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# Potential of Gasification in the U.S. Refining Industry

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D. Gray
G. Tomlinson



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## Disclaimer

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# Table of Contents

| Section | | Page |
|---|---|---|
| Background | | 1 |
| Purpose of the Report | | 1 |
| The Current U.S. Refinery Situation | | 2 |
| The Future U.S. Refinery Situation | | 2 |
| Macroscopic Economic Analysis of U.S. Refineries | | 6 |
| Single Plant Analysis at A Typical U.S. Refinery | | 11 |
| Economic Analysis of Single Plants | | 13 |
| Conclusions | | 15 |
| List of References | | 17 |
| Appendix A | Capital and Operating Cost Summaries | A-1 |

# List of Figures

| Figure | | Page |
|---|---|---|
| 1 | Conversion Processes | 6 |
| 2 | Payback Period Versus Natural Gas Price for Pet Coke Gasification (Ref WOP $21.30/BBL) | 8 |
| 3 | Payback Period Versus Natural Gas Price for Pet Coke Gasification (High WOP $27.33/BBL) | 9 |
| 4 | Payback Period Versus Natural Gas Price for Pet Coke Gasification (Ref WOP $21.30/BBL, Pet Coke $-10/Ton) | 10 |
| 5 | Payback Period Versus Natural Gas Price for Pet Coke Gasification (Ref WOP $21.30/BBL, 1.25 Times Capital) | 10 |
| 6 | Single Refinery Coke Gasification Configurations | 12 |
| 7 | Return on Equity Versus Gas Price for Reference World Oil Price | 14 |
| 8 | Return on Equity Versus Gas Price for High World Oil Price | 14 |
| 9 | Return on Equity Versus Gas Price for Low World Oil Price | 15 |
| 10 | Return on Equity Versus World Oil Price for Gas Price Proportional to World Oil Price | 16 |
| 11 | Conclusions | 16 |

# List of Tables


| Table | | Page |
|---|---|---|
| 1 | U.S. Refineries with Coking Units of 1,000 TPD or Greater | 3 |
| 2 | Coking Capacity by State | 4 |
| 3 | Assumptions Regarding Situation in 2010 | 5 |
| 4 | Summary of Situation in 2010 | 6 |
| 5 | Baseline Assumptions | 7 |
| 6 | Configuration Summary for Single Refinery Analysis | 11 |
| 7 | Financial Assumptions for Single Refinery | 13 |

## Background

In Europe there is a move towards utilization of petroleum residuals as a feed for gasification in refineries to make electric power and other products. In the United States refineries have not fully embraced this concept at this time. This is partly because refinery practice in the U.S. is different from Europe. Whereas in Europe visbreaking and hydrocracking are used for processing heavy ends, in the U.S. the preferred approach to residual treatment is coking. Petroleum coke (pet coke), the product of this processing technique, can be used for fuel or for carbon product manufacture depending on quality.

There is, however, in the U.S. an emerging interest in petroleum coke utilization as a feed for gasification. The El Dorado refinery in Kansas already has a small gasification unit operating on coke for power production. The Motiva refinery in Delaware and Farmland Industries in Coffeyville, Kansas, will be bringing coke gasification plants on line in 2000.

As refiners are pushed towards producing cleaner, lower-sulfur transportation fuels from poorer quality crudes, pet coke could be used as a source of hydrogen, a commodity that will be in great demand as the Tier 2 regulations take effect. Pet coke could also be used to produce refinery power, and excess power could be sold. In a deregulated electric power industry, refiners may choose to become power providers. Other products can also be produced once the pet coke is converted into clean synthesis gas. These other products include Fischer-Tropsch (F-T) liquids. F-T liquids are zero sulfur, paraffinic hydrocarbons that can be classified as ultra-clean transportation fuels. Zero sulfur, high cetane F-T diesel could be used as a blending stock to assist refiners in meeting ultra low sulfur diesel specifications.

## Purpose of the Report

The National Energy Technology Laboratory (NETL) requested that Mitretek undertake a study to assess the potential of using pet coke in U.S. refineries as a feed to produce a variety of products including hydrogen, electric power, and F-T fuels. The approach taken was to identify those U.S. refineries that currently produce enough coke to warrant gasification facilities. Assumptions were then made to estimate the likely pet coke situation in 2010. That year was chosen to allow sufficient time for construction of coke gasification facilities and because, by that time, it is expected that refineries will be required to produce fuels with sulfur contents below 30 ppm. A macroscopic approach was used to estimate the economic impact of large-scale coke gasification in all U.S. refineries having over 1000 tons per day (TPD) of coke production. Several scenarios were investigated including production of combinations of hydrogen, power, and F-T liquids. This approach identified the preferred product combinations that yielded the shortest payback periods. The final approach in this analysis was to analyze coke utilization at a single refinery. Again, several product combinations were investigated, and the plant return on equity was estimated for each of the combinations.

## The Current U.S. Refinery Situation

The Oil and Gas Journal publishes a complete list of U.S. refineries every year.[1] This was used to prepare Table 1. This identifies all U.S. refineries having coke production greater than 1000 tons per day. In total, 35 refineries were identified. Most of these are in California (10 refineries) followed by Texas (8) and Louisiana (6). Coking capacity by state is summarized in Table 2. A total of almost 95,000 tons per day of Pet coke is produced in these