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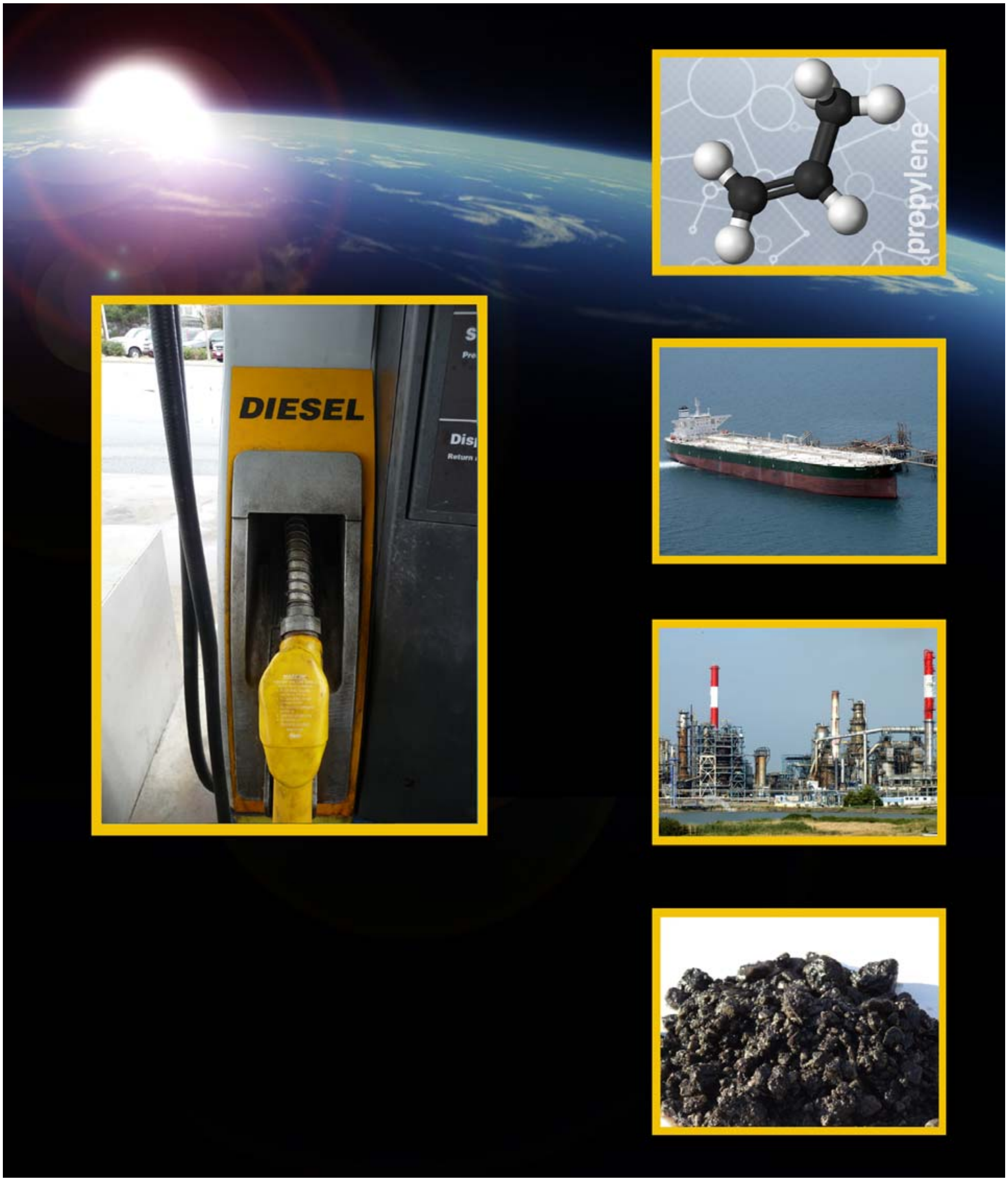

Opportunity Crudes Report II:
Technologies & Strategies for Meeting Evolving Market & Environmental Challenges

An updated and expanded study of the 2006 Report titled "*Opportunity Crudes: Technical Challenges and Economic Benefits*"

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1 INTRODUCTION

Opportunity crudes (opcrudes)—heavy sour crudes, oilsands/bitumen, extra-heavy oil, high acid crudes, and oil shale—offer good values for refiners that can take advantage of low quality, inexpensive grades when oil prices are volatile and light-heavy crude price differentials are consistently wide. However, with evolving market and legislation environs since our last report on the subject in 2006, processing opcrudes is not straightforward and poses many complicated issues, which refiners must overcome. The decision of processing opcrudes requires a more integrated approach than before, involving corporate functions in oil trading and procurement, crude blending and scheduling, business analysis and planning, products marketing, refinery operations and engineering, energy efficiency improvements, plant utilities, climate change legislation, environmental regulations, safety and corrosion management, waste disposal, and so on. Furthermore, it is a long-term commitment since an opcrudes refinery commands much higher capital costs than a plant just handling light sweet crudes.

To tackle current and pending changes in the marketplace and environmental legislation, this study (1) examines the critical factors of the changes and the implications to refineries processing opcrudes, (2) identifies and analyzes the state-of-the-art and emerging refining technologies that facilitate opcrudes processing, and (3) recommends strategies based on technology solutions for our clients to successfully process opcrudes.

2 REPORT METHODOLOGY

Primary sources of information include personal communication with technology holders and catalyst and additive suppliers; extensive literature searches and evaluations; in-depth patent analyses and reviews; and insightful technology and business strategy assessments by a team of analysts and consultants.

3 REPORT SCOPE AND FOCUS

Key discussions begin in **Section 3** with a survey of recent and proposed specifications for motor gasoline, middle distillates, and residual fuel oil, as well as climate change legislation around the world. **Section 4** identifies current worldwide supply and demand of motor gasoline, middle distillates, residual fuel oils, and propylene to assess consumption trends as well as market potential and dynamics. **Section 5** highlights the latest technologies and competition among suppliers and vendors serving the opportunity crudes industry. **Section 6** delineates the various types of opportunity crude available and outlines considerations for how these crudes can be best incorporated into refinery crude slates. **Section 7** discusses technology advances for processing opportunity crudes in crude desalting, crude distillation, coking, solvent deasphalting, visbreaking, resid FCC, resid hydrotreating, resid hydrocracking, and integrated schemes. This Section also examines the latest advancements in supporting systems, such as hydrogen production and sulfur plants. Separate sections are devoted to the impacts of upstream operations and carbon capture. **Section 8** summarizes oil company strategies for handling opportunity crudes based on publicly available information and presents the results of a direct global survey conducted by Hydrocarbon Publishing Company from late 2010 to early 2011. To conclude this Report, **Section 9** analyzes the critical factors affecting the opportunity crude industry in the next two decades and makes valuable recommendations for refiners processing or considering processing opportunity crudes. The overall objective is to provide our clients with the latest knowledge and strategies to tackle evolving market and legislation challenges when processing opportunity crudes.

