**HYDROCARBON PUBLISHING COMPANY**

Translating Knowledge into Profitability℠

# REFINERY $CO_2$ MANAGEMENT STRATEGIES

Technology Solutions to Reduce Carbon Footprint
and Meet Business Sustainability Goals

# REFINERY $CO_2$ MANAGEMENT STRATEGIES PROSPECTUS (APR. 2010)

## TABLE OF CONTENTS

## Background

For the global refining industry, the challenges ahead will come from numerous directions—volatile oil prices, poor-to-meager demand growth, new and upcoming mandates for ultra-clean and high-quality fuels, required reductions in plant waste discharge and air emissions, the expanding role of biofuels in the energy mix, and environmental concerns over greenhouse gas emissions. At the same time, refiners must satisfy traditional objectives, such as the need to provide steady fuel supply to consumers, the constant drive to save energy and improve efficiency, and the need for refinery upkeep to maintain safe and reliable operations. On the financial side, refiners must maintain adequate operating cash flows to secure crude supply and to fund revamps and expansions in order to keep up with the competition.

In the next decade or so, environmental issues addressing climate change and $CO_2$ emissions will determine the sustainability of many refiners since the impending regulations pose direct impacts on their financial performance and market competition. The world is counting down to the UN climate change meeting in Copenhagen, Denmark in December, where leaders will try to agree upon a successor to the Kyoto Protocol. Such a commitment—which would require binding participation from all countries involved—could signal major changes for businesses in energy-producing countries. The following table summarizes GHG emissions rules around the world, except Russia, non-EU Eastern Europe, and the Middle East.

**TABLE 1: WORLDWIDE GHG EMISSIONS REGULATIONS**

| Country/region | GHG emissions reduction deadline |
|---|---|
| US | House bill HR 2454 targets cuts in GHG emissions from 2005 levels by 17% by 2020 and 80% by 2050 (as of July 16, 2009). |
| Canada | Targeting 20% cut from 2006-2020 and 60-70% cut through 2050. In 2012, oilsands operations will begin and construction of new dirty-coal plants will be banned. |
| Latin America/Caribbean | Mexico: plans to cut 50MM tons (~8%) of emissions by 2012. The country will also slash 200K mt/y of refinery emissions through carbon credits. |
| EU | Emissions Trading Scheme demands its 27 members to cut 21% of emissions from 2005 levels by 2020. |
| Africa | South Africa: hopes to cap its emissions by 2020-2025 and reduce emissions by 2050. |
| Asia-Pacific | • Australia: plans 60% cut from 2000 levels by 2050 and 5-25% reduction from 2000 levels by 2020.<br>• China: has goal to cut emissions by almost 50% on emissions-per-dollar basis by 2020.<br>• Japan: aiming for 6% cut from 1990 levels from 2008-2012 under Kyoto Protocol. Under the Action Plan for Achieving a Low-Carbon Society, Japan is targeting a reduction in current emissions of 60-80% by 2050.<br>• New Zealand: plans 10-20% cut below 1990 levels by 2020.<br>• South Korea: will reduce emissions by 2020 based on three different choices: 4% cut from 2005 levels, 8% increase from 2005 levels, or keep levels steady to 2005. |

## Report Scope and Methodology

This report focuses on the latest technology and know-how of four main drivers of refinery carbon management strategy: (1) energy efficiency improvement; (2) cogeneration (combined heat and power, and integrated gasification combined cycle); (3) electricity from renewable sources; and (4) carbon capture and sequestration/storage.

Primary sources of information for this report include direct input from refiners and technology holders; extensive literature searches and evaluations; in-depth patent reviews and analyses; and technology and business strategy assessments by experienced practitioners. The study also offers a unique feature that examines key climate change strategies and policies by many oil companies around the world, based on our recent direct survey of refiners and comprehensive analyses of their positions as released to the media and presented in annual reports.

### Sources and Factors Affecting Refinery $CO_2$ Emissions

According to the US Dept. of Energy's Energy Information Administration (EIA), in 2006 global, energy-related emissions of $CO_2$ totaled 29.195B mt, and petroleum refining was responsible for approximately 5% of this total. Refinery emissions can be almost entirely attributed to fuel combustion, which is in turn affected by the types of crudes processed and the product slates chosen.

More specifically, most of the emissions of $CO_2$ from refineries are due to stationary combustion devices. These emissions are also referred to as energy-related emissions. At a hypothetical 250K-b/d refinery with a hydrogen plant and an FCCU, the $CO_2$ emissions from various sources, as estimated by the American Petroleum Institute, are listed in the following table.

**TABLE 2: $CO_2$ EMISSIONS FROM REFINERY SOURCES**

| Source (fuel used) | Number of units | $CO_2$ emissions, MM mt/y |
|---|---|---|
| Combustion, stationary devices | | 2.960 |
| Steam boilers (refinery gas) | 10 | 1.160 |
| Process heaters (refinery gas) | 40 | 1.130 |
| FCCU CO boilers (refinery gas) | 1 | 0.079 |
| Internal combustion engines (natural gas) | 12 | 0.036 |
| Gas turbines (natural gas) | 3 | 0.378 |
| Flares | N.A. | 0.154 |
| Incinerators for SRU and tail gas treatment | 4 | 0.020 |
| Combustion, indirect | | 0.033 |
| Purchased electricity | -- | 0.033 |
| Venting | | 2.570 |
| Hydrogen plant (natural gas) | N.A. | 0.367 |
| Hydrogen plant (refinery gas) | N.A. | 0.232 |
| FCCU regenerator (coke) | 1 | 1.970 |
| Crude tanks | N.A. | -- |
| Maintenance and turnaround | N.A. | Included with flaring |

Refinery fuels include: coke; light hydrocarbon gases and liquid fuels, both of which are internally produced; and imported natural gas. It is clear that, per unit of energy, the refinery fuels differ significantly in the amounts of $CO_2$ that are produced by their combustion, with natural gas having about one half the emissions of coke, as illustrated in the table below.

