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REFINERY CO_2 MANAGEMENT STRATEGIES

Technology Solutions to Reduce Carbon Footprint
and Meet Business Sustainability Goals

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PROSPECTUS

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1.1 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. **Table 1** 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 83% by 2050 (as of July 16, 2009).
Canada	Targeting 20% cut from 2006-2020 and 60-70% cut through 2050.
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 (ETS) 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. • China: has goal to cut emissions by almost 50% on emissions-per-dollar basis by 2020. • 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. • New Zealand: plans 10-20% cut below 1990 levels by 2020. • South Korea: will reduce emissions by 2020 based on three different choices: 8% increase from 2005 levels, or keep levels steady to 2005, or 4% cut from 2005 levels. • Taiwan: plans 30% cut by 2020 from 2005 levels.

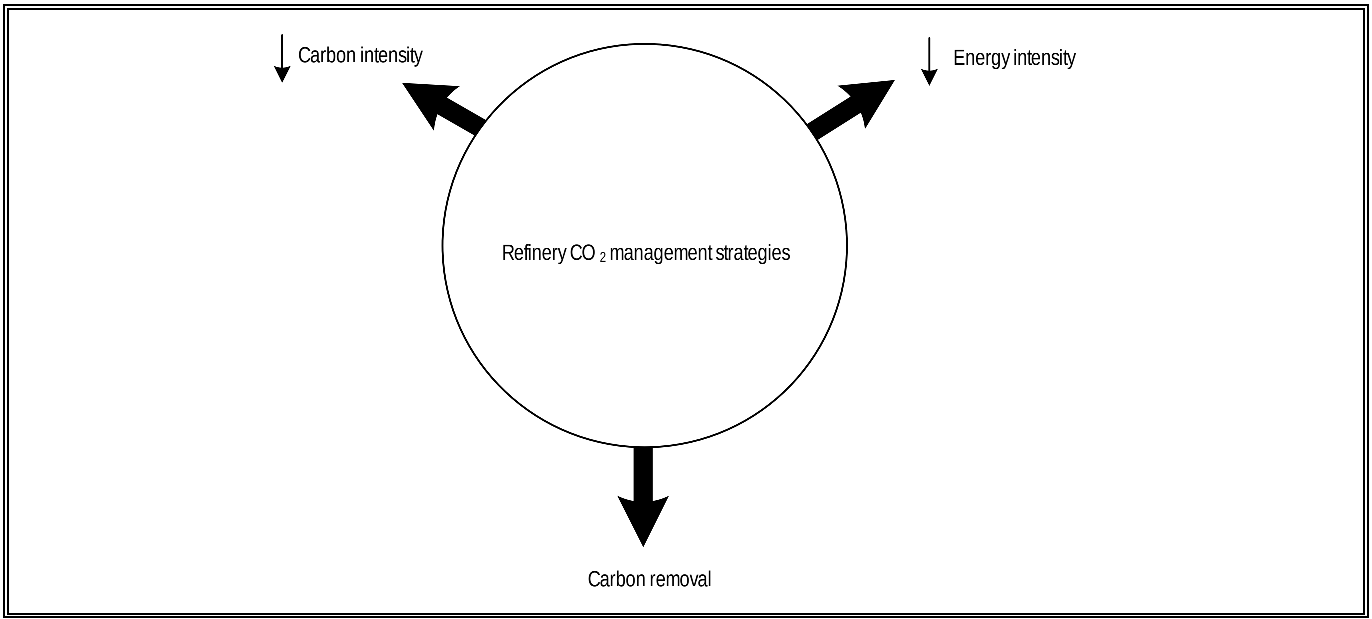
1.2 Report Methodology

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.

1.3 Report Focus and Scope

This Report focuses on three fundamental strategies to mitigate CO_2 emissions in a refinery based on a simple carbon balance. As illustrated in **Figure 1**, these strategies are to decrease carbon intensity, lower energy intensity, and remove carbon via capture and sequestration. These three strategies can be implemented by several approaches or tactics: selection of feedstock crudes and combustion fuels, types of fuels products, improvements in refinery energy supply and demand, and carbon capture and sequestration.

FIGURE 1: THREE STRATEGIES OF REFINERY CO_2 MANAGEMENT



1.3.1 Refinery CO_2 Inventorying and Reporting

According to the US Energy Information Administration (EIA), global, energy-related emissions of CO_2 totaled 29.195B mt in 2006, 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. As a major source of CO_2 emissions, it is increasingly important for refiners to inventory CO_2 emissions. In fact, companies have given five business reasons for inventorying their GHG emissions:

- Manage risks associated with GHGs and identify opportunities for reducing their emissions;
- Allow for public reporting of emissions and for participating in voluntary programs;
- Enable participation in mandatory reporting programs;
- Enable participation in GHG markets; and
- Gain recognition for taking voluntary actions.

Preparation of an emissions inventory comprises several functions—estimating/measuring, accounting, and reporting. The first of these is concerned with individual sources. The second involves collecting source data for an operation or business entity while maintaining links to source identities and locations. The third is concerned with aggregating the emissions data to the levels that are appropriate or mandated for different uses, such as participation in an Emissions Trading Scheme (ETS). It is obvious that the first two functions must be performed so as to allow for reporting at different levels of aggregation. Verifiability is a requirement for an inventory report, and this, too, will impact the estimating/measuring and accounting functions. This Report dedicates a separate section on inventorying and reporting refinery CO_2 emissions according to international standards (e.g. International Panel on Climate Change, IPCC), guidelines from industry associations (e.g. American Petroleum Institute), and requirements from government agencies (e.g. US EPA and European Commission.)

1.3.2 Impacts of Crude Types, Combustion Fuels, and Product Slate on CO2 Emissions

The majority of refinery CO_2 emissions are sourced from stationary combustion devices that convert a portion of fuel oil, purchased natural gas, and/or other high-Btu feedstreams into heat, steam, and power for processing. These emissions are also referred to as energy-related emissions. An estimation of CO_2 emissions from various point sources at a hypothetical 250K-b/d refinery with a hydrogen plant and an FCCU is shown in **Table 2,** as provided by the American Petroleum Institute.