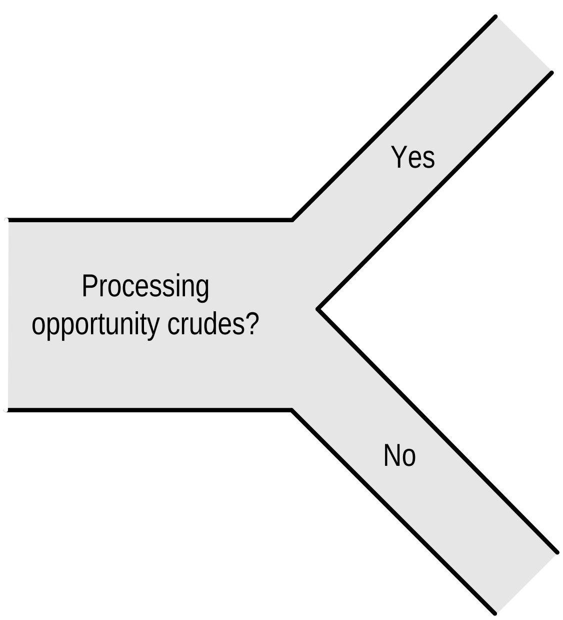
3.1 Prospects of Processing Opportunity Crudes to 2030

Opportunity crudes, as the name implies, are the types of crudes offering benefits to buyers (in this case refiners) who can take advantage of the lower costs driven by higher supply than demand. The prospect is only viable for sophisticated, well-equipped refineries, which are capable of processing these low-quality grades.

Since significant capital investments are required when processing opportunity crudes and paybacks are years away, economic assessments should be based on long-term outlooks, say 15-20 years. Short-term market fluctuations and immediate financial rewards are of lesser importance. Furthermore, due to the international and highly competitive nature of the oil industry, missed opportunities could be fatal to future sustainability of any player in the world.

The global refining industry is at a crossroads in terms of processing opportunity crudes and the costs and benefits (or threats and opportunities) issues associated with the business endeavor and operational commitment must be carefully examined. **Figure 1** portrays urgent issues facing refiners in the opcrudes business due to evolving market and legislation conditions in the coming decades.

FIGURE 1: URGENT ISSUES WHEN PROCESSING OPCRUDES IN THE FUTURE



Positive Issues

- Increasing petroleum fuel demand in developing nations
- Expanding (recoverable) reserves of non-conventional crudes
- Volatile oil prices and supply uncertainty
- “Dieselization”
- Rising propylene demand
- Higher coking margins than cracking margins
- Competitive advantages and sustainability strategies

Negative Issues

- LCFS and crude carbon intensity regulations
- Climate change and refinery emissions legislation
- Biofuels competition and higher vehicle fuel efficiency
- Lower residual fuel oil demand
- Refining business uncertainty in OECD nations
- Inherently higher processing costs
- Competition from nonconventional crudes, NG condensates, and shale oil

At present, there are two contrasting strategies playing out in the global refining world. On one hand, some refiners are closing down less sophisticated, light oil refineries, turning them into terminals, or putting them up for sale. Examples include Sunoco's 150K-b/d Eagle Point refinery in New Jersey and 85K-b/d Tulsa refinery in Oklahoma (both in the US), ConocoPhillips's 260K-b/d Wilhelmshaven plant in Germany, Shell's 107K-b/d Harburg complex in Germany and 80K-b/d Gothenburg facility in Sweden, and Total's 137K-b/d Dunkirk refinery in France. On the other hand, some refiners have decided to process heavier oils and make more high-valued fuels for the market, e.g. Marathon Petroleum's 106K-b/d Detroit refinery in the US and Repsol's 100K-b/d Cartagena refinery in Spain.

This Report analyses and compares the threats and opportunities. The goal is to shed light on the long-term prospects of processing opcrudes and recommend strategies to our clients so that they not only can sustain the business, but also prosper in a long haul.

3.2 Major Drivers in Processing Opportunity Crudes

The Report has identified five major drivers behind the successful processing of opportunity crudes to 2030; these five drivers are directly related to refining margins, which equals to the difference between revenues and costs. The first three drivers, namely increasing distillate yield and quality, converting high sulfur fuel oil into valuable products such as diesel and gasoline, and boosting propylene, contribute to the revenues. On the other hand, the latter two drivers—mitigating fouling and corrosion and reducing carbon footprint—help to lower operating costs.

The relation between the five drivers and the margins obtained from processing opcrudes is illustrated in the following equation:

$$Margins = f(\uparrow distillate, \downarrow HSFO, \uparrow propylene) - f(\downarrow fouling\ and\ corrosion, \downarrow CO_2 emissions)$$

- **Increasing distillate yield and quality** is the top priority, due to diesel/gasoil deficits in Europe and Latin America. These deficits create export opportunities for US, Middle Eastern, and Asian refiners.

- **Displacing high-sulfur fuel oil** is important, as demand for this product is diminishing due to more stringent environmental legislations, including the Annex VI amendments to the MARPOL agreement, which require sulfur reduction in bunker fuels.

- **Boosting propylene output** remains the right strategy for refiners and petrochemical producers to benefit from continued, surging demand for polypropylene and propylene derivatives worldwide and rising shale gas use in steam crackers.

- **Mitigating fouling and corrosion** should receive a good deal of attention in the refining industry, since billions of dollars in operating budgets are wasted each year to combat the effects of these issues, particularly as sediment formation remains a major concern in opcrudes handling and more high-acid crudes are processed.
- **Minimizing carbon footprint** could go straight to the bottom line as energy-efficient processes and energy-saving catalysts burn less fuel and reduce CO_2 emissions.

3.2.1 Increasing Middle Distillates Yield and Quality

Middle distillates—consisting of diesel/gasoil, jet fuel, kerosene, and heating oil—are projected to collectively comprise 45% of the global demand barrel by 2015, up from 35% in 2005. In its 2010 *World Oil Outlook*, the IEA predicted that a rising share of diesel cars in developing nations will raise the volumes of diesel/gasoil nearly 10MM b/d from 2009 to 2030. Overall, global fuel consumption is clearly shifting towards middle distillates and light products with 55% growth for middle distillates and 32% for gasoline and naphtha.

Discounted opportunity crudes are difficult to process and many yield significantly less straight-run, distillate-range material compared to benchmark crudes. However, for refineries equipped to upgrade bottom-of-the-barrel material, opportunity crudes may be able to provide larger quantities of total diesel yield due to higher quantities of gas oil and residual fractions as shown in **Table 1**.

