -20, -10, and +10. Until the new specification went into effect in 2002, each pour point grade of diesel fuel was further classified by allowable sulfur content into premium (*gaoji* 高级), first level, or “super” (*yiji* 一级), and qualified (*hege* 合格). These distinctions were abolished in the new specification and the more restrictive sulfur specification of the premium grade adopted for all pour-point grades. Cetane specifications were not raised in the new standard, but the 1994 standard allowed a fairly large exemption of 40 cetane minimum for diesel produced from intermediate base crudes and containing FCC cycle oil as a blendstock. Given the relatively low volume of hydrocracking capacity in China, FCC cycle oil has traditionally been a substantial blendstock in light diesel production. The new standard restricts this by excluding the FCC cycle oil diesels from this exception.

China plans to further tighten quality standards for gasoline and diesel. According to Sinopec, allowable sulfur in gasoline will be reduced to 200 ppm for gasoline supplied to Beijing, Shanghai and Guangzhou beginning in January 2003 and perhaps to the rest of the country by 2008 (Q/SHR007-2000 "Urban Vehicle Gasoline"). In this proposed revision, allowable olefin content will be further reduced to 30% by volume and the combined volume of olefins and aromatics to not more than 60%. Sinopec also plans to reduce the allowable sulfur content of gasoline supplied to Beijing during the 2008 Olympics to no more than 30 ppm.

Similarly, Sinopec plans to reduce the allowable sulfur in diesel fuel supplied to Beijing, Shanghai and Guangzhou to no more than 300 ppm and raise cetane to a minimum of 50 beginning in 2003 (Q/SHR008-2000 "Urban Vehicle Diesel"), while the rest of the country may see a reduction in allowable sulfur to 500 ppm but without a change in cetane standard. By 2008, Beijing (and perhaps Shanghai and Guangzhou) may be supplied with diesel fuel of 30 ppm allowable sulfur and 53-55 minimum cetane.

1.2. Current Challenges

China is committed to increasing the quality of petroleum products, but the industry faces two broad challenges to achieving this goal. One broad area of challenge is the near-term feedstock and technology issues related to tightening specifications on products produced from China's 'traditional' crude slate of heavy low-sulfur domestic crudes. The second, longer-term area of challenge is the technology and feedstock issues related to the maintenance or further tightening of product quality standards—particularly sulfur—in the face of the inevitable rise in the proportion of higher-sulfur imported crudes in China's processing slate.

The technical base of China's refineries reflects both the nature of China's domestic crude supply as well as the variety and volume of products demanded by consumers; the system is operated primarily to produce gasoline, diesel, and petrochemical feedstocks (gasoil and naphtha). The primary upgrading technology for the production of gasoline and diesel is fluid catalytic cracking (FCC) and resid fluid catalytic cracking (RFCC), total capacity of which is equivalent to about 35% of distillation capacity. FCC and RFCC units can be operated in various modes to either maximize a low-octane naphtha stream for gasoline blending, or to maximize a low-cetane cycle oil stream for diesel blending. A typical blendstock added to FCC naphtha to achieve the higher octane finished gasoline is reformate, produced from naphtha processed in reformers, but in China, reformers have traditionally been used as the source of benzene, toluene and xylenes (BTX) for the petrochemical industry in the production of plastics, fibers and other chemicals. These components of reformate are the source of the high octane value of reformate; after extraction, however, the resultant raffinate has little gasoline octane blending value. Although historically up to 80% of reformer capacity was dedicated for petrochemical feedstock production, new reformer capacity installed in the 1990s has allowed refiners to make increasing use of reformate for gasoline blending. Nonetheless, 80% of the gasoline blending pool today still consists of FCC naphtha.

Coking is heavily used to upgrade the ‘bottom’ of the barrel. Bottoms upgrading is necessary because the heavy nature of Chinese crudes results in high yields of fuel oil on primary distillation (generally 55% or more), and relatively low yields of light and middle distillates. Consequently, most final products contain substantial proportions of cracked materials, which are generally of lower quality than straight-run feedstocks. With regard to product quality and specifications, the system thus faces a number of challenges, as summarized in Table 8.

Table 8: Quality Issues Related to China’s Current Processing Configuration

Specification	**Challenge**	**Technology Options and New Approaches to Blending**
Sulfur	High sulfur levels in diesel and fuel oil; 1% S average in 40% of diesel; insufficient desulfurization capacity; high cost of hydrogen	• Increase desulfurization capacity • Expand hydrogen production • Emerging technologies: catalytic distillation • Dilution via zero-sulfur blendstock
Octane	Insufficient octane blending materials to completely eliminate 70 MON gasoline and produce higher octane gasolines.	• Increase reformer capacity • Raise alkylation unit utilization • Expand oxygenate production • Increase FCC capacity • Increase isomerization capacity • Use ORI (octane requirement increase) controllers (combustion chamber deposit [CCD] additives)
Lead	Alternatives in short supply; feedstock gases for alkylation diverted to petrochemical use; no large-scale oxygenate production; aromatics extracted from most reformate for petrochemical use	• Increase reformer capacity • Raise alkylation unit utilization • Expand oxygenate production • Increase FCC capacity • Increase isomerization capacity • Use ORI (octane requirement increase) controllers (combustion chamber deposit [CCD] additives)
Reid Vapor Pressure	Need to reduce evaporative loss	• Increase gas fractionation capacity (debutanization) • Adjust distillation range
Cetane	Low cetanes from heavy reliance on FCC cycle oil as blend stock; limited SR middle distillate yield; insufficient hydrotreating and hydrocracking capacity	• Increase hydrotreating capacity • Increase hydrocracking capacity • Install hydrodearomatization (HDA) (Synsat/Synshift) • Expand use of cetane additives
Smoke	Diesel deficit leads to yield maximization from deep cutting; high percentage of FCC cycle oil in final product.	• Reduce T95 temperature • Increase hydrotreating capacity • Increase hydrocracking capacity • Install hydrodearomatization

Specification	Challenge	Technology Options and New Approaches to Blending
		(HDA) • Create urban diesel blend
Aromatics	Currently at fairly low levels in gasoline owing to reformate shortage; potentially larger problem; at high levels in diesel from reliance on FCC cycle oil, adding to smoke problem.	• Limit reformate use in gasoline blend • Raise alkylation unit utilization • Expand oxygenate production • Increase deep hydrotreating capacity • Increase hydrocracking capacity • Install hydrodearomatization

Solutions for many of these technical challenges are achievable though increased investment in the sector, and China has indeed focused investment in the last few years on upgrading existing refineries and has generally disallowed the establishment of new grassroots refineries. Progress has been hampered by an even greater investment focus—and greater perceived urgency—on the petrochemical segment, which produces basic petrochemical products such as polyethylene and polystyrene, for which China has become over 50% import-dependent. With the restructuring of the sector in 1998, investment by the oil companies in marketing rose dramatically, offsetting investment in refining. Sinopec, for example, raised investment in marketing from ¥2.1 billion (US$256 million) in 1998 to ¥16.1 billion (US$1.96 billion) in 2000, while investment in refining fell from ¥10.8 billion (US$1.3 billion) to ¥5.5 billion (US$670 million) over the same period.

This slow-down and decline in refinery investment raises some question about China's ability to respond effectively to the second and longer term challenge to the refining industry and its ability to further tighten product quality standards to meet environmental goals. Since becoming a net importer of oil in 1993, imports of crude oil alone have risen dramatically, reaching 70 million tonnes (1.4 million b/d) in 2000. By 2005, imports are projected to reach at least 95 million tonnes (1.9 million b/d) and at least 108 million tonnes (2.16 million b/d) or more by 2010. Given the limited ability of China's refining infrastructure to handle and process high-sulfur crudes such as Arab Light or Iranian Light common on the international export market, China has to date relied on a judicious selection of lower sulfur crudes for import from countries such as Indonesia, Malaysia, Papua New Guinea, Oman, Angola, Libya, and even at times from the North Sea. With the volume of imports growing, China's own purchasing pattern has even had an impact on the international market; the higher demand for scarcer low-sulfur crudes has at times widened the price differential with higher-sulfur grades. Nonetheless, in recognition that long-term supply stability requires dependence on the major Middle Eastern producers, China has begun to convert selected coastal refineries to process higher-sulfur grades, including refineries at Maoming, Guangzhou, Zhenhai, Shanghai, Jinling, and Qilu. Currently, total primary distillation capacity designed to handle higher sulfur crudes is about 19 million tonnes and about 7 million tonnes higher sulfur crudes were actually processed in 1999.

Conversion of refineries for handling higher sulfur crudes involves, first, replacement of the 'soft' steel in distillation units, piping, and other equipment exposed directly the corrosive impact of the sulfur compounds in the crude and intermediate streams. Second, to reduce the sulfur content in final products to meet even current specification requirements, additional hydrotreating and hydrodesulfurization units will be necessary, both of which require large volumes of hydrogen for operation. As most imported crudes yield larger volumes of light and middle distillates from primary distillation compared to Chinese crudes, less upgrading of bottoms will be necessary, and new blending recipe1s may help improve the quality of final products. It is unclear, though, whether the current plans to expand capacity of high-sulfur-crude processing will at the same time allow even further tightening of quality specifications in other areas of environmental concern, particularly in the areas of low and ultra-low sulfur diesel, higher octane gasoline without the use of lead-based additives, lower smoke and higher cetane in diesel. The capital-intensive nature of refining requires that the national oil companies mobilize substantial budgetary resources to achieve a number of parallel and competing goals: expansion of refinery upgrading units; conversion to high-sulfur processing; and expansion of petrochemical processing capacity as well as of the supply of petrochemical feedstock. This provides further uncertainty with regard to the state companies' ability to achieve yet another goal: that of producing cleaner fuels to reduce environmental emissions.

1.3. What is the Question?

This study investigates the question, what are China's refining options in light of a future of changing gasoline and diesel quality specifications? China has plans to harmonize its gasoline and diesel fuel specifications with European standards, generally lagging by a few years the European adoption schedule. A key hypothesis of the study is that the existing capital plant and the refinery technology in place will not be adequate to produce a full output slate of these cleaner-burning fuels, particularly in light of rapid growth in domestic demand. This is so despite the rapid expansion of the Chinese refining industry over the past decade. With the need for further investments looming on the horizon, Chinese refiners already have set a number of expansion and modernization plans in motion. Part of our goal with this work is to identify the technologies needed and the levels of investment that will be required under a set of future scenarios wherein gasoline and diesel specifications are successively tightened. Because refinery expansion plans already are underway, there may be opportunities to plan modernization in phases, or to jointly plan units so as to achieve advantageous feedstock relationships, or to plan larger units that enjoy economies of scale. We explore the issue of how the Chinese refining industry will adapt to change, how it might grow and invest, and how much it might cost to produce the new fuels.

2. Methodology

2.1. Basics of Linear Programming

Because the issue of refining and fuel reformulation in China must be assessed in a quantitative and systematic fashion, Trans-Energy Research Associates' portion of the study of reformulated gasoline and diesel in China relies on linear programming, also known as LP modeling or optimization modeling, as a key analytical methodology.

LP problems provide the optimal (often thought of as least-cost, highest-profit, or most efficient) solution to systems of ***n*** equations in ***m*** variables, where ***m*** is larger than ***n***. Typically, there are infinite solutions to such a problem. Any solution is called a "feasible vector." The goal is to find the "optimal feasible vector." Performing the search for the optimal feasible vector on a trial-and-error basis would take so long as to make most refinery problems insoluble. Consider the following simple example of crude slate selection:

Purchase a crude slate that provides a minimum of 100 kb/d of naphtha and 100 kb/d of fuel oil from the following choices:

	Crude 1	Crude 2	Crude 3
	Cost $10/b	Cost $15/b	Cost $20/b
Naphtha Yield	10%	30%	50%
Middle Distillate Yield	20%	30%	40%
Fuel Oil Yield	70%	40%	10%

It can be seen from this simple example that buying 1000 kb/d of crude 1 satisfies the goal, with quite a bit of surplus fuel oil. Buying 333.4 kb/d of crude 2 also satisfies the goal. Buying 1000 kb/d of crude 3 satisfies the goal with a great deal of surplus naphtha. We could mix our purchases, buying 120 kb/d of crude 1 plus 180 kb/d of crude 3. If cost is not a factor, we could dispense with the mathematics and simply purchase 1000 kb/d or more of any of these crudes. There are an infinite number of solutions, but clearly some are much more efficient than others are. A simple problem like the one above can be solved by hand, given a bit of time and perhaps a calculator, but real refining problems are much more complex. LPs find the most efficient solution set.

The main components of a linear programming problem are:

1. A set of n variables $x_1, x_2, \ldots x_n$. These are sometimes called "activities" in linear programming.
2. A function $F(x_1, x_2, \ldots x_n)$ of the variables. F is linear, which means that it can be written in the form $F(x_1, x_2, \ldots x_n) = c_1x_1+c_2x_2+\ldots c_nx_n$, where the c_i are constants. F is called the "objective function."
3. A set of linear (in)equalities relating to the n variables. These are called the "constraints" in the LP problem. The ith constraint may be written $a_{i1}x_1 + a_{i2}x_2 + \ldots + a_{in}x_n \leq b_i$. Each a_{ij} and b_i is a constant. In some cases, the inequality may be $\geq$, but this is just a sign change, and in some cases the constraint may be an equality. The b_i are referred to as the "right hand side," or RHS of the constraint.
4. A requirement that each x_i be positive, $x_i \geq 0$

Given the definitions above, the linear programming problem is:
Maximize f(x) subject to
$a_{i1}x_1 + a_{i2}x_2 + \ldots + a_{in}x_n \leq b_i$ for i=1…m and
$xj \geq 0$ for j=1…n

The first algorithm for solving LPs in a systematic fashion was published by G.B. Dantzig in 1948. More efficient variations of Dantzig's algorithm were developed thereafter, and the most common technique now used is the Revised Simplex Algorithm. This algorithm has been implemented on mainframes and desktop personal computers. Trans-Energy Research Associates, Inc., builds and operates its own LP models.

The overall cost of the solution is tracked in the model's objective function (OBJ.) The model output will show the solutions to each equation and variable. For example, the equation and variables showing crude purchases will show the volume of each crude purchased and the total amount spent. The amount of catalytic cracking activity will be shown as the volume of cat cracker feed loaded onto the cat cracking process vector. Dividing the volume of feed by the cat cracker capacity provides the unit's utilization rate (e.g., 25 kb/d of feed to a 30 kb/d cat cracker indicates around 83% utilization.)

2.2. Linear Programming and Petroleum Refining

One of the principal reasons the Trans-Energy/LBL/CPCC team has selected the LP approach is that LPs are the most commonly used methodology for refinery modeling, and for good reason. In an LP, the columns or variables typically represent actual processes in the refinery, and are more firmly grounded in reality than more theoretical, macro models.

For example, there will be a column representing the atmospheric distillation of, say, Daqing crude. The total volume of this crude may vary, but the activity on the column, which also is the value of the variable for the model run, is the total volume of Daqing (or Daqing-type crude, which could also include similar crude streams) used. The sum of loading on all of the crude vectors will amount to total Chinese refinery inputs of crude by type. When tracking refinery unit utilization, there will be a column (or columns) representing downstream refinery units, such as catalytic cracking units. The loading on these columns will represent the actual amount of feed moving through the cat crackers, which when divided by the capacity will yield the utilization rate.

The equations in an LP often make intuitive sense. For example, the equation representing diesel production may be something along the lines of:
Diesel supply = straight-run diesel + hydrocracked diesel + hydrotreated diesel + light-cycle oil + treated light cycle oil + downblended kerosene + imported diesel - exported diesel.

Strict reformulation of diesel in China may change not only the volumes of individual diesel blendstocks in the equation, but may also add new elements and subtract others.

For example, an ultra-low sulfur diesel may contain no light cycle oil material, may eliminate all straight-run diesel and kerosene, and may add deeply desulfurized blendstocks. The equation might change along the lines of:

Diesel supply = hydrocracked diesel + hydrotreated diesel + deep-desulfurized diesel + aromatics-saturated diesel + downblended desulfurized kerosene + imported diesel - exported diesel

Thus, it is often far easier to interpret LP output than output from other types of modeling methodologies. This being the case, it is also easier to identify problem areas and debug the model. The modeler also can adopt simple naming conventions for the variables and equations.

Linear program modeling is the petroleum industry standard in terms of refinery modeling. In the case of petroleum refining and trade, there are multiple inputs to the processing center, since there are many crude oils and feedstocks at varying prices and availabilities. Within the processing center, there are multiple technologies and pathways to transform the raw materials into finished products. The products are simultaneously produced. (That is, there is really no feasible way to refine a barrel of crude and produce only gasoline.) There are multiple outputs to sell in local or distant markets. Essentially all modern refineries use detailed LP models to optimize operations. Some of these models may consist of literally thousands of equations in multiple thousands of variables. Optimization models are used to find least-cost pathways to meet certain conditions or constraints set by the modeler. In a refinery sense, this may include:

- The selection of a crude oil slate, plus other feedstocks and blendstocks,
- Selection of refinery unit modes and intensities,
- Pre-treating feeds for downstream units,
- Channeling intermediate streams (such as feeds and gases) from one unit to the next,
- Consumption of catalysts, hydrogen, water, electricity, and purchased natural gas,
- Blending of finished petroleum products to meet market demands and quality specifications,
- Producing and/or purchasing oxygenates for reformulated gasolines,
- Buying and selling products and intermediate streams.

LP modeling is data-intensive in several ways. First, a great deal of data is required to build, debug and calibrate the models. Second, building scenarios for analysis requires a solid understanding of the market issues at play. Third, running the scenarios and analyzing the output requires the ability to wade through solution sets for hundreds of equations in thousands of variables to determine what the model output really means. Although some of the issues listed above may not seem particularly relevant to the current study of Chinese gasoline and diesel, the fact that there are so many "moving parts" in a large model means that any changing virtually any variable or constraint can change optimum solutions in unexpected ways. Data quality is of paramount importance in building models that provide useful outputs, and modeler experience is of paramount importance in interpreting output and translating data output into useful insights into the market. This is the main reason that the research team worked closely with Chinese refiners and government agencies to developing the input data sets for the model work.

2.3. What LPs Can Tell You and What They Cannot Tell You

LPs are at their most powerful when they are used for scenario analysis, testing the impacts of various changes in elements such as cost, market availability, demand, quality, feedstock types and prices, trade options, capital investment options, and so forth. They are rarely considered useful if all that is required is a single, static image of the future.

The effectiveness and accuracy of LPs are also dictated by the quality of the data used to prepare them. As noted, building a refinery system LP is data intensive, and many of the data inputs are a process of estimation—essentially, the model must distill a complex real-world system down into a computer-based system of linear equations, and such a process is never perfect. While modeling work may shed light on the reasonableness of various data inputs, they generally cannot pinpoint exact values. As an example, we did not have an explicit figure on demand for petroleum coke in China, so we inserted into the tableau an approximate figure of 25 kb/d for the year 2000 calibration runs. We did have trade data for that year: coke exports were officially reported at 23.8 kb/d, while imports were 0.7 kb/d. With demand of 25 kb/d, this resulted in an inferred 48.1 kb/d of refinery output of coke. This was a good fit with the model work. The model runs for 2000 produced 46.1 kb/d of coke and exported 21.1 kb/d—which leads to the conclusion that 25 kb/d of coke demand is a reasonable approximation. The model, therefore, did not pinpoint a number, but validated the approximation.

LPs are also highly sensitive to price, as typically they are designed and run in cost-minimization or profit-maximization mode. If a refinery system operates in a highly controlled market where price signals are confused, an LP is unlikely to be a useful tool. While it might be possible to build and calibrate a refinery LP for such a market, the model would contain so many constraints and so many upper and lower bounds that it would have little leeway to search for lower cost, more efficient solutions.

2.4. Gasoline and Diesel Reformulation Issues and CHREF2

Transport fuel quality standards historically were promulgated mainly to ensure minimum performance criteria in various engine types. As such, fuel properties often have been modified to keep pace with developments in automotive engineering. For gasoline engine performance, the most important fuel properties have been the antiknock engine performance, the most important fuel properties have been the antiknock characteristics, the boiling range, and the Reid vapor pressure, or RVP. Engine knocking, or "pinging," indicates insufficient octane, which is measured as RON, or Research Octane Number and MON, Motor Octane Number. EURO standards specify both RON and MON, so our model blends gasoline to a minimum octane rating (R+M)/2 that is the average of the two numbers. (Chinese standards typically have specified RON or MON, but not both.) The boiling range and RVP govern ease of startup, tendency toward vapor lock, fuel economy, and evaporative loss. Too high an RVP, for example, indicates too great a tendency for hydrocarbons in the fuel tank to flash into vapor. Not only can this prevent ignition, it contributes to evaporative fuel loss and unburned hydrocarbons directly into the atmosphere.

For diesel engine performance, the cetane number measures ignition properties. The cetane number is inversely related to the aromatics content, so in some situations aromatics per se are not regulated, but indirectly their percentage volume in the pool is limited when a high cetane number is specified. Other important properties are the distillation range, the pour point, the flash point, and the sulfur content. In terms of emissions, reducing sulfur levels has been found to reduce not only sulfurous compound emissions but other pollutants as well, such as particulate matter. Controlling the distillation range via a T95 specification also is intended to reduce emissions by reducing the amount of the heaviest fractions (including some of the heavy aromatics) in the finished pool.

In Asia and around the world, gasoline and diesel specifications are changing. The timelines and stringency of the specification changes vary from country to country, but certain commonalities stand out.

In terms of reformulating gasoline, the most common measures taken include a full phaseout of the use of lead compounds as octane enhancers while maintaining minimum octane levels, controls on RVP to reduce evaporative loss, reduction of sulfur levels, controls on benzene and aromatics content, and addition of oxygenates in some markets. Reformulating diesel typically involves improvement of cetane numbers, reduction in aromatics content, reduction of sulfur content, and control of the distillation range. A phased approach toward gasoline reformulation might involve, for example, first, the phaseout of lead and the adoption of RVP and sulfur standards; second, controls on benzene, aromatics, olefins and boiling ranges; third, further tightening of standards, such as reducing the maximum benzene content from 3.5% by volume to 1.0% by volume, and reducing allowable sulfur levels from, say, 300 parts per million (ppm) to 150 ppm (the level in EURO3 gasoline) and then to 50 ppm (the level in EURO4 gasoline.) A phase approach toward diesel reformulation might call for an immediate reduction in sulfur content to 500 ppm, followed by further cuts to 350 ppm (the EURO3 standard) and then 50 ppm (the EURO4 standard,) along with perhaps improvements in cetane number, controls on boiling range, and restrictions on aromatics content.

3. Model Assumptions and Results

3.1. Summary of the Scenarios

Ten scenarios were developed for testing in the model, including a base case of the actual situation in 2000, a base case and three alternatives for 2005, a “2008 Olympics” case, and a base case and three alternatives for 2010. A summary of the scenarios is shown in Table 9.

Table 9. LP Model Scenarios Of Chinese Gasoline and Diesel Quality

Scenario Number	**1. Base**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	2000 Actual	**2005 Base (Euro 2)**	**2005 Euro2 + 35% Euro 3**	**2005 Euro3**	**2005 Euro2 + 35% Euro 4**	**2008 Euro3 + 15% Euro 4**	**2010 Base (Euro3)**	**2010 Euro3 + 15% Euro 4**	**2010 Euro3 + 40% Euro 4**	**2010 Euro3 + 15% Euro 5**
90, 93, and 97 Octane										
RVP psi max		9	8.70	8.70	7.98	7.98	8.70	7.98	7.98	7.00
Sulfur ppm max	1000/800	500	150	150	50	50	150	50	50	10
Olefins vol% max	35	35	18	18	14	14	18	14	14	14
Aromatics vol% max	40	40	42	42	35	35	42	35	35	35
Benzene vol% max	25	5	1	1	1	1	1	1	1	1
Oxygen wt% min/max	2.7	2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7
Automotive Diesel										
Cetane no.	45	49	51	51	55	55	51	55	55	55
Sulfur ppm max	2000	500	350	350	50	50	350	50	50	10
Aromatics vol%										
Polycyclic aroms %			11	11	4	4	11	4	4	4
T95 %		370	350	350	340	340	350	340	340	340
Density (at 15degC)		820-860	845 max	845 max	845 max	845 max	845 max	845 max	845 max	845 max

Note: In mixed scenarios, the specifications shown are those of the more stringent specification. In Scenarios 2 and 3, current specifications on olefins, aromatics, benzene, and oxygen have been added.

These scenarios derive from discussions with SEPA, Michael Walsh, Sinopec and other related experts in the oil and transportation sectors in China and abroad. It was decided that the base case should be product specifications in place in 2000 for three grades of gasoline and for automotive diesel (Scenario 1). As noted in section 1.1.5, “automotive diesel” in all cases refers to the estimated volume of diesel production destined for transportation use as opposed to boiler or other industrial uses. Even though in the 2000 base case there is no distinction between the product specification for automotive vs non-automotive diesel, this distinction is important in future scenarios as it defines the volume of final diesel production subject to increasingly stringent specifications. In the model, non-automotive diesel was assumed to maintain a 0.2% maximum sulfur specification, while the specifications assumptions for automotive diesel were varied by scenario.