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

Since stationary combustion is the most significant contributor to refinery emissions, it is important to investigate the specific fuels that are combusted in a refinery to meet utility demands. Refinery fuels typically include: coke; light hydrocarbon gases and residual fuel oil, both of which are internally produced; and imported natural gas. It is clear that, on the basis of energy content, the refinery fuels differ significantly in the amount of CO_2 that is produced during combustion; as illustrated in **Table 3,** natural gas fuels emit approximately one half of the CO_2, per unit of energy, that is produced from the combustion of petroleum coke.

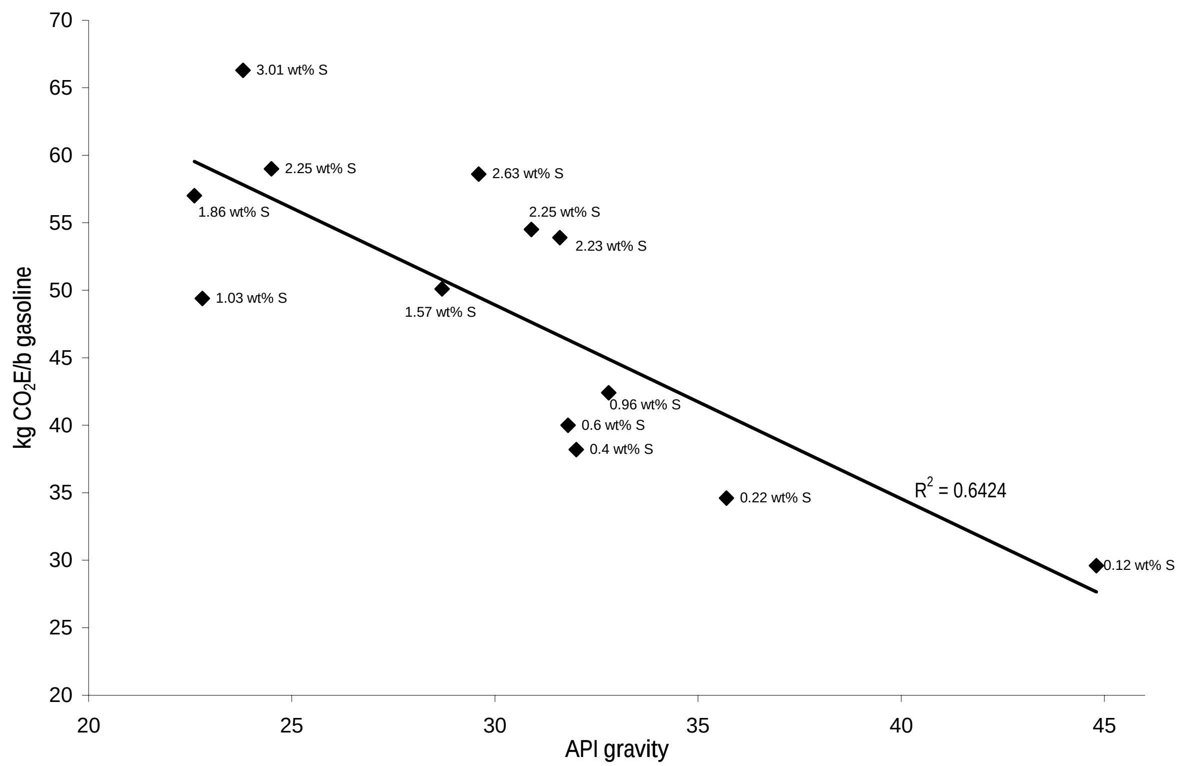
TABLE 3: CO_2 EMISSIONS PRODUCED BY CONSUMPTION OF REFINERY FUELS

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

Additionally, as it 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 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), which, in turn, lead to higher CO_2 emissions per barrel of crude processed. 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 a greater percentage of low-carbon fuel gas and less coke, fuel oil, and other higher-carbon streams. Additionally, many heavy, sour crudes will also contain high levels of nitrogen and metal contaminants, requiring further processing and adding to refinery CO_2 emissions. 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, as explained in the Report.

Figure 2 shows the relationship between refinery CO_2-equivalent emissions per barrel of gasoline produced and crude quality in terms of sulfur content and API gravity.

FIGURE 2: REFINERY CO_{2E} EMISSIONS AS A FUNCTION OF CRUDE QUALITY



The noted effects of crude quality on refinery GHG emissions have several implications for <u>opportunity crudes processing</u>. First, refiners looking to take advantage of these crudes will now have to consider the resulting effects on refinery CO_2 emissions. Depending on crude and CO_2 prices, many crude discounts may be negated by the cost to emit CO_2. Essentially, the CO_2-emitting potential of a crude will have an impact on its value according to the cost of carbon. This situation will influence both upstream and downstream decision making. <u>Consequently, crude discount models may begin incorporating a crude's CO_2 potential alongside other quality measurements, like API gravity, TAN, and sulfur content</u>.

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 <u>allocation of refinery CO_2 emissions to individual petroleum</u>

products is extremely useful for refiners wanting to control the 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. As explained in this Report, one approach which 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.

This Report is designed to evaluate how the production of CO_2 by refineries is being impacted by the combustion 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. Furthermore, case studies are presented to examine the costs and benefits of various options.

1.3.3 Energy Efficiency Improvements

Although there are many approaches to energy management, this Report is laid out in terms of supply-side vs. demand-side energy requirements in order to ensure a thorough evaluation of generation, distribution, and consumption of refinery heat, steam, and power.