**TABLE 3: $CO_2$ EMISSIONS PRODUCED BY CONSUMPTION OF REFINERY FUELS**

| Fuel | Refinery use | $CO_2$ emissions factor | |
|---|---|---|---|
| | | MM mt/quad (MM mt/EJ) | Mass or volume basis |
| Natural gas | • Fired heaters<br>• Steam boilers | 53.15 (50.38) | 120.6 lb/1,000ft$^3$<br>1.932 mt/1,000m$^3$ |
| Refinery gas | • Fired heaters<br>• Steam boilers | 64.10 (60.80) | -- |
| Distillate fuel oil | • Fired heaters<br>• Steam boilers | 73.19 (69.37) | 940.1 lb/b<br>2.682 mt/m$^3$ |
| Residual fuel oil | • Fired heaters<br>• Steam boilers | 78.87 (74.76) | 1,093.4 lb/b<br>3.119 mt/m$^3$ |
| Coke | • FCCU regenerator | 102.10 (96.78) | 1,356.5 lb/b<br>3.870 mt/m$^3$<br>3.384 mt/mt |
| Coal | N.A. | 93.20 (88.34) | 2.16 mt/mt |

As is known in the refining industry, crude quality plays a major role in determining refinery GHG emissions; lower API gravity and higher sulfur content correlate to increased refinery $CO_2$ emissions. Not surprisingly, crudes with lower API gravity and higher sulfur content also correlate to 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). These correlations are thought to be attributed to two major factors. First, lighter, sweeter crudes require less conversion and desulfurization; and second, for lighter, sweeter crudes, the refinery's energy requirements are met by more low-carbon fuel gas and less coke, fuel oil, and other higher-carbon streams. On the other hand, many heavy, sour crudes will also contain high levels of nitrogen and metals, requiring further processing and adding to refinery $CO_2$ emissions per barrel of crude processed. However, even crudes with similar API gravity, sulfur, nitrogen, and metals content will not necessarily yield similar amounts of $CO_2$ per unit of product produced, because other crude properties such as the distribution of hydrocarbons (i.e., naphtha, distillates, gas oil), and the type of heteroatom compounds play a role in emissions, as well.

A refiner can perform a life-cycle assessment (LCA) or "well-to-wheels" analysis of the environmental impacts of different transportation fuels. In fact, the allocation of refinery $CO_2$ emissions to individual petroleum products is extremely useful when a refinery wants to control its variable costs associated with $CO_2$ emissions from different products. The complexity of today's refineries—in which a given product (e.g., gasoline) is involved with several refining units and a given refining unit produces multiple products—means that there is no unique way to allocate emissions to finished products. One approach that has been used is to perform the allocation in a way that reflects how the refinery's emissions would be changed by a quantitative variation in the product slate, as discussed in this Report. An example is shown in the following table.

**TABLE 4: $CO_2$ EMISSIONS FROM VARIOUS REFINERY CONFIGURATIONS**

| Refinery configuration* | $CO_2$ emissions, mt $CO_2$/mt product | | | | |
|---|---|---|---|---|---|
| | LPG | Naphtha + gasoline | Diesel | Fuel oil | Overall refinery, mt $CO_2$/mt crude |
| HSK | 0.297 | 0.287 | 0.138 | 0.185 | 0.205 |
| HSK + VB + FCC | 0.943 | 0.416 | 0.172 | 0.374 | 0.337 |
| HSK + VB + HCU | 0.362 | 0.500 | 0.174 | 0.290 | 0.325 |
| HSK + DC + HCU | 0.318 | 0.420 | 0.171 | 0.503 | 0.329 |
| HSK + VB + FCC + HCU | 0.478 | 0.414 | 0.204 | 0.445 | 0.362 |

*HSK—hydroskimming, VB— visbreaking, FCC— fluid catalytic cracking, HCU— hydrocracking

However, there are concerns with the allocations mentioned above. One is that they might not reflect what happens when marginal changes occur in the product slate. At present, schemes are being developed that use linear programming.

This Report looks at how production of $CO_2$ by refineries is being impacted by the fuels that are being used, the crudes that are being processed, and the product slate that is being produced. The allocations of emissions to specific refinery fuels and products are also covered. There are detailed discussions on the implementation of refinery carbon accounting; i.e., means for monitoring and estimating $CO_2$ emissions. Furthermore, case studies are presented to examine the costs and benefits of various options and to identify competition in market supply and demand of combustion fuel, crude oils, and refined products on regional and global bases.

## Energy Efficiency Improvements

Efficient use of energy has both economic and environmental benefits. For industries, while it lowers production costs and raises productivity, it also reduces emissions of various pollutants, including GHGs like $CO_2$. As an economic factor, the cost of $CO_2$ emissions changes the calculation of the value of energy efficiency improvements, and so it may provide viability for energy-saving projects that otherwise would not be economical. Regardless of the cost of $CO_2$ emissions (as determined by government regulations and/or market forces), projects that improve refinery energy efficiency can provide a positive return on investment in the current economy.

Our 2007 Report on Energy Management (titled "Future Refinery Operations to Meet Fuel Supply Security and Environmental Requirements") provides details on opportunities and means for refiners to improve energy efficiency. Coverage of energy efficiency in the present Report, however, is in terms of reducing the use of energy sourced by the combustion of fossil fuels. Specifically, this report focuses on energy and fuel savings in refining operations and provides quantitative estimates translating energy savings into $CO_2$ emissions reductions.

For refiners, energy matters should be viewed from two alternative perspectives to ensure a comprehensive improvement approach. Considering strategies to optimize both the supply side and the demand side of refinery energy usage will provide refiners with the opportunity to maximize the benefits of an energy-saving project. Supply-side energy efficiency focuses on improving the efficiency of utility generation to ultimately lower the necessary input of natural gas, petcoke, coal, fuel oil, or fuel gas to meet plant demands. The demand side of energy efficiency—which will be discussed later and organized by processing unit—involves reducing the energy consumption of each process in the plant on a per-barrel-of-throughput (or product) basis.

Due to the impending implementation of carbon cap and trade systems, investment in energy savings on both the supply and demand sides must now include a factor accounting for the cost of carbon emissions. This Report will translate the benefits from (1) improving energy supply efficiency and (2) lowering overall energy demand into economic savings and actual $CO_2$ reductions.

## Supply Side

Utility generation to meet refinery requirements is one of the largest consumers of energy in the plant, accounting for around 40% of a refinery's total operating costs, and utility management techniques can be applied to steam, heat, and electric power systems in a refinery with varying investment requirements and benefits. According to the US Dept. of Energy's 2002 Manufacturing Energy Consumption Survey (MECS), 1.717 quad of the energy distributed to conversion units went to fired heaters, 0.017 quad was for process cooling, and 0.178 was for driving machinery like pumps, compressors, mixers, etc. Also, 0.672 quad was sent directly to processing units as steam. It is clear that the single greatest demand for energy in the refinery comes from fired heaters, with steam in second place. The survey indicates that the losses in energy before reaching the processing units was 31.5% of the total supplied, or 0.976 quad. If energy management could save 10% of that, or about 0.1 quad, then this could reduce $CO_2$ emissions by 5-10MM mt/y, depending on the overall mix of fuels. This reduction is about 2-4% of the total emissions in 2002. Specific opportunities for savings in the supply, transmission, and conversion of energy along with corresponding reductions in $CO_2$ emissions are discussed in this Report.