For 2005, three scenarios were developed. The base case scenario for 2005 reflects further strengthening of product specification beyond those listed in Table 7 to the equivalent of the Euro 2 standards for nationwide implementation, the major difference from current standards being the reduction in allowable sulfur in diesel to 500 ppm from 2000 ppm (Scenario 2). Scenario 3 combines a baseline Euro 2 specification with the implementation of Euro 3 standards in selected cities. SEPA has designated certain cities as "pilot cities" for use of both cleaner and alternative fuels, and Sinopec has estimated that those cities account for about 35% of total demand for gasoline and transport diesel. There is precedence already for distinguishing product specifications by region such as done here; already, China has implemented new gasoline specifications first in Beijing, Shanghai, and Guangzhou prior to nation-wide use. The final scenario for 2005 assesses the impact of moving beyond regional distinctions to full national implementation of Euro 3 standards (Scenario 4). Scenario 5 duplicates the thinking behind Scenario 3 in terms of providing cleaner fuels meeting Euro 4 standards first to the major cities prior to national implementation.

A standalone 2008 scenario (Scenario 6) was developed in recognition that Beijing is likely to require cleaner fuel standards for the city prior to and during the Olympic games of 2008. Although this change is currently under consideration, it is not clear if it will apply only to Beijing or to the top three cities of Beijing, Shanghai and Guangzhou, which account for an estimated 15% of demand for these fuels. In this model assessment, the rest of the country is assumed to have already reached Euro 3 levels, while the three cities move to Euro 4.

The final five scenarios of 2010 continue the assessment of increasing the stringency of product quality specifications. In this year, the base scenario is assumed to be the nationwide adoption of Euro 3 standards for gasoline and transport diesel (Scenario 7). Scenario 8 parallels Scenario 6 in the adoption of Euro 4 standards for the top three cities, but implemented 2 years after the Olympics. Scenario 9 is more aggressive, adopting the Euro 4 standard in the wider set of "clean fuel" cities, where total demand for gasoline and transportation diesel is estimated to have risen to 40% of the total, compared to 35% in Scenario 5. Scenarios 10 is the most aggressive of the set and assumes the adoption of the stringent Euro 5 standards in the three major cities s requiring a drop to only 10 ppm sulfur in gasoline and 10 ppm sulfur in diesel fuel. This final scenario represents a 99% reduction in allowable sulfur in these fuels within a ten-year period.

In general, the scenarios test two different approaches to increasing product quality. One is going for nation-wide implementation of a single set of product quality specifications (ignoring current regional and seasonal differences in gasoline RVP, for example), and the second looks at the possible differences in investment requirements by first tightening product specification in the major cities (the "clean fuel cities" or the three major cities) prior to national implementation. Such an approach has international precedents as well and could be a way to mitigate the investment requirements to bring the country to the same product specification level simultaneously.

3.2. Model Assumptions

3.2.1. Refinery Configuration

The baseline configuration of China's refining system as used in the model is shown in Table 10. These figures aggregate the combined capacity of Sinopec, CNPC, and the remaining regional and local refineries. Although many of these regional and local refineries are slated to be shut down or combined with Sinopec or CNPC refineries, their total refining capacity is only about 7% of the total in terms of distillation capacity, and even less—in most cases zero—in terms of upgrading capacity.

Table 10 Current Refinery Configuration in China

Unit Name	Million Tonnes	Thousand Barrels per Day (kb/d)
Atmospheric and Vacuum Distillation (AVDU)	276.0	5,520
Fluid Catalytic Cracking (FCC)	19.7	394
Resid Fluid Catalytic Cracking (RFCC)	69.4	1,388
Deep Catalytic Cracking (DCC)	3.5	70
Hydrocracking (HDC)	12.9	258
Delayed Coking (DC)	20.6	412
Thermal Cracking/Visbreaking	8.7	174
BTX Extraction (BTX)	5.9	118
Catalytic Reforming	15.2	304
Alkylation	1.4	28
C5/C6 Isomerization	-	
Naphtha, Kerosene, & Diesel Hydrotreating (HDT)	28.0	560
Vacuum Gas Oil (VGO) Desulfurization	-	
Resid Hydrodesulfurization (HDS)	5.2	104
Lubes	4.0	80
Solvent Deasphalting (SDA)	9.9	198
Asphalt	4.9	98
MTBE	1.0	20
H_2 Production	0.6	12

In order to increase the usefulness of the scenario results, the model also takes into account the refinery expansions already underway or likely to be completed by 2005. Given that the model takes into account the existing base of refining technology in the selection of new technology to build, it is important to include these developments to avoid overstating the need for new units in response to tighter product specifications beyond what is already current expected. The assumed capacity expansions are further detailed in Section 3.4.1 (p. 58). Since these are current investments, however, they are considered in the calculation of upgrading costs for each future scenario.

3.2.2. Crude Oil Supply

As noted, China is a major producer of crude oil, and many oil-prospective areas remain to be developed, particularly in the western provinces. Chinese oil quality is typically very good—low in sulfur, with good straight-run middle distillate properties, and with fuel oils suitable for cracker feed. Nonetheless, in the longer term China will be relying more on imported crude oil, with Middle Eastern sour (higher sulfur) crudes coming to play a larger role in the refinery slate. In the past, it has been possible for China to avoid making certain sour crude investments because of the widespread availability of sweet (low sulfur) crudes. In the future, we assume that any new refinery investment will be geared to handle sour crudes, and as will be discussed in more detail in the Results section, the model tended to import less expensive sour crudes as soon as the option was made available to invest capital in the refining industry.

Representing the Chinese crude slate in CHREF2 involved modifying crude oil assays for a range of Chinese domestic, Asian, Middle Eastern, African and European crudes. These span across a wide spectrum of quality, from very light, sweet crudes (typified by Malaysian, African, and North Sea crudes) to sour, fairly heavy crudes (typified by Arab Heavy and Iranian Heavy crudes.) The higher quality crudes are assumed to command a price premium. The model inputs included the types of crudes, their prices and transport costs in US dollars per barrel, and their upper bounds of availability in 2005, 2008 and 2010. These input assumptions are detailed in the table following in the section on pricing.

The crude purchase tables are designed to give a good range of options for the future crude slate without going too far in one direction or another. International market forces dictate prices, and it is assumed that certain volumes of certain types of crudes will always be available for a price. Logically, if a major buyer such as China entered the market for a huge volume of, say, Angolan light sweet crude (represented by Cabinda-type in the model,) the price of light sweet African crudes might tend to rise relative to other crudes. If the price premium grew too large, however, the incentive to purchase Angolan crudes would be lessened, and one or more Chinese refiners would switch to other types—perhaps light sours, with the proper investments. Thus, crude prices tend to track one another, and price differentials between crude types rarely get so wide that some crudes are hugely under- or over-priced relative to others. Crude transport costs also figure into the choice of crude slate, in the model and in the real world. For example, transport costs for North Sea sweet crudes are significantly higher than those for Asian light sweet crudes. But the transport cost differential would become insignificant if the price of Asian sweet crudes went too high. European sweet crudes would tend to flow to Asia, exerting downward pressure on prices.

Further constraining the crude purchase decision is the role of upper bounds, or UBOUNDS. For Chinese domestic crudes, the UBOUNDS are modified from CPCC's forecast of crude production, which sets an upper limit on domestic crude use. For imported crudes, the UBOUNDS are not so much based on physical production, but instead on assumed market availability. For example, Malaysian crude production over the coming years is expected to be in the range of 500-700 kb/d, yet we set the upper bound of Tapis crude purchase at 42 kb/d only. The reasons are, first, that Malaysian refineries will process the majority of Malaysian Tapis-type output (or Tapis "look-alikes" in other Asian countries,) and second that there are a host of other customers besides China. While having a low-sulfur crude slate would make it easier for Chinese refiners to meet future EURO fuel sulfur standards, market realities limit the amount of sweet Asian crudes available to China. The next tier of supply would be African and Northern European—at a higher price.

3.2.3. Pricing

As China has increasingly become integrated into the world oil market, its domestic pricing has increasingly reflected world market prices. The trend is not surprising, as China has moved from domestic self-sufficiency to a near one-third external dependency on oil imports. As the US discovered by the late 1970s, it is nearly impossible to maintain a separate domestic pricing structure for oil when a substantial portion of supply is imported. In the current study, we assume as well that China will face international market prices for its crude and product imports and exports, separated from international prices only by the level of tariff on imports, which is expected to fall as WTO rules fully come into play in the oil sector in three to five years. Transportation prices for imports and exports also reflect international shipping prices, and in some cases are tiered by volume, reflecting the higher cost of importing crude or products from more distant locations as local availability is depleted.

The crude cost and freight assumptions discussed above are presented here in a more detailed table, showing the prices and availabilities used as inputs to the model in our scenarios of 2005, 2008 and 2010 (Table 11). Also included is a brief guide to the general types of crudes used. Note that the crude streams need not be exactly as named; e.g., Murban need not be only Murban crude, but may also represent other Middle Eastern light, medium sulfur crudes. Oman and Murban are two of the higher-quality Middle Eastern crudes in the model, and their availabilities are limited to 200 kb/d each in 2010. The dominant crudes are assumed to be similar to the Saudi Arabian, Kuwaiti, and Iranian lights and heavies. The model is not required, technically, to import crude at all, but in general the model kept crude runs high, and relied upon domestic refining to meet the majority of product demand. Within this framework, there was variability in the types and volumes of foreign crudes selected. The purchased crudes are detailed further in the section on Model Results.

Table 11

Crude Types and Costs Represented in CHREF2 Model, 2005, 2008 and 2010
(costs in $/b, bounds in kb/d)

Guide to Crude Names and Types:

Code	Name	General Type
BUY.ALT	Arab Light	Light, high sulfur
BUY.ARH	Arab Heavy	Heavy, high sulfur
BUY.OMA	Oman	Light, med sulfur
BUY.MUR	Murban	Light, med sulfur
BUY.KUW	Kuwait	Light, high sulfur
BUY.IRH	Iran Heavy	Heavy, high sulfur
BUY.IRL	Iran Light	Light, high sulfur
BUY.BRE	Brent	Light, low sulfur
BUY.CAB	Cabinda	Light, low sulfur
BUY.MIN	Minas	Light, low sulfur
BUY.TAP	Tapis	Light, low sulfur
BUY.DAQ	Daqing	Light, low sulfur
BUY.ARU	Arun	Condensate
BUY.SHE	Shengli	Heavy, med sulfur
BUY.NAN	Nanhai Light	Light, low sulfur
BUY.HUA	Huabei	Med, low sulfur

2005	CRUDECOST	UBOUND	CTRANSCOST
BUY.ALT	$ (22.90)	1,500.0	$ (1.78)
BUY.ARH	$ (22.20)	1,000.0	$ (1.74)
BUY.OMA	$ (23.56)	180.0	$ (1.28)
BUY.MUR	$ (23.62)	180.0	$ (1.82)
BUY.KUW	$ (22.40)	350.0	$ (1.74)
BUY.IRH	$ (22.49)	300.0	$ (1.58)
BUY.IRL	$ (22.52)	300.0	$ (1.66)
BUY.BRE	$ (23.22)	200.0	$ (1.98)
BUY.CAB	$ (23.12)	100.0	$ (1.92)
BUY.MIN	$ (22.82)	62.0	$ (0.99)
BUY.TAP	$ (24.72)	42.0	$ (1.03)
BUY.DAQ	$ (23.48)	589.0	$ (1.68)
BUY.ARU	$ (25.45)	11.0	$ (1.58)
BUY.SHE	$ (20.15)	301.4	$ (1.36)
BUY.NAN	$ (22.90)	205.5	$ (2.01)
BUY.HUA	$ (23.48)	909.6	$ (1.24)

2008	CRUDECOST	UBOUND	CTRANSCOST
BUY.ALT	$ (24.16)	2,600.0	$ (2.47)
BUY.ARH	$ (23.46)	2,000.0	$ (2.43)
BUY.OMA	$ (24.95)	180.0	$ (1.98)
BUY.MUR	$ (25.24)	180.0	$ (2.51)
BUY.KUW	$ (23.49)	400.0	$ (2.43)
BUY.IRH	$ (23.71)	330.0	$ (2.28)
BUY.IRL	$ (23.77)	420.0	$ (2.35)
BUY.BRE	$ (25.05)	200.0	$ (2.67)
BUY.CAB	$ (24.95)	100.0	$ (2.61)
BUY.MIN	$ (24.65)	54.8	$ (1.68)
BUY.TAP	$ (26.55)	42.0	$ (1.72)
BUY.DAQ	$ (24.74)	556.2	$ (2.37)
BUY.ARU	$ (27.93)	12.6	$ (2.28)
BUY.SHE	$ (21.41)	293.2	$ (2.06)
BUY.NAN	$ (24.16)	246.6	$ (2.71)
BUY.HUA	$ (24.74)	838.1	$ (1.94)

2010	CRUDECOST	UBOUND	CTRANSCOST
BUY.ALT	$ (25.00)	4,500.0	$ (2.94)
BUY.ARH	$ (24.30)	2,500.0	$ (2.90)
BUY.OMA	$ (25.88)	200.0	$ (2.44)
BUY.MUR	$ (26.32)	200.0	$ (2.98)
BUY.KUW	$ (24.22)	400.0	$ (2.90)
BUY.IRH	$ (24.50)	350.0	$ (2.74)
BUY.IRL	$ (24.62)	420.0	$ (2.82)
BUY.BRE	$ (26.27)	200.0	$ (3.13)
BUY.CAB	$ (26.17)	100.0	$ (3.08)
BUY.MIN	$ (25.87)	50.0	$ (2.15)
BUY.TAP	$ (27.77)	42.0	$ (2.19)
BUY.DAQ	$ (25.58)	534.2	$ (2.84)
BUY.ARU	$ (29.58)	13.7	$ (2.74)
BUY.SHE	$ (22.25)	287.7	$ (2.52)
BUY.NAN	$ (22.90)	274.0	$ (2.01)
BUY.HUA	$ (23.48)	790.4	$ (2.40)

The model in general found its nameplate crude distillation capacity adequate, but it should also be noted that the total crude availability in the model adds up to a volume well beyond existing and planned capacity. For example, in the year 2010 scenarios, we assume that up to 4,500 kb/d of Arab light type crude is available for purchase—a volume higher than recent actual crude runs for all streams. But part of the model's function is to decide on the most cost-effective strategy to meet the requirements of the market. We expect the model to purchase crude only as necessary, and it did not over-expand capacity to raise crude runs and excessively boost product exports.

International prices also are set in the model for products and blendstocks. China is a fairly active product trader, often with seasonal trades and import-export patterns influenced by the country's expansive geography and large number of coastal metropolitan areas. Table 12 presents the price assumptions used in the model, along with the assumed transport costs and product import duties. During the course of this EF project, China formally entered the World Trade Organization, or WTO. Because of membership in this organization, we assume that product import duties will be reduced to 2% for all products by the year 2008, relative to duties in the 6-9% range in 2000 and an assumed 5-6% range by 2005.

Table 12

China Model Price Assumptions, Product and Blendstocks
(1999 Constant $/barrel)

Product	2000	transp	duty%	2005	transp	duty%	2008	transp	duty%	2010	transp	duty%
Naphtha	$29.61	$1.31	6%	$25.70	$1.52	6%	$27.14	$1.66	2%	$28.10	$1.76	2%
Euro2 Reg	$31.08	$1.29	9%	$27.10	$1.50	5%	$29.44	$1.64	2%	$31.00	$1.73	2%
Euro2 Prm	$33.08	$1.29	9%	$29.60	$1.50	5%	$32.36	$1.64	2%	$34.20	$1.73	2%
Euro3 Reg	$32.58	$1.29	9%	$28.70	$1.50	5%	$31.10	$1.64	2%	*$32.70*	$1.73	2%
Euro3 Prm	$34.28	$1.29	9%	$30.40	$1.50	5%	$32.80	$1.64	2%	*$34.40*	$1.73	2%
Euro4 Reg	$33.88	$1.29	9%	$30.40	$1.50	5%	$32.80	$1.64	2%	*$34.40*	$1.73	2%
Euro4 Prm	$35.68	$1.29	9%	$32.20	$1.50	5%	$34.72	$1.64	2%	*$36.40*	$1.73	2%
Euro5 Reg	$34.28	$1.29	9%	$30.80	$1.50	5%	$33.20	$1.64	2%	*$34.80*	$1.73	2%
Euro5 Prm	$36.08	$1.29	9%	$33.00	$1.50	5%	$35.28	$1.64	2%	*$36.80*	$1.73	2%
Kero/jet Fuel	$34.25	$1.28	9%	$29.90	$1.48	9%	$32.60	$1.63	2%	$34.40	$1.72	2%
Diesel 0.2%S	$33.50	$1.31	6%	$29.15	$1.52	6%	$31.91	$1.66	2%	$33.75	$1.76	2%
Diesel <0.05%S Euro2	$34.50	$1.31	6%	$30.15	$1.52	6%	$32.91	$1.66	2%	*$34.75*	$1.76	2%
Diesel <0.015%S Euro3	$35.00	$1.31	6%	$30.65	$1.52	6%	$33.29	$1.66	2%	$35.05	$1.76	2%
Diesel <0.005%S Euro4	$35.50	$1.31	6%	$31.15	$1.52	6%	$33.73	$1.66	2%	$35.45	$1.76	2%
Diesel <0.001%S Euro5	$36.00	$1.31	6%	$31.65	$1.52	6%	$34.23	$1.66	2%	$35.95	$1.76	2%
MSFO 2% S	$25.00	$1.27	12%	$21.00	$1.47	6%	$22.20	$1.61	2%	$23.00	$1.71	2%
LPG	$19.77	$2.50	6%	$18.57	$2.90	5%	$21.46	$3.18	2%	$23.38	$3.36	2%
MTBE	$35.70	$2.29		$35.70	$2.65		$38.72	$2.91		$40.74	$3.08	
Asphalt	$24.80	$1.77	9%	$20.20	$2.05	6%	$20.50	$2.25	2%	$22.20	$2.38	2%
Lubes	$40.00	$2.80	9%	$39.00	$3.25	6%	$42.00	$3.56	2%	$42.00	$3.76	2%

Note: Import duties are assumed to be reduced to 2% by 2008 by China entry into WTO

3.2.4. Capital Costs

One of the primary hypotheses of the current project is that China's refinery technology in-place will not be sufficient to aggressively reformulate gasoline and diesel to EURO standards. As such, a number of refinery expansion and upgrade investments have been made already, with projects scheduled to be operational by 2005 to produce EURO 2 fuels. Moving beyond this, however, will require additional investment by Chinese refiners. The CHREF2 model incorporates vectors that allow capital expansion of the various types of refinery units. When the model is confronted with new, stricter specifications in each scenario, it must choose how much of each type of capacity to build in order to comply with the requirements. The investments are made according to capital costs provided by CPCC and Trans-Energy Research Associates. These costs by unit type are presented in Table 13. These costs reflect equipment costs only and do no include offsites (utilities, storage, pipelines), labor, land acquisition charges, loan interest, taxes, and other related costs. Depending on the project, these other costs could raise total costs by an additional 25% to 50% or more.

Table 13

China Forecast Onsite Refinery Investment Costs

	Capacity 10 K tonnes	Capacity kb/d	Cost 10 K RMB	Cost MnUS$
Sour Crude Unit (CDU)		90.0		$ 36.00
Vacuum distillation (VDU)		55.0		$ 25.00
Gasoline-related Investments:				
Cat Reforming (CCR)*	80	18.6	35000	$ 42.27
Cat Reforming (REF)*	60	14.0	27000	$ 32.61
C5/C6 Isom		6.0		$ 10.00
HF Alky		7.0		$ 24.00
Hydrotreating:				
Naphtha HDS		25.0		$ 9.40
Kero HDS	80	17.1	8000	$ 9.66
Diesel HDS	80	16.2	18100	$ 21.86
VGO HDS	80	15.8	29000	$ 35.02
Resid HDS	200	36.2	150000	$ 181.16
H2, steam reforming, 10 K NM^3/hr	2		11000	$ 13.29
mmcf/d	70.6			
Cracking:				
Visbreaking		25.0		$ 19.00
Delayed Coking	100	18.1	28500	$ 34.42
FCC		30.0		$ 50.00
RFCC	140	25.3	40000	$ 48.31
VGO HDC, Mid pressure	150	29.6	50000	$ 60.39
VGO HDC, high pressure	140	27.6	56000	$ 67.63
Miscellaneous:				
Lubes HT	30	5.8	56800	$ 68.60
Asphalt	40	7.1	13200	$ 15.94

* Including Naph HDS

Note: capacities in tonnes and costs in RMB provided by CPCC, others are Trans-Energy Research

3.2.5. Transport Costs

Transport costs are detailed in the above sections on crude and product prices. Adding a transport cost to a commodity is a way of reflecting the geography of the market. In general, the more distant the external market, the higher the per-barrel transport cost. This “transport penalty” also reduces the likelihood of the model relying overmuch on international markets to satisfy Chinese domestic demand and to absorb excess production. Although China is an active product trader and also both imports and exports crude oils, the main emphasis of the industry is to meet domestic demand, not to serve as an entrepôt refining center. Adding transport costs in the model is not only a more realistic representation of the market, it also eliminates any potential for the model to massively expand domestic refining in order to serve as an export refiner. Since trade is not free, the model imports only those products it finds uneconomical to produce, and exports only those products that truly are surplus to domestic requirements.

The model also incorporates a two-tier transport cost structure that discourages the model from relying too extensively on imports to meet demand. In the model, a specific volume of on-spec EURO quality fuel is assumed to be available in the local market at a reasonable transport cost. However, the second tier of imports is assumed to cost substantially more, since it is assumed that the country would have to source product from more distant sources if it became a serious importer of EURO spec fuels. The two-tier transport costs apply only to the main liquid fuels, and not to commodity imports such as LPG and naphtha.

3.2.6. How to Read and Interpret the Results: Issues to Keep in Mind

Before summarizing the model results, it is important to summarize a number of assumptions and conventions used in developing the model to help put the results in the proper context.

- The estimated equipment costs of current refinery expansion plans to 2005 are included in the cost calculations concerning gasoline and diesel upgrading and sulfur removal (see, for example, Table 25, p. 64). However, the tables concerning the capacity of new units constructed for each scenario exclude these unit capacities. The unit expansion plans represented in Table 24 (p. 60) reflect *additional* construction beyond what is already likely to take place by 2005.
- The cost basis for calculation of each of the scenario results includes equipment costs only. It does not include offsites (utilities, storage, pipelines), labor, land acquisition charges, loan interest, taxes, and other related costs. Depending on the project, these other costs could raise total costs by an additional 25% to 50% or more, and thus raise the cents/gallon estimate of increasing gasoline and diesel quality.
- The model is a “single-system” model of China’s refineries that treats the existing 50 to 60 individual refineries as one unit. This allows for certain efficiencies in intermediate stream-swapping, for example, at a level that does not occur in a geographically dispersed industry such as China’s (but is quite apparent in a concentrated system such as on the US Gulf Coast). This may result in understatement of the number of new units that need to be built and the total costs.
- The diesel pool in focus here is not the total diesel pool, but the volume estimated to be used in vehicles for transportation purposes. See Section 1.1.5 (p. 9) for a full discussion of the adjustments made to estimate transportation diesel demand. If the entire pool of diesel were required to be upgraded to the new specifications, the costs were undoubtedly be much higher still. All gasoline, however, is subject to the new specifications.
- The standard measurement unit used in the oil industry in China is metric ton, or tonne, with prices in Chinese RMB yuan per tonne. Internationally, however, barrels-per-day expressed in US dollars is the norm. As the Chinese unit is in weight terms, and the international norm is in volume terms, there is not a single conversion factor to go from one to the other, as each product has a different specific gravity. The conversion factors for the main products are shown in Table 14. As the CHREF2 model

used in this study was developed and extended from ones used elsewhere internationally, using Chinese data, it too adopts the common international volume unit. The background material in this report, however, retains the use of China's standard units, but the discussion of the model and model results are expressed in volume and US dollar terms (assuming RMB¥8.2=US$1).