1.3.3.1 Supply Side

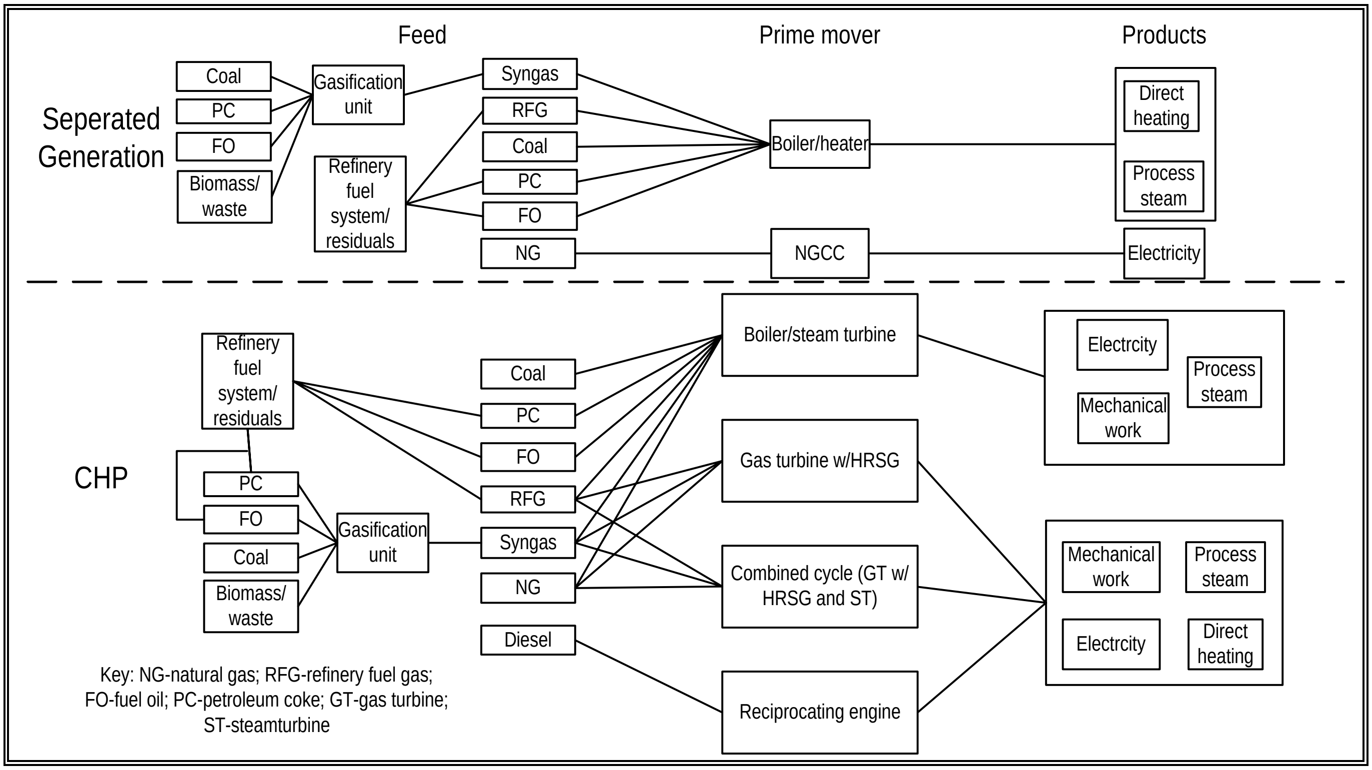
The most significant consumers of fuel in a refinery are the **process heaters**; accordingly, the largest emitter of CO_2 in a refinery plant is attributed to stationary combustion. Almost every refinery process is carried out at elevated temperatures, and a great deal of energy is spent to achieve these high temperatures. As a result, any thorough energy management strategy should look to the efficiency of process heat supply as an opportunity to improve overall plant efficiency, provide fuel savings, and reduce CO_2 emissions coming from the processing plant. Conventional fired heaters operating at ~80% efficiency can be enhanced with the installation of several auxiliary components with a range of investment costs to improve efficiency up to about 93%. Additionally, advanced technologies exist that operate with efficiencies closer to 95% that require somewhat larger capital investments. For example, depending on the temperature of the exhaust gas, fuel consumption can be reduced anywhere from 13% to 51% by preheating combustion air. The reduction in fuel consumption translates into an improvement in heater efficiency of 8-18%. Additionally, recent attention to limitations placed on harmful NO_X emissions coming from stationary combustion sources has forced refiners to evaluate combustion systems, and has further increased the interest in process heaters improvements. Heater configuration can influence maximum efficiencies for process heating applications. While many of the adjustments made to limit NO_X emissions have actually increased fuel consumption (i.e., low NO_X burners) and subsequently increased CO_2 emissions, some technology options are available to improve the overall efficiency and reduce both NO_X and CO_2 emissions.

Similarly, significant energy savings can be realized from the optimization of refinery **steam systems**. In the average refinery, about 25-30% of the consumed energy can be attributed to the steam system.

Conventional steam generation boilers operate in the efficiency range of 75-80%, depending on the type of boiler and the fuel used. A number of relatively low-investment process improvements are available to increase this number by up to ~8%. Furthermore, novel, high efficiency boilers are being developed that integrate steam generation and heat recovery technologies to bring the overall efficiency of industrial steam generation systems up to ~94%, while reducing NO_X emission to <9 ppm (i.e., US DOE's Super Boiler). Energy efficiency gains will result in fuel consumption reductions that will, in most cases, provide the economical justification for the specified improvement project. Feed flexibility of modern boilers will also allow refiners to take advantage of byproduct fuels to improve economics and justify boiler revamp or replacement projects. When a price is assigned to carbon emissions, economic gains from energy efficiency improvements are further improved, as they will inevitably lead to a reduction in CO_2 emissions. While boilers have many of the same opportunities for energy efficiency improvements as process heaters due to the use of a furnace, there are also some unique opportunities as outlined in the Report, particularly concerning the heat content and consumption of feedwater.