Power, steam, and heat consumption in refineries represents a massive portion of overall plant energy demands. With increasing overall crude throughput, more stringent product specifications (e.g., sulfur), and the processing of heavier crudes, the consumption of both electricity and steam has been increasing over the past several decades.

The first step in supply-side energy management is to evaluate the plant's total utility demand. Electricity requirements to drive pumps, compressors, motors, fans, cooling systems, lighting, etc. for the average refinery approach 8% of the total energy demand, versus approximately 30% for steam. The average refinery's heat consumption rate ranges between 330K Btu/bbl and 550K Btu/bbl. Once plant demands are determined, the focus of supply-side energy efficiency is to improve the overall efficiency of utility generation to meet energy demands with a lower combustion fuel input.

The combustion efficiency improvements identified in this Report, along with the installation of efficient cogeneration units, can help refiners improve energy management in steam, heat, and power generation.

### *Power, Heat, and Steam Supply via Cogeneration (or CHP)*

For separate generation of electricity, steam, and heat, the achievable efficiency of each process is limited by the best available technology. For power generation, average efficiency is usually in the range of 30-45%; state-of-the-art steam boilers provide approximately 80% efficiency; and the efficiency for the average furnace installed in a refinery is estimated at 70-82%. To add to this, many refiners are operating older units that were designed below current state-of-the-art efficiency ratings and/or operating units that have decreased in efficiency due to natural occurrences related to service time (i.e., fouling). Combined heat and power generation efficiency can approach 80%, resulting in an overall efficiency improvement of 27% compared to generating the utilities separately. A limiting factor for refiners, however, may be the sourcing of utilities. If a particular refinery traditionally imports electricity, then the installation of cogeneration technology may not be as attractive as it would be to a refiner that generates all utilities onsite.

The basic need for clean, cost-effective, efficient power is present in every refinery operation throughout the world. However, oil refiners have traditionally been skeptical about constructing power plants onsite due to their limited electricity requirements (usually about 60 MW for a stand-alone refinery) and the capital intensity of such projects. Besides the legislative requirements of capping $CO_2$ emissions, the recent trend toward liberalization of the electricity market (particularly in the EU) combined with an increasing need to dispose of refinery waste streams has led many to reconsider their options. Combined heat and power (CHP), or cogeneration (cogen), has emerged as an efficient way to meet increasing energy demands while maintaining superior environmental performance. In 2002, it was estimated that 26% of electric power consumed by refineries was generated by onsite cogen operations. Traditional CHP methods primarily include gas turbines, reciprocating engines, microturbines, combined boiler/steam turbine configurations, and combined-cycle implementations.

Despite these factors, CHP installations have decreased in recent years; however, the contemporary trend to cap emissions ($CO_2$, $NO_X$, etc.) has once again jump-started the research and development effort for cogeneration technology. Cogeneration is widely viewed as an effective option to improve efficiency and meet environmental standards in the future for large-scale industrial plants.

In the refining sector, the installation of CHP will largely depend on plant demands and the capabilities of each type of system. Reciprocating engines and microturbines are best suited for facilities requiring a significant amount of electricity, while the heat supplied may be limited to low-pressure steam or hot water. Alternatively, gas and steam turbines (and also combined-cycle implementations of the two) produce a significant amount of high-temperature exhaust that can be used to generate high-pressure steam or used directly for process heating in addition to the electricity supplied.

This Report will evaluate currently available CHP technologies to determine those most applicable to the refining industry in terms of efficiently meeting a refiner's heat and power demands. Additionally, a study of current and future R&D trends will provide an estimate of the emerging cogeneration technologies that may be of interest for refiners moving forward.

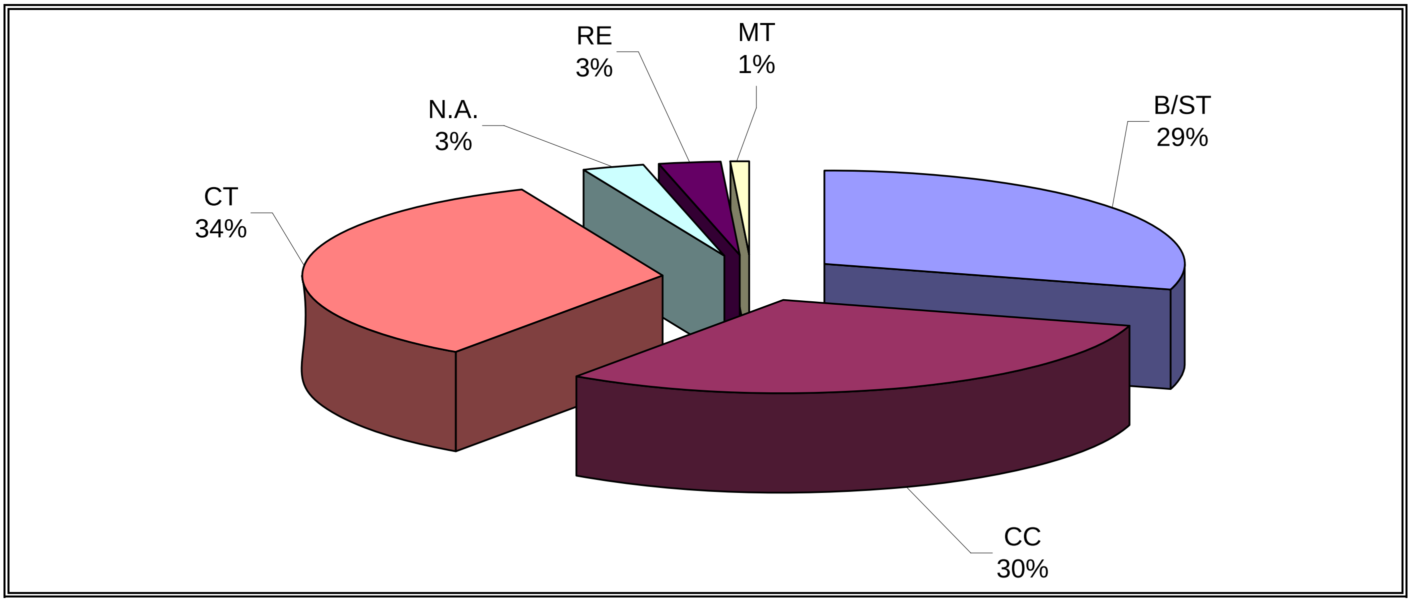
Other factors that may contribute to the value of these technologies include the polygeneration of additional utilities (e.g., hydrogen) and the ability of refiners to profitably export excess electricity, heat, hydrogen, and/or chemical feedstocks to other industrial, residential, and commercial consumers. The following table displays calculations for the efficiency of common CHP systems being fired on natural gas.