Table 14 Unit Conversion Factors Used in China Refining Study

One million tonnes of:	equals this many million barrels	and this many kb/d
Crude oil	7.30	20.0
LPG	11.60	31.8
Naphtha	8.50	23.3
Gasoline	8.53	23.4
Kerosene	7.74	21.2
Diesel	7.46	20.4
Fuel Oil	6.66	18.2

3.3. Model Results

3.3.1. Baseline Calibration

The CHREF2 model was calibrated on year 1999-2000 data on refinery crude inputs, refinery unit capacities and yield patterns, product quality, product trade, and product demand. Calibration exercises are essentially a back-and-forth iterative process, where the model is run with a representation of actual inputs with actual refinery unit capacities, targeting historical demand at a given set of properties. Coefficients are modified until the model results are reasonably consistent with historical patterns. A "perfect fit" is not the goal. The principal objective is to create a sound analytical tool for measuring the impacts of changing fuel quality specifications. Constraining the model so severely that it is essentially forced to match past years is not a desired outcome, and in many ways it might not even be possible. Models rarely calibrate perfectly for a variety of reasons:

- The crude slate and the crude prices are an approximation, with "types" of crudes aggregated to simplify the modeling.
- The model is run on an average annual basis, with no accounting for seasonality (e.g., such factors as seasonal heating fuel imports in winter, or greater output of agricultural fuels during the planting or harvesting seasons, or greater imports of jet fuel during tourist season, and so forth.)
- The prices are annual averages as well, whereas actual markets may have great volatility that stimulates purchases at low prices and exports at high prices.
- The model tests China as a single large refining system, which also assumes that demand across the country can be met from the same system. In reality, China's geography dictates that southern provinces and the Hong Kong SAR import fuel, while refining centers to the north may export fuel. The model therefore calculates net trade only, without capturing in-and-out trade of the same product types.

- The model runs in a profit-maximization framework, and actual market conditions are at times influenced by social and political considerations.

One of the findings during the calibration runs was that the model found some of the catalytic cracking units largely uneconomical to operate. In the model's profit-maximization framework, it made little sense to run these units to eliminate diesel imports and to increase gasoline exports. The gasoline exports would have to be quite lucrative, and recent history has shown that they were not. Asia is now a net exporter of gasoline, a situation that weakens gasoline prices. Therefore, the model simulations of 2000 ran the RCC units at low utilization rates. The result was that the model created a lower yield of light products and a higher yield of fuel oil—that is, some of the fuel oil that was catalytically cracked in the year 2000 and converted to light products such as gasoline was not cracked at all in the model. The model results therefore diverge from what were apparent historic actual values, but this merely indicated the model's interpretation of economic benefits and was not considered a technical or mathematical flaw in the model.

Table 15

Model Calibration: CHREF2 Model Output vs. Historical Data

2000 Inferred Petroleum Product Balance
('000 barrels/day)

	Production	Imports	Exports	Demand
LPG	331.0	153.1	72.8	457.6
Naphtha/BTX	426.4	2.9	16.0	419.2
Gasoline	928.5	-	106.4	822.1
Kerosene	146.7	47.8	37.6	156.9
Diesel	1,365.2	5.3	11.3	1,359.2
Fuel Oil	424.8	259.6	5.6	678.8
Other:	190.8	28.1	27.6	191.3
Asphalt	*78.1*	24.8	2.8	100.1
Lubes	*64.6*	2.6	1.0	66.2
Coke	*48.1*	0.7	23.8	*25.0*
total	3,813.4	496.8	277.3	4,085.1

2000 CHREF2 Model Output Petroleum Product Balance
('000 barrels/day)

	Production	Imports	Exports	Demand
LPG	271.5	186.1		457.6
Naphtha/BTX	366.7	52.5		419.2
Gasoline	854.4		32.3	822.1
Kerosene	156.9			156.9
Diesel	1,359.2			1,359.2
Fuel Oil	492.7	186.1		678.8
Other:	206.0	6.4	21.1	191.3
Asphalt	100.1			100.1
Lubes	59.8	6.4		66.2
Coke	46.1		21.1	*25.0*
total	3,707.4	431.1	53.4	4,085.1

Note: coke demand was estimated at 25 kb/d

Table 15 presents the apparent 2000 petroleum product balance, comparing derived refinery output with demand, with imports and exports balancing supply and demand. Juxtaposed against this is the model's output petroleum product balance. As noted, model output of light products was lower than apparent actual values, in part at least because the model did not choose to maximize cracking and gasoline exports. The model's total output is also lower than apparent actual output, indicating perhaps that crude runs were higher than thought, or perhaps that there were some non-crude feedstocks entering the system (such as cracker feedstock, or catalytic reformer feedstock.) Both of these seem like reasonable explanations. First, crude runs may actually have been a bit higher than thought because China had been trying to shut down some small, inefficient refineries in recent years, and some of these may still have been running crude in 2000. Second, the close integration of certain refineries with the petrochemical sector may have promoted some back-and-forth of feeds, particularly naphtha-range material for aromatics production or miscellaneous hydrocarbons for ethylene production. Finally, the model chooses which fuel to use for refinery operations themselves, and the model may burn fuelgas, LPG, naphtha, or fuel oil for this purpose. It may also purchase fuel from outside the refinery system. In reality, an isolated refinery may have limited sources of fuel, but in a single-refinery model, the fuel choices are more varied.

Those caveats aside, we found a reasonably good fit between the model output and the measured year 2000 balance. The model exports some gasoline and petroleum coke, and imports mainly LPG, fuel oil, and naphtha, along with a small amount of lubricating oil. A better fit could be achieved through forcing more crude through the system and manually raising cat cracker utilization rates until gasoline exports reached the 106 kb/d recorded in 2000, versus the 32 kb/d the model exported, but adding such constraints would make little sense for our scenario analysis of 2005, 2008 and 2010. Directionally, the model results match history, and we concluded that the model was a good tool for analysis of future scenarios. In the future scenarios, quality specifications and demand by type are the only variables modified, and the goal is to identify how the system reacts to these changes alone. Accordingly, the model results are more comparative than absolute; that is, we are more concerned with the relative changes in the model solution sets wrought by the changes in gasoline and diesel quality than we are with the absolute values in the solution sets.

3.3.2. Demand by Scenario

The modeling work analyzed ten scenarios, with the year 2000 serving as Scenario 1 for baseline purposes. Scenarios 2 through 5 apply to the year 2005, Scenario 6 focuses on 2008, and Scenarios 7 through 10 are for the year 2010. As noted, the scenarios are defined by gasoline and diesel demand by varying EURO grade. Six of the scenarios are combinations of fuel types, where it is assumed that the major metropolitan areas adopt stricter standards ahead of the more rural areas of the country. Table 16 provides a detailed look at product demand by grade for the scenarios. These scenarios and the model results on gasoline and diesel blending pools are discussed in the section following.

Table 16

Chinese Product Demand, kbpd, with breakdown of grades by scenario

		Per cent of demand:									
		Euro2	100%	65%	0%	65%	0%	0%	0%	0%	0%
		Euro3	0%	35%	100%	0%	85%	100%	85%	60%	85%
		Euro4	0%	0%	0%	35%	15%	0%	15%	40%	0%
		Euro5	0%	0%	0%	0%	0%	0%	0%	0%	15%
		scen 1	scen 2	scen 3	scen 4	scen 5	scen 6	scen 7	scen 8	scen 9	scen 10
			Base					Base			
			05EURO2	05EURO2&3	05EURO3	05EURO2&4	08EURO3&4	10EURO3	10EURO3&4	10EURO3&4	10EURO3&5
	1999	2000	2005	2005	2005	2005	2008	2010	2010	2010	2010
Gasoline	798.8	822.1	997.9	997.9	997.9	997.9	1,077.5	1,134.1	1,134.1	1,134.1	1,134.1
GE2.R	683.7	690.5	828.2	538.4	-	538.4	-	-	-	-	-
GE2.P	115.0	131.5	169.6	110.3	-	110.3	-	-	-	-	-
GE3.R				289.9	828.2	-	760.2	941.3	800.1	564.8	800.1
GE3.P				59.4	169.6	-	155.7	192.8	163.9	115.7	163.9
GE4.R				-	-	289.9	134.2	-	141.2	376.5	-
GE4.P				-	-	59.4	27.5	-	28.9	77.1	-
GE5.R				-	-	-	-	-	-	-	141.2
GE5.P				-	-	-	-	-	-	-	28.9
Kero/Jet	146.3	156.9	207.8	207.8	207.8	207.8	240.6	265.1	265.1	265.1	265.1
Diesel	1,267.2	1,359.2	1,725.0	1,725.0	1,725.0	1,725.0	1,959.4	2,135.8	2,135.8	2,135.8	2,135.8
DE2	532.2	397.6	819.4	532.6	-	532.6	-	-	-	-	-
DE3			-	286.8	819.4	-	836.6	1,110.6	944.0	666.4	944.0
DE4			-	-	-	286.8	147.6	-	166.6	444.2	-
DE5			-	-	-	-	-	-	-	-	166.6
IDO	764.5	777.6	905.6	905.6	905.6	905.6	975.3	1,025.2	1,025.2	1,025.2	1,025.2
Fuel Oil	655.1	678.8	715.3	715.3	715.3	715.3	734.8	748.1	748.1	748.1	748.1
LPG	416.3	457.6	794.5	794.5	794.5	794.5	972.3	1,112.3	1,112.3	1,112.3	1,112.3
Asphalt	81.1	100.1	120.8	120.8	120.8	120.8	130.9	138.1	138.1	138.1	138.1
Naphtha	390.1	419.2	815.1	815.1	815.1	815.1	972.8	1,094.5	1,094.5	1,094.5	1,094.5
Lubes	63.3	66.2	75.8	75.8	75.8	75.8	85.7	93.0	93.0	93.0	93.0
Total	3,818.1	4,060.0	5,452.1	5,452.1	5,452.1	5,452.1	6,174.0	6,721.0	6,721.0	6,721.0	6,721.0

The naming conventions in the table are simplified, with “GE2.R” signifying gasoline, EURO2, Regular grade, “GE3.P” denoting gasoline, EURO3, Premium grade, “DE4” signifying diesel, EURO4, and so forth. Gasoline and diesel shares and types change by scenario, while demand for other products such as fuel oil, LPG and naphtha remain constant. Gasoline demand growth rates are somewhat modest, with a fraction of demand growth assumed to shift to LPG, where growth rates are forecast at 7% per year from 2005 through 2010.

3.3.3. Scenario 1: 2000 Base Case

The year 2000 base case gasoline and diesel blending pools correspond with the calibration final run discussed above. The gasoline and diesel blending pools are fairly simple, as the following Figure 2 and Figure 3 illustrate. A summary table of these numbers by fuel and scenario appears at the end of this section (Table 17).

Figure 2

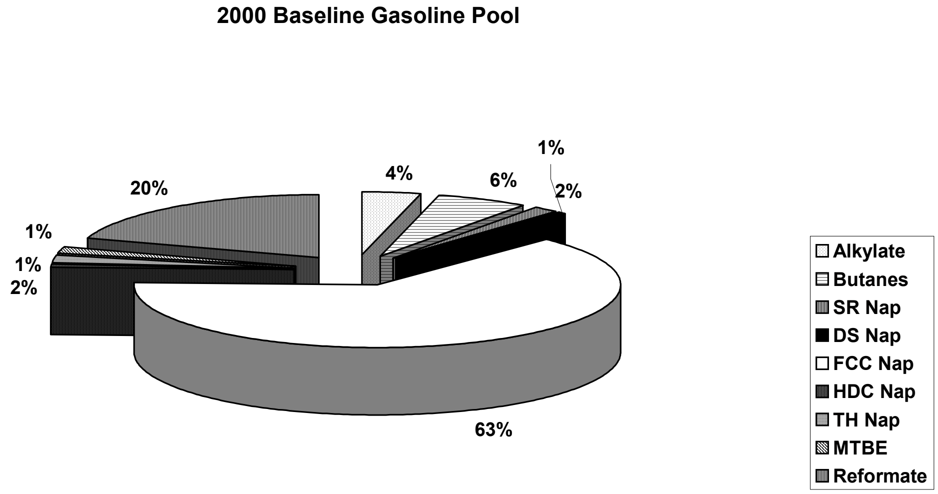
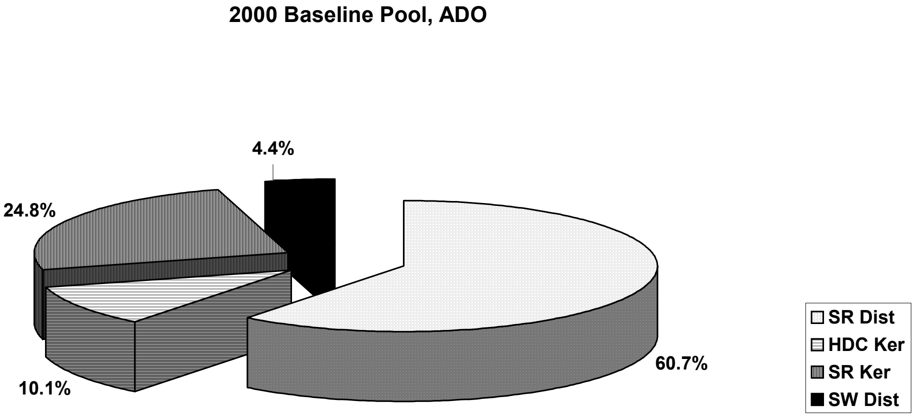


Figure 3



Gasoline was composed primarily of catalytically cracked naphtha (also known as cat naphtha or FCC naphtha,) with reformate, butanes, alkylate and other miscellaneous streams. Automotive diesel was mainly straight-run middle distillates, indicating that the 0.02% sulfur standard in place was not terribly binding; the refinery system had enough straight-run material from low-sulfur crudes that it did not require much by way of hydrotreating and hydrocracking. The following figures compare gasoline and diesel blending pools by scenario, showing how specification changes may prompt changes in product blending.

3.3.4. Scenario 2: 2005, EURO2 standards (Base Case)

The following two figures display the gasoline and diesel blending pools used to create EURO2 standard gasoline and diesel for Chinese demand in 2005. EURO is the Base Case.

Figure 4

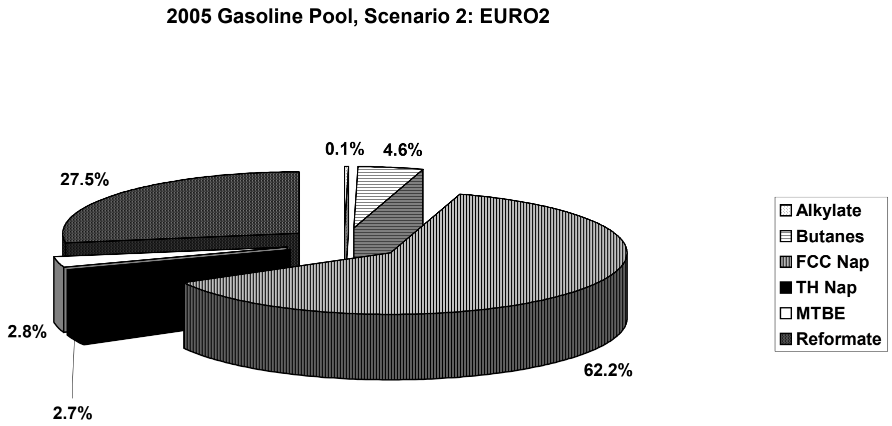
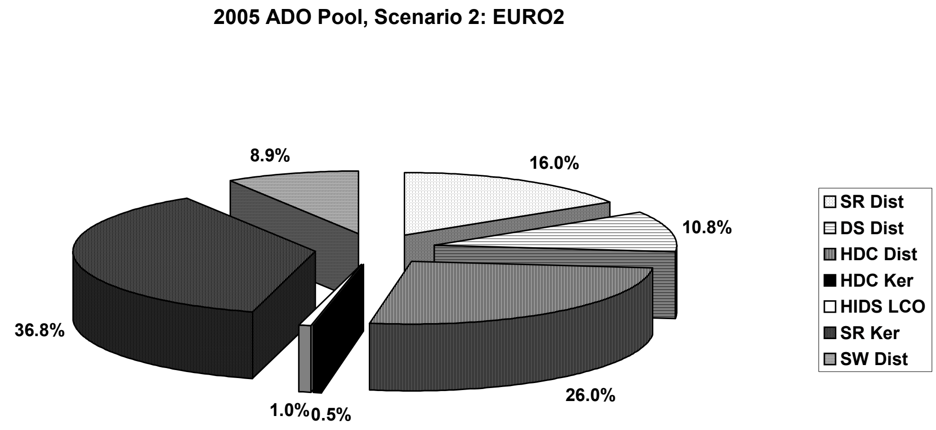


Figure 5



3.3.5. Scenario 3: 2005, EURO2 65% and EURO3 35%

The following two charts show the blending pools used to create gasoline and diesel under scenario 3, 65% EURO2 fuel and 35% EURO3 fuel.

Figure 6

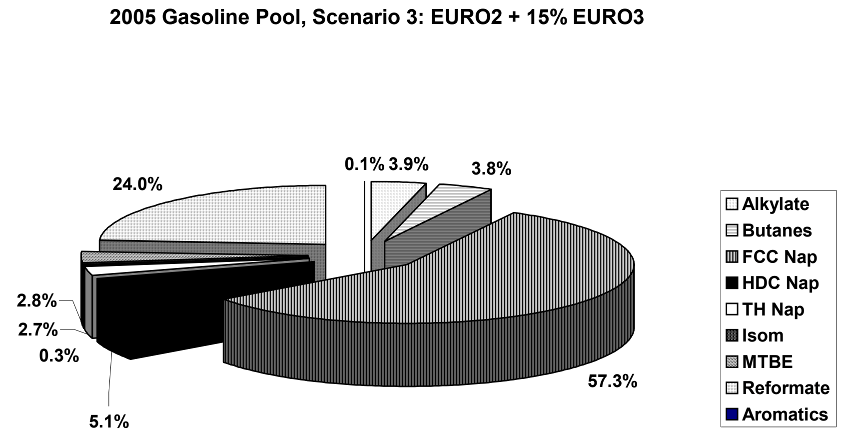
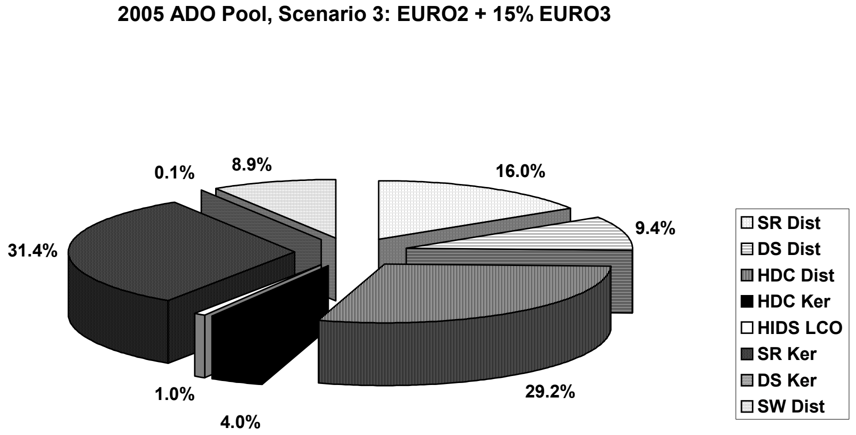


Figure 7



3.3.6. Scenario 4: 2005, EURO3 standards, all China

The following two charts display the blending pools used to create gasoline and diesel under Scenario 4, EURO3 standards country wide in 2005.

Figure 8

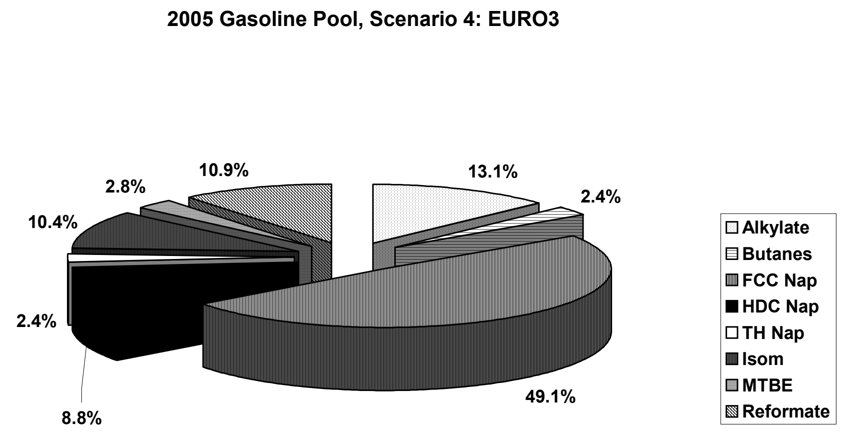
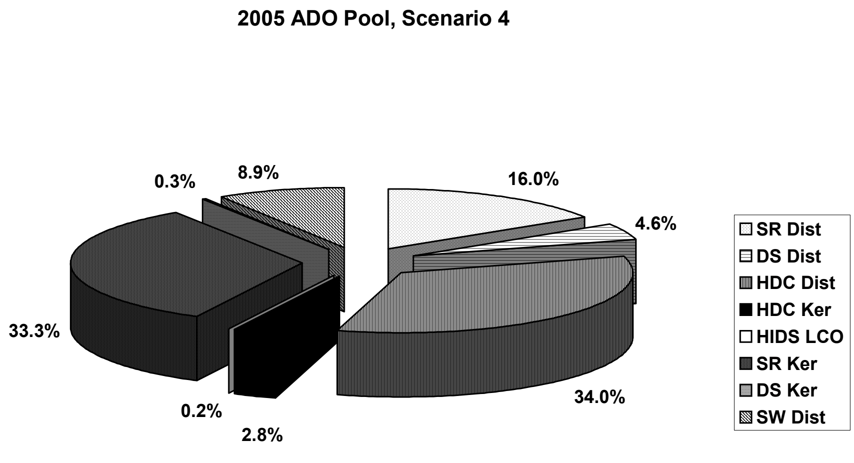


Figure 9



3.3.7. Scenario 5: 2005, EURO2 65% and EURO4 35%

The following figures display blending pools for gasoline and diesel under Scenario 5, 65% EURO 2 fuels and 35% EURO4 fuels.

Figure 10

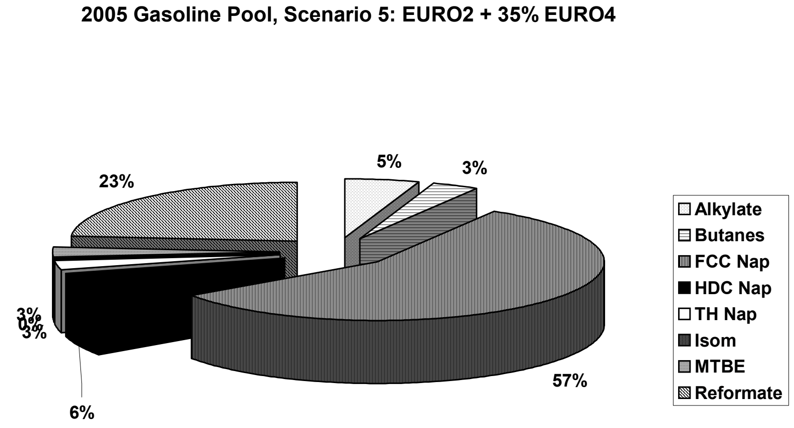
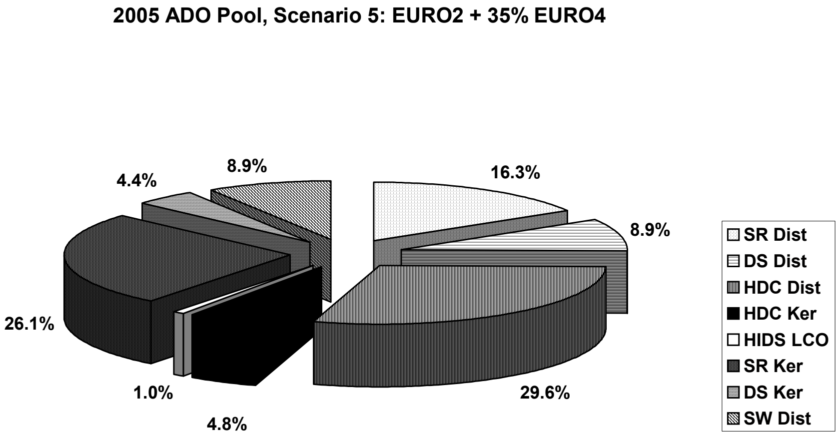


Figure 11



3.3.8. Scenario 6: 2008, EURO3 85% and EURO4 15%

The following charts show blending pools for the 2008 Scenario 6, 85% EURO3 fuels and 15% EURO4 fuels.