TABLE 1: GAS OIL AND RESIDUAL FRACTIONS OF OPPORTUNITY CRUDES

Region	Crude	API gravity, °	Sulfur, wt%	TAN, mg KOH/g	VR	VGO	AGO	Distillate	Naphtha
Benchmarks									
N. America	WTI	40.8	0.34	0.1	9	24.3	8.1	23.5	32.4
Europe	Brent	38.3	0.37	0.07	10.2	28	14.8	10	33.8
High TAN									
W. Africa	Escravos	34.2	0.15	0.53	6.5	29.6	20.2	12	30.8
S. America & Caribbean	Hamaca	25.9	1.62	0.7	20.8	32	16.4	12	16.8
Middle East & N. Africa	Lavan	36.29	1.44	0.71	10.8	23.6	24.8	10.1	28.9
Far East	Duri	20.8	0.2	1.27	44	33.3	12	5.6	5.1
Europe	Captain	19.2	0.7	2.4	27.1	50.3	16.4	4.8	1.4
Heavy sour									
S. America & Caribbean	Maya	21.5	3.4	0.43	37	24	9	14	15
Europe	Tempa Rossa	20.4	5.44	0.05	36.6	17.4	15.9	10.9	19.2
N. America	Hondo Monterey	19.4	4.7	0.43	38.7	25	6.2	15	15.1
Middle East & N. Africa	Eocene	18.4	3.97	0.2	30.6	38.2	12.1	6.6	12.1

Region	Crude	API gravity, °	Sulfur, wt%	TAN, mg KOH/g	VR	VGO	AGO	Distillate	Naphtha
Benchmarks									
Canadian crude and blends									
Canada	Synthetic Crude Oil	33	N.A.	N.A.	0.3	36.7	N.A.*	37.7	25.3
Canada	Lloydminster Blend	20.7	3.31	0.79	41.2	25.7	N.A. *	18.1	15
Canada	WCS	20.5	3.51	0.93	36.7	25.7	N.A. *	16	21.7
Canada	Athabasca	8.44	4.5	3.5	57	28	N.A. *	14	1
*AGO is divided between VGO and distillate categories									

The Report compares the distillation cuts of different opportunity crudes (including high-TAN, bitumen-derived, and heavy sour crudes) to analyze the effect of crude choice on a refiner's ability to increase middle distillate yields.

3.2.2 Displacing High-sulfur Fuel Oil

Heavy oils contain significant bottom fractions with vacuum residual portions as high as 40%. If not converted, residual fuel oils pose economic and environmental difficulties for refiners. On the other hand, fuel oil prices directly impact the value of heavy oils. For instance, in late Jan. 2011, demand and prices for Angola's heavy crudes were falling on weakening fuel oil cracks and consumption.

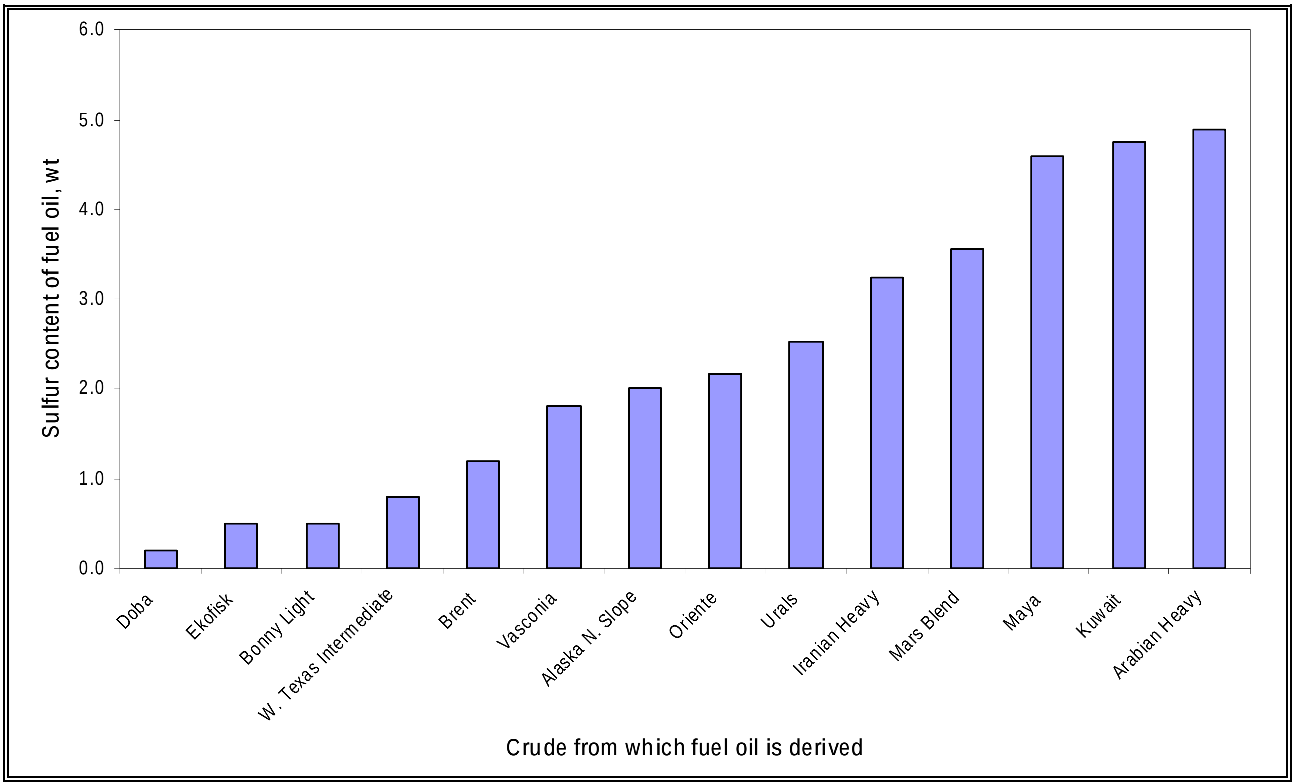
There are two major outlets for residual fuel oil: bunker fuel and power plant combustion. In addition, fuel oil is sold as feedstock to fuel refineries and petrochemical plants. However, the overall consumption of residual fuel oils has been declining in most regions due to environmental concerns and inter-fuel competition.

The increasing popularity of natural gas as a low-carbon (and low-sulfur), efficient combustion fuel has limited the use of fuel oil in power production, refineries, and other sectors, resulting in an oversupply in many areas. In North America and Europe, SO_X emissions from fossil fuel-powered electricity plants have been regulated for some time. Some developing regions, including China, are planning similar legislation to reduce emissions from fossil fuel-fed power stations. Furthermore, the presence of contaminants in residual refinery streams (e.g., vanadium content in pitch, asphaltenes, and petroleum coke) has drawn the attention of environmentalists, who question the impact these harmful compounds may have on the atmosphere when these residual refinery streams are burned as combustion fuels.

Motivated by environmental concerns over SO_X emissions from ocean-going vessels, the International Maritime Organization (IMO) in the Annex VI amendments to the MARPOL agreement in Oct. 2008 requires lowering of sulfur specifications of global marine fuels—also known as bunker fuels or fuel oil No. 6—from 4.5% in 2010 to 0.5% between 2020 and 2025. For the emissions control areas (ECAs) such as the Baltic Sea Area, the North Sea English Channel, and waters off of the North American coast, the sulfur limits will be lowered from 1 wt% in 2010 to 0.1 wt% after 2015.