Some refiners operate onsite **power production** plants. The configuration, size, and efficiency of these plants largely depend on the selected prime mover, plant demands, and the ability to sell excess power back to the grid. Refinery power plants differ from *cogeneration or CHP* (combined heat and power) plants in that the recovered heat is primarily used to produce more electricity in a power plant, whereas refinery-CHP plants utilize waste heat to meet process demands with some additional power production. Implementing the simultaneous cogeneration of heat and power from a single fuel input will generally lower plant emissions compared to the separated generation of each utility. A flow scheme of the various utility supply options is displayed in **Figure 3**. It is estimated that an efficiency improvement of about 27% can be gained by switching to CHP from stand-alone electricity and steam production in a large-scale industrial setting. Not only will this improvement provide for more economical steam and power generation, but the reduced fuel consumption will result in lower CO_2 emissions as well. However, it is important to note that legislation may play a role in determining the benefits of onsite CHP units. Since refineries typically meet a large fraction of their electricity requirements with electricity from the grid, displacing this with electricity generated onsite may increase plant emissions (even though CHP is more efficient) if refineries are responsible for the CO_2 emissions from the electricity generated onsite, but not for indirect emissions attributed to offsite electricity generation; of course, even if refiners are not responsible for indirect emissions, the effect of CO_2 prices will likely be felt through a price increase for grid electricity. So while it may still be beneficial to build an onsite CHP plant regardless of emissions allocation, the option must be carefully weighed with consideration to current utility supply options, available resources, and regional legislation.

FIGURE 3: OPTIONS FOR MEETING REFINERY STEAM, HEAT, AND POWER DEMANDS



Cogeneration is not a specific technology, yet it is a concept that can be applied in several different ways. Technologies included in cogeneration are steam or gas turbines, combined-cycle systems, microturbines, and reciprocating engines. Cogeneration provides energy savings when it replaces low-efficiency, standalone means of generating heat and electricity. Typical fuel savings are in the range of 10-20%. There are three basic technology options for refinery cogeneration. These configurations will be favored for refiners over the alternatives (i.e., reciprocating engine, fuel cells, etc.) due to the lower power-to-heat ratios that match up well with refinery utilities demands:

- Steam cycle (boiler with a steam turbine);
- Simple-cycle gas turbine with heat recovery steam generator (HRSG); and
- Combined-cycle: gas turbine with HRSG and a steam turbine (distillate feed, natural gas combined cycle, and IGCC).

This Report investigates the benefits of various cogeneration options including an offshoot of combined-cycle CHP technology—known as *integrated gasification combined cycle* (IGCC)—which incorporates the use of a gasifier upstream of the combined cycle gas to produce syngas that is subsequently combusted in the gas turbine. Primary drivers for the development and implementation of IGCC are feed flexibility (e.g., heavy oils and residues, petroleum coke, coal, waste streams, etc) and the potential to implement carbon capture, resulting in a low emissions power station. An additional benefit that may attract future refiners to invest in IGCC technology is the polygeneration potential to supply not only heat and power to the refinery utility systems, but also to supply hydrogen for clean fuels production.

This Report undertakes three types of case studies for a hypothetical 100K-b/d refinery to illustrate the benefits available from improving supply side energy efficiency in a processing plant. First, the total annualized cost of separated generation of steam and electricity is examined at CO_2 prices between $0 and $200/mt for NG-fired, coal-fired, and fuel-oil-fired boilers. The purpose is to identify the competitive advantage of these three types of boilers in the future carbon-constrained environment with and without the assumption that refiners are responsible for paying the indirect emissions associated with grid electricity production. Secondly, fourteen case studies are performed to evaluate the deployment of two generalized CHP schemes—boiler with a back-pressure steam turbine and gas turbine with a HRSG (with or without duct burning)—while varying the nominal electric ratings; the combustion fuels selected; the outputted power-to-heat ratios; and the electricity import/export options to meet the supply gap or deal with excess electricity production. Thirdly, various refinery utility supply scenarios are analyzed by comparing options of separated generation via steam boilers and imported grid electricity, CHP using steam turbines and imported grid electricity, CHP using boilers with steam turbines meeting 100% electricity and steam demands, CHP using NG-fed boilers and various steam turbines, gas turbines with or without duct burning, and so on. Conclusions are drawn to quantify the impact of CO_2 costs and emissions regulations methodology on the supply of refinery utilities, and to highlight the most attractive technological approaches to efficiently meet refinery energy demands.

1.3.3.2 Demand Side

Efficiently distributing heat throughout the refinery is a very important aspect of improving overall plant efficiency and reducing GHG emissions. In every refinery, multiple streams of feedstock and product are pumped from unit to unit and are frequently heated and cooled. This heating and cooling requires large amounts of energy, and by integrating the streams that need to be heated with those that need to be cooled, the energy input required can be greatly reduced. The more effectively these streams are integrated through heat exchanger networks (HENs), the less energy input is required. Therefore, there are three principal areas to focus on when trying to improve the overall heat distribution efficiency: (1) improving the efficiency of the individual heat exchanger, (2) improving the efficiency of the HEN, and (3) waste heat recovery.

One of the major factors affecting the energy efficiency of individual **heat exchangers** is fouling. Fouling decreases heat transfer and efficiency in furnaces, boilers, heat exchangers, and other process units by forming a layer of material with low thermal conductivity on the heat transfer surfaces. In order to overcome the decrease in heat transfer efficiency due to fouling, more fuel is required. The excess fuel consumption results in an increase in both energy costs and CO_2 emissions. It is estimated that fouling results in the loss of about $14MM/y in a typical 100K-b/d refinery via increased downtime, energy costs, and lost efficiency (not including the cost of the additional CO_2 emitted). Overall, fouling costs refineries in the US over $2B/y and refineries around the world a total of about $11B/y. On a feed basis, the effects of fouling have been estimated to increase energy requirements by 12.3K Btu/bbl of crude processed (12.98 MJ/bbl). Because of the high cost of fouling, many refineries are looking to alternative methods to prevent or reduce fouling from occurring. Alternative ways to manage fouling include the use of chemical additives, the implementation of anti-fouling technologies (e.g., tube inserts or baffles); the replacement of equipment with new, fouling-resistant units; and the adjustment of operating conditions. This Report discusses novel heat exchanger technologies in detail, and further, compares heat exchanger retrofit options (e.g. online cleaning, tube inserts, baffles, dual-enhanced heat exchangers, anti-foulant additives, coatings, etc) in terms of capital cost, additional operating costs, fouling reduction benefits, and technology limitations. The same criteria are used to review various heat exchanger designs for new installations including “low-fouling”, spiral tube, Kenics, twisted tube, plate, shell-and-plate, and spiral plate heat exchangers.