**TABLE 5: EFFICIENCY OF NATURAL GAS-FIRED CHP SYSTEMS**

| Prime mover (fuel) | Nominal capacity, MW | Effective electrical efficiency, % | Steam/heat output, MM Btu/hr (MW) | Power-to-heat ratio | CHP efficiency, % | $CO_2$ emissions lb/MWh |
|---|---|---|---|---|---|---|
| Gas turbine w/HRSG (NG) | 1-40 | 49-66 | 8.31 (2.4)-129.27 (37.8) | 0.47-1.06 | 66.3-72.1 | 1,079-1,877 |
| Microturbine | 0.035-0.250 | 46.7-58.9 | 0.17 (0.051)-1.20 (0.351) | 0.53-0.69 | 63.8-71.2 | 1,377-1,736 |
| Reciprocating engine (NG)* | 0.1-5 | 67-78 | 0.61 (0.179)-15.23 (4.500) | 0.56-0.79 | 73-79 | 1,024-1,404 |
| Steam turbine (chemical plant) | 0.5-15 | 75.1-77.8 | 19.6 (5.7)-386.6 (113.2) | 0.09-0.13 | 79.5-79.7 | N.A. |
| Fuel cell (PAFC) | 0.2 | 81.9 | 0.850 (0.249) | 0.80 | 81 | 0.035 |
| Fuel cell (PEM) | 0.01-0.20 | 53.58-65.01 | 0.04 (0.012)-0.72 (0.211) | 0.85-0.95 | 65-72 | 0.06 |
| Fuel cell (MCFC) | 0.3-1.2 | 56.48-56.67 | 0.48 (0.141)-1.90 (0.557) | 2.13-2.16 | 62 | 0.02 |
| Fuel cell (SOFC) | 0.125 | 74.02 | 0.34 (0.1) | 1.25 | 77 | 0.05 |
| *Heat recovered as hot water | | | | | | |

A survey of all US refinery-related CHP facilities was conducted based on both the fuel type and the prime mover. As can be seen in the following figure, combustion turbines (CT) made up the largest demographic with 34% of the CHP plants, while combined-cycle (CC) and boiler/steam turbine (B/ST) plants followed closely with 30% and 29%, respectively. The remaining 7% of US cogeneration plants utilized reciprocating engines (RE—3%) and microturbines (MT—1%) with information for the remaining 3% being unavailable.

**FIGURE 1: BREAKDOWN OF REFINERY-RELATED CHP FACILITIES IN THE US**



Refiners have already begun to invest in CHP technologies to take advantage of the improvement in energy efficiency with a strong ROI, and the implementation of carbon-cap-and-trade policies in many regions around the world will further improve the economics of such projects. Recent refinery cogeneration projects that are discussed in this Report include:

- ExxonMobil's 126-MW CHP at the company's Antwerp refinery in Belgium;
- Chevron's Richmond, California refinery in the US is planning a 43-MW CHP plant using a GE turbine;
- BP's Whiting, Indiana refinery in the US installed a 525-MW plant that cost about $210MM;
- StatoilHydro's Mongstad, Norway refinery is planning a 280-MW cogen plant to be started in 2010;
- Tesoro's Salt Lake City refinery in the US started up a 22-MW CHP project and has realized a simple payback period of 4.2 years.

### *Cogeneration using IGCC*

In the refining sector, one emerging cogeneration option is Integrated Gasification Combined Cycle (IGCC). This technology capitalizes on both market trends and the constant drive to improve efficiency and integration within the refinery. Furthermore, hydrogen supply is considered to be an increasingly important issue in hydrocarbon processing. Many processing units throughout a typical oil refinery use large volumes of $H_2$, which can become a great financial burden. Refiners can take advantage of these situations by <u>integrating large, efficient integrated gasification combined-cycle plants into their facilities to cheaply generate power and steam, as well as a significant supply of hydrogen gas</u>.

Gasification converts a range of carbonaceous feedstocks into clean syngas for the production of hydrogen, steam, chemicals, and electricity. Currently, coal accounts for 49% of this feedstock, petroleum provides 37%, and the remaining 14% is provided by a combination of natural gas, petroleum coke (petcoke), and biomass/waste. In the next few years, the majority of new gasification projects will involve the use of coal as the primary feedstock. However, the processing of petroleum refinery residues, petcoke, and waste streams will have an added significance in a GHG-constrained world.

The syngas from a gasifier can be sent to a CO shift reactor for $H_2$ and chemicals production or be routed to combined-cycle turbines as part of an IGCC plant for power generation. IGCC is considered the most efficient conversion method to process solid feeds to yield electricity. Several IGCC operations are associated with refinery applications around the world to process low-value residues and petcoke for the production of power, steam, and $H_2$. The addition of an IGCC complex in an existing refinery also offers a more cost-effective approach to reducing emissions than other abatement technologies. The actual reductions that can be achieved include 40% of $CO_2$ emissions and 80% of $SO_X$, $NO_X$, CO, and particulate emissions. Additionally, interest in carbon capture and sequestration (e.g., for enhanced oil recovery in nearby, declining oil fields) is a key selling point for IGCC projects. High $CO_2$ concentration in gasification product streams provides needed economy of scale, and the benefits would be further magnified when combined with gasification of biomass in the future. Furthermore, recent US legislation included in the Energy Policy Act of 2005 authorized $1.65B for clean coal projects, including $800MM specifically for IGCC. The EPA also allotted $300MM in tax credits for gasification projects not directly associated with power generation. Government involvement in the development of gasification and clean coal processes will hasten the progress and availability of these breakthrough technologies. A number of refiners have already turned to IGCC technologies, and additional projects are in the planning, engineering, and construction phases:

- Valero's Delaware City (US) IGCC project was started up in 2002 and cogenerates the equivalent of 283.68 MWe of energy;
- Four refinery-related IGCC plants have been installed in Italy (Sannazzaro, Falcanora, Puertollano, and Priolo Gargallo) to cogenerate a total of 1,513 MWe of energy equivalent;
- Esso Singapore's Jurong Island refinery cogenerates the equivalent of 198.57 MWe via IGCC fed by refinery residuals;
- Furthermore, several IGCC plants remain in the planning stages in the US, fed by coal and/or petcoke and other refinery residuals.

This Report analyzes the growing importance of IGCC for CHP generation. IGCC can take advantage of a wide range of available feedstocks to efficiently and cleanly meet a refinery's utility needs.