Obtaining a low-sulfur fuel oil is particularly difficult for refiners of opportunity crudes, which are often high in sulfur. As shown in **Figure 2**, the type of crude processed will directly impact the sulfur content of the residual fuel oil produced. Heavy, sour crudes such as Maya will result in a much higher sulfur content fuel oil than light, sweet crudes such as West Texas Intermediate. [Note: The fuel oil is composed of 85% vacuum resid and 15% straight-run kerosene.]

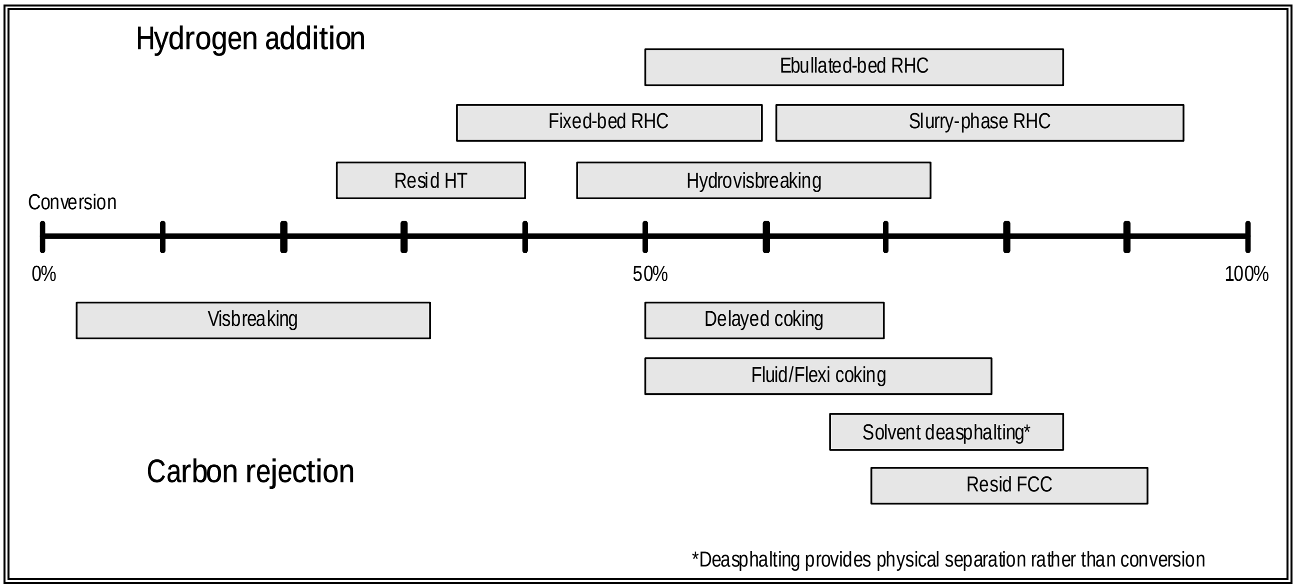
FIGURE 2: SULFUR CONTENT IN FUEL OILS AROUND THE WORLD



Sulfur reduction via hydrotreating of bunker fuel to less than 0.1 wt% will hike refinery investment in capacity of desulfurization, hydrogen production, and sulfur removal. This endeavor is cost prohibitive, at a minimum of $1B per refinery. In the meantime, stringent sulfur specifications enacted on bunker fuels have prompted many marine vessels to consider a switch to lighter distillate fuel oils and diesel. Regulations to cut emissions from marine bunker fuels could result in a 50% jump in demand for middle distillates while reducing the sale of residual fuels by over 66%, according to various market estimates. There are other options to comply with the IMO requirements, though they are not expected to be widely adopted in the near term due to lack of commercial experience. These options include on-board SO_X scrubbing and using LNG instead of high sulfur fuel oil.

The technologies discussed throughout Section 7 of the Report are capable of providing various levels of residue conversion. **Figure 3** provides a graphical summary of the achievable residue conversion level for each technology. Refiners looking to optimize liquid yields and displace fuel oil production will strive to maximize conversion through technology selection. Pushing conversion levels to the maximum achievable level for each technology can be accomplished by implementing many of the processing strategies discussed. Capital and operating costs will also be a factor during technology selection, and it is notable that as the achievable conversion is pushed towards a maximum, the technologies that apply catalysts (e.g., RFCC, resid HC) and incorporate hydrogen (e.g., resid HT, resid HC) will incur significantly higher operating costs than those that rely on thermal processing mechanisms (e.g., coking, visbreaking).

FIGURE 3: ACHIEVABLE RESIDUE CONVERSION WITH ADVANCED TECHNOLOGIES



For refiners processing heavy opportunity crudes, declining demand for residual fuel oils presents a particularly challenging problem. Many opportunity crudes contain large quantities of residual material that can be both energy intensive and cost-intensive to upgrade. Therefore, it is important to identify economical options for upgrading these heavy fractions through operating changes and small process modifications, or through more significant upgrades, when necessary.