In addition to improving the heat transfer efficiency of individual heat exchangers, it is very important to look at the system as a whole and optimize the **heat exchanger network (HEN)**. The key to improving the energy efficiency and reducing the CO_2 emissions associated with heat distribution is through process integration. By integrating the process streams that require heating with those that require cooling, less hot and cold utilities are required. This integration can substantially reduce the energy requirements of a plant. Many different methods have been developed to optimize the heat integration. Pinch analysis is an effective and widely used tool to optimize heat integration. In refinery applications, pinch technology has been used in both the design phase and in retrofit applications to optimize HENs. This method has proven especially useful in optimizing the crude preheat train. When applied to HENs, the goal of pinch analysis is to integrate the process streams that need heating and cooling in such a way as to use the least amount of utilities with the lowest number of heat exchangers possible to get all the streams to the desired temperatures. This integration reduces energy consumption and therefore lowers GHG emissions in the plant. Although pinch analysis is still widely used, there has been a lot of work done in recent years to develop mathematical programming models, as identified in this Report. Mathematical programming approaches can take into account factors such as the current plant layout and piping systems, equipment constraints, and process operating conditions by incorporating these criteria as mathematical equations in the model. Computers then automatically solve these sets of equations to produce the desired optimized HEN design. Mathematical programming models can be developed to minimize utilities, optimize process conditions, and account for the capital and operating costs of new heat exchangers, piping, and heat exchanger relocation. The current drawback with these mathematical programming models, however, is the computing intensity required.

Another consideration with respect to heat management in the refinery is **waste heat recovery**. For every one megawatt the refinery recovers from waste heat, about 2.4K mt/y in emissions savings is realized.

Depending on the temperature and mass flow rate, waste heat can be used in many different ways, such as preheating feedstreams, preheating air used in combustion furnaces, preheating boiler feedwater, or generating steam directly with waste heat boilers. It can also be used to provide cooling to product streams by means of absorption chillers. For plants that flare excess fuel gas under normal operating conditions, capturing and using the energy in these streams is another opportunity to improve energy efficiency. This Report undertakes case studies to evaluate the environmental and financial benefits of several options (e.g. preheating combustion air for boiler, installing economizers for boilers, implementing boiler blowdown heat recovery, and installing a flare gas recovery unit) for waste heat recovery. Furthermore, the combined cost of energy requirements and CO_2 emissions are then calculated for each measure for various CO_2 prices up to $100/mt.

Due to the substantial heat demand of the major refinery processing units, steam has become one of the most important utilities to consider in an energy management program. There are three options for reducing the energy input required: reduce the demand from process units, increase efficiency of steam production, and increase the efficiency of steam distribution. Optimizing the **steam distribution system** can be a very beneficial way to reduce plant CO_2 emissions. This Report looks at various options based on potential fuel savings and estimated payback: improving insulation, installing improved steam tracer, steam trap maintenance, automatic steam trap monitoring, repairing leaks, installing condensate return, minimizing vented steam, isolating unnecessary steam lines, and conducting steam system pinch analysis. Again, case studies are performed for the options.

Although **electricity usage** makes up only about 5% of a refinery's energy requirements, there are still opportunities to reduce energy consumption and CO_2 emissions. Since motor systems account for 80% of electricity used in a refinery, this is the main focus of electricity reduction measures. Motors are used throughout the refinery to run many pieces of equipment such as pumps, compressors, and fans. Through various improvement steps, motor efficiency can be improved 12-15% on average. This Report compares the energy requirements and CO_2 emissions for four different motors; a rewound motor, a standard efficiency motor, a motor meeting the US EPACT standards, and a motor meeting NEMA Premium standards (highest standards); and recommends motor improvement options.

As to **strategic application of energy efficiency improvements in refining processes**, **Table 4** summarizes the energy consumption of processing units in US refineries in 2001. [The total value for FCC does not include the amount from coke combustion for the cracking reaction, which produces considerable energy.] Processes that are major consumers and discussed in detail in this Report are emphasized in boldface.

TABLE 4: ENERGY CONSUMED IN 2001 BY US REFINING PROCESSES

Process	Fuel, TBtu	Steam, TBtu	Electricity, GWh	Total, TBtu
Desalter	0.2	0.0	265.7	1.1
Crude distillation unit	359.2	243.5	3613.0	687.8
Vacuum distillation unit	115.5	126.1	845.8	282.1
Thermal cracking	84.1	-10.5	4485.3	85.8
Fluid catalytic cracking	108.2	0.5	23.9	132.8
Hydrocracking	68.5	36.9	5680.7	135.9
Catalytic reforming	206.1	101.3	3416.3	349.4
Hydrotreating	253.2	270.1	15455.4	656.6
Deasphalting	16.1	0.3	213.8	17.2
Alkylation	13.1	121.1	2640.7	179.3
Aromatics	11.7	4.1	291.5	18.0
Asphalt	59.6	0.0	740.7	62.1
Isomerization	90.3	39.9	398.3	143.5
Lubes	87.5	2.5	1247.0	95.0
Hydrogen production	268.2	0.0	893.9	271.2
Sulfur recovery	0.0	-81.2	108.5	-105.1

The Report investigates opportunities to reduce the energy consumption of each major energy consuming process (those in boldface above) individually. For each process, potential projects targeting the major source(s) of CO_2 emissions are discussed. The report identifies opportunities that require a wide range of capital investment—from very low investments, such as adjusting operating conditions, to revamps and new units that require significant investments. Additionally, the economics of implementing such projects are presented with regards to the tradeoff between capital investment and cost savings from energy and CO_2 reductions at a range of CO_2 prices.