Figure 12

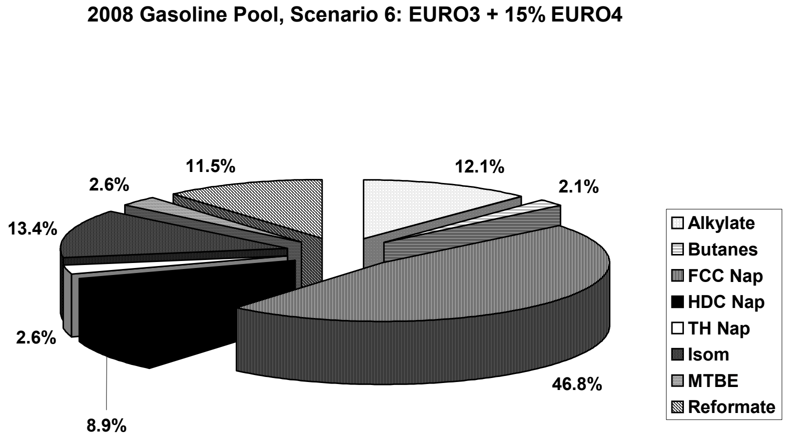
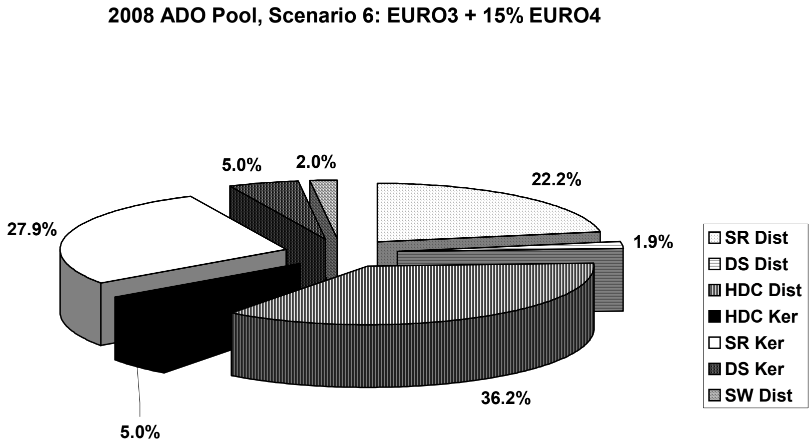


Figure 13



3.3.9. Scenario 7: 2010, EURO3 standards (Base Case)

The following charts present Scenario 7 gasoline and diesel blending pools, EURO3 fuels countrywide in 2010

Figure 14

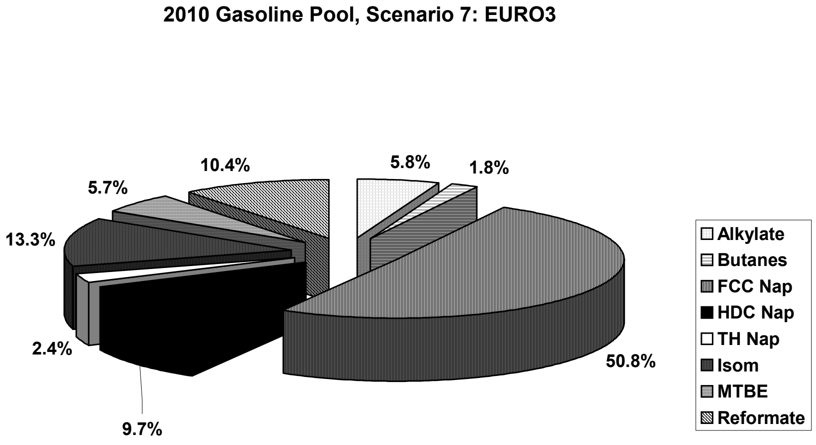
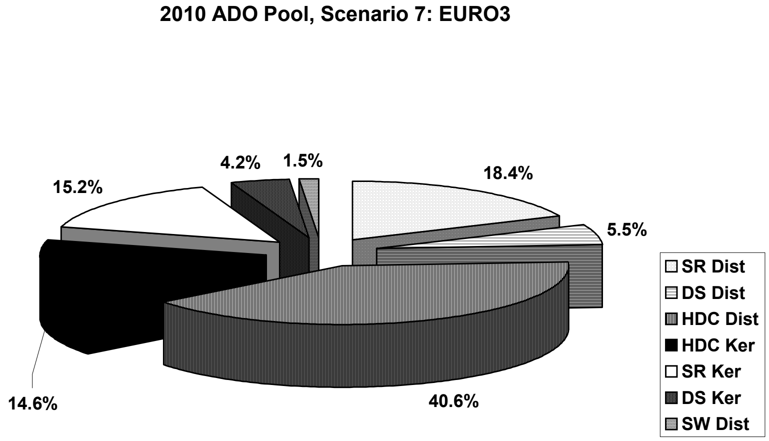


Figure 15



3.3.10. Scenario 8: 2010, EURO3 85% and EURO4 15%

The figures below present the gasoline and diesel blending pools for Scenario 8, 85% EURO3 and 15% EURO4 fuels.

Figure 16

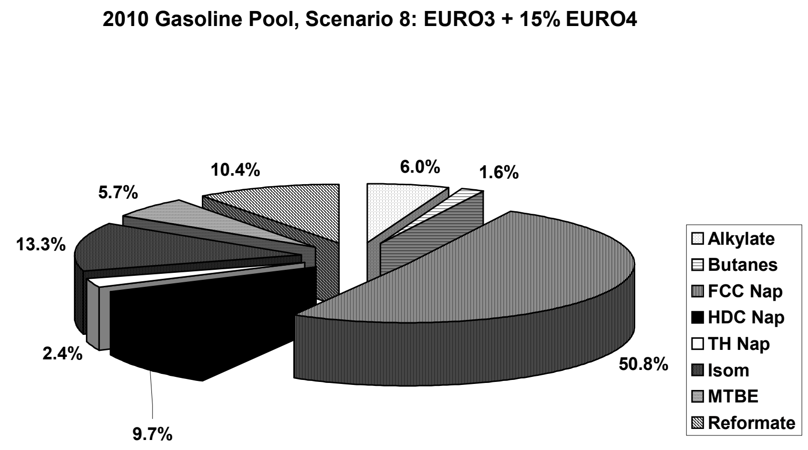
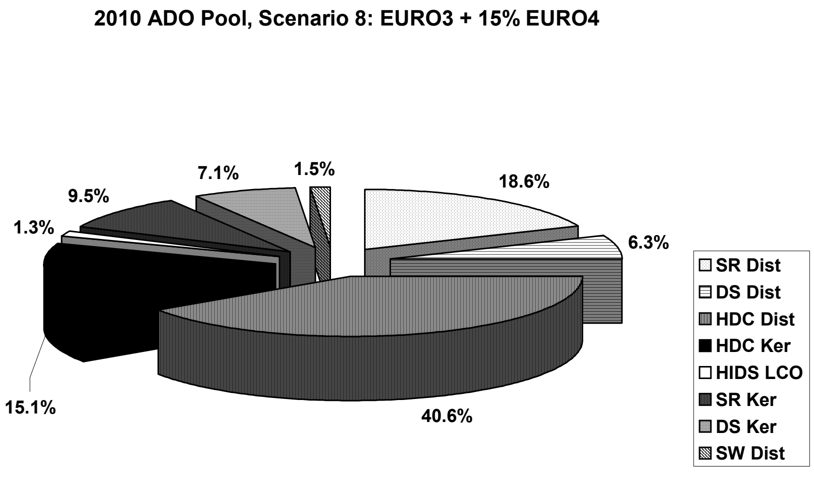


Figure 17



3.3.11. Scenario 9: 2010, EURO3 60% and EURO4 40%

Gasoline and diesel blending pools for Scenario 9 appear in the figures below, 60% EURO3 fuels and 40% EURO4 fuels.

Figure 18

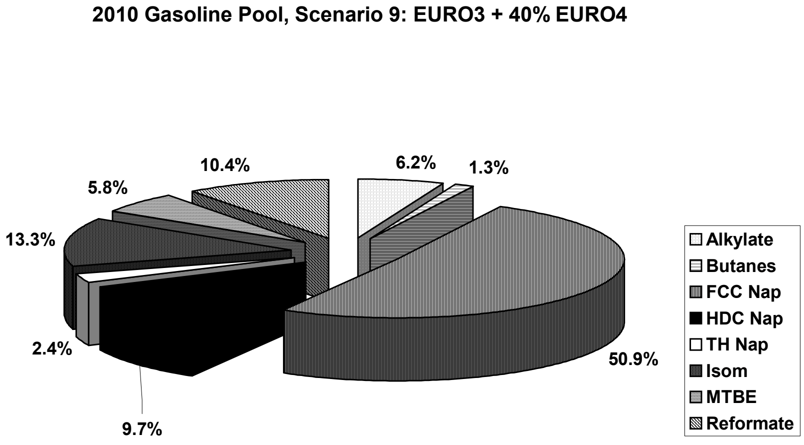
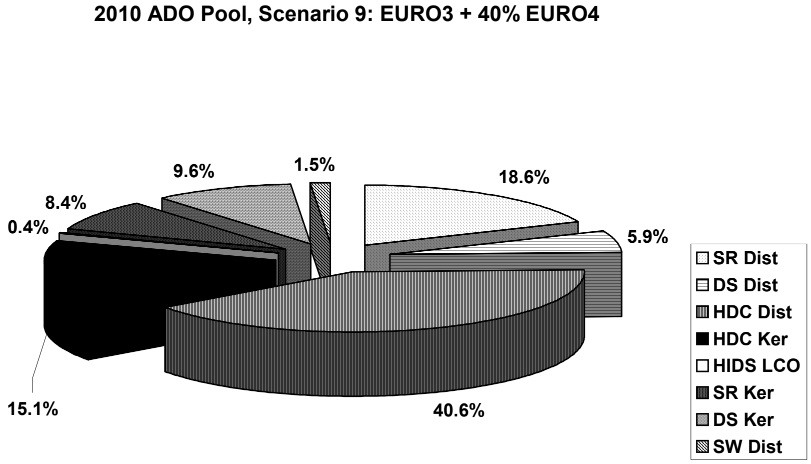


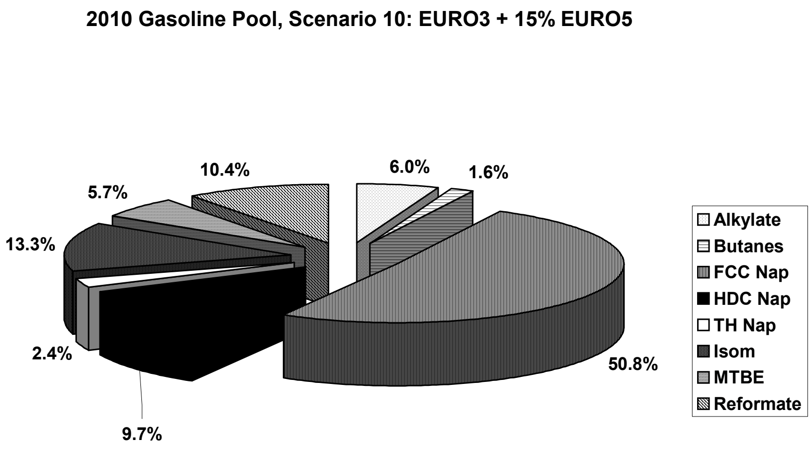
Figure 19



3.3.12. Scenario 10: 2010, EURO3 85% and EURO5 15%

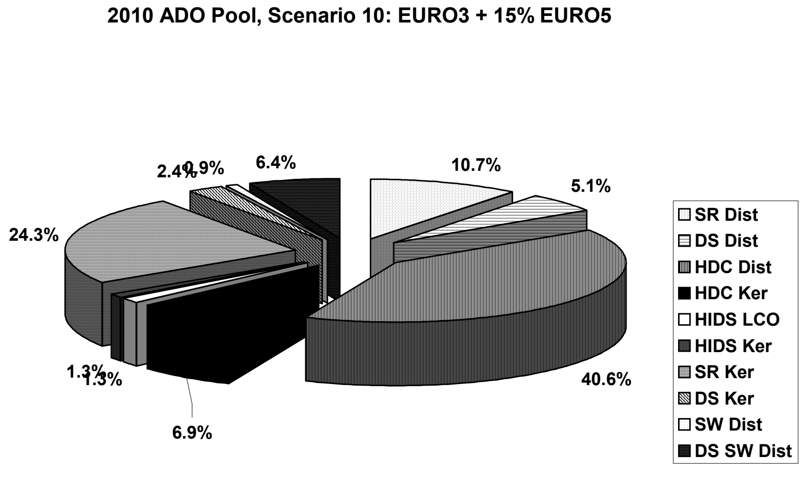
The figures below show gasoline and diesel blending pools for Scenario 10, 85% EURO3 fuels plus 15% EURO5 fuels.

Figure 20



2010 Gasoline Pool, Scenario 10: EURO3 + 15% EURO5

Figure 21



2010 ADO Pool, Scenario 10: EURO3 + 15% EURO5

Table 17 . Summary of Blend Pool by Fuel and Scenario

(% of total finished product pool)

GASOLINE BLENDING POOLS

	2005 Scenario 2	2005 Scenario 3	2005 Scenario 4	2005 Scenario 5	2008 Scenario 6	2010 Scenario 7	2010 Scenario 8	2010 Scenario 9	2010 Scenario 10
Alkylate	0.1%	3.9%	13.1%	5.3%	12.1%	5.8%	6.0%	6.2%	6.0%
Butanes	4.6%	3.8%	2.4%	3.4%	2.1%	1.8%	1.6%	1.3%	1.6%
FCC Nap	62.2%	57.3%	49.1%	56.5%	46.8%	50.8%	50.8%	50.9%	50.8%
HDC Nap	0.0%	5.1%	8.8%	5.6%	8.9%	9.7%	9.7%	9.7%	9.7%
TH Nap	2.7%	2.7%	2.4%	2.6%	2.6%	2.4%	2.4%	2.4%	2.4%
Isom	0.0%	0.3%	10.4%	0.3%	13.4%	13.3%	13.3%	13.3%	13.3%
MTBE	2.8%	2.8%	2.8%	2.8%	2.6%	5.7%	5.7%	5.8%	5.7%
Reformate	27.5%	24.0%	10.9%	23.5%	11.5%	10.4%	10.4%	10.4%	10.4%
Aromatics	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

DIESEL BLENDING POOLS

	2005 Scenario 2	2005 Scenario 3	2005 Scenario 4	2005 Scenario 5	2008 Scenario 6	2010 Scenario 7	2010 Scenario 8	2010 Scenario 9	2010 Scenario 10
SR Dist	16.0%	16.0%	16.0%	16.3%	22.2%	18.4%	18.6%	18.6%	10.7%
DS Dist	10.8%	9.4%	4.6%	8.9%	1.9%	5.5%	6.3%	5.9%	5.1%
HDC Dist	26.0%	29.2%	34.0%	29.6%	36.2%	40.6%	40.6%	40.6%	40.6%
HDC Ker	0.5%	4.0%	2.8%	4.8%	5.0%	14.6%	15.1%	15.1%	6.9%
HIDS LCO	1.0%	1.0%	0.2%	1.0%	0.0%	0.0%	1.3%	0.4%	1.3%
HIDS Ker	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%
SR Ker	36.8%	31.4%	33.3%	26.1%	27.9%	15.2%	9.5%	8.4%	24.3%
DS Ker	0.0%	0.1%	0.3%	4.4%	5.0%	4.2%	7.1%	9.6%	2.4%
SW Dist	8.9%	8.9%	8.9%	8.9%	2.0%	1.5%	1.5%	1.5%	0.9%
DS SW Dist	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.4%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Note: These blending pools are CHREF2 model solution sets and should not be taken as exact "recipes" for reformulated fuels. Blendstock properties will vary.

3.3.13. Reformulating Gasoline and Diesel: Blendstocks and Quality Tradeoffs

We have identified how the Chinese gasoline and diesel blending pools change under the various scenarios. Now we must define the main types of blendstocks and how they relate to the key quality specifications in the scenarios of 2005-2010. For gasoline, there are many quality constraints, including octane, RVP (Reid vapor pressure,) olefins, benzene, aromatics, sulfur, and distillation properties. Blending is a complex operation, with any number of constraints to be met simultaneously. The LP model conducts the blending in its profit-maximization framework. For example, in terms of gasoline blending, alkylate is the only major blendstock that simultaneously meets all quality constraints, but it would be prohibitively expensive to use alkylate as the primary blendstock, since cat cracked naphtha and reformate are far more prevalent in China. This material would have to be exported—an inefficient solution. The model therefore decides how intensively to run all units, blends all available streams until quality constraints are met, and when additional alkylate is required and is cost-effective, the model builds more alkylation capacity. MTBE, as the table shows, satisfies all constraints except for RVP. MTBE also is expensive, however, so the model purchases and blends it only when needed to raise pool octane and dilute the levels of aromatics, olefins and benzene. The model offsets MTBE's slightly higher volatility by blending low-RVP components such as alkylate, reformate, and heavy FCC naphthaTable 18 presents a listing of quality tradeoffs for key gasoline blendstocks.

Table 18

Quality Tradeoffs for Key Gasoline Blendstocks

	[>89.5 (R+M)/2] High Octane?	[< 7 RVP] Low RVP?	[<14 vol %] Low Olefins?	[< 1 vol %] Low Benzene?	[< 35 vol %] Low Aromatics?
Butanes	**YES**	***NO***	**YES**	**YES**	**YES**
Alkylate	**YES**	**YES**	**YES**	**YES**	**YES**
Isopentane	**YES**	***NO***	**YES**	**YES**	**YES**
C6 Isomerate	***NO***	**YES**	**YES**	**YES**	**YES**
Lt FCC Naphtha	**YES**	***NO***	***NO***	***NO***	**YES**
HV FCC Naphtha	***NO***	**YES**	***(Varies)***	**YES**	***NO***
Reformate	**YES**	**YES**	**YES**	***NO***	***NO***
HDC Naphtha	***NO***	***NO***	**YES**	**YES**	**YES**
Thermal Naphtha	***(Varies)***	***(Varies)***	***NO***	***(Varies)***	**YES**
MTBE	**YES**	***NO***	**YES**	**YES**	**YES**
LSR Gasoline	***NO***	***(Varies)***	**YES**	**YES**	**YES**

Notes: LSR=light straight run, HDC=hydrocracked, FCC=cat cracked

Diesel blending is simpler than gasoline blending, though there are many possible blendstocks. The main criteria varying in the scenarios are cetane and sulfur, and to a lesser extent aromatics, density and distillation (generic specifications such as flash point do not vary by scenario and are not discussed here.) In China, the main contributors to the finished automotive diesel pool have been straight-run gasoils and kerosenes, much of which comes from naturally low-sulfur crude. As sulfur standards grow tighter, however, even low-sulfur middle distillates may not comply with the standards. For example, straight-run diesel from Chinese Daqing crude is lower in sulfur than current standards require, but it exceeds the 150-ppm sulfur maximum standard specified by EURO3, so this key blendstock in the current diesel pool will eventually require further treatment. For essentially any middle distillate, however, intensive hydrotreating will improve quality and theoretically can reduce sulfur levels to near zero. Table 19 compares quality tradeoffs for a few key diesel blendstocks. For most conventional hydrotreaters, the sulfur content in the treated diesel is a function of the sulfur level of the feed. Therefore, an extremely high-sulfur straight-run diesel may still violate sulfur constraints even after hydrotreating. High-intensity hydrotreating is more costly, but it removes a larger percentage of the feed sulfur. Hydro-dearomatization is an extremely intensive process that not only can reduce sulfur levels to zero, it also saturates aromatics and hugely improves cetane numbers. Therefore, HDS, HIDS, and HDA middle distillates vary by quality.

Hydrocracking produces the most uniformly high-quality diesel (and kerosene/jet fuel) blendstocks. This is the only conversion process developed to maximize output of high-quality middle distillates; coking and catalytic cracking can produce diesel-range material, but its quality is generally poor. Light cycle oils from cat cracking and thermal gasoils from coking and other thermal processes typically must be hydrotreated before blending into high-quality automotive diesels, or else they must be blended down into industrial or railroad diesel pools.

Table 19

Quality Tradeoffs for Key Diesel Blendstocks

	[> 50 Cetane] High Cetane?	[< 0.05 wt %] Low Sulfur?	[< 0.005 wt %] Ultra-Low Sulfur?	[< 20 vol %] Low Aromatics?
HDC Diesel	YES	YES	YES	YES
Lt. Cycle Oils	*NO*	*NO*	*NO*	*NO*
Thermal Diesel	*NO*	*NO*	*NO*	*NO*
SR Diesel--Arab Lt	YES	*NO*	*NO*	*NO*
SR Diesel--Tapis	YES	YES	*NO*	YES
SR Diesel--Daqing	YES	YES	*NO*	YES
SR Diesel--Cabinda	YES	YES	*NO*	YES
HDS Diesel	YES	YES	*(varies)*	*(varies)*
HIDS Diesel	YES	YES	*(usually)*	*(usually)*
HDA Diesel	YES	YES	YES	YES

Note: HDC=hydrocracked, SR=Straight run, HDS=hydrodesulfurized,
HIDS=high-intensity hydrodesulfurized, HDA=hydrodearomatized

3.3.14. Comparison of Blending Pools

The changes in Chinese gasoline and diesel quality specifications have been shown to have an impact on the types of blendstocks used in creating finished products. Gasoline blending pools have shown more variability than diesel pools in general, because there are more types of blendstocks used and a longer list of quality criteria. In this section, our objective is to explore some of the key trends in product blending and to identify the types of blending tradeoffs Chinese refiners may have to make in the future. While the scenarios are not strictly comparable from 2000 to 2005, 2008 and 2010 (because many other factors vary, such as demand levels, prices, and crude production,) the percentage trends in key gasoline and diesel blendstocks still are illustrative. A few key examples follow.

First, we have noted that butanes are highly volatile, though they tend to be used in gasoline blending for several reasons: they are inexpensive, very high octane, and free of regulated hydrocarbons such as benzene, aromatics, and olefins. We also noted that MTBE is a desirable gasoline blendstock in all areas except that its RVP is slightly high.

EURO 3 gasoline has a slightly tighter RVP constraint than EURO 2 gasoline (8.7 psi vs. 9.0 psi,) and EURO 4 gasoline tightens RVP again to 7.98 RVP. We might hypothesize, therefore, that the switch to EURO 4 (and 5) gasoline would reduce the use of butanes in gasoline. Figure 22 illustrates that this was indeed a CHREF2 model result. As the figure shows, in the year 2000, butanes accounted for over 6% of the gasoline pool, but this level fell to around 3-4% in the 2005 scenarios and fell to below 2% in the scenarios of 2010. The RVP constraint is the main determinant of butane use, and as noted MTBE also has a slightly high RVP. But as gasoline becomes more strictly reformulated, MTBE use in the model also rose—offset in part by the reduction in butane use. In the 2000-2008 scenarios, MTBE accounted for less than 3% of the gasoline pool. By the 2010 scenarios, however, MTBE's contribution to the gasoline pool rose to nearly 6%. This level of usage was calculated as cost-effective by the model in the absence of an oxygen requirement; that is, while some gasoline reformulations require an oxygenate such as MTBE, the EURO standards do not adopt a minimum. They do set a maximum of 2.7% oxygen by weight. The MTBE was purchased by the model solely for its other properties. Because MTBE is relatively expensive, the willingness of the model to purchase the blendstock is indicative of a certain difficulty in producing EURO 3, 4, and 5 spec gasoline.

The EURO 3 gasoline standards also set maximum olefins levels of 18% by volume, an aromatics maximum of 42% by volume, and a maximum benzene content of 1.0% by volume. EURO 4 further reduces olefins to 14% and aromatics to 35% maximum. As the tables on quality tradeoffs noted, reformate and catalytically cracked naphthas are the main source of aromatics and benzene in gasoline. FCC naphthas and coker naphthas are the main source of olefins. We would expect the model to reduce the volumes of reformate and FCC naphtha blended by the time EURO 3 standards are adopted, and to reduce them again when EURO 4 and 5 specifications are adopted. Once again, the model results verify the expectation. As Figure 23 shows, FCC naphtha contributed 63% to the gasoline pool in 2000, and still accounted for 62% of the pool under EURO 2 standards. As EURO 3 and EURO 4 were phased in, however, the share of FCC naphtha fell to around 57%, and fell as low as 49% in the all-EURO 3 scenario. By the 2008-2010 scenarios, FCC naphtha blending has fallen to around 47-51% of the pool.