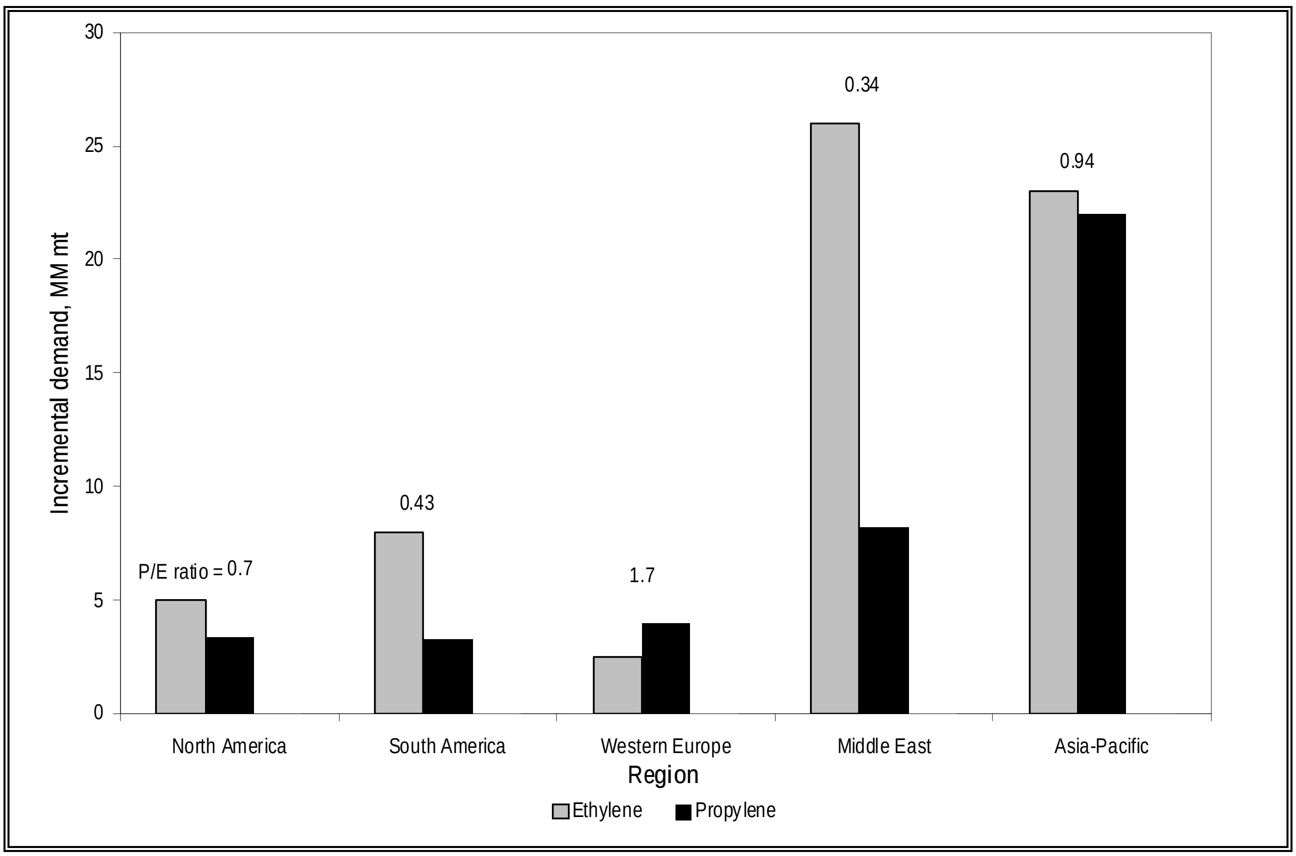
3.2.3 Boosting Propylene Make

Petrochemical (PC) production will continue to rise around the world in order to satisfy growing consumer markets, rising motor vehicle production, expansion in energy and telecommunication industries, and other sectors. Renewable sources to replace fossil fuels for petrochemicals production are still decades away, especially, due to the sheer volume of materials required. The future role of opportunity crudes as a major source of petrochemical manufacturing cannot be underestimated as conventional oil reserves are declining. In the meantime, oilsand producers have considered PC production as a means to reduce carbon footprint by diverting byproduct offgas to chemical producers.

The current market situation for propylene reflects mixed global demand growth following the worldwide economic recession, according to Chemical Market Associates Inc. (CMAI). CMAI estimates that developing regions (China, India) will experience rapid growth, while more developed regions (the EU, the US) will see slower growth. Propylene demand was pegged at 69MM mt/y in 2006 and was expected to rise to 88MM mt/y by 2011. According to other estimates, global demand for propylene is expected to increase by 34MM mt over the period of 2008-2015, for a 4.5%/y average annual increase.

Figure 4 shows projected regional incremental demand (total demand minus existing demand) of propylene and ethylene from 2007-2020. Please note that the numeric value located above the two bars for each region is the propylene-to-ethylene (P/E) ratio for the region.

FIGURE 4: REGIONAL INCREMENTAL ETHYLENE AND PROPYLENE DEMAND, 2007-2020



Globally, propylene end-use in the polymer and chemical markets is divided approximately as follows: polypropylene (PP) 64%, acrylonitrile 9%, propylene oxide 8%, oxo alcohols 8%, other 7%, and cumene 4%. Polypropylene is one of the best-selling plastics, second only to polyethylene. The largest consumer is the automobile industry. In the 1980s, the average car contained about 10 kg of PP as car makers preferred to use costly, high-performance plastics; however, as cost pressures began to shape the industry, PP with enhanced engineering properties became more attractive to auto firms. By 2010, the average car contained more than 65 kg of the polymer.

Currently, global propylene supply comes from steam crackers (66%), refinery FCCUs (29%), and on-purpose units (5%). However, future production of propylene from steam will likely decrease as chemical producers take advantage of low NG prices because of increasing availability of shale gas. It is projected that FCC propylene will capture approximately 38% of the predicted demand expansion. Furthermore, propylene produced from FCCUs has become increasingly valuable for alkylation processes. Higher ethanol use in gasoline blending requires more alkylate to blend down and meet RVP requirements. In the US, share of alkylate in Californian gasoline when ethanol is introduced (6% of the composition) has climbed to 23% from 17% when MTBE (12% of the composition) was allowed. In refinery operation, RFCC is being favored for producing this petrochemical from very heavy feeds, including resids.

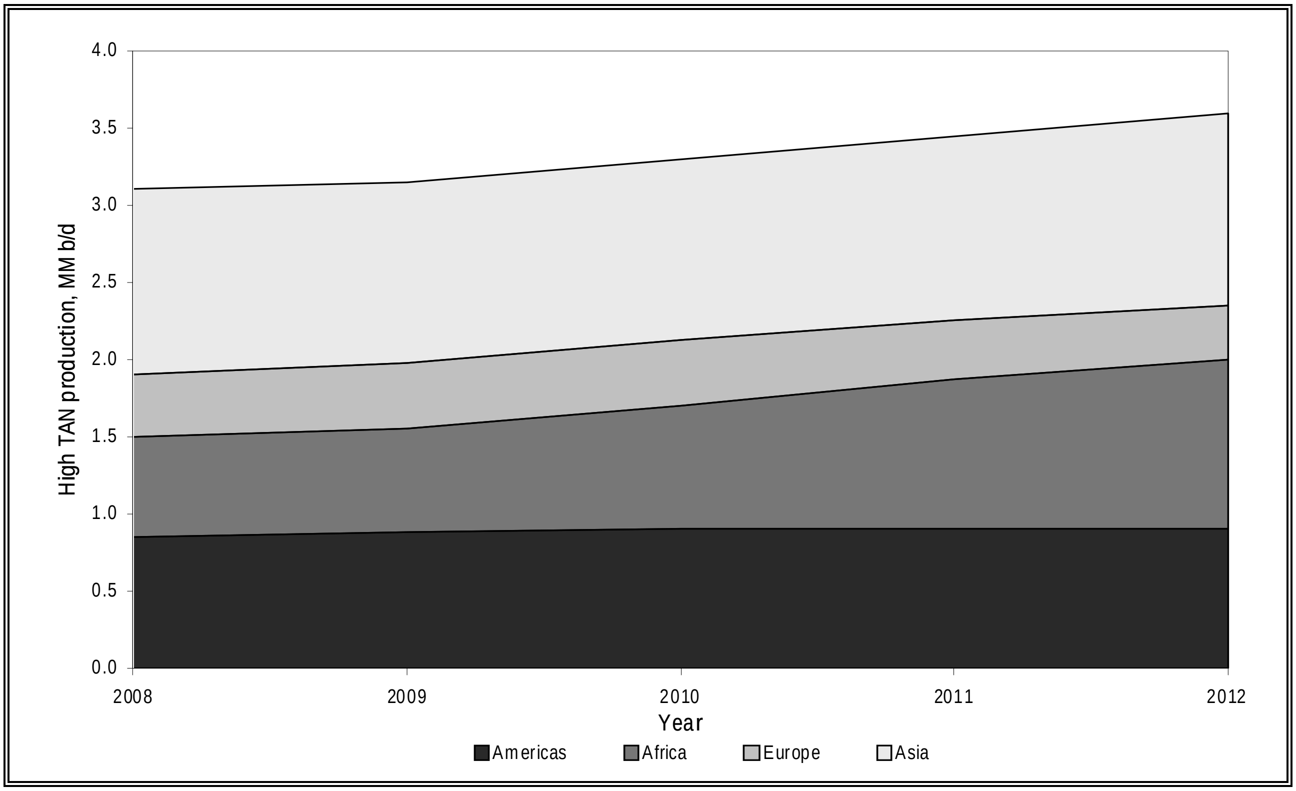
3.2.4 Mitigating Fouling and Corrosion Problems

Processing opportunity crudes requires higher capital and operating costs than dealing with conventional crudes. It is a difficult decision for most refiners in the developed nations when facing weak fuel demand and poor refining margins. In addition to expanding sulfur plant and hydrogen plant capacities, processing heavy oil and high TAN crudes incur extra costs because of potential fouling and corrosion problems that lead to poor energy efficiency and increased maintenance requirements.