1.3.4 Renewable Sources of Energy Used in Refineries

The use of renewable energy is growing around the world as countries are looking to curb GHG emissions while energy demand is increasing. The use of renewable energy by refiners can help to curb GHG emissions, and also, allow refiners to supplement grid purchased electricity with renewable electricity produced onsite. Also, by investing in renewable technologies refiners can take advantage of current government programs (subsidies, renewable portfolio standards) that promote renewable electricity use. To provide benchmarking of the best available renewable energy technologies as of early 2010, this Report focuses on: (1) an overview of current state-of-the-art technologies for solar, wind, biomass, geothermal, and hydrokinetic electricity generation; (2) the economic feasibility of applying these state-of-the-art technologies in a refinery setting; and (3) case studies for solar and wind technologies that take into account a carbon credit/tax to identify the costs of implementing these technologies in a refining application.

Governmental policies, particularly subsidies, play a key role in the economic viability of renewable technologies. Several governments around the globe provide subsidies—and in some cases large subsidies—for every kWh of renewable electricity produced to help make renewable electricity cost competitive with conventional electricity and encourage investment in and use of renewable sources of energy. There are some instances, though, of governments over subsidizing renewables and actually looking to cut back on subsides. France is scaling back their wind subsidy by 2% while Germany is decreasing both PV solar (8-10% depending on size) and wind (1%) subsidies. Reducing subsidies on alternative sources of energy is not novel, as Germany did the same thing with subsidies on biodiesel a few years back. While government subsidies are helpful in promoting investment in and use of renewables, they may not be able to be counted on at current levels over the long term. Other governmental programs, such as the renewable portfolio standards (RPS) in certain states in the US, can also lead to increased use of renewable electricity. Programs like the RPS allow the refiner to sell any excess renewable electricity they produce back to the grid.

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.

1.3.4.1 Wind

Wind power is the second most cost effective renewable, behind only large scale hydroelectric plants, and the costs are also favorable when compared to traditional means of power generation. Wind farms can generate an estimated 25-35 times the energy invested with an "energy payback" time of just 3-8 months. Current estimates for levelized costs of onshore wind generated electricity ranges from \$0.029-0.10/kWh. Capital cost estimates for new wind facilities are in the range of \$1,750/kW. Capacity factors (currently at 36%) also play a key role in determining the levelized cost of wind energy. Recently, the capacity factors for wind turbines have been improving with improvements in equipment performance. However, unlike other renewable technologies, wind technology is considered fairly mature and thus low rates in terms of cost improvements are assumed. Unlike technology or capacity improvements in other forms of renewable energy, a doubling of installed wind capacity equates to only a 1% decrease in capital costs. In this Report, several case studies are performed to examine the economic feasibility of wind farms for refinery installation.

1.3.4.2 Solar

Currently, many companies are looking into harnessing solar power for use in electricity production. One of the ways is through converting the sun's radiant energy directly into electricity using photovoltaic cells. The photovoltaic (PV) effect causes the sunlight shining on solar cells to be converted into an electric current by absorbing photons onto the cell and then releasing electrons. Another technology for solar electricity production is a concentrating solar power (CSP) system. In CSP systems, optics are used to concentrate beam radiation, the portion of solar radiation that is not spread by the atmosphere. The concentrated beam radiation captured by CSP systems is turned into high-temperature heat that can then be used for electricity generation or as a driver for reactions that produce fuels (hydrogen or syngas). CSP technology can be broken into three categories: parabolic trough, power towers (also called central receiver concentrator), and dish-stirling engine systems (also called parabolic dishes). Estimating the cost of producing electricity using solar PV technology is a function of the cell's efficiency, typically ≤15% depending on the material system used and the total cost of installing the PV cell. Capital costs associated with PV cell modules are determined using the ratio of the cost of the module per unit of area (\$/m^2) divided by the maximum amount of electricity that can be delivered per unit area (the PV cell modules efficiency multiplied by 1,000 W/m^2). In this Report, several case studies were performed looking at the economic feasibility of PV solar modules within a refinery.

1.3.5 Carbon Capture and Sequestration (or Storage)

"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 Statoil'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 addresses 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. Examination is conducted with 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.

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 Report turns to a scenario analysis. Using a simple model, the total cost to the refiner, C_{tot}, is defined in equation below.

$$C_{tot} = \frac{[CO2_{cap}]P_c + [CO2_{ref} - CO2_{cap}][C_a + 1.1(C_s - C_{EOR/EGR})]}{CO2_{ref}}$$, in \$/mt CO_2 produced by refinery before capture.

$CO2_{ref}$ and $CO2_{cap}$ are the amount of net CO_2 emitted by the refinery without capture and with capture, respectively, in mt/y; P_c is the price to emit CO_2 in \$/mt, whether through taxation or a cap and trade mechanism; C_a is the cost of CO_2 avoided in \$/mt; C_s is the cost of sequestration in \$/mt, including both transport and storage; and $C_{EOR/EGR}$ is the product value of CO_2 for enhanced oil recovery/enhanced gas recovery (EOR/EGR) applications. In reference to the base case, the worst and best case scenarios are undertaken to analyze the impacts of carbon cost and the product value of CO_2. And the results offer very valuable insights into the feasibility of carbon capture in a refinery setting. The total cost of CO_2 (C_{tot}) 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. The effects of such costs on individual companies will vary. An analysis is performed to compare ExxonMobil, Valero, and Sunoco. The first company is a global, integrated oil company; the second is a medium-sized, predominantly US-based refiner; and the third is a smaller, US-based refiner.

1.3.6 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 impacts of these benefits depend on how one can turn the impending challenges into opportunities in the marketplace. Furthermore, carbon management requirements could mean complete overhauls of operations ranging from the types of crude feeds purchased; separation and conversion technologies being used; product slate distribution; and utilities deployment to the 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.

Taking these developments into account, this Report sets out to identify the specific steps and strategies that oil companies are taking to help curb GHG emissions. The data were gathered via two methods: (1) a direct survey sent to oil companies (excluding any E&P concerns) around the globe, and (2) a comprehensive search of company websites and press releases. Both the survey and information search focused on four key areas: (1) energy efficiency improvements; (2) cogeneration; (3) renewable power sources; and (4) carbon capture and sequestration (CCS) and future legislative preferences.