Figure 22

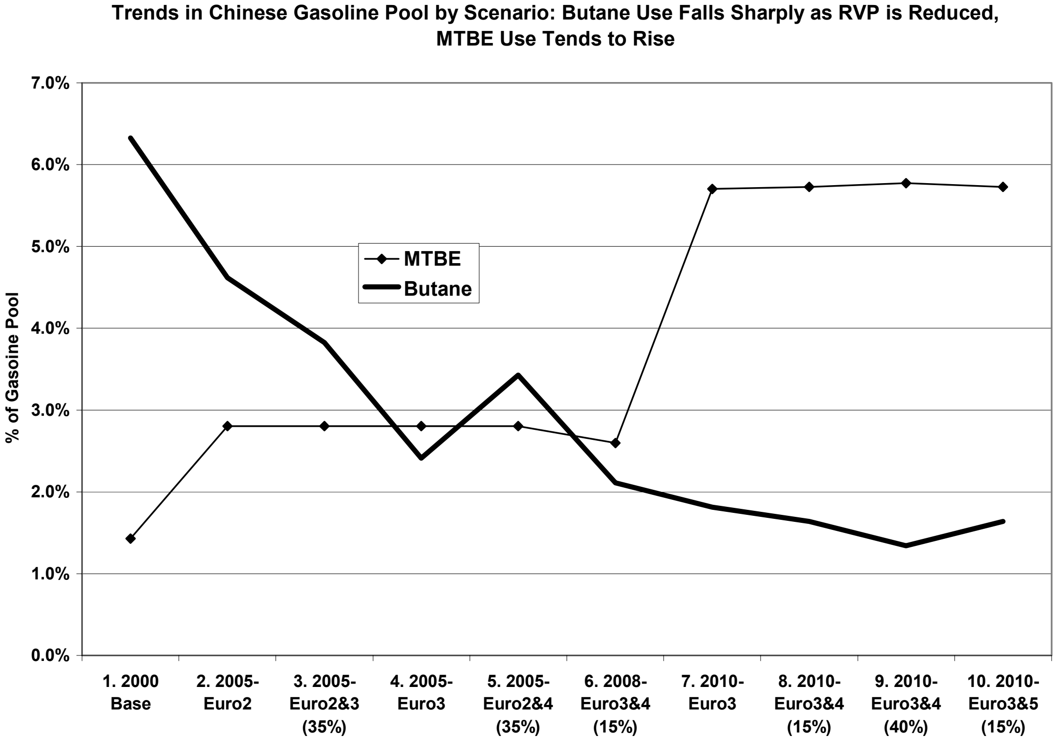
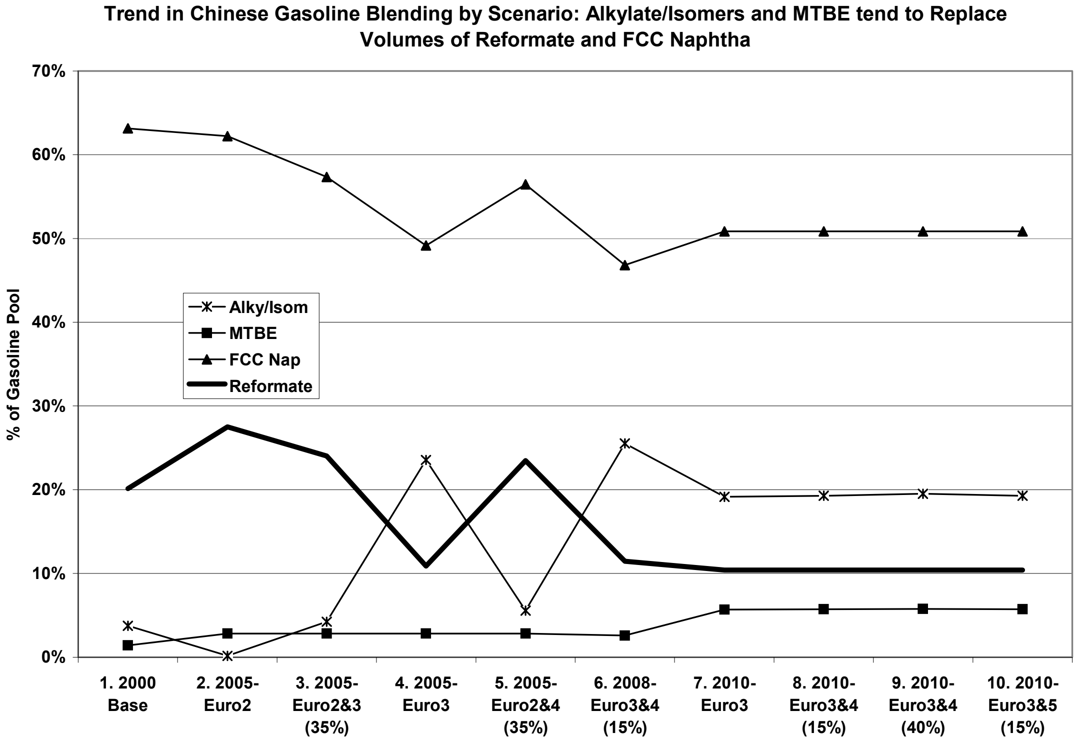


Figure 23

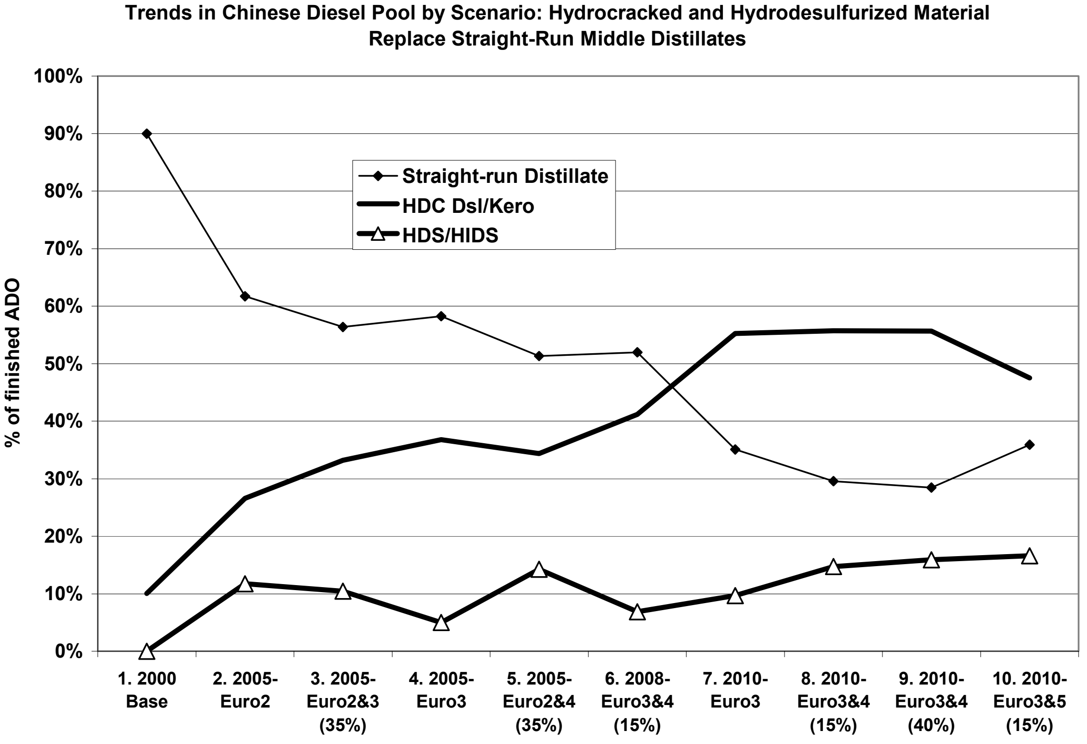


Reformate blending also fell as benzene and aromatics standards were tightened in the model. As the figure shows, in the 2000 and 2005 EURO 2 cases, reformate accounted for 20-27% of the gasoline pool, yet this share fell to just 11% in the all-EURO 3 scenario and fell again to 10.4% in the 2010 scenarios.

With a reduced reliance on the traditional blendstocks (butanes, FCC naphtha, and reformate,) the lost volume of gasoline had to be restored. In the model, MTBE replaced a small part only of the lost volume. As the figure shows, there was major growth in the use of alkylate and isomerate. Alkylate and isomers contributed less than 4% to the gasoline pool in 2000, yet this share grew to 24-25% in some of the 2005-2008 scenarios. By 2010, the share was around 19%, with some of the remainder replaced by additional MTBE.

Diesel blending has been a relatively uncomplicated process in China, in part because domestic crudes easily meet the sulfur standard of 0.2% by weight (2000 ppm.) Yet EURO 2 standards reduce sulfur levels to 500 ppm, EURO 3 standards reduce levels to 350 ppm, EURO 4 standards adopt a strict 50 ppm standard, and EURO 5 standards move the maximum allowable sulfur level down to the very difficult 10 ppm level. Even a low-sulfur crude slate cannot satisfy these requirements. We expected therefore that the model would reduce the blending of straight-run middle distillates into the finished diesel pool. Figure 24 presents the trend in diesel blending. Straight run material accounted for nearly 90% of the diesel pool in 2000, with this share falling to 51-62% in the 2005-2008 scenarios and just 28-36% in the 2010 scenarios. These volumes were replaced primarily by hydrocracked middle distillates, with hydrotreated material also growing in importance. Hydrocracked middle distillates accounted for around 10% of the automotive diesel pool in 2000, 27-37% in the 2005 scenarios, 41% in the 2008 scenario, and in the range of 48% to 56% in the scenarios of 2010. Hydro-desulfurized and high-intensity hydro-desulfurized material accounted for 5-14% of the pool in the 2005-2008 scenarios, with this share growing to 10-17% in the 2010 scenarios. In the near term, it may be possible to expand the role of straight run middle distillates in the total pool via judicious selection of the crude slate. By increasing the purchase of crudes with exceptionally low-sulfur middle distillates, Chinese refiners could postpone the need for capital investment—but this option would not serve as a permanent solution. In the longer term, even low-sulfur crudes will require hydrodesulfurization if the country moves to EURO 4 and EURO 5 standards. Middle distillate sulfur levels of 10-50 ppm are next to impossible to achieve without some sort of sulfur removal treatment.

Figure 24



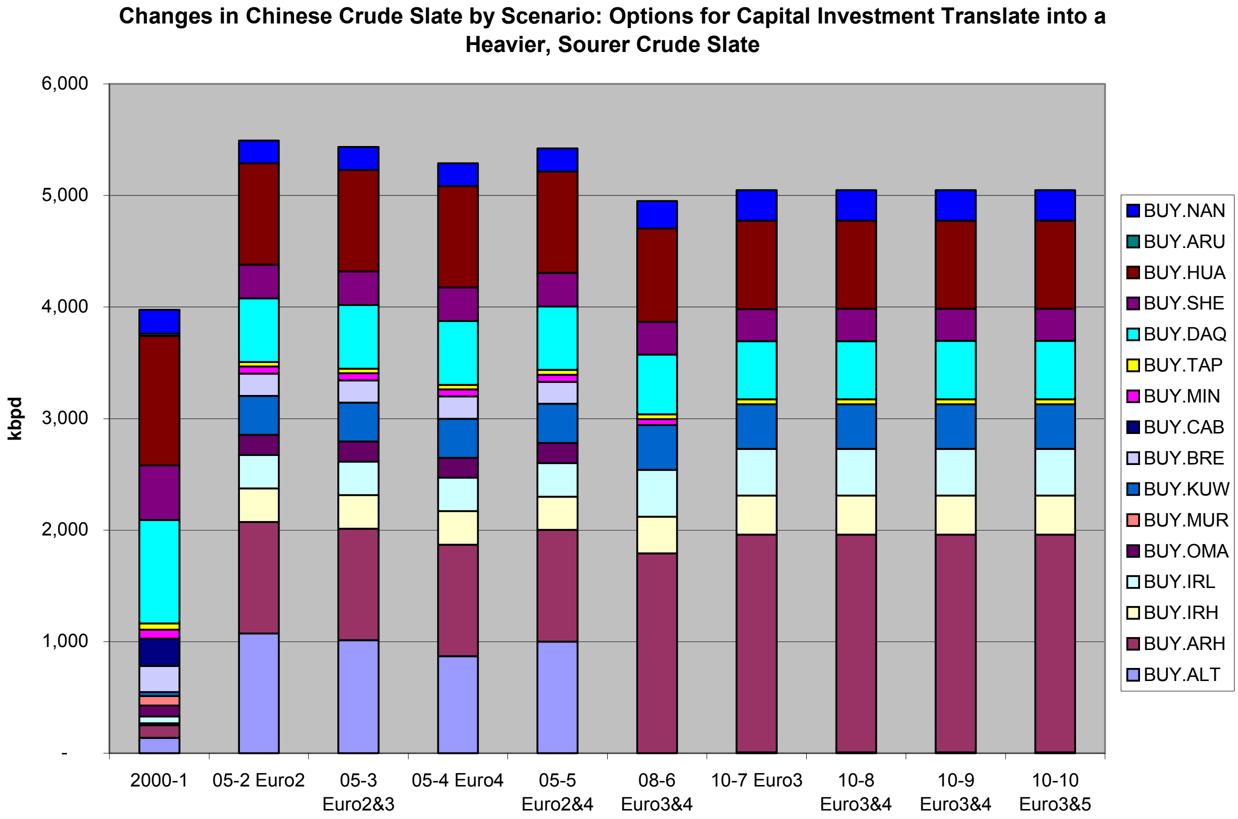
3.3.15. Comparison of Crude Slates

As noted, the Chinese crude slate is low in sulfur on average, and domestic crudes are of generally good quality. Domestic output, however, is limited, and is not expected to be adequate to meet Chinese demand in the future. Already the country imports crude oil, and imports of high-sulfur Middle Eastern crudes are forecast to rise—Middle Eastern crudes are simply too dominant in the international marketplace. As discussed above in the section on pricing, in the model we make an array of crudes available for purchase, with given prices, market availabilities, and transport costs. The model then makes the crude purchase decision. While strategically it will be possible for Chinese refiners to postpone certain sour-crude related investments by purchasing a higher quality crude slate, the model in fact did not select this option, choosing instead to minimize crude purchase costs and build the necessary sulfur removal technologies. There are even indications that the model could have gone further with this type of activity, purchasing even heavier, sourer crudes if the price was low enough.

The China Model has representations of sixteen crude types ranging from high-sulfur, light and heavy Middle Eastern crude, to low-sulfur African, European and Asian crudes, to Chinese domestic crudes and one condensate. While the crudes are given specific names, they may be viewed as crude "types;" that is, "Arab Light" crude may be representative of Arab Light crude plus other similar Middle Eastern light sour crudes. Crudes such as these are abundant in supply, and they typically serve as "swing" crudes, purchased to meet the incremental demand remaining after domestic or proximal resources have been allocated. They may be assumed to be available in unlimited quantities, given practical constraints; i.e., China could theoretically purchase, say, five million barrels per day of swing crudes, but local demand would not warrant such a level, and the model never attempted to purchase abnormally high levels of crude.

Comparing total refinery capacity against actual crude runs, it can be seen that China's crude refinery utilization has actually been quite low—typically 75%-80% in recent years. Crude runs were around 3.7 million bpd in 2000, versus a nameplate crude capacity of around 5.5 mmbpd. As demand grows, however, utilization rates begin to climb in the model simulations. The Model crude slate is detailed in the Figure 25 and Table 20 following. These display how crude purchases by type compared by scenario, and also show how crude purchases generally rose between 2000 and 2005, but then tended to fall between 2005 and 2010.

Figure 25



One of the interesting results concerning the Chinese crude slate selection is that the higher quality, higher priced foreign crudes began to decline, particularly by 2008-2010. These include North Sea Brent, Angolan Cabinda, and Indonesian Minas (though Minas is generally thought of as a Daqing "look-alike" crude.) Malaysian Tapis continued to be purchased. These low-sulfur crudes are available for purchase, but the model opts instead to buy the heavier, sourer Middle Eastern crudes. Even the two higher-quality

Middle Eastern crudes, Murban and Oman, were cut from the slate. This is an important finding, which may seem counter-intuitive. After all, why would the model avoid low-sulfur, high quality crudes when product quality specifications are getting more stringent?

Table 20

Model Purchases of Crude Slate by Scenario

	Scenario:									
	1	2	3	4	5	6	7	8	9	10
	2000	05 Euro2	05 Euro2&3	05 Euro3	05 Euro2&4	08 Euro3&4	10 Euro3	10 Euro3&4	10 Euro3&4	10 Euro3&5
BUY.ALT	138	1,073	1,013	869	1,001		6	7	7	7
BUY.ARH	112	1,000	1,000	1,000	1,000	1,790	1,952	1,952	1,952	1,952
BUY.IRH	17	300	300	300	300	330	350	350	350	350
BUY.IRL	62	300	300	300	300	420	420	420	420	420
BUY.OMA	100	180	180	180	180					
BUY.MUR	83	-	-							
BUY.KUW	37	350	350	350	350	400	400	400	400	400
BUY.BRE	233	200	200	200	200					
BUY.CAB	245		-							
BUY.MIN	80	62	62	62	62	55				
BUY.TAP	56	42	42	42	42	42	42	42	42	42
BUY.DAQ	928	570	570	570	570	536	524	524	524	524
BUY.SHE	489	301	301	301	301	293	288	288	288	288
BUY.HUA	1,160	910	910	910	910	838	790	790	790	790
BUY.ARU	20		-							
BUY.NAN	215	206	206	206	206	247	274	274	274	274
Total Crude	3,974	5,493	5,434	5,289	5,421	4,951	5,047	5,047	5,047	5,047

	2000	05 Euro2	05 Euro2&3	05 Euro3	05 Euro2&4	08 Euro3&4	10 Euro3	10 Euro3&4	10 Euro3&4	10 Euro3&5
ME Sour	366	3,023	2,963	2,819	2,951	2,940	3,129	3,129	3,129	3,129
ME Med	183	180	180	180	180	-	-	-	-	-
Domestic	2,812	1,987	1,987	1,987	1,987	1,914	1,876	1,876	1,876	1,876
AP Sweet	136	104	104	104	104	97	42	42	42	42
Oth Sweet	478	200	200	200	200	-	-	-	-	-
Total	3,974	5,493	5,434	5,289	5,421	4,951	5,047	5,047	5,047	5,047
% ME	14%	58%	58%	57%	58%	59%	62%	62%	62%	62%

Crude Naming Conventions:

Foreign Crudes, Mideast		**Foreign Crudes, AP/Afr/Eur**		**Domestic Crudes**	
BUY.ALT	Arab Light	BUY.BRE	Brent	BUY.DAQ	Daqing
BUY.ARH	Arab Heavy	BUY.CAB	Cabinda	BUY.SHE	Shengli
BUY.IRH	Iran Heavy	BUY.MIN	Minas	BUY.HUA	Huabei
BUY.IRL	Iran Light	BUY.TAP	Tapis	BUY.ARU	Condensate
BUY.OMA	Oman			BUY.NAN	Nanhai Lt
BUY.MUR	Murban				
BUY.KUW	Kuwait				

This result suggests strongly that the most economical course of action will be to rely on capital investment within the country's refining sector to prepare for a future of poorer quality—and thus less expensive—crude oils. It may even be worthwhile to investigate the option of purchasing crudes even heavier and sourer than those presented here. One reason this may also be feasible is discussed in more detail below, but it concerns asphalt production. The crudes best-suited for asphalt production in general are heavy and sour, including some American and Middle Eastern streams not represented in the China model. Asphalt production was never sufficient to meet demand in our scenarios, and asphalt imports were a steady feature in the model results. As additional investments are made in China, a side avenue possibly worth exploring may be the purchase of specific crudes for asphalt (and perhaps lubricating oil) production.

The model's logic appears to be that, since capital investment will be required to meet EURO specifications in any case, the investments should result in a refining industry that will capitalize on raw materials of the lowest possible cost. The specifications eventually grow so exacting that straight-run products from even the highest quality crude oils require additional processing before they can be blended into finished product. For example, a straight-run diesel from a low-sulfur crude may have a sulfur content of 100-400 parts per million (ppm.) This was adequate when sulfur specifications were in the range of 500 (EURO2) to 2000 ppm (current Chinese specification,) but EURO3 standards limit diesel sulfur to 150 ppm, EURO4 to 50 ppm, and EURO5 to an extremely low 10 ppm. In the future, low sulfur straight-run diesels also will require hydrodesulfurization.

As a final side note on crude slate selection, we note that the crude slate here varies from the results provided in the interim report. In the interim findings, Arab Heavy crudes were purchased in unusually large volumes. CPCC commented on this finding, and we agreed that the price differential between Arab Light type crude and Arab Heavy crude was too wide, particularly if China entered the market as a major buyer (this would likely exert upward pressure on the Arab Heavy price.) We narrowed the crude price differentials for this final report. While re-running the model, we also noted a second factor that skewed the model toward heavy crudes: the export value of petroleum coke was too high. It was these two factors (too low an Arab Heavy price and too high a coke price) that prompted the model to purchase Arab Heavy crude, build coking capacity, and export coke.

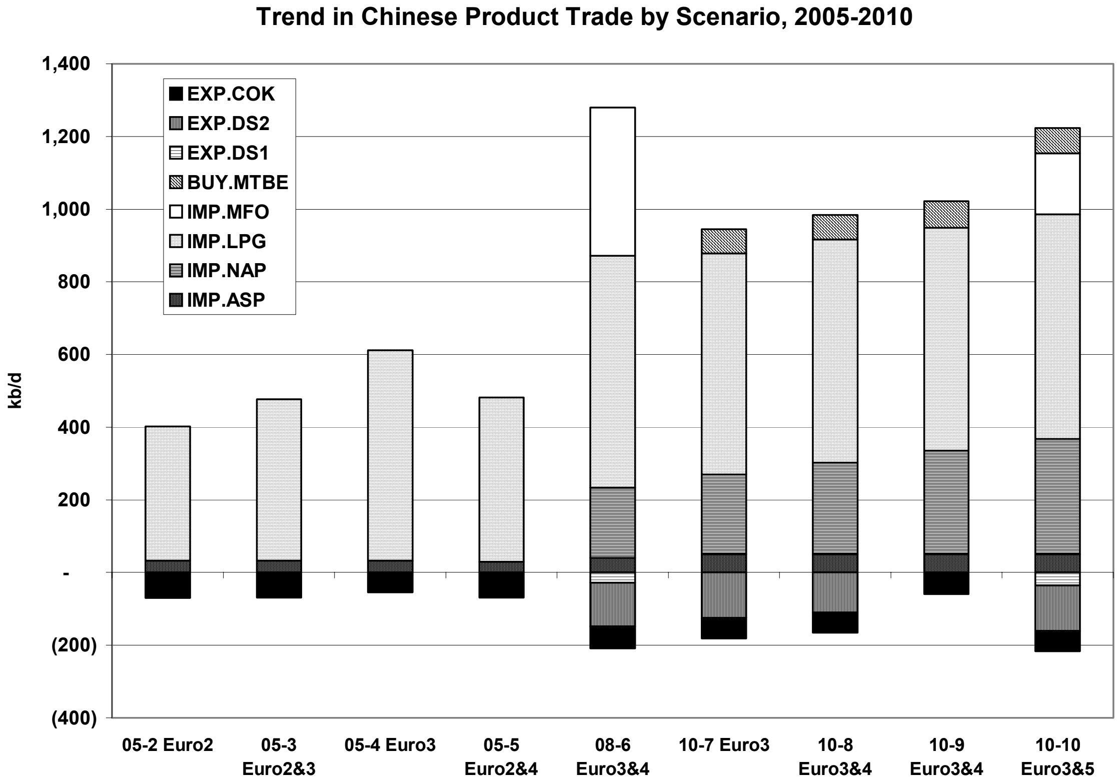
3.3.16. Product Trade Patterns

China already is a significant oil trading country, with many classes of products imported and exported. LPG and fuel oil have been the chief products imported, while exports have been mainly gasoline. The model allows products to be bought and sold on the international market, subject to transport costs and duties. The model also includes a step function for imports, where it is assumed that a certain quantity of EURO standard product is available on the open market for a reasonable cost, but that larger volumes will be imported from more distant sources at a higher transport cost. For the most part, this feature did not come into play in the modeling work; the model chose to build capacity to produce EURO fuels rather than relying upon imports. The main product imports were LPG, naphtha, fuel oil, and asphalt—typically the less expensive, non-specification products. However, it is significant that import volumes of naphtha and LPG grow quite large. If Chinese LPG demand continues to grow as forecast, Chinese LPG imports will surpass even Japan's within the coming five years or so. This may or may not cause supply concerns in China, since comparatively the new LPG volumes used in the transport sector still are quite modest when compared to gasoline and diesel. Additionally, China may become a significant importer of naphtha as a petrochemical feedstock, with import levels rivaling South Korea's.

A steady feature in the model output is petroleum coke exports. However, we made no rigorous forecast of coke demand, or of its use within the refining and industrial sector. "Export" in this case, therefore, may be seen merely as product leaving the refinery but not necessarily being sold on the export market. For our modeling purposes, we did not focus on auxiliary products such as coke, asphalt and lubes. In terms of gasoline and diesel, the model results showed two interesting developments: first, the appearance of MTBE imports by 2010, and second, an exportable surplus of EURO-spec diesel by 2008.

The MTBE purchases reveal that by 2010, even with the capacity additions made, the model has a difficult time producing sufficient high-octane gasoline blendstocks free of "bad actors" such as olefins, benzene and other aromatics. At this point, the model looked outside the refining system for additional gasoline blendstocks. Also as discussed in the section prior on blending pools, the model expanded the use of isomers and alkylate in the gasoline pool, reducing reliance upon butanes, cat cracked naphtha, and reformate.

Figure 26



The diesel exports suggest that China could become a net exporter of middle distillates if capacity additions are large enough to fully meet gasoline demand. In no case did Chinese refining fully meet LPG and naphtha demand, but in all cases the refining system made the investments necessary to produce on-spec (and higher value) gasoline. In the scenarios of 2010, the model imported vast quantities of LPG and naphtha at the light end of the barrel, plus asphalt at the heavy end. Running additional crude barrels served to supplant imports at both ends, plus created an exportable surplus of diesel fuel.

The model results on product trade are presented in Figure 26 above and in Table 21 following.