It is estimated that fouling issues are resulting in the loss of around 7MM b/y of refining capacity, and that this problem is likely to worsen as refineries process greater volumes of heavier crude. Asphaltenes—which makeup the highest molecular weight, most polar, and most aromatic fraction of crude oil—have been blamed for a range of processing problems including extensive fouling and poor desalter performance. While these molecules can be quite problematic for refiners, ongoing research is helping to resolve some of the issues.

High acid crudes (HACs), or crudes with high TAN, are projected to make up 11% of the total crude volume processed worldwide by 2011. High-TAN crudes, generally defined as those with a total acid number >0.5 mg KOH/g of oil, can be found around the world in places such as Brazil, China, the North Sea, Venezuela, and West Africa. The quantity of high-acid crude production has been steadily increasing. **Figure 5** shows the estimated increase in high-TAN crude production from 2008-2012, according to Purvin & Gertz. It can be seen that total high-acid crude production is expected to increase by over 16% from 2008-2012.

FIGURE 5: HIGH-TAN CRUDE PRODUCTION, 2008-2012



These crudes have the potential of offering refiners significant economic benefits due to crude price discounts; however, realizing these benefits requires overcoming the negative impacts of high acidity on product yields and quality, and on the reliability and operations of the refinery. Processing a high-acid crude can be risky due to its extreme corrosiveness to processing equipment, which can cause extensive damage, decrease production, and even trigger unexpected refinery outages. In addition, HACs are known to produce diesel with a low cetane number.

3.2.5 Minimizing Carbon Footprint

Improving the energy efficiency of the refinery is the best way to reduce refinery CO_2 emissions. It is estimated that about 28% of the energy that is consumed in the refining process is lost prior to use. This loss, coupled with the large amount of energy consumed by an average refinery, makes it easy to see that there is a great deal of room for improvement. Furthermore, it is estimated that a one-point reduction in the Solomon Energy Intensity Index (EII) is estimated to save approximately $1.7MM/y in terms of fuel costs at a fuel price of $5/MMBtu, making energy efficiency programs not only good for the environment, but also economically attractive, regardless of the price assigned to CO_2 emissions.

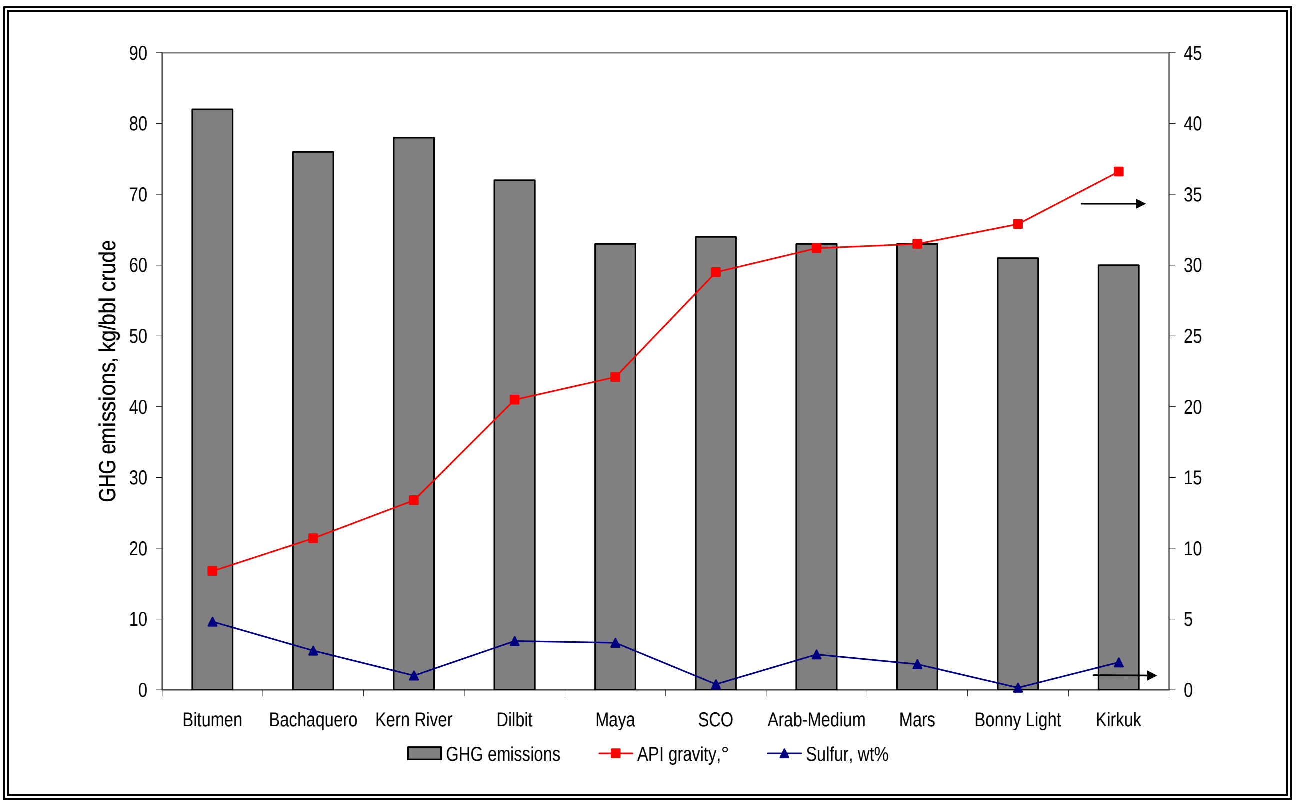
Some US states and the European Union have focused on carbon content of transportation fuels as a way to reduce CO_2 emission from fossil fuels. California is currently the only state in the US to put in place a

Low Carbon Fuel Standard (LCFS.) The standard is based on the GHG emission evolved from the production of a particular fuel on a lifecycle basis. By 2020, the state will require all distributors of oil products to lower their carbon intensity by 10%. California's LCFS seeks to rank crude grades by carbon intensity, spurring fears within the state's refining sector that the government could try to ban certain crudes. According to initial crude screenings, a number of imported crude types would receive a "fail" grade under the LCFS.