## Demand Side

Looking at the demand side of energy efficiency can also provide significant energy savings and reductions in $CO_2$ emissions for refiners on a per-barrel-of-throughput basis. Ultimately, management strategies that focus on more energy-efficient processing technologies for either new installations or revamps will reduce the fuel input required for the refinery and directly translate into reduced $CO_2$ emissions. Additionally, utilizing waste heat and reusing carbon-containing offgases for combustion will lower the amount of $CO_2$ being released into the atmosphere. Specific technology improvements that can be applied throughout the refinery will result in energy savings and $CO_2$ emissions reductions.

### *Utilities*

Managing utility distribution systems (i.e., heat, steam, electricity, etc.) can provide opportunities to reduce the overall demand for these utilities. Substantial improvements relating to energy efficiency can be made to heat distribution systems. Heat is distributed throughout a refinery system through various Heat Exchanger Networks (HENs). Optimizing HENs as well as improving heat exchanger performance will increase energy savings. Additionally, energy savings can be realized through optimization of steam distribution. Some of the most intense steam-consuming processes include steam cracking, distillation, and process heating. The US DOE estimates that an energy savings of about 12% can be realized at most refineries from optimizing steam systems. PINCH analysis, which uses a systematic analysis of the first and second laws of thermodynamics, can be used to match sources and sinks for both heat and steam systems to improve the efficiency of the distribution systems and reduce the overall plant demand. PINCH analysis will be particularly useful for optimizing HENs in the refinery. Other energy-intensive units, such as furnaces, boilers, and refrigeration units, offer the opportunity to recover and redistribute heat to minimize fuel consumption. This Report further examines heat and steam systems and the impact that optimization of the distribution network through PINCH analysis and simple maintenance can have on the energy efficiency of the utility system.

In terms of energy sources, the vast majority of the energy for process heating comes from fuels, as discussed above. In contrast, more than half of cooling needs are met by electric power, and this is also the source for most of the energy required for operating machinery. This Report presents opportunities and new technologies that may be implemented in refineries to limit electricity losses during distribution to electricity-intensive processes and equipment.

Conventional refining requires a great deal of hydrogen, and furthermore, refinery hydrogen demand has been expanding at a rapid rate due to more stringent specifications for refined products. Many refiners view the $H_2$ production and distribution networks similar to a utility system, and therefore integration can be achieved through PINCH analysis. Improvements in energy efficiency during hydrogen production in steam reformers can lead to an increase in overall energy savings; however, these advances will be discussed in the section 'Strategic Application of Energy Efficiency Improvement in Refining Processes.' Hydrogen recovery is another way to save money on hydrogen production. Important factors in hydrogen recovery are cost and purity of the recovered $H_2$ streams. Current technologies include cryogenic distillation, pressure swing and thermal swing adsorption, and membranes. This Report offers strategies to manage refinery hydrogen distribution systems and improve $H_2$ recovery to reduce overall energy consumption and $CO_2$ emissions associated with $H_2$ use.

### *Process Hardware and Operations*

To improve demand-side energy efficiency in processing units, refiners have many options relating to installed hardware and revamp opportunities and adjustments in process operations. Hardware advancements can be categorized into five general areas: heat transfer/recovery, separation, reaction vessels/metallurgy, auxiliary equipment (vacuum ejectors, pumps, valves, etc.), and catalyst considerations.

- **Heat Transfer/Recovery.** Heat transfer efficiency of heat exchangers will impact the refiner's ability to recover wasted heat from refinery processing units. Fouling and scaling of refinery heat exchangers effectively limits the efficiency of heat exchangers, and steps to avoid these occurrences are wide ranging. Some options for refiners include conducting maintenance activities, using chemical additives to reduce deposits, and implementing state-of-the-art technologies designed to limit fouling. Self-cleaning and zero-fouling heat exchangers are currently available and can significantly improve energy efficiency and lower $CO_2$ emissions. Alfa Laval recently announced that a planned replacement of older heat exchangers in a Russian refinery would result in an annual reduction in energy consumption of 340 MW, translating to an estimated $CO_2$ emissions reduction of 850K mt/y. Other minor improvements can be made to heat exchangers, such as installing tube inserts to improve turbulent flow, resulting in better heat transfer. Steam tracing techniques are also discussed in relation to refinery energy consumption and $CO_2$ emissions.

- **Separation Techniques.** Improving efficiency of separation in distillation and fractionation units will help to reduce the energy required for some of the more energy-intensive processes in the refinery. Improvements to distillations trays, settling units, and fuel gas and hydrogen recovery techniques are the primary focus of this section. Combining multiple distillation units (i.e., atmospheric and vacuum towers) into one divided-wall column can significantly reduce the amount of heat required for separation, and will have the additional benefit of reducing plot space for the distillation units. Progressive distillation technologies typically provide a more efficient use of process heat and result in reduction of heat demand from the distillation columns. Improved tray configuration may also contribute to separation efficiency. In terms of fuel gas and hydrogen recovery, membrane and adsorption processes are considered low-energy alternatives to conventional cryogenic separations. A look into R&D work on industrial-scale membrane technologies is included to evaluate those options that would be favorable for refinery implementation.

- **Reaction Vessel/Metallurgy.** Metallurgy and configuration of refinery reaction vessels will impact the energy demand of specific processes. Low-profile reactors for various processes are beneficial for refiners with plot space limitations and also to provide maximum efficiency by allowing lower pressure and temperature operations with shorter residence times.
- **Auxiliary Equipment.** Conventional motors, pumps, fans, and compressors are used in refineries to convert electricity into process work. In the latter three, motor use will account for about 95% of the electrical consumption and, therefore, optimization of these units will primarily focus on optimization of the motor. Motor systems account for 80% of electricity used in a refinery. About 55% of this electricity is lost due to conversion inefficiencies and distribution problems. Through various improvements, motor efficiency can be improved by about 12-15%, on average. The best way to improve efficiency within this area is to use both a systems approach while also looking to improve individual components. Motor, pump, and fan optimization can encompass several different concepts. Beyond the size of the pump, several other areas that can lead to inefficiencies include unnecessary operation of backup pumps, varying flow rate requirements, excessive noise, heat or vibration, and inadequate piping systems. Novel vacuum generating technologies (e.g., ejectors) can also yield efficiency improvements, as creating a vacuum environment is often a very energy-intensive process.
- **Catalyst and Process Design Considerations.** The refining catalyst industry is constantly producing novel catalyst formulations and shapes to enhance process yields and improve product quality. Some of these technologies may also result in significant energy savings for refiners. Catalysts with improved activity at lower temperatures and pressures can alleviate the demand for heat in some processes. For example, commercially-available solid acid alkylation processes have been claimed to reduce power consumption by 50% compared to conventional liquid acid technologies. Improved catalyst recycle/regeneration strategies can also offer limited improvements in the total energy consumption of processing units. On the process side, hydrogen-saving two-phase hydroprocessing, low-temperature fluidized-bed hydrotreating, and emerging energy-powered product treating methods (e.g., SulphCo's Sonocracking$^{TM}$ technology) are examples of energy efficiency and $CO_2$ reduction technologies refiners should consider.