Table 21

Chinese Product Trade by Model Scenario, 2005-2010

Scenario:	05-2 Euro2	05-3 Euro2&3	05-4 Euro3	05-5 Euro2&4	08-6 Euro3&4	10-7 Euro3	10-8 Euro3&4	10-9 Euro3&4	10-10 Euro3&5
IMP.ASP	33	33	33	30	40	50	50	50	50
IMP.NAP					193	220	252	286	318
IMP.LPG	369	444	579	452	638	608	614	613	618
IMP.MFO					408				168
BUY.MTBE						66	68	73	70
EXP.DS1	-	-	-	-	(28)	-	-	-	(36)
EXP.DS2	-	-	-	-	(120)	(125)	(110)	(3)	(125)
EXP.COK	(70)	(69)	(55)	(69)	(61)	(56)	(56)	(56)	(56)
Total Imports	402	477	612	482	1,280	945	984	1,022	1,223
Total Exports	(70)	(69)	(55)	(69)	(208)	(181)	(166)	(59)	(217)

ASP=asphalt, NAP=naphtha, LPG=liquefied petroleum gas, MFO=medium sulfur fuel oil, MTBE=methyl tertiary butyl ether
DS1=diesel, spec 1, DS2=diesel, spec 2 (varies by scenario,) COK=petroleum coke

3.4. Capital Investment in Chinese Refining: Current Plans and Additional Model Expansions

3.4.1. 2005 Expansions Underway, and Additional Model Expansions by Scenario, 2005, 2008 and 2010

Chinese refiners already are planning for a future of tighter petroleum product specifications, and in fact have made and are making massive investments in the refining sector. Yet a key hypothesis of this study is that the investments made and underway will not be sufficient if large segments of the Chinese market aggressively reformulate gasoline and diesel to EURO 3-5 standards. Therefore, the CHREF2 model was built to allow capital expansion in all key refining technologies. The model also incorporated an advanced diesel-oriented technology, hydro-dearomatization, or HDA, because in the earlier phase of work one of the selected scenarios of 2010 included CARB (California Air Resources Board) specification fuels. CARB diesel strictly limits diesel aromatics. The CARB option was later eliminated in favor of EURO 5, which was considered a more logical continuation of the Chinese specification scenarios. The EURO standards regulate only polycyclic aromatics, and this specification was not binding given the overwhelming reliance on hydrocracking and hydrotreating in future years. HDA technology was therefore not built in the model simulations.

As noted in the section on refinery capacity, a number of expansions are underway that will in part allow China to produce higher quality fuels nationally by 2005. We include the cost of these expansions in our total cost assessment. A summary of the additions to baseline capacity used in the model is shown in Table 23. Of this list, the volume of upgrading capacity is most critical. In none of the 2005 scenarios did the model fully utilize the primary distillation capacity, so it was not a binding constraint, but representing the increase in hydrocracking, for example, was important to insure the model accounted for the increase in volume and, more importantly, product quality that this represented.

A brief guide to the key technologies and abbreviations is provided here for ease of reference (Table 22).

Table 22

Refinery Technology Naming Conventions and Brief Guide

CDU	Crude Distillation Unit
VDU	Vacuum Distillation Unit
HDC	Hydrocracker (converts fuel oil to middle and light distillates)
VBR	Visbreaker (reduces fuel oil viscosity and converts some to lighter products)
NDS	Naphtha Desulfurizer (gasoline-range material desulfurizer)
HDF	Hydrofiner (desulfurizes feed to cracking units)
DCK	Delayed Coker (converts heavy fraction to light and middle distillates plus coke)
HDA	Hydrodearomatization (saturates aromatics in middle distillates, essentially eliminates sulfur)
IC5	Isomerization C5 (creates high octane gasoline blendstocks)
ALK	Alkylation (creates high-octane gasoline blendstocks)
IC4	Isomerization C4 (creates high-octane gasoline blendstocks)
H2	Hydrogen (required for all desulfurizers and hydrocrackers)
LUB	Lubricants (lubricating oil plant)
RDS	Resid Desulfurizer (desulfurizes residual fuel oil, also for RCC feed pre-treatment)
CRF	Catalytic Reformer (creates high-octane, high-aromatics gasoline blendstocks)
HDS	Hydrodesulfurizer (middle distillate desulfurizer)
FCC	Fluid Catalytic Cracker (converts heavy gasoils to light and middle distillates)
RCC	Resid Catalytic Cracker (converts resid to light and middle distillates)
ASP	Asphalt (asphalt unit)
BTX	Aromatics (benzene, toluene, xylene extraction)
MTBE	Methyl tertiary butyl ether

Table 23

Chinese Refinery Investments Underway by 2005

(kb/d)

Model Name	Unit type	KB/D
BLD.CDU	Crude distillation	439.6
BLD.HDC	Hydrocracking	381.6
BLD.VBR	Visbreaking	19.1
BLD.DCK	Delayed Coking	146.6
BLD.RCC	Resid cat cracking	204.5
BLD.IC5	Isomerization	3.0
BLD.LUB	Lubes	5.2
BLD.RDS	Resid desulfurizing	11.4
BLD.ASP	Asphalt	33.9
BLD.CRF	Cat reforming	87.3
BLD.MTBE	MTBE	3.9
BLD.FCC	Fluid cat cracking	9.3
BLD.BTX	Aromatics extraction	19.5
BLD.HDS	Hydrodesulfurization	575.1

When confronted with the new specification scenarios, however, the model built capacity beyond the units already planned. Table 24 shows the units built by type and scenario in the model simulations. In the scenarios of 2005, the model built additional visbreaking, feed hydrofining, hydrogen, alkylation, naphtha desulfurizing, isomerization and lubes, with variations by scenario. For example, the major expansion of isomerization, alkylation, and hydrogen occurred under Scenario 4, where the entire country was assumed to adopt EURO 3 fuels instead of EURO 2 or instead of EURO2 & 3 or EURO 2 & 4 combinations.

Table 24

Chinese Model Refinery Unit Capacity Expansion By Scenario, 2005, 2008, 2010

	Scenario: 05-2 Euro2	05-3 Euro2&3	05-4 Euro3	05-5 Euro2&4	08-6 Euro3&4	10-7 Euro3	10-8 Euro3&4	10-9 Euro3&4	10-10 Euro3&5
BLD.HDC						18.0	17.8	17.4	18.0
BLD.VBR	550.0	550.0	550.0	550.0	307.6				
BLD.NDS	32.8								
BLD.HDF	675.2	652.2	616.5	648.0	476.5	128.1	128.3	128.9	128.3
BLD.DCK						53.2	53.3	53.3	53.3
BLD.RCC						267.7	267.7	267.7	267.7
BLD.IC5			104.2		145.5	152.6	152.6	152.6	152.6
BLD.ALK		11.4	103.0	24.6	102.9	38.1	39.7	42.4	39.7
BLD.H2		129.5	463.8	150.7	696.8	861.5	862.1	863.1	866.5
BLD.LUB	16.3	16.3	16.3	16.3	29.6	39.4	39.4	39.4	39.4
BLD.RDS					560.5	1,100.0	1,100.0	1,100.0	1,100.0

In the model run of the Scenario 6, 2008 EURO 3 & 4, the model again built visbreaking and hydrofining, but shifted its strategy considerably. It built less of these technologies and instead built resid desulfurizing (RDS) and additional hydrogen. RDS not only desulfurizes whole resid, which then makes it suitable for resid cat cracking (RCC), it also serves as a type of "mild hydrocracking," since some of the resid is actually hydrocracked in the intensive desulfurization process. The model also expanded its gasoline output by building around 103 kb/d of alkylation capacity and 145 kb/d of isomerization capacity. As before, it expanded lube oil capacity to keep pace with demand growth.

By 2010, the model strategy shifted once again. The relatively mild visbreaking technology was not selected at all, and priority shifted even more to RDS technology and additional hydrogen. By the 2010 scenarios, the model also built additional conversion capacity in the form of RCC units (the RDS units prepare feed,) plus some additional coking and hydrocracking.

3.4.2. Types of Capital Investment by Scenario

Refinery outputs are jointly produced, meaning that the crude and other feedstocks processed in the various units typically contribute to a wide array of outputs. This has often frustrated economists who would like to be able to theorize on the exact "cost of production" for individual refinery products. We make no pretense of calculating a true "cost of production" for the EURO fuels produced here, but instead we use the model results to apportion capital costs to gasoline and diesel using some simplified rules. Although many refinery technologies contribute to more than one product, some technologies are heavily geared toward gasoline production while others are geared toward middle distillate production.

In our cost estimates, we attribute the cost of alkylation, naphtha desulfurization, catalytic reforming, isomerization, MTBE, and BTX to gasoline alone. Investments in these technologies are shown in Figure 27. We attribute the cost of hydrocracking and hydrodesulfurization to diesel alone. The other technologies are divided between the two, including some of the other sulfur-removal oriented technologies. Sulfur-related investments are shown in Figure 28.

Figure 27

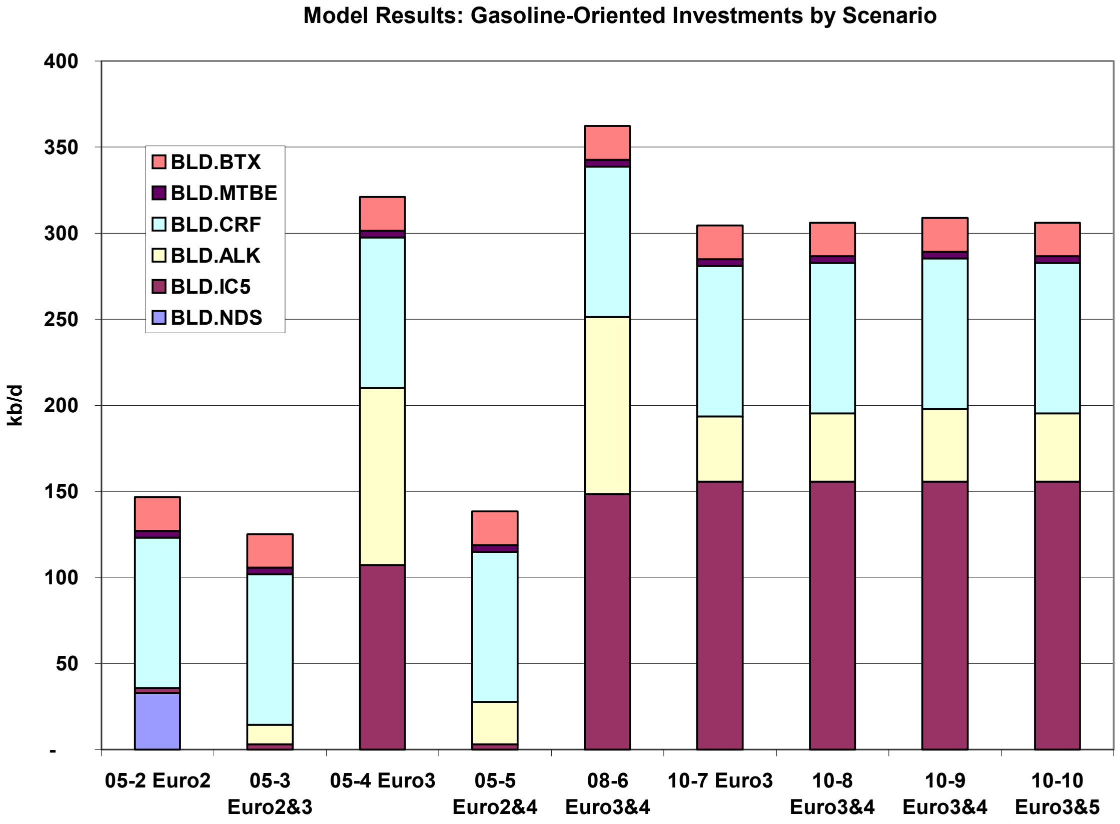
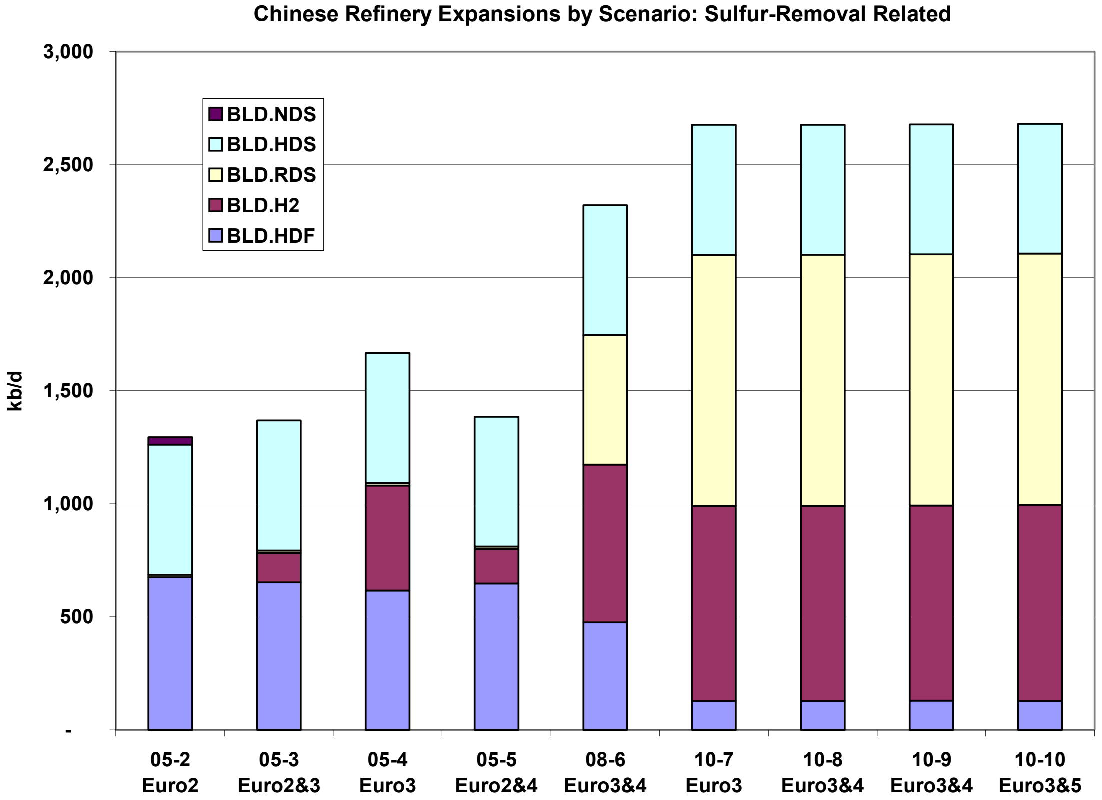

Model Results: Gasoline-Oriented Investments by Scenario
kb/d
400
350
300
250
200
150
100
50
-
BLD.BTX
BLD.MTBE
BLD.CRF
BLD.ALK
BLD.IC5
BLD.NDS
05-2 Euro2
05-3 Euro2&3
05-4 Euro3
05-5 Euro2&4
08-6 Euro3&4
10-7 Euro3
10-8 Euro3&4
10-9 Euro3&4
10-10 Euro3&5

Figure 28



3.4.3. Calculating Capital Costs and Apportioning to Gasoline and Diesel

Table 25 calculates the total daily costs of the capital investments in Chinese refining by scenario, and also calculates a grand total in billions of US dollars. The daily costs are presented in thousands of US dollars. The scenarios of 2005 have capital costs that range from $1.09 to $1.25 million dollars per day, translating into around $0.4 to $0.46 billion per year. The 2008 scenario had a cost of $1.83 million dollars per day, or $0.67 billion per year. The 2010 scenarios had costs quite close together, in the vicinity of $2.33-2.34 million per day, or around $0.85 billion per year.

Table 25

Chinese Refinery Unit Capacity Expansion Costs By Scenario

Daily cost in '000$

	Scenario:								
	05-2 Euro2	05-3 Euro2&3	05-4 Euro3	05-5 Euro2&4	08-6 Euro3&4	10-7 Euro3	10-8 Euro3&4	10-9 Euro3&4	10-10 Euro3&5
BLD.CDU	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4
BLD.HDC	197.7	197.7	197.7	197.7	197.7	207.0	206.9	206.7	207.0
BLD.VBR	91.6	91.6	91.6	91.6	52.6	3.1	3.1	3.1	3.1
BLD.NDS	2.6	-	-	-	-	-	-	-	-
BLD.HDF	317.3	306.5	289.7	304.5	223.9	60.2	60.3	60.6	60.3
BLD.DCK	59.1	59.1	59.1	59.1	59.1	80.5	80.6	80.6	80.6
BLD.HDA	-	-	-	-	-	-	-	-	-
BLD.RCC	82.6	82.6	82.6	82.6	82.6	190.6	190.6	190.6	190.6
BLD.IC5	1.1	1.1	37.8	1.1	52.4	54.9	54.9	54.9	54.9
BLD.ALK	-	8.3	74.7	17.8	74.6	27.6	28.8	30.7	28.8
BLD.IC4	-	-	-	-	-	-	-	-	-
BLD.H2	-	21.5	77.0	25.0	115.7	143.0	143.1	143.3	143.8
BLD.LUB	54.2	54.2	54.2	54.2	87.8	112.5	112.5	112.5	112.5
BLD.RDS	12.1	12.1	12.1	12.1	606.2	1,178.1	1,178.1	1,178.1	1,178.1
BLD.ASP	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
BLD.CRF	43.1	43.1	43.1	43.1	43.1	43.1	43.1	43.1	43.1
BLD.MTBE	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
BLD.FCC	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
BLD.BTX	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
BLD.HDS	164.0	164.0	164.0	164.0	164.0	164.0	164.0	164.0	164.0
Total	1,092.7	1,109.0	1,250.9	1,120.1	1,827.0	2,332.0	2,333.3	2,335.5	2,334.1
Bn $/year	$ 0.399	$ 0.405	$ 0.457	$ 0.409	$ 0.667	$ 0.851	$ 0.852	$ 0.852	$ 0.852

We apportion the costs to gasoline and diesel as follows (Table 26 and Table 27).

Table 26

Chinese Refinery Expansions Apportioned as Gasoline-Oriented Investments:

Daily cost,'000$	Scenario:								
	05-2 Euro2	05-3 Euro2&3	05-4 Euro3	05-5 Euro2&4	08-6 Euro3&4	10-7 Euro3	10-8 Euro3&4	10-9 Euro3&4	10-10 Euro3&5
BLD.CDU	$ 14.9	$ 14.9	$ 14.9	$ 14.9	$ 14.9	$ 14.9	$ 14.9	$ 14.9	$ 14.9
BLD.HDC	$ 9.9	$ 9.9	$ 9.9	$ 9.9	$ 9.9	$ 10.4	$ 10.3	$ 10.3	$ 10.3
BLD.VBR	$ 36.7	$ 36.7	$ 36.7	$ 36.7	$ 21.0	$ 1.2	$ 1.2	$ 1.2	$ 1.2
BLD.NDS	$ 2.6	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
BLD.CRF	$ 43.1	$ 43.1	$ 43.1	$ 43.1	$ 43.1	$ 43.1	$ 43.1	$ 43.1	$ 43.1
BLD.MTBE	$ 2.3	$ 2.3	$ 2.3	$ 2.3	$ 2.3	$ 2.3	$ 2.3	$ 2.3	$ 2.3
BLD.BTX	$ 8.3	$ 8.3	$ 8.3	$ 8.3	$ 8.3	$ 8.3	$ 8.3	$ 8.3	$ 8.3
BLD.RCC	$ 41.3	$ 41.3	$ 41.3	$ 41.3	$ 41.3	$ 95.3	$ 95.3	$ 95.3	$ 95.3
BLD.HDF	$ 158.7	$ 153.3	$ 144.9	$ 152.3	$ 112.0	$ 30.1	$ 30.2	$ 30.3	$ 30.1
BLD.DCK	$ 29.5	$ 29.5	$ 29.5	$ 29.5	$ 29.5	$ 40.3	$ 40.3	$ 40.3	$ 40.3
BLD.IC5	$ 1.1	$ 1.1	$ 37.8	$ 1.1	$ 52.4	$ 54.9	$ 54.9	$ 54.9	$ 54.9
BLD.ALK	$ -	$ 8.3	$ 74.7	$ 17.8	$ 74.6	$ 27.6	$ 28.8	$ 30.7	$ 28.8
BLD.IC4	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
BLD.H2	$ -	$ 6.4	$ 23.1	$ 7.5	$ 34.7	$ 42.9	$ 42.9	$ 43.0	$ 43.2
BLD.RDS	$ 3.6	$ 3.6	$ 3.6	$ 3.6	$ 181.9	$ 353.4	$ 353.4	$ 353.4	$ 353.4
BLD.FCC	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6
Total gasoline	$ 353.6	$ 360.3	$ 471.8	$ 370.0	$ 627.6	$ 726.4	$ 727.7	$ 729.9	$ 727.9
Bn $/year	$ 0.129	$ 0.132	$ 0.172	$ 0.135	$ 0.229	$ 0.265	$ 0.266	$ 0.266	$ 0.266
cents/gal cost	0.844	0.860	1.126	0.883	1.387	1.525	1.528	1.532	1.528

Table 27

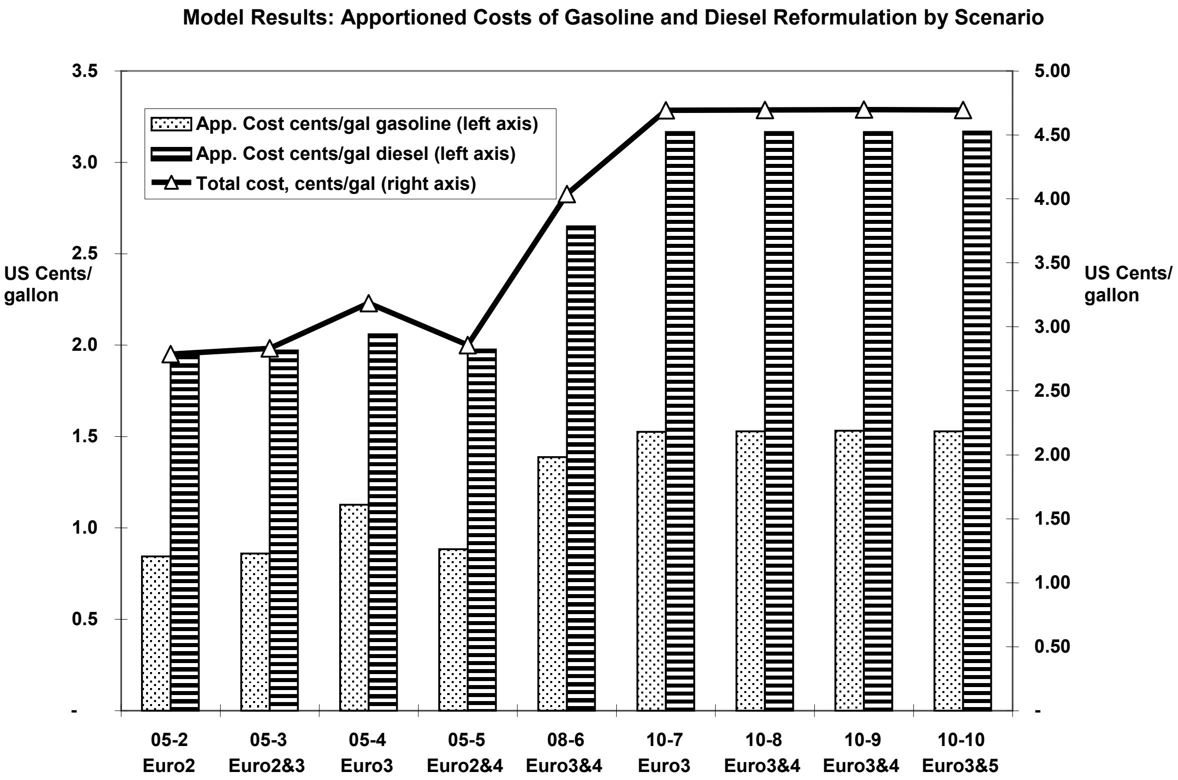
Chinese Refinery Expansions Apportioned as Diesel-Oriented Investments:

Daily cost,'000$

	Scenario:								
	05-2 Euro2	05-3 Euro2&3	05-4 Euro3	05-5 Euro2&4	08-6 Euro3&4	10-7 Euro3	10-8 Euro3&4	10-9 Euro3&4	10-10 Euro3&5
BLD.CDU	$ 22.4	$ 22.4	$ 22.4	$ 22.4	$ 22.4	$ 22.4	$ 22.4	$ 22.4	$ 22.4
BLD.HDC	$ 187.8	$ 187.8	$ 187.8	$ 187.8	$ 187.8	$ 196.7	$ 196.6	$ 196.3	$ 196.6
BLD.VBR	$ 55.0	$ 55.0	$ 55.0	$ 55.0	$ 31.6	$ 1.8	$ 1.8	$ 1.8	$ 1.8
BLD.NDS	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
BLD.HDF	$ 158.7	$ 153.3	$ 144.9	$ 152.3	$ 112.0	$ 30.1	$ 30.2	$ 30.3	$ 30.1
BLD.DCK	$ 29.5	$ 29.5	$ 29.5	$ 29.5	$ 29.5	$ 40.3	$ 40.3	$ 40.3	$ 40.3
BLD.HDA	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
BLD.RCC	$ 41.3	$ 41.3	$ 41.3	$ 41.3	$ 41.3	$ 95.3	$ 95.3	$ 95.3	$ 95.3
BLD.H2	$ -	$ 15.0	$ 53.9	$ 17.5	$ 81.0	$ 100.1	$ 100.2	$ 100.3	$ 100.7
BLD.RDS	$ 8.5	$ 8.5	$ 8.5	$ 8.5	$ 424.4	$ 824.7	$ 824.7	$ 824.7	$ 824.7
BLD.HDS	$ 164.0	$ 164.0	$ 164.0	$ 164.0	$ 164.0	$ 164.0	$ 164.0	$ 164.0	$ 164.0
BLD.FCC	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6	$ 1.6
Total diesel	$ 668.8	$ 678.4	$ 708.8	$ 679.9	$ 1,095.5	$ 1,477.0	$ 1,477.0	$ 1,477.1	$ 1,477.6
Bn $/year	$ 0.244	$ 0.248	$ 0.259	$ 0.248	$ 0.400	$ 0.539	$ 0.539	$ 0.539	$ 0.539
cents/gal cost	1.943	1.971	2.060	1.975	2.650	3.166	3.167	3.167	3.168
Total	$ 1,022.4	$ 1,038.7	$ 1,180.6	$ 1,049.8	$ 1,723.1	$ 2,203.4	$ 2,204.7	$ 2,206.9	$ 2,205.5

Notes: “Total” is gasoline and diesel apportioned costs combined, in thousand dollars per day. Totals may not sum owing to exclusion of certain investment costs in lubricants and asphalt.