1.3.6.1 Direct survey

The survey, titled "Refinery CO_2 Management Survey," contained roughly 20 questions and was conducted via email across the global refining community in the summer of 2009. Surveys were sent out to process engineers, maintenance engineers, operations managers, unit managers, and others in an attempt to establish what steps refiners are actively taking to reduce their carbon footprints. The survey focused on energy management practices, views on carbon management, preferences for CO_2 pricing, CCS, and power sources. Chi Square statistical tests were performed on the data to determine statistical significance. The majority of the responses came from refineries in North America and Europe.

1.3.6.2 Company websites and press releases

While the results of the direct survey were submitted by individual refineries, a wide-ranging search of oil company websites and press releases was completed to determine corporate policies in regard to curbing refinery GHG emissions. Oil companies around the globe seem to be actively engaged in utilizing energy efficiency programs and combined-heat-and-power plants at their operations. A number of firms are also involved in consortiums researching the possibilities of using CCS to help curb GHG emissions.

An area in which many oil companies appear to differ is the use of renewable energy for reducing GHG emissions. Although the direct survey yielded insignificant data regarding the use of renewable energy use in a refinery, publicized information revealed some trends in this regard. In contrast to the position taken by US and Canadian firms, most European and Asian oil companies favor a cap-and-trade system over a carbon tax. As expected, many small, independent refiners and oil concerns—particularly in Africa—provided no climate change position or carbon strategies in any public announcements, and their inputs are not included in **Table 5** below. This Report includes detailed company policy and strategy information of each individual company.

TABLE 5: SUMMARY OF CARBON MANAGEMENT POLICIES AND STRATEGIES BY OIL COMPANIES

Company	Country	Energy efficiency	Combined heat and power	Renewable energy (excluding biofuels)	Carbon capture and storage (CCS)	Position in carbon pricing (CT or CCT)
United States						
Chevron		✔	✔	✔	✔ [a]	CT
ConocoPhillips		✔	✔	✔	✔ [a]	CCT[b]
ExxonMobil		✔	✔		✔	CT
Flint Hills Resources		✔	✔			
LyondellBasell		✔				
Marathon Petroleum		✔	✔		✔	CT
Valero Energy		✔	✔	✔		
Canada						
Husky Energy		✔	✔		✔ [a]	
Imperial Oil		✔	✔ [a]		✔ [a]	CT
Irving oil		✔	✔	✔	✔ [a]	
Suncor Energy		✔	✔	✔	✔ [a]	CCT[b]
Latin America and Caribbean						
Ecopetrol	Colombia	✔				
Petrobras	Brazil	✔	✔	✔	✔ [a]	
Pemex	Mexico	✔	✔			CCT
Petroperu	Peru		✔			
Western Europe						
BP	UK	✔	✔	✔	✔	CCT
CEPSA	Spain	✔	✔		✔ [a]	
Eni	Italy	✔	✔	✔	✔ [a]	CCT
ERG	Italy	✔	✔	✔	✔ [a]	CCT
Galp Energia	Portugal	✔	✔	✔	✔ [a]	
Hellenic Petroleum	Greece	✔	✔	✔		
Motor Oil Hellas	Greece	✔	✔	✔		
OMV	Austria	✔	✔	✔	✔ [a]	CCT
Repsol YPF	Spain	✔	✔	✔	✔ [a]	CCT
Royal Dutch Shell	UK/ Netherlands	✔	✔	✔	✔	CCT
Saras	Italy	✔	✔	✔	✔ [a]	CCT
Statoil	Norway	✔	✔	✔	✔	CCT
Total	France	✔	✔	✔	✔	

Company	Country	Energy efficiency	Combined heat and power	Renewable energy (excluding biofuels)	Carbon capture and storage (CCS)	Position in carbon pricing (CT or CCT)
Eastern Europe, CIS						
Czech Refining	Czech Republic	✔				
MOL	Hungary	✔	✔	✔	✔ [a]	
Rosneft	Russia	✔	✔			
Middle East						
ADNOC (Takreer)	UAE	✔		✔	✔ [a]	
Saudi Aramco	Saudi Arabia	✔	✔		✔ [a]	
Tupras	Turkey	✔	✔	✔		
Asia-Pacific						
Attock Refinery	Pakistan	✔		✔		
Caltex Australia	Australia	✔				CCT
Cosmo Oil	Japan	✔	✔	✔	✔ [a]	CCT
CPC	Taiwan	✔			✔ [a]	
Hindustan Petroleum	India	✔	✔	✔		
Idemitsu Kosan	Japan	✔		✔		
Indian Oil	India	✔	✔	✔		
Japan Energy	Japan	✔				
New Zealand Refining	New Zealand	✔				
Nippon Oil	Japan	✔	✔	✔		
Pertamina	Indonesia			✔		
PetroChina	China	✔		✔	✔ [a]	
Petronas	Malaysia	✔	✔			
Sinopec	China	✔		✔		
SK Energy	South Korea	✔			✔ [a]	

[a]Not a commercial carbon-capture project, but part of consortium researching CCS possibilities
[b]Not final company decision, but leaning toward

1.3.7 Strategic Analysis and Recommendations

Major oil companies are very proactive in formulating strategies and taking steps to comply with future CO_2 cap legislation. In the name of business sustainability, the impact on the bottom line must first be considered when investing in any sort of project to cut carbon emissions. This fact may explain why the use of energy management and/or energy efficiency programs is such a popular method for refiners looking to curb GHG emissions. The direct survey and search of company climate change policy announcements led to the same conclusion. Refiners prefer energy efficiency improvement programs that are easily obtainable and from which they can quickly recoup their investment—often referred to as the "low-hanging fruit" of GHG emissions mitigation options.

On the other hand, short- and medium-term concerns (i.e., depressed demand, poor margins, market erosion by biofuels, and decreasing consumption in developed nations due to higher vehicle fuel efficiency), have not distracted companies from impending regulatory requirements for GHG emissions. As a result, refiners are also pursuing other loner-term carbon footprint reduction options, such as renewable energy (solar and wind) and CCS projects. The next decade could be a very challenging time for refiners, but it could also provide opportunities for well-prepared companies to expand market shares at the expense of less prepared businesses, particularly small ones, which are lack of resources and have no strategy for tackling and adapting to the not-so-distant, costly climate change legislation as revealed in the survey and search. Despite uncertainties, many developed countries and China are expected to slash GHG emissions by 2020, just ten years away.