Process operation strategies to promote energy efficiency are primarily related to various process monitoring, optimization, and control techniques. Several different companies offer energy and $CO_2$ management software programs to be used during the planning and operating stages of oil refining. The majority of these programs can be easily operated by refinery personnel after basic training. Some of the more advanced programs may require more in-depth training that is often offered by the company. In general, these software packages use onsite and historical data to set operational targets and efficiency goals. The data is used to generate predictive models with optimized designs. During operation, several of these programs can be used as process monitors and for advanced process control.

This Report will assess a wide range of technology advances used to improve energy efficiency and reduce $CO_2$ emissions in an industrial setting. The technologies and operational techniques will be evaluated with a focus on implementation in a refinery setting to provide energy use and $CO_2$ reductions with a positive return on investment, regardless of the price of carbon allowances.

### Strategic Application of Energy Efficiency Improvements in Refining Processes

To manage energy effectively in a refinery setting, it is not only necessary to explore improvements on a site-wide basis but also focus on individual processing units' contribution to energy performance. This Report will serve to assist refinery operators in identifying the main contributors to energy inefficiency on an individual unit basis, as well as offer several methods to improve savings. The latest technological developments are discussed in the previous sections to present a glimpse into the future of refining technology and processes. Many of the strategies discussed here are commercially proven and supported by success stories from various refineries throughout the world.

- The *crude distillation unit* (CDU) is the largest energy consumer in a refinery, and overall savings of up to 55% ($5.9MM/y in a 5MM-mt/y [100K-b/d] refinery) can be achieved by improving energy use in this unit. Fouling control, heat integration, and novel technologies can be implemented to realize these savings.
- In the *FCCU*, a net energy producer, energy use can be reduced by 28% by implementing power recovery operations, minimizing heat loss, and implementing various other improvements.
- An estimated 31.5% energy savings is available in the *catalytic hydrotreater* through improved heat recovery with PINCH analysis and optimization of the preheater configuration.
- Additional strategies are discussed in this Report identifying methods to reduce energy consumption by 23% in the *catalytic reformer* and 38% in the *alkylation unit*; furthermore, various other energy-saving measures in remaining refinery process units are discussed.

The recommendations of this Report offer efficiency improvements through revamps and retrofits as well as designing grassroots refineries with integration as a primary focus. Following the discussion of various technology options and advances, potential improvements are discussed on a unit-by-unit basis to target the most effective areas for energy savings and emissions reductions in the refinery.

## Using Renewable Sources of Energy

At the Renewable Energy Finance Forum—Wall Street 2009, Don Paul, current executive director of the Univ. of Southern California's Energy Institute and former chief technical officer of US oil major Chevron, recently cited five reasons why he believes Big Oil will be a major player in the renewable energy business: (1) an increase in alternative fuels would allow firms to divert natural gas from existing petroleum refining operations to market, (2) existing production sites can be converted to solar and wind power projects, (3) power infrastructure can be integrated with NG as a backup for other feedstocks, (4) geothermal power is a natural fit with the oil and gas industry, and (5) opportunities for biofuels integration already exist. However, a recent report by the US National Research Council titled "Electricity from Renewable Resources: Status, Prospects, and Impediments" noted that renewables are currently not used on a large scale because of lower cost-competitiveness of these technologies when compared to conventional sources of electricity, a lack of sustained policies, and infrastructure problems associated with moving renewable electricity to distant areas of demand. One way of making the cost of renewables more competitive with conventional energy sources is through a set cost for carbon emissions.

Recognizing the need to both mitigate GHG emissions and provide greater complementary sources of energy, several governments around the world are taking steps to boost the amount of power being produced from renewable sources by offering incentives to companies investing in renewables. Policy initiatives from governments, including feed-in tariffs, renewable portfolio standards, greenhouse gas controls, and a production tax credit, would greatly benefit the future growth of renewable energy use globally. Already there are initiatives in place in the EU, where renewable energy sources are to account for 20% of all power generated in 2020, up from 13.9% in 1997. China is looking to invest 3 trillion CNY ($440B) in solar, wind, and other renewable energy resources by 2020. In the US, beginning in 2012, $15B/y will be invested in renewable energy research, with funding provided by the auctioning of carbon emissions permits.

According to the American Petroleum Institute (API), the US oil and gas industry has already invested $6.7B in renewable energies like biofuels, solar panels, and wind turbines. Oil companies outside the US are also actively pursuing alternative power sources as a means to mitigate $CO_2$ emissions caused by the use of conventional electricity. Some of the applications target refinery operations, for example:

- BP has partnered with Chevron to build and operate a 22.5-MW wind farm at the jointly-owned Nerefco refinery near Rotterdam, the Netherlands. The project costs $23MM and generates enough electricity to supply 20K homes in the Netherlands while reducing $CO_2$ emissions by 20K mt $CO_2$/y.
- Indian Oil Corp. has commenced operations at its first wind power venture at Kandla in Gujarat, India. Electricity generated at the 21-MW wind farm is being used to power IOC's fuel storage and oil pipeline operations in Gujarat.
- Valero started up a 10-MW wind farm just outside of its McKee refinery in the Texas Panhandle in the US on March 31, 2009. The farm currently contains six turbines, but Valero hopes to expand this to 33 turbines by 2010 and raise the power-generating capacity of the farm to 50 MW.

- MOL is currently working on a project at the Duna Refinery in Hungary to use solar energy for lighting electricity and hot water generation. MOL has performed the technical assessment and selected buildings for the project. The refiner is looking to place the solar cells above buildings that consume large amounts of hot water and above some parking places to generate 23 kW of electricity to cover some public lighting consumption at the refinery.
- Shell Oil's Martinez, CA refinery in the US has installed a solar-powered circulator called the SolarBee, which aerates the waste treatment pond at a remote location. The new circulator, which replaces a diesel-power brush aeration system, is said to save $10K/y in energy costs over the alternative of hard-wired aerators and, most importantly, has consistently met the odor cap.

Only during the last few years have refiners begun looking into replacing conventional electricity with renewable sources, largely because of the poor economics of existing technologies and a lack of incentive and motivation to reduce carbon footprint on the refiners' part. However, the operating environment has changed as environmental governing bodies in developed nations are calling industries to reduce GHG. Non-complying companies will be subject to fines.