Figure 29



By apportioning the capital costs across gasoline and diesel, we derive a per-gallon cost associated with each scenario. For these calculations, we exclude investments in auxiliary products such as lubes and asphalt. The summary of these per-gallon costs is presented in

Figure 29. In the year 2005, the least-expensive option was Scenario 2, all EURO 2 fuels, with an additional gasoline cost of 0.844 cents per gallon. The most expensive option was Scenario 4,all EURO 3 fuels, with a per-gallon additional cost of 1.126 cents/gallon. Scenario 6 of 2008 (EURO 3 and 4 fuels) added 1.387 cents per gallon to the cost of gasoline. Costs under the 2010 scenarios were very close, with Scenario 7 (all EURO 3) the least costly at 1.525 cents/gallon and Scenario 9 (EURO 3 plus 40% EURO 4) the most costly, adding an additional 1.532 cents/gallon to the cost of gasoline.

Diesel reformulation cost roughly twice as much as gasoline reformulation. In our scenarios of 2005, the least expensive option was again Scenario 2, all EURO 2, which added 1.943 cents/gallon to the cost of diesel. The most expensive option was again Scenario 4, which added 2.06 cents/gallon. Scenario 6 (year 2008) had an additional diesel cost of 2.65 cents/gallon. In the scenarios of 2010, once again the costs were very similar, in the vicinity of 3.166-3.168 cents/gallon for all scenarios.

4. Conclusions

The costs we calculate for reformulating Chinese gasoline and diesel to EURO standards ranges from 2.8 to 3.2 cents per gallon inclusive in 2005, 4.04 cents per gallon in 2008 and around 4.7 cents per gallon in 2010. By European and US standards, these costs are well within acceptable parameters, but we also must acknowledge that per-capita GDP is substantially lower in China than in the developed OECD countries. Again, these costs are based on equipment expansion costs and may be 25-50% higher if offsites, labor and other costs are included.

Given China's well-developed refinery base, the model shows that it would be least expensive for China to follow the "US Gulf Coast" model of investing in significant upgrading and hydrotreating capacity to allow the processing of the cheaper and lower quality crudes available in the market. Indeed, it is likely that the refinery configuration developed in the 2005 and 2010 scenarios would allow the processing of even heavier and lower quality—and cheaper—crude oils than the slate offered in the model. Compared to China's current situation, however, increasing product quality, and particularly reducing allowable sulfur content, will require significant investment in pretreatment units, either feed hydrofining units as was the focus of the 2005 results, or resid desulfurization units in the 2010 scenarios.

In general, mixed standards in which the major urban areas adopted stricter standards that the rest of the country were somewhat cheaper to achieve than a single standard nationwide. This is particularly pronounced in the 2005 results, in which achieving Euro 3 or Euro 4 standards in the major urban areas representing 35% of total demand was some $50 million a year cheaper than going to Euro 3 standards nationwide. By 2010, however, the need for new capacity to achieve much higher product quality and to supply the additional demand reduces these differences. The costs of achieving Euro 3 standards nationwide in 2010 barely differs from the costs of implementing Euro 4 (35%) or Euro 5 (15%) while the rest of the country met Euro 3 standards.

As mentioned earlier, the value of modeling exercises such as this one is in comparing scenario results to each other instead of in forecasting of exact investment directions or costs. Moreover, the model seeks the least-costly way to achieve the demand and quality requirements of each scenario, but alternatives do exist. Given numerous competing investment requirements that the Chinese oil companies face (particularly in expanding petrochemical production), it is possible to defer some of the near-term capital equipment investment in refining by judiciously selecting a slate of higher quality import crudes, taking advantage of the quality of the raw material instead of the capacity to upgrade lower-quality feed. Although this may reduce the equipment expenditures in the near term, it is likely that total system costs (borne by different entities, including consumers) would be higher than that described in the scenario results.

Aside from the volume and composition of the crude slate, the general product trade pattern does not shift substantially as a result of the various upgrading scenarios. Currently, China is highly import-dependent on LPG and fuel oil, and the high levels of LPG imports continues in all future scenarios. Similarly, until recently, China required supplemental imports of naphtha for its petrochemical industry; as demand for feedstock continues to grow strongly, imports of naphtha appear again in the 2010 scenarios. The only major shift in trading patterns is a moderate volume of diesel exports in the 2010 scenarios. Although China has been a large importer of diesel fuel in the past, the types of upgrading units necessary for improving product quality (such as hydrocracking) also increase product yields for diesel. Nonetheless, at around 125,000 b/d, these export volumes are not very large.

Improving Transport Fuel Quality in China: Implications for the Refining Sector: Addendum 1

Supplemental Scenarios 11 and 12
September 2002

Trans-Energy Research Associates, Seattle, WA
Lawrence Berkeley National Laboratory, Berkeley, CA

Table of Contents

1. Background

Overview of the Main Study

The main study cited in this addendum is *Improving Transport Fuel Quality in China: Implications for the Refining Sector*, May 2002, funded by the Energy Foundation. Trans-Energy Research Associates, Inc. and Lawrence Berkeley Laboratory prepared the report, with technical assistance from the China Petrochemical Consulting Corporation. To provide a brief background, the larger study provides a detailed look at China's oil market, the refining industry, product quality and the market for transport fuels. China has plans to harmonize its gasoline and diesel fuel quality specifications with European (EURO) standards, generally lagging by a few years the European adoption schedule. The EF study investigates the question, what are China's refining options in light of a future of changing gasoline and diesel quality specifications?

Despite an ambitious refinery expansion program during the 1990s, a major hypothesis of the study was that the Chinese refining industry would be unable to fully meet Chinese demand for a full output slate of EURO type fuels, particularly as demand continues to grow. Part of our goal with this work is to identify the hydrocarbon processing technologies needed and the levels of investment that will be required under a set of future scenarios wherein gasoline and diesel specifications are successively tightened. Because refinery expansion plans already are underway, there may be opportunities to plan modernization in phases, or to jointly plan units so as to achieve advantageous feedstock relationships, or to plan larger units that enjoy economies of scale. We explore the issue of how the Chinese refining industry will adapt to change, how it might grow and invest, and how much it might cost to produce the new fuels.

The main analytical methodology used was a custom-built linear program (LP) model of the Chinese refining system. (The methodology is described in the main study, and the discussion is not replicated here.) The model, abbreviated a CHREF2, was then used to investigate refinery behavior under a range of scenarios for the years 2005, 2008, and 2010. The model simulated the full range of activities:

1. Crude slate selection, purchase and transport
2. Other feedstock and blendstock use
3. Purchase and use of consumables such as power, water, catalysts
4. Refinery process unit utilization and all intermediate flows
5. Product blending to quality specifications
6. Satisfaction of domestic demand
7. Product import and export

The scenario analysis involved setting levels of demand and quality specifications for each scenario, originally including four of 2005, one of 2008, and four of 2010. The main variables were demand levels by product type and product quality (EURO2, EURO3, EURO4, and EURO5 fuels.) For example, Scenario 5 specifies 65% EURO2 fuel plus 35% EURO4 fuel in the year 2005. The 35% volume is used to approximate demand in major urban areas. These combination scenarios assume that the metropolitan areas adopt more rigorous fuel standards more quickly than rural areas. The model scenarios are summarized in the table following.

Table 1. LP Model Scenarios Of Chinese Gasoline and Diesel Quality

Scenario Number	1. Base 2000 Actual	2 2005 Base (Euro 2)	3 2005 Euro2 + 35% Euro 3	4 2005 Euro3	5 2005 Euro2 + 35% Euro 4	6 2008 Euro3 + 15% Euro4	7 2010 Euro3	8 2010 Euro3 + 15% Euro4	9 2010 Euro3 + 40% Euro4	10 2010 Euro3 + 15% Euro5	*NEW* 11 2010 Euro 4	*NEW* 12 2010 Euro 5
90, 93, and 97 Octane												
RVP psi max		9	9	8.70	7.98	8.70	8.70	8.70	7.98	7.98	7.98	7.98
Sulfur ppm max	1000/800	500	500	150	50	150	150	150	50	10	50	10
Olefins vol% max	35	na	na	18	14	18	18	18	14	14	14	14
Aromatics vol% max	40	na	na	42	35	42	42	42	35	35	35	35
Benzene vol% max	25	5	5	1	1	1	1	1	1	1	1	1
Oxygen wt% min/max	2.7			0/2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7	0/2.7
Automotive Diesel												
Cetane no.	45	49	49	51	55	51	51	51	55	55	55	55
Sulfur ppm max	2000	500	500	350	50	350	350	350	50	10	50	10
Polycyclic aroms %				11	4	11	11	11	4	4	4	4
T95 %		370	370	350	340	350	350	350	340	340	340	340
Density (at 15degC)		820-860	820-860	845 max	845 max	845 max	845 max	845 max	845 max	845 max	845 max	845 max

Note: the mixed scenarios using a percentage of an alternative specification will be based on the percent of demand in the 12 SEPA pilot cities.

Purpose of the Addendum to the Main Study

In July 2002, the Energy Foundation hosted in Beijing a seminar on fuel sulfur levels. The authors presented the results of the main study at the seminar, which included participants from government, academia, and industry. One of the suggestions was that the model be used to analyze two additional scenarios of 2010: Scenario 11, where the entire country adopted EURO4 standards, and Scenario 12, where China adopted EURO5 standards. The Energy Foundation approved the additional work, which was carried out by Trans-Energy Research Associates using the existing model structure. These two new scenarios are also presented in the table. This addendum provides the results of the new scenarios. For ease of comparison, a number of the key tables and charts from the main study are replicated here with the new scenarios appended. In this respect, the addendum may also serve as a brief summary of the overall study results, minus the background data and discussion. Readers interested in additional details may peruse the full study as needed.

One of the findings of the study was that the combination scenarios (i.e., those that adopted stricter standards for 35-40% of the Chinese market and left the rest of the country at more relaxed standards) were generally less expensive to achieve, as might logically be expected. However, the cost differentials were not always extremely large. Additionally, implementing a dual-standard program in China would have its own difficulties. For example, a vehicle designed for EURO4 fuel might purchase EURO2 fuel in the countryside, potentially damaging onboard emission control equipment. The new scenarios adopt aggressive fuel quality standards countrywide by the year 2010, obviating these problems. One hypothesis behind the new scenarios was that, since the main study revealed that a great deal of refinery investment would be needed in all cases, the incremental cost of adopting the more rigorous countrywide standards might not be excessive.

2. Scenario 11 and 12 Results and Comparison with Other Scenarios

Gasoline and Diesel Blending Pools

The CHREF2 model blends literally hundreds of possible blendstocks into finished products, choosing the optimum mixes to meet quality criteria. Blending tradeoffs were discussed in the main study, but in general the model selects the best blend for producing fuels that simultaneously satisfy quality objectives such as octane, RVP, aromatics and olefins levels for gasoline and cetane and sulfur levels for diesel. Note that the model solutions are not to be taken as an exact "recipes" for reformulated fuels. The blendstock properties will vary from refinery to refinery, for example. These are the model's blending pools. Table 2 summarizes the blending pools for the scenarios, including the new scenarios of 2010.

Table 2.

Comparison of Gasoline and Diesel Blending Pools by Scenario, Scenarios 1-12
(% of total finished product pool)

New Scenarios:

GASOLINE BLENDING POOLS

	2005	2005	2005	2005	2008	2010	2010	2010	2010	*2010*	*2010*
	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	*Scenario 11*	*Scenario 12*
Alkylate	0.1%	3.9%	13.1%	5.3%	12.1%	5.8%	6.0%	6.2%	6.0%	6.6%	6.7%
Butanes	4.6%	3.8%	2.4%	3.4%	2.1%	1.8%	1.6%	1.3%	1.6%	0.6%	0.6%
FCC Nap	62.2%	57.3%	49.1%	56.5%	46.8%	50.8%	50.8%	50.9%	50.8%	49.6%	49.6%
HDC Nap	0.0%	5.1%	8.8%	5.6%	8.9%	9.7%	9.7%	9.7%	9.7%	10.7%	10.5%
TH Nap	2.7%	2.7%	2.4%	2.6%	2.6%	2.4%	2.4%	2.4%	2.4%	2.5%	2.5%
Isom	0.0%	0.3%	10.4%	0.3%	13.4%	13.3%	13.3%	13.3%	13.3%	13.1%	13.4%
MTBE	2.8%	2.8%	2.8%	2.8%	2.6%	5.7%	5.7%	5.8%	5.7%	6.1%	6.0%
Reformate	27.5%	24.0%	10.9%	23.5%	11.5%	10.4%	10.4%	10.4%	10.4%	10.7%	10.7%
Aromatics	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

DIESEL BLENDING POOLS

	2005	2005	2005	2005	2008	2010	2010	2010	2010	*2010*	*2010*
	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	*Scenario 11*	*Scenario 12*
SR Dist	16.0%	16.0%	16.0%	16.3%	22.2%	18.4%	18.6%	18.6%	10.7%	4.5%	0.0%
DS Dist	10.8%	9.4%	4.6%	8.9%	1.9%	5.5%	6.3%	5.9%	5.1%	17.0%	0.0%
HDC Dist	26.0%	29.2%	34.0%	29.6%	36.2%	40.6%	40.6%	40.6%	40.6%	41.7%	22.7%
HDC Ker	0.5%	4.0%	2.8%	4.8%	5.0%	14.6%	15.1%	15.1%	6.9%	14.3%	3.3%
HIDS LCO	1.0%	1.0%	0.2%	1.0%	0.0%	0.0%	1.3%	0.4%	1.3%	0.0%	11.0%
HIDS Ker	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%	6.8%	0.0%
SR Ker	36.8%	31.4%	33.3%	26.1%	27.9%	15.2%	9.5%	8.4%	24.3%	9.6%	1.3%
DS Ker	0.0%	0.1%	0.3%	4.4%	5.0%	4.2%	7.1%	9.6%	2.4%	2.6%	19.5%
SW Dist	8.9%	8.9%	8.9%	8.9%	2.0%	1.5%	1.5%	1.5%	0.9%	0.7%	0.0%
DS SW Dist	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.4%	1.5%	10.6%
HIDS SW Dist										1.3%	0.0%
HIDS THLGO										0.1%	0.0%
HDA Dist											10.7%
HDA Ker											9.6%
HDA THLGO											11.3%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Note: These blending pools are CHREF2 model solution sets and should not be taken as exact "recipes" for reformulated fuels. Blendstock properties will vary.

The gasoline pools for scenarios 11 and 12 differed mainly in the slightly higher reliance on MTBE, alkylate, and hydrocracked naphtha (HDC naphtha) at the expense of butanes and FCC naphtha. Diesel blending was considerably more complex, however, with the addition of new blendstocks from hydrodearomatization (HDA) technologies. For EURO5 diesel, conventional diesel hydrotreating was no longer sufficient. No straight-run diesel was blended, and very little straight-run kerosene was used. Most blendstocks were high-intensity desulfurized streams, hydrocracked streams, or the new HDA streams.

Scenario 11, 2010 All EURO4 Fuels Blending Pools

Figure 1

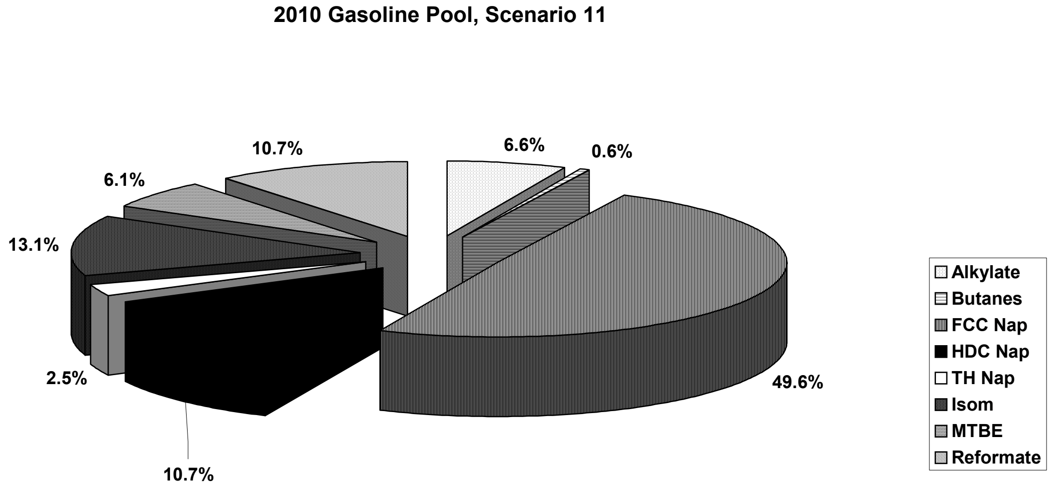
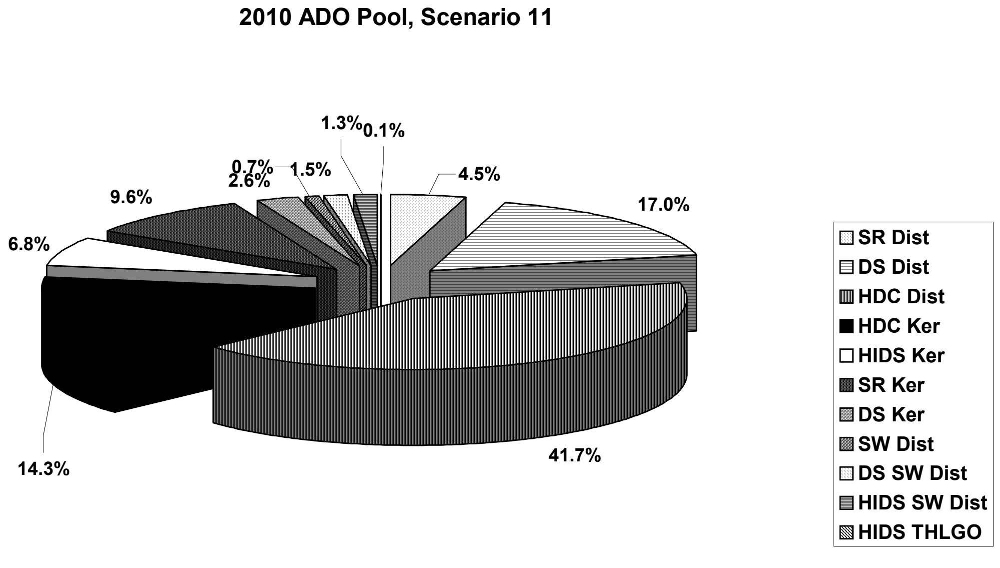


Figure 2



Scenario 12, 2010 All EURO5 Fuels Blending Pools

Figure 3

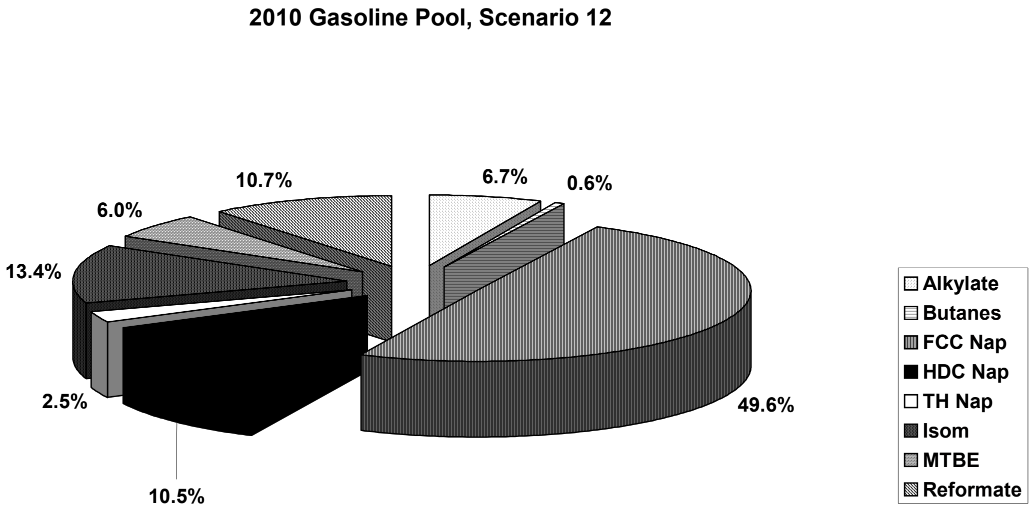
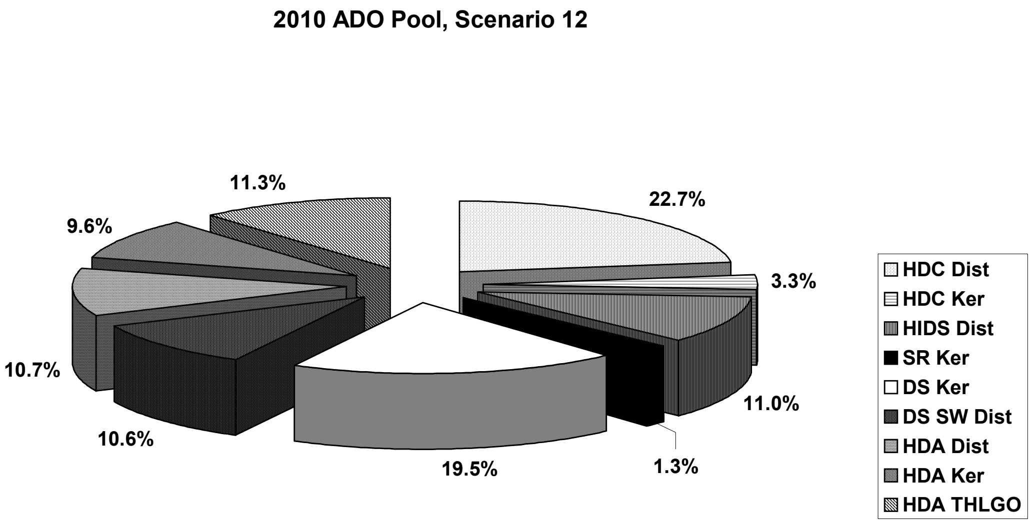


Figure 4



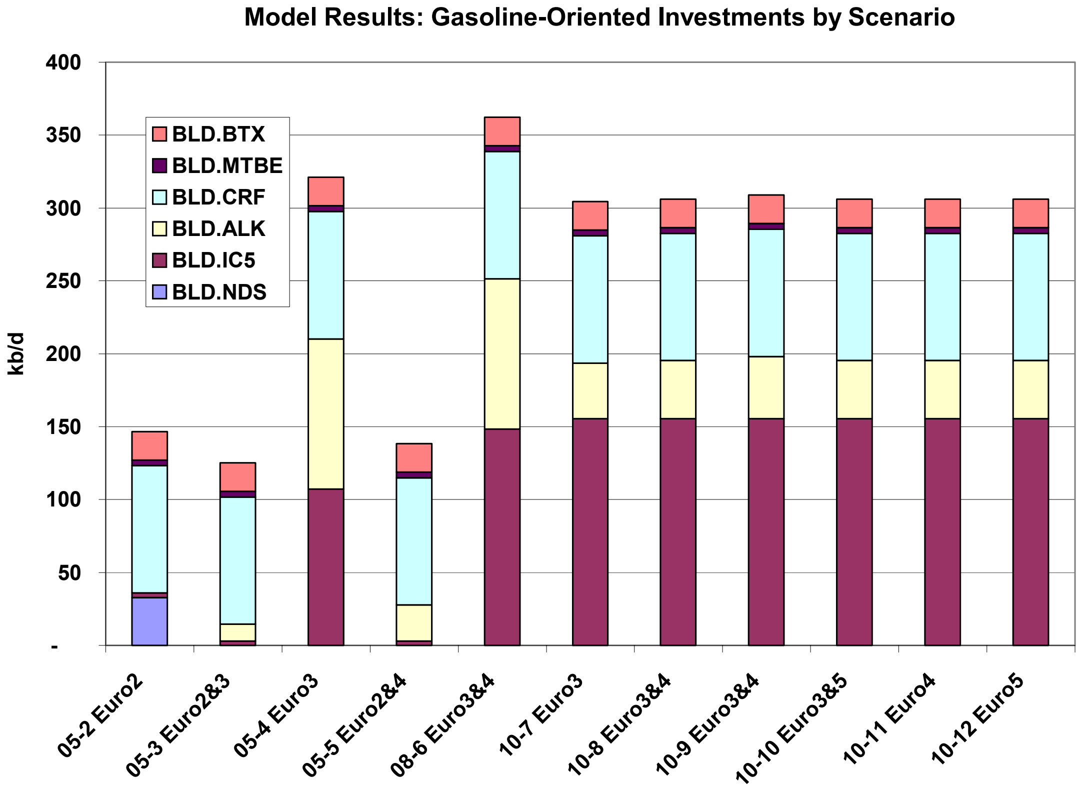
Refinery Capacity Expansions by Scenario

In all cases, meeting Chinese demand for higher-quality fuel will require capital investment in refining. The model selects the appropriate technology types and capacities based on the least-cost solution to meeting product demand and quality in each scenario.