The Report concludes with a comprehensive analysis of the critical issues facing refiners in the next decade or so. In particular, the analyses focus on technology trends, situations of refineries in different regions of the world, and recommendations of refinery CO_2 management strategies for sustaining long-term profitability.

1.4 Table of contents, list of tables, list of diagrams

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1.6 Previously Published Reports

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- Future Refinery Operations to Meet Fuel Supply Security and Environmental Requirements (published in December 2007)
- Opportunity Crudes: Technical Challenges and Economic Benefits (published in May 2006)
- Advanced FCC Technology to Improve Refinery Profitability (published in March 2005)
- Advanced Hydrotreating and Hydrocracking Technologies to Produce Ultra-Clean Diesel Fuel (published in January 2004)
- Advanced Ultra-Clean Motor Gasoline Production Technology: Technical and Economic Assessments of the Latest Refinery Processes/Catalysts/Hardware; Innovations to Increase

Yields of Alkylate, Iso-octane and Isomerate; and Novel Specialty Additives (published in October 2002)

- Meeting Ultra-Low-Sulfur Fuel Specifications and Increasing Liquid Product and Propylene Yields via the Latest Advances in Coking, Resid FCC, and Resid Hydroprocessing Technologies (published in September 2001)
- Advanced Clean Middle Distillates Production Technology-Technical and Economic Assessments of Latest Refinery Process/Catalysts/Hardware, Novel Commercial Additives, Emerging Fuel Alternatives, Innovative Engine Designs, and Exhaust After-Treatment Techniques (published in March 2000)

1.7 Our Clients

US & CANADA
Air Products and Chemicals
Albemarle Catalysts
Aspen Technology
BASF Catalysts
Bechtel
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CB&I
CDTECH
Chevron
Citgo Petroleum
ConocoPhillips
Criterion Catalysts & Technologies
ExxonMobil
Flint Hills Resources
Fluor
Foster Wheeler
Giant Industries
Haldor Topsoe
Hess
Honeywell
Husky Oil (Canada)
Imperial Oil (Canada)
INTERCAT
Invensys Intelligent Automation
Irving Oil (Canada)
Jacobs Engineering
KBR
LyondellBasell
Marathon Petroleum
Motiva Enterprises
PQ
Praxair
Saint Gobain-Norpro
Shell Canada (Canada)
Stone & Webster/Shaw Group
STRATCO/Du Pont
Sud Chemie/United Catalysts
Suncor Energy (Canada)
Sunoco
Syncrude Canada (Canada)
Tesoro
UOP
Valero Refining
W.R. Grace/Davison
WorleyParsons

EUROPE

Agip Petroli (Italy)

Albemarle Catalysts (the Netherlands)

AMEC Engrg. (UK)

Axens (France)

BP Int'l (UK)

BP Oil Espana (Spain)

CEPSA (Spain)

Chimec SpA (Italy)

Davy Process Technology (UK)

DEA Mineralol AG (Germany)

Edeleanau GmbH (Germany)

EniTecnologie (Italy)

Fortum Oil and Gas Oy (Finland)

Haldor Topsoe (Denmark)

Hellenic Fuels and Lubricants AE (Greece)

Holborn Europa Raffinerie GmbH (Germany)

IPLOM (Italy)

ISAB (Italy)

Johnson Matthey (UK)

KBC Process Tech (UK)

MiRO Mineraloelraffinerie Oberrhein (Germany)

MOL RT Hungarian Oil & Gas (Hungary)

Motor Oil (Hellas) Corinth Refineries, S.A. (Greece)

OMV Refining & Marketing GmbH (Austria)

Petroleos del Norte SA (Spain)

Rafineria Gdanska SA (Poland)

Repsol YPF SA (Spain)

Scranraff (Sweden)

Shell Global Solutions (the Netherlands)

Slovnaft, as (Slovakia)

Snamprogetti (Italy)

Statoil (Norway)

Techimont (Italy)

Technip Italy (Italy)

TOTAL (France)

Uhde GmbH (Germany)

Wintershall AG (Germany)

LATIN AMERICA/CARIBBEAN

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ENAP (Chile)

EG3 SA (Argentina)

Hovensa (V.I.)

Intevep SA (Venezuela)

IMP (Mexico)

ISAURA SA (Argentina)

Pemex (Mexico)

Petrobras (Brazil)

Petroleos de Venezuela SA

Petroperu (Peru)

Petrotrin (Trinidad and Tobago)

Petrox SA (Chile)

Refineria Dominicana (Dom. Rep.)

Refineria Isla (Curazao) SA (Neth. Antilles)

YPF S.A. (Argentina)

MIDDLE EAST

Abu Dhabi Nat'l Oil (UAE)

King Fahd University of Pet. & Min. (Saudi Arabia)

Kuwait Institute for Scientific Research (Kuwait)

Kuwait National Petroleum (Kuwait)

Qatar National Oil Distribution Co (Qatar)

Saudi Aramco (Saudi Arabia)

Tupras Genel Mudurlugu (Turkey)

AFRICA

Caltex Oil (S. Africa)

Engen Petroleum (S. Africa)

Nat. Pet. Ref. of S.Africa (Pty) Ltd.

Suez Oil Processing (Egypt)

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Attock Refinery (Pakistan)

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Chinese Petroleum (Taiwan)

Chiyoda (Japan)

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Idemitsu Kosan (Japan)

Indian Oil Corp. (India)

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New Zealand Refining (New Zealand)

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Petron (the Philippines)

Petronas (Malaysia)

Research Institute of Petroleum Refining/CPCC (China)

Shell Co of Australia (Australia)

Singapore Rfg (Singapore)

Sinopec (China)

SK Corp. (S. Korea)

Thai Oil (Thailand)