The European Parliament has prompted legislators to look at carbon intensity of crudes processing in the region as a way to implement Article 7a of the Fuel Quality Directive (FQD). The International Council on Clean Transportation has identified the two largest upstream emission sources: oilsand extraction and NG flaring. The EC plans to spend six months, in 2011, studying potential changes to the Renewable Energy Directive (RED) and FQD.

In the age of increasingly strict CO_2 legislation, the impact of crude selection on the refinery CO_2 footprint must be taken into account. Crudes with lower API gravity and higher sulfur content require greater energy intensity (energy per barrel of crude processed) and process intensity (combined capacity of vacuum distillation, coking, thermal cracking, FCC, and hydrocracking divided by the capacity of the atmospheric distillation unit). Accordingly, lower API gravity and higher sulfur content lead to increased refinery CO_2 emissions. **Figure 6** shows the impact of crude choice on refinery greenhouse gas (GHG) emissions.

FIGURE 6: EFFECT OF CRUDE CHOICE ON REFINERY GHG EMISSIONS



3.3 Latest Technologies to Satisfy the Drivers

The core of the Report is Section 7 (over 700 pages), which discusses the latest technology advances in specific details for processing opcrudes. Section 7.1, Whole Crude Treating and Separation Processes, comprises discussions centered around the crude desalter and the distillation plant. The technologies disclosed in Section 7.1 are primarily oriented toward mitigating fouling and corrosion issues not only in the desalter and distillation unit (and including the crude preheat train), but in downstream units as well. Additionally, some of the adjustments made to the distillation plant can enhance the quantity of gas oil-range feed that are available for downstream conversion units, indirectly resulting in an increase of distillate and propylene yields.

Section 7.2, Resid Upgrading Processes, contains information on the major refining processes that are utilized to process residual refinery streams into high-quality products. Traditional residue upgrading processes—coking, visbreaking, and solvent deasphalting—are covered, in addition to novel conversion process—resid FCC, resid hydrotreating, and resid hydrocracking. The selection and operation of the resid upgrading scheme that is applied will largely determine the refiner's ability to meet the five primary objectives when processing increasing volumes of opportunity crudes with a specific emphasis on increasing distillate yield and quality, displacing high sulfur fuel oil production, and boosting propylene yield. Some strategies are also presented to mitigate fouling and corrosion and to minimize the carbon footprint of these units, but investment in these technologies will mostly be justified by their ability to produce high quality products.

Section 7.3, Heavy Oil and Middle Distillate Upgrading Processes, includes some additional technologies for heavy oil hydroprocessing and upgrading strategies for diesel-range streams. It is notable that the production of liquid streams that are close to meeting final product specification is difficult with many of the technologies discussed in Section 7.2. As a result, further upgrading of many lower-quality distillate-range streams is needed. Specifically, products from the resid upgrading units processing opportunity crudes-derived streams are commonly high in sulfur, metals, and aromatics. Select processing technologies and operational strategies that are explicitly designed to handle low-quality gas oil-range products to yield high-quality diesel-range streams are disclosed.

The Report examines the current technologies of each bottom-of-the-barrel processing unit in detail and provides recommendations for three investment levels. The first investment level consists of operational adjustments that can be made in refining processes. The solutions are largely focused on the optimization of operating conditions (i.e., temperature, pressure, residence time, etc.) and are generally considered to be low-cost solutions. The impact of these adjustments, however, may be somewhat limited due to constraints on processing equipment and auxiliary units.

The second investment level requires hardware and catalysts changes available to refiners to increase distillate yield and quality when processing opportunity crudes. In general, these strategies and solutions are better served to meeting the specific goals than the operational adjustments; the solutions, however, are more costly than simply implementing operational changes. Improvements in the design of reactor internals, the addition of auxiliary equipment, the application of chemical additive packages, and the optimization or deployment of advanced catalyst systems characterize the majority of the solutions. In application, low-to-moderate cost optimization options will likely require a balanced approach in applying the strategies and solutions in these first two categories.

The third investment level represents the most capital-intensive alternatives for improving a refiners' ability to process opportunity crudes. The installation of modified processes, revamps of older process units, and the installation of new process equipment can be completed to meet one or more of the objective while processing additional volumes of opportunity crudes. Furthermore, the solutions will typically provide a significant advantage over those discussed in categories one in two in terms of increasing residue conversion and enhancing product quality or yield. For a grassroots refinery, the solutions recommended in this option can be used as a guide for selecting a refinery configuration that will enable the processing of low-cost opportunity crudes. **Table 2** presents operational and technology solutions of each bottom-of-the-barrel unit to satisfy the five major drivers.

TABLE 2: OPERATIONAL AND TECHNOLOGY SOLUTIONS TO SATISFY MAJOR DRIVERS WHEN PROCESSING OPPORTUNITY CRUDES

Process unit	Increasing distillate yield and quality	Displacing high-sulfur fuel oil	Boosting propylene output	Mitigating fouling and corrosion	Minimizing carbon footprint
Crude desalting and treating	N.A.	N.A.	N.A.	√	√
CDU	√	√	N.A.	√	√
Coking	√	N.A.	N.A.	√	√
Visbreaking	√	√	N.A.	√	√
Solvent deasphalting	√	√	N.A.	N.A.	√
Resid FCC	√	√	√	√	√
Resid HT	√	√	√	√	√
Resid HC	√	√	N.A.	√	√
Heavy oil HC	√	N.A.	N.A.	√	N.A.
Heavy oil HT	√	√	√	√	N.A.
√ : numerous options are available at various investment levels, N.A.: not applicable					

The benefits of the combined implementation of the process technologies are covered in Section 7.4, Integration of Residue Conversion Technologies. Opportunities are mostly related to enhancing distillate quality and yield and displacing high sulfur fuel oil. Opportunities to minimize the refiner carbon footprint are also common when considering integrated processes due to the ability to optimize utility usage between energy intensive process operations.

For refiners processing an increasingly large quantity of residue-containing streams, a number of integrated strategies have been defined in commercial offerings, operational experiences, and patented processing schemes with the aim of improving flexibility, efficiency, and overall plant profitability. In general, the selectivity and yield of light products is enhanced by increasing the complexity of the residue conversion scheme; however, due to limited capital available for investment and the considerable operating costs of some of these techniques (e.g., due to catalyst cost or hydrogen demands), there is no one-size-fits-all solution. Refiners will need to balance their current plant configuration with the desired goals of the project and capital/operating costs to come up with the solution that can provide the maximum return on investment.

Previous studies have indicated that the application of a single residue conversion unit will provide a quicker return on investment than the application of integrated or sequential residue conversion technologies. However, this Report identifies the technological development of emerging residue upgrading technologies, coupled with the commercial offerings of integrated bottoms processing schemes by a number of technology suppliers. The work clearly demonstrates that superior benefits can be realized with the application of integrated schemes in terms of product selectivity and yield, process flexibility, energy consumption, capital and operating costs, and environmental emissions.