Gasoline-Oriented Investments

Gasoline-oriented investments focused on isomerization, catalytic reforming, and alkylation for most scenarios, with lesser amounts of MTBE expansion and aromatics extraction capacity. Additions by technology type and scenario are presented in Figure 5.

Figure 5

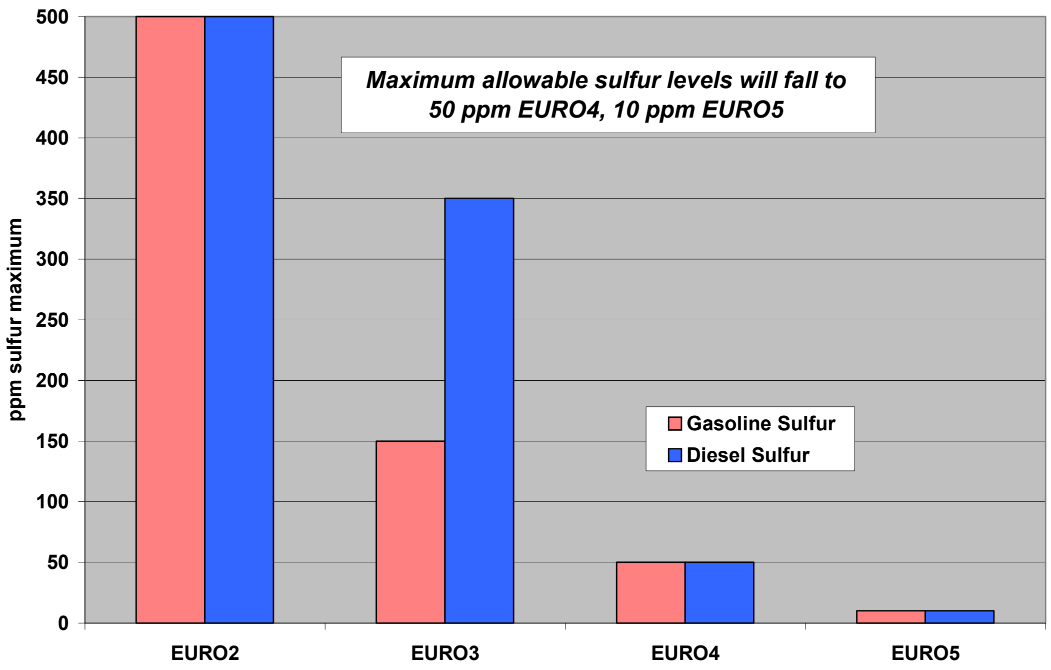


Sulfur Removal Related Investments

In our analysis, sulfur removal will be one of the main challenges facing Chinese refiners in the quest to adopt EURO standards. As the following figure shows, EURO2 sulfur maxima are 500 ppm (parts per million.) EURO3 standards call for 150-ppm sulfur for gasoline and 350-ppm sulfur for diesel. EURO4 standards reduce sulfur maxima to 50 ppm for both fuels. Then EURO5 will reduce sulfur levels to ultra-low levels of just 10 ppm.

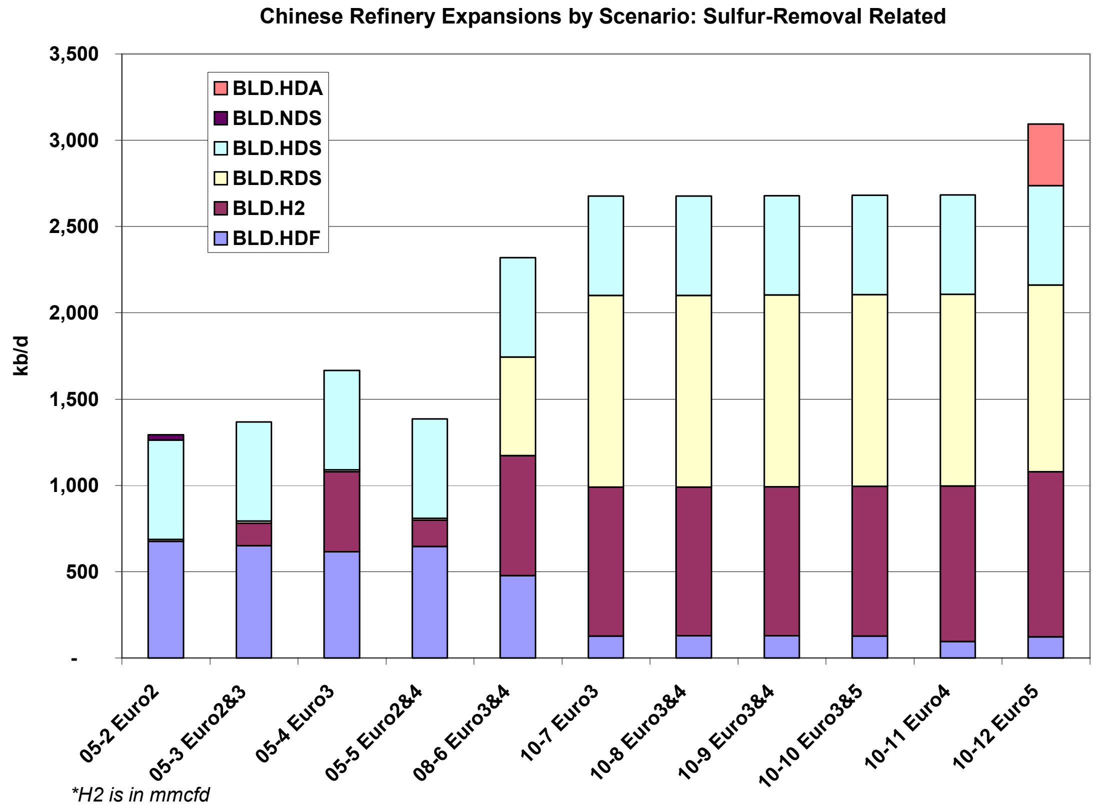
Figure 6

Tightening Fuel Sulfur Levels in EURO Fuels



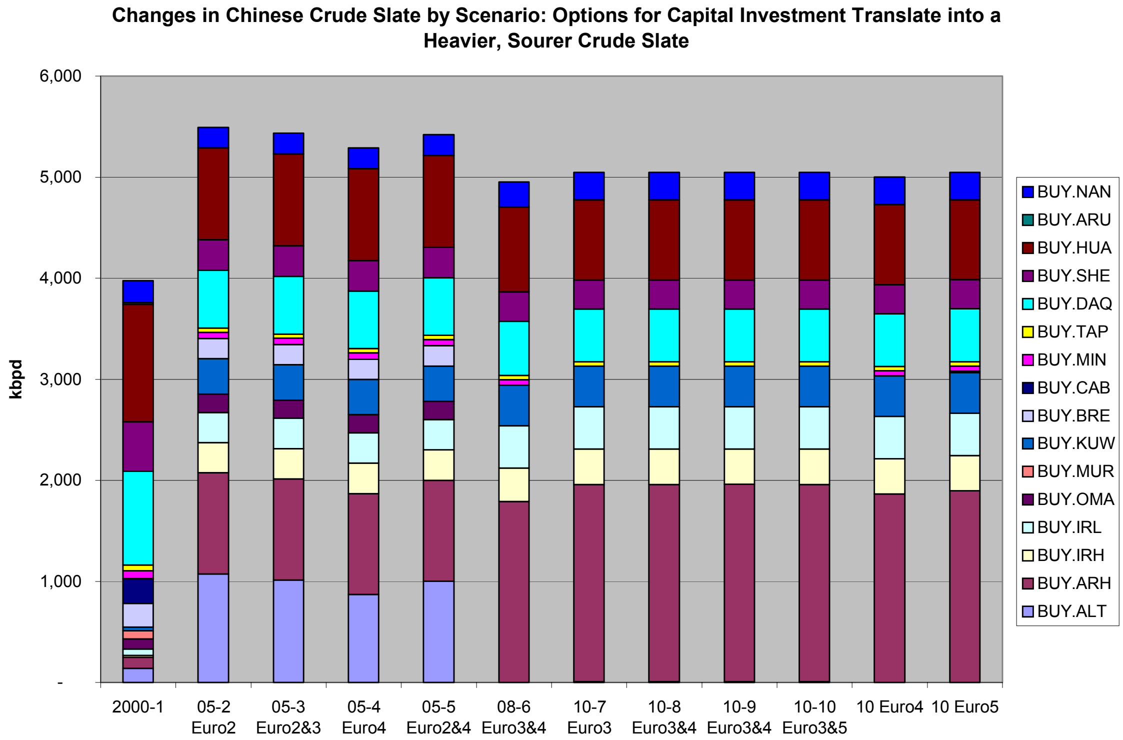
The model selects the best strategy to remove sulfur from blendstocks. The following figure shows sulfur-removal related investments by scenario. In the scenarios of 2005, investments focused on cracker feed pre-treatment (BLD.HDF) with the associated hydrogen units. By 2008-2010, the focus shifted to resid desulfurizing (BLD.RDS,) once again with the associated hydrogen needed to run the units. An interesting contrast is seen between the investments made in Scenario 11 and Scenario 12. The only difference between these two scenarios is the sulfur level. To produce 10-ppm sulfur diesel in Scenario 12, the model opted to build hydrodearomatization, an advanced technology that can transform very difficult middle distillate feeds into extremely high-quality diesel, with high-cetane numbers and essentially no sulfur or aromatics. In our modeling work, EURO5 standards were the only standards requiring investment in this technology.

Figure 7


Chinese Refinery Expansions by Scenario: Sulfur-Removal Related

*H2 is in mmcfd

Figure 8


Changes in Chinese Crude Slate by Scenario: Options for Capital Investment Translate into a Heavier, Sourer Crude Slate

Crude Slate Selections by Scenario

Figure 8 summarizes refinery crude slates by scenario. One of the key findings of the work is that an ambitious refinery investment program in China will create options to purchase a heavier, sourer crude slate, thus cutting feedstock costs. The new scenarios 11 and 12 were also in line with this finding except for a slightly higher volume of low sulfur crude purchases (Minas type from Indonesia and North Sea Brent in these cases.) The details on crude slate selection by type are included in Table 3, with volumes in thousand barrels per day.

Model Purchases of Crude Slate by Scenario

Scenario:	1	2	3	4	5	6	7	8	9	10	11	12
	2000	05 Euro2	05 Euro2&3	05 Euro3	05 Euro2&4	08 Euro3&4	10 Euro3	10 Euro3&4	10 Euro3&4	10 Euro3&5	10 Euro4	10 Euro5
BUY.ALT	138	1,073	1,013	869	1,001		6	7	7	7		
BUY.ARH	112	1,000	1,000	1,000	1,000	1,790	1,952	1,952	1,952	1,952	1863.598	1895.291
BUY.IRH	17	300	300	300	300	330	350	350	350	350	350	350
BUY.IRL	62	300	300	300	300	420	420	420	420	420	420	420
BUY.OMA	100	180	180	180	180							
BUY.MUR	83	-	-									
BUY.KUW	37	350	350	350	350	400	400	400	400	400	400	400
BUY.BRE	233	200	200	200	200							14.929
BUY.CAB	245		-									
BUY.MIN	80	62	62	62	62	55					50	50
BUY.TAP	56	42	42	42	42	42	42	42	42	42	42	42
BUY.DAQ	928	570	570	570	570	536	524	524	524	524	524.2	524.2
BUY.SHE	489	301	301	301	301	293	288	288	288	288	287.7	287.7
BUY.HUA	1,160	910	910	910	910	838	790	790	790	790	790.4	790.4
BUY.ARU	20		-									
BUY.NAN	215	206	206	206	206	247	274	274	274	274	274	274
Total Crude	3,974	5,493	5,434	5,289	5,421	4,951	5,047	5,047	5,047	5,047	5,002	5,049

	2000	05 Euro2	05 Euro2&3	05 Euro3	05 Euro2&4	08 Euro3&4	10 Euro3	10 Euro3&4	10 Euro3&4	10 Euro3&5	10 Euro4	10 Euro5
ME Sour	366	3,023	2,963	2,819	2,951	2,940	3,129	3,129	3,129	3,129	3,034	3,065
ME Med	183	180	180	180	180	-	-	-	-	-	-	-
Domestic	2,812	1,987	1,987	1,987	1,987	1,914	1,876	1,876	1,876	1,876	1,876	1,876
AP Sweet	136	104	104	104	104	97	42	42	42	42	92	92
Oth Sweet	478	200	200	200	200	-	-	-	-	-	-	15
Total	3,974	5,493	5,434	5,289	5,421	4,951	5,047	5,047	5,047	5,047	5,002	5,049
% ME	14%	58%	58%	57%	58%	59%	62%	62%	62%	62%	61%	61%

Crude Naming Conventions:

Foreign Crudes, Mideast	
BUY.ALT	Arab Light
BUY.ARH	Arab Heavy
BUY.IRH	Iran Heavy
BUY.IRL	Iran Light
BUY.OMA	Oman
BUY.MUR	Murban
BUY.KUW	Kuwait

Foreign Crudes, AP/Afr/Eur	
BUY.BRE	Brent
BUY.CAB	Cabinda
BUY.MIN	Minas
BUY.TAP	Tapis

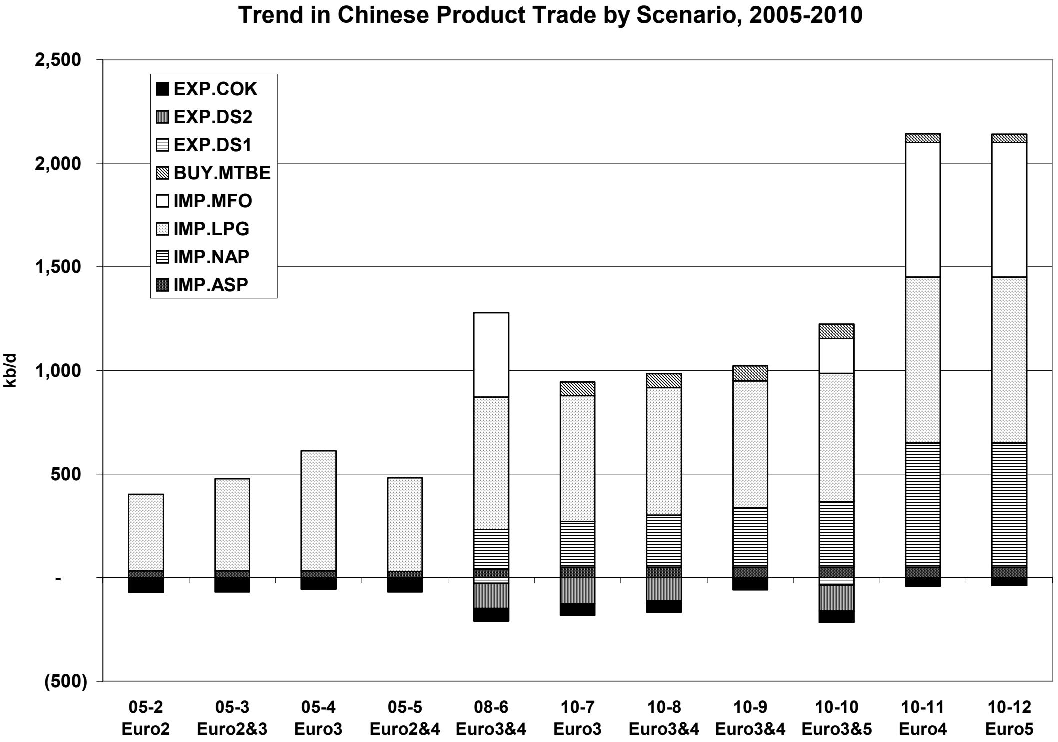
Domestic Crudes	
BUY.DAQ	Daqing
BUY.SHE	Shengli
BUY.HUA	Huabei
BUY.ARU	Condensate
BUY.NAN	Nanhai Lt

Table 3

Product Trade Patterns by Scenario

China's main product imports are LPG, naphtha, and fuel oil. Relatively speaking, these are low-cost commodity imports, and their quality specifications were unchanged from scenario to scenario. The model results indicated that low-cost products (or specialty products such as asphalt) would continue to be imported, while the Chinese refining system focused primarily on producing high-value transport fuels. Product exports were fairly small, generally petroleum coke and, in some scenarios, diesel. The results are presented in Figure 9.

Figure 9



Gasoline and Diesel Additional Costs by Scenario

Although this addendum contains only two new scenarios, the following tables present model calculations of the incremental costs of gasoline and diesel for all scenarios, 2005, 2008 and 2010 in Tables 4, 5 and 6. The results are summarized side-by-side in Figure 10. In general, the model predicts that costs will rise as time proceeds, with per-unit costs rising successively from 2005 to 2008 and 2010. However, the year 2010 scenarios show a fairly stable price increase, with only the new scenario 12 (EURO5) displaying a significant increase in diesel costs (around 0.9 fen/litre.)

Table 4

Incremental Fuel Costs: CHREF2 Model Results for 2005 Scenarios

	Scenario: 05-2 EURO2	05-3 65%EURO2 & 35%EURO3	05-4 EURO3	05-5 65%EURO2 & 35%EURO4
Gasoline costs	**$ 353.6**	**$ 360.3**	**$ 471.8**	**$ 370.0**
Diesel costs	**$ 668.8**	**$ 678.4**	**$ 708.8**	**$ 679.9**
Total Cost	**$ 1,092.7**	**$ 1,109.0**	**$ 1,250.9**	**$ 1,120.1**

	Scenario: 05-2 EURO2	05-3 65%EURO2 & 35%EURO3	05-4 EURO3	05-5 65%EURO2 & 35%EURO4
Gasoline cost c/g	**0.844**	**0.860**	**1.126**	**0.883**
Diesel cost c/g	**1.943**	**1.971**	**2.060**	**1.975**
Gasoline cost fen/l	**1.772**	**1.805**	**2.364**	**1.854**
Diesel cost fen/l	**4.081**	**4.140**	**4.325**	**4.149**

Table 5

Incremental Fuel Costs: CHREF2 Model Results for 2008

000 $/day	**Scenario:** **08-6 85%EURO3 & 15%EURO4**
Gasoline costs	**$ 627.6**
Diesel costs	**$ 1,095.5**
Total Cost	**$ 1,827.0**
Cents/gallon	
Gasoline cost c/g	**1.387**
Diesel cost c/g	**2.650**
Gasoline cost fen/l	**2.912**
Diesel cost fen/l	**5.566**

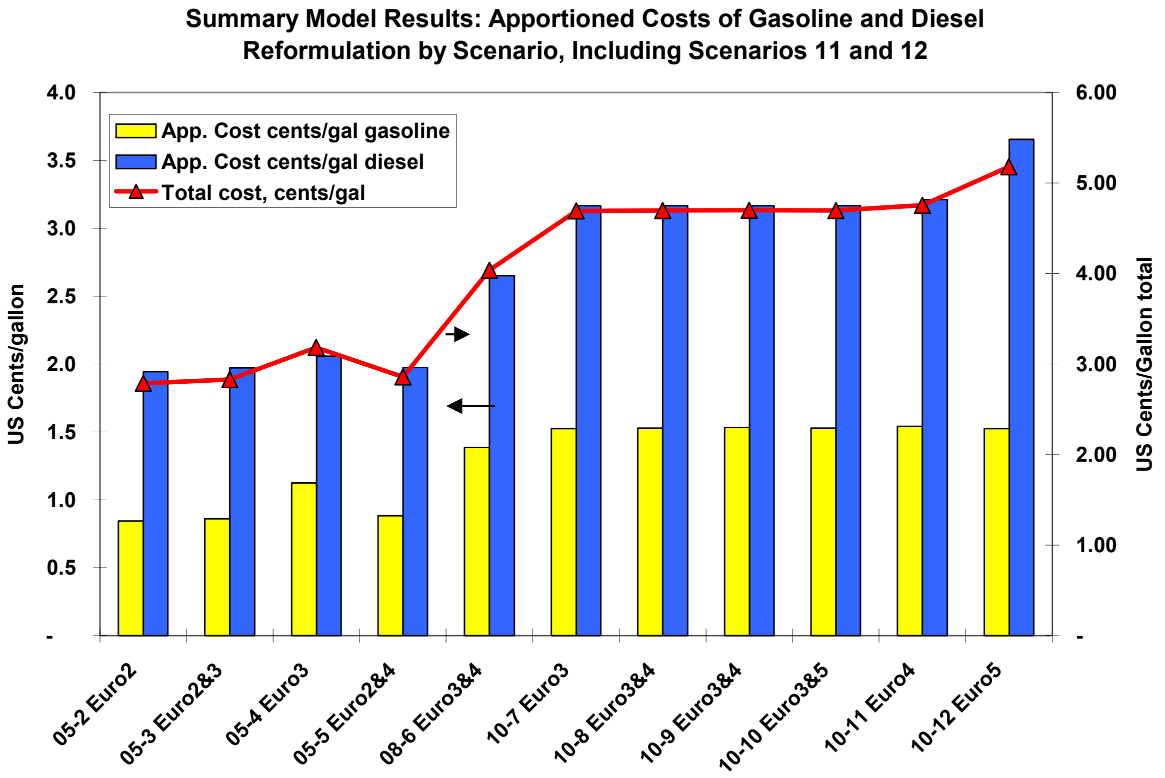
Table 6

Incremental Fuel Costs: CHREF2 Model Results for 2010 Scenarios

Scenario:	10-7 EURO3	10-8 EURO3& 15% EURO4	10-9 EURO3& 40% EURO4	10-10 EURO3 & 15% EURO5	10-11 EURO4	10-12 EURO5
Gasoline costs	$ 726.4	$ 727.7	$ 729.9	$ 727.9	$ 729.9	$ 727.9
Diesel costs	$ 1,477.0	$ 1,477.0	$ 1,477.1	$ 1,477.6	$ 1,497.7	$ 1,704.8
Total Cost	$ 2,332.0	$ 2,333.3	$ 2,335.5	$ 2,334.1	$ 2,335.5	$ 2,334.1

Scenario:	10-7 EURO3	10-8 EURO3& 15% EURO4	10-9 EURO3& 40% EURO4	10-10 EURO3 & 15% EURO5	10-11 EURO4	10-12 EURO5
Gasoline cost c/g	1.525	1.528	1.532	1.528	1.542	1.524
Diesel cost c/g	3.166	3.167	3.167	3.168	3.211	3.655
Gasoline cost fen/l	3.203	3.208	3.218	3.209	3.238	3.201
Diesel cost fen/l	6.650	6.650	6.650	6.652	6.743	7.675

Figure 10



3. Conclusion

The Chinese refining industry already has undergone a massive buildup and expansion program, and additional changes already are underway. Our analysis indicates that these changes alone will not be sufficient to meet demand for more stringent EURO specification fuels. In all of our model scenarios, refinery investments were made above and beyond those already firmly planned. While some of the investments were oriented toward conversion and balancing the demand barrel, by far the majority was quality-related. Gasoline-related units focused on isomerization, alkylation, and catalytic reforming. The main emphasis, however, was on sulfur removal. In the two new scenarios of 2010, sulfur standards were stricter, particularly in scenario 12, EURO5. As such, there was a shift to hydrodearomatization technologies capable of essentially eliminating sulfur in diesel streams. While this added to the incremental cost of diesel (approximately 0.9 fen/liter,) it may be that the additional costs are not prohibitive, given the already ambitious goals for fuel quality improvement and the relatively low capital construction costs in China. This will be an important policy issue; in an era of economic growth and competing demands on capital, what are the true costs and benefits of fuel reformulation, and how will plans and programs be adopted and implemented?