There are many hurdles for the refining industry to adopt alternative power onsite. The most important obstacle is technological know-how, which is outside the scope of refiner expertise. To circumvent this challenge and speed up the learning curve, refiners can either form partnerships with renewable energy companies or purchase the technology outright from outside vendors. The second impacting consideration is the cost-benefit factor, as carbon allowance is now part of the operating costs. Going forward, allocation of investment budgets could be difficult at times of weak refining margins due to fuel demand destruction in developed nations. Introduction of new energy sources means the rework of refinery energy balances in addition to finding space for new equipment. As demonstrated by the examples above, renewable energy can be used in various processing units and utility systems. Furthermore, a piecemeal or fragmented approach when introducing renewable energy is deemed wasteful of investments. Therefore, a comprehensive evaluation of both the availability of state-of-the-art technologies and refinery internal configurations and suitability must be undertaken based on short and long-term bases, particularly the need to estimate the benefits of $CO_2$ reduction in the future.

This Report focuses on the latest renewable energy developments that use wind, solar, biomass, geothermal, and tidal wave energy to generate electricity for refinery applications. The technologies must be economically viable and significantly reduce $CO_2$ emissions, compared with conventional electric supply on a life-cycle basis. The study also examines geographical locations, regulatory requirements, and tax policies in its case studies so as to present the economic advantages of traditional renewable sources as well as other innovations (e.g., a gas turbine driven by petroleum coke/biomass-generated hydrogen) being developed around the world. This

Report will present a checklist and a road map on how to implement renewable sources in refineries in different regions of the world over the next 30 years.

## Carbon Capture

"Carbon capture and storage," also referred to as "carbon capture and sequestration," or CCS, is regarded as an essential technology to meet the GHG reduction goals deemed necessary to avoid the forecasted irreversible effects of climate change. It is the only GHG reduction method that decouples fossil fuel usage from $CO_2$ emissions. Carbon capture R&D activities are mostly tailored to coal-fired power plants, the largest stationary source of $CO_2$ emissions. However, the refining industry, along with other sectors such as steel and cement production, is beginning to investigate CCS as a viable method of reducing GHG emissions. It is thought that, as the price to emit $CO_2$ rises, these energy-intensive industries will find CCS more worthy of investment. In fact, refiners are already investing to some degree, as is exemplified by work during Phase II of the $CO_2$ Capture Project, an international collaboration of oil companies. Phase II focused partly on refinery carbon capture developments.

CCS involves the production and recovery of carbon dioxide from industrial processes and is typically followed by drying and compression to approximately 2.2K psi (15 MPa) so that it may be shipped to storage sites via pipeline. The captured $CO_2$ can be injected into depleted oil and natural gas fields (DOGFs) and saline aquifers; it can be used for the recovery of methane from unminable coal seams and to recover oil and gas from DOGFs; it can be stored in the ocean by various mechanisms; or, alternatively, the $CO_2$ can be used as a chemical feedstock or for algal biofuel production, among other applications. Carbon-capture methods are commonly grouped into three technological categories: pre-combustion, oxycombustion, and post-combustion.

The predominant advantage of pre-combustion carbon capture is the availability of a high-partial-pressure $CO_2$ stream for capture. The method consists of converting a hydrocarbon fuel into syngas, followed by water-gas shift (WGS) to produce a $CO_2$ and $H_2$ stream from which $CO_2$ can be separated. For the refiner, this most often refers to the steam methane reformer (SMR), although FLEXICOKER, partial oxidation, autothermal reforming, and gasification units may also be in use in some refining complexes.

Oxycombustion—also called oxyfiring or oxyfuel combustion—refers to combustion with pure oxygen. Its advantage lies chiefly in the fact that, ideally, only water and $CO_2$ are produced in the effluent stream, which is cooled to condense and remove water vapor. Close to 100% of the $CO_2$ is captured at purities of 80-98%. Since $N_2$ is not present in the oxygen feed, $NO_X$ emissions are also reduced by an order of magnitude. In practical application, this technique often requires a $CO_2$-rich flue gas recycle to limit burner temperatures, which increases energy consumption. Refinery candidates for oxycombustion capture are, in principle, any process employing combustion; although, in practice, only the largest combustion sources of $CO_2$ would be considered. These emitters include the large boilers associated with the power/steam plant, major process heaters such as those on the CDU and catalytic reformer, and the FCCU regenerator. Oxycombustion requires an air separation unit (ASU) and some level of burner and oxygen injection system modification.

Post-combustion methods are end-of-pipe solutions for industrial combustion processes. Flue gases for post-combustion capture generally have less than 15% $CO_2$ and are near atmospheric pressure. In the refinery, any combustion exhaust is a candidate, but only the largest, high-partial-pressure sources of $CO_2$ are practical considerations. Such sources include the FCCU regenerator, the power/steam plant, or any large, combined stack.

The prospect of refinery carbon capture is primarily centered around one question: will the project achieve a desirable NPV? Unfortunately, the associated risks with carbon capture, particularly the unknown cost to emit $CO_2$, are making this question hard to answer. If refiners had a better sense of the cost to emit or capture $CO_2$, decisions could be made with greater confidence. In other words, making the decision to capture $CO_2$ depends heavily on reliably predicting profitability, and much less on technological feasibility. A reliable prediction of profitability will, in turn, depend heavily on accurate cost estimates of capture technologies and confidence in knowing the price of $CO_2$. The importance of a stable carbon price is exemplified in the case of StatoilHydro's Mongstad refining complex. There, the decision to capture $CO_2$ has already been made, thanks to a consistent Norwegian $CO_2$ tax.

For refiners considering CCS, the Report will address five key issues with detailed analyses and recommendations.

**Capturability.** This study reveals the most favorable capture areas in the refining complex. To this end, we provide a qualitative ranking of refinery units in terms of their prospect for carbon capture, or "capturability." Of course, the unique characteristics of each refinery will play a large role in determining which units are most amenable to capture.

**Capture Cost.** Cost data for refinery carbon capture is not widely published. Refiners can, however, undertake their own initial studies to prioritize units based on capture cost. We examine two widely-used metrics for carbon-capture cost analysis: cost of $CO_2$ avoided ($C_a$) and cost of $CO_2$ captured ($C_c$).

**Transport, Storage, and Other Costs.** The cost of $CO_2$ avoided ($C_a$) is generally applied to the emitting unit, although transport and storage costs must be factored in as well. These costs will vary based on the transport distance, the storage method, and the political and business environment of the CCS project. In order to portray some of the cost dynamics associated with $CO_2$ capture, and to illustrate the point at which refiners might choose to capture carbon instead of paying to emit, this turns to a scenario analysis, correlating cost of total $CO_2$ produced and refinery $CO_2$ emissions avoided by capture.