3.4 Auxiliary Systems

Process advances and operational strategies discussed in Section 7.5, Auxiliary Systems, are primarily related to improving the efficiency of the hydrogen and sulfur plants when the duty to these units is increased. The processing of opportunity crudes will increase the stress on both of these systems, particularly as refiners work to upgrade low quality heavy oils into clean transportation fuels. More hydrogen will be required for hydrotreating and hydrocracking operations, while increased sulfur plant capacity will be required for refiners processing high sulfur-content crudes.

The strategies and optimization measures that refiners take to improve the hydrogen plant mainly focus on expanding capacity and reducing energy requirements and CO_2 emissions. The optimum technology/strategy to meet these goals is largely dependent on the individual hydrogen plant and refinery needs. In particular, steam export requirements play a large role in determining the best technology as many measures that increase energy efficiency or capacity of the hydrogen plant decrease steam export. There are various options for refiners trying to increase hydrogen availability and reduce the CO_2 footprint of the hydrogen plant in refineries.

Currently, the refinery hydrotreating capacity is expanding as the volume of sour crudes requiring treatment is increasing. As a result, additional sulfur waste gases are produced and increased sulfur recovery capacity is required. Stricter regulations are also driving refineries to remove higher percentages of sulfur, which demands more investment. Acid gas removal systems, Claus units, and tail gas treatment units (TGTUs) are the three major components of a plant used for sulfur recovery. There is a synergy of these three processes. Moreover, various options for refiners trying to improve energy efficiency/reduce the CO_2 footprint of the sulfur plant or improve sulfur recovery are available

3.5 Impacts of Upstream Operations on Downstream Processing

Section 7.6, Impacts of Upstream Upgrading, relays opportunities for upstream producers to apply advanced process technologies to improve the quality of opportunity crude-derived refinery feeds. Depending on market conditions and future legislative activity, shifting some or all of the resid upgrading processes to upstream plants may present the most viable option for handling opportunity crudes in the future.

Upgrading technologies for upstream processes are driven to achieve four goals: (1) constrain operating costs, (2) improve syncrude quality in order to meet refinery requirements, (3) reduce utilization of natural gas, and (4) expand the product range. Traditional upgrading generally relies on either coking or ebullated-bed hydroprocessing for primary upgrading, with hydrotreating used as a secondary process to reduce sulfur and nitrogen levels. Upgrading sites are split between those that upgrade at the production site and those that conduct it at other locations where it may be integrated with an existing refinery. However, what does it mean to current coking or ebullated-bed hydroprocessing technologies when low-carbon fuel standard and crude carbon intensity must be taken into consideration in crude selection for a refiner? Some of the emerging upgrading technologies, based on innovations in conventional thermal cracking and hydroprocessing as well entirely different approaches described in this section may provide our clients with some answers.

3.6 Carbon Capture and Sequestration in Upgraders and Refineries

Technologies to apply "Carbon capture and storage," also referred to as "carbon capture and sequestration," or CCS on oilsand upgraders and refining units are covered in Section 7.7. In the past, carbon capture R&D activities were mostly tailored to coal-fired power plants, the largest stationary source of CO_2 emissions. However, under Phase 1 of the American Recovery and Reinvestment Act, the US Dept. of Energy (DOE) earmarked $1.4B, in June 2009, for one dozen CCS projects from industrial CO_2 emitters, including refineries, and significantly, excluding coal-fired power plants. In fact, refiners have already invested to some degree, as is exemplified by work during Phase II of the CO_2 Capture Project (CCP), an international collaboration among BP, Chevron, ConocoPhillips, Eni, Petrobras, Royal Dutch Shell, and Suncor Energy. Phase II focused partly on refinery carbon capture developments.

Currently, there are eight active CCS projects for upstream applications and ten refinery projects, many of which are located in Europe and North America. For instance, CCP group CO_2 commenced a pilotplant testing for a full-burn FCCU at a Petrobras research facility in Parana, Brazil in April 2011 to examine the economic and technical viability of retrofitting an FCCU for CO_2 capture via oxycombustion. The DOE in 2009 awarded the Sweeny Gasification Project with $3MM to convert byproducts from ConocoPhillips's 247K-b/d Sweeny refinery in Texas, US into electricity by using an integrated gasification combined cycle. Air Products and Chemicals received $253MM to design and construct a CCS project by Sept. 2015 at Valero's Port Arthur, TX refinery (US), where 1MM mt CO_2/y will be captured from two steam methane reformers. Shell submitted an application in 2010 for its Quest Carbon Capture and Storage project in Canada, an application of CCS technologies for oilsands. The project is expected to capture 1MM mt/y of CO_2 from the Scotford Upgrader's steam methane reformers.

Refinery CO_2 emissions come mostly from the combustion of fuel (e.g., furnaces) for steam and electricity production, and for FCC catalyst regeneration. There is also "chemical" CO_2 (not from combustion), most notably coming from the hydrogen plant. Broken down by refinery units, the key emitters include the hydrogen plant, the gasification unit, the power plant/cogen facility, and the FCCU. In refineries, half of the CO_2 emissions are attributed to process heaters. The section details basic approaches in CCS applicable to both upstream and downstream sectors: pre-combustion, oxycombustion, and post-combustion.

3.7 Survey of Company Strategies in Processing Opportunity Crudes

Section 8 analyzes how current and future market and legislation changes will impact business strategies for refiners in the coming decade. In order to gain this insight, an extensive direct survey was conducted in late 2010 and early 2011 among many oil companies around the world. The goal was to measure the industry's directions in processing opportunity crudes in light of changing market and legislation outlooks. The survey contained 14 questions, which can be viewed here.

To complement the questionnaire, the Report also undertook a wide-ranging search of company strategies from publicly available information (e.g., websites and press releases) to reveal trends in processing opportunity crudes, producing middle distillates, reducing refinery carbon footprint, and so on. The companies are located in the US, Canada, Latin America, Western Europe, and Asia-Pacific.

3.8 Strategic Analyses and Recommendations

Since crude can represent up to 50% of the clean fuel production expense, crude selection is the most important decision refiners have to make on a daily basis. The criteria to determine which crudes to acquire include oil source reliability and term deals, delivery advantage, discounts versus other crudes (opportunity cost), plant operational flexibility, potential processing problems and risks, mitigation options and costs, environmental concerns, and product demand mix. Refinery operations should capture the economy of scale; improve the refinery complexity; get access to local, deficit markets; and create synergies with adjacent facilities to minimize operating costs and maximize product values. As the market dynamics and environmental legislation requirements change, refiners must critically examine internal capability and modify strategies accordingly in order to remain low-cost producers to serve the market while remaining profitable, excelling in competition, and meeting long-term business goals. Therefore, the Report performs SWOT (Strength, Weakness, Opportunity, and Threat) analyses in Section 9: Strategic Analyses and Recommendations. It is separated into three parts: (1) Prospects of Processing Opportunity Crudes to 2030, (2) Technology-driven strategies based on six typical refinery configurations, which can satisfy the five major drivers, and (3) Scenario study for refiners in different parts of the world. As the global refining industry is at a crossroads and faces many uncertainties in coming decades, the ultimate objective is to shed light onto technologies and strategies to meet evolving market and legislation challenges in coming decades.

4 PRICING INFORMATION

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