**Financial Impacts on Individual Refiners.** The total cost of $CO_2$ will vary depending on a refiner's circumstances. With the right capture technology and $CO_2$ product value, a refiner may pay \$5/mt or less to deal with $CO_2$. If conditions are ideal, CCS may even be profitable. On the other hand, differing circumstances could dictate a refiner paying $30/mt or more to address $CO_2$ if carbon prices reach their projected value by 2020. We present the effects of such costs on integrated oil firms, as well as on large and small independent refiners.

**Coordinating Capture, Transport, and Storage.** Even if a refiner finds the total cost to emit to be small or even negative and wishes to proceed with carbon capture, the initiation of the project cannot occur before transport and storage become available. That is to say, none of the three components of CCS make sense without the other two. To encourage the foundations of transport and storage networks, research activity concerning the technical, economic, and legal aspects of transport and storage is underway. The study discusses their availability and significance to actual deployment of CCS.

## Company Policies and Strategies in Carbon Management

This Report does not take any position in the debate over anthropogenic global warming. However, analysts and consultants preparing this study strongly advise that global refiners proactively formulate their $CO_2$ reduction strategies since government bodies, especially in developed nations, have enacted many climate change laws and guidelines.

Similar to the fuel reformulation regulations imposed on refiners in the last two decades, refiners who plan ahead and strategically implement tactics always benefit at the expense of less-prepared competitors. The overall scheme is how one can turn the impending challenges into opportunities in the marketplace. Furthermore, carbon management requirements could mean complete overhauls of operations ranging from types of crude feeds purchased, separation and conversion technologies being used, product slates, and utilities deployment, to existing relationships with suppliers and customers. The question is, "What will the refining business be by 2020, 2030, and 2050?" Many oil companies have already looked into this question and formulated basic strategies, as published on company websites and in recent company reports. To name a few:

**ADNOC:** "Overall [$CO_2$ emissions] reduced by 2%, which resulted from a 16% reduction in ADCO due to reduced flaring and fuel consumption, 7% reduction from GASCO, and 62% effect of GIP commissioning of Bunduq in previous year. Long-term, we can only achieve large-scale reductions of $CO_2$ emissions via alternative means and new technology (e.g., re-injection, sequestration, carbon capture, etc.). We are reviewing our strategic options for these."

**BP:** "We will participate across the hydrocarbon value chain to explore for, develop, and produce more fossil fuel resources that the world needs; efficiently manufacture, process, and deliver better and more advanced products; and be a material contributor to the transition to a low-carbon future…In Alternative Energy, we are focusing our investment activity in new energy technology and low-carbon energy businesses, which we believe will provide long-term options to meet energy demand and provide BP with significant long-term growth potential. These are wind, solar, biofuels, and carbon capture and storage (CCS)."

**ExxonMobil:** "Remained on target to improve energy efficiency by at least 10% between 2002 and 2012 across our worldwide refining and chemical operations…Reduced upstream hydrocarbon flaring by about 30%…Established flare management protocol in Nigeria, Angola, and Malaysia to rigorously monitor and manage flare events…Continued to make energy efficiency improvements both internally and for our customers…Added 125 MW of electric capacity through the startup of new, energy-efficient cogeneration facilities in Antwerp, Belgium."

**Japan Energy:** "We are making significant efforts to raise awareness of promoting energy savings and reducing environmental impact, while at the same time proactively installing and upgrading equipment at refineries and other production facilities for greater energy efficiency."

**Royal Dutch Shell:** "Our focus on managing $CO_2$ emissions remained strong. We continued to reduce the greenhouse gas emissions from the facilities we control or operate. These emissions have fallen by more than 30% since 1990, largely because of operational improvements like reduced flaring. We are involved in a number of demonstration projects for technology to capture and store $CO_2$ safely underground, including the first research pilot in Europe to inject $CO_2$ onshore. We would like these projects to move ahead faster and are working with governments to help them put the policies and incentives in place to speed up the development of this critical technology."

**StatoilHydro:** "Carbon dioxide emissions in 2008 have been as expected and approximately the same [as] in 2007. Carbon dioxide emissions decreased from 14.6M mt in 2007 to 14.4MM mt in 2008. Entering the production phase at Snøhvit at the beginning of the year caused increased emissions, while planned maintenance during the summer at several EPN installations reduced emissions. There has been a small increase in $CO_2$ emissions in NG and a small decrease in $CO_2$ emissions in M&M [manufacturing and marketing] due to planned maintenance and closure of plants."

**Suncor Energy:** "[We] established a team of senior leaders to identify the best opportunities for improving energy efficiency and for reducing greenhouse gas emissions across our operations. We continued to investigate and advance potential emissions-reducing technologies, including carbon capture and storage."

**Total:** "To reduce our greenhouse gas emissions, for example, we are working to gradually eliminate flaring of associated gas in our oil production operations and to increase the energy efficiency of our processes through sustained capital spending. In 2009, we'll be starting up a commercial carbon-capture-and-storage (CCS) pilot in Lacq, France. This is genuinely critical research: keep in mind that, according to the Intergovernmental panel on Climate Change (IpCC), CCS could eliminate 20-40% of global carbon emissions."

**Valero Energy:** "[We will] continue to improve energy efficiency and conservation at our facilities, continue to pursue recovery projects that will help mitigate $CO_2$ emissions, include 'carbon costs' in the financial evaluation of and decision-making related to strategic capital projects, [and] evaluate low-carbon opportunities for the production of transportation fuels, electricity, and chemicals."

Unfortunately, the majority of the information provided by these companies has been deemed vague, and as a result, is not considered to be very useful for our clients. Therefore, this section of the Report is devoted to identifying and analyzing company positions, benchmarking the industry norms, and recommending the directions our clients should take to stay ahead of the competition and sustain their businesses while achieving national energy security and environmental goals. To complement this discussion, the study also includes the results of a recent global refinery survey on carbon management strategies. So far, we have received responses from refiners on all inhabited continents. The questionnaire is extensive, covering company views on carbon cap and trade vs. carbon tax, energy management and efficiency approaches, power production and cogeneration, goals for adopting renewable energy sources, plans for carbon capture and storage, and more.

# TABLE OF CONTENTS

## (abbreviated)

Please visit http://www.hydrocarbonpublishing.com/ReportP/report2010toc.pdf for the complete TOC

ORDER INFORMATION

Please click http://www.hydrocarbonpublishing.com/store/product.php?productid=C00900&srchkey= to order this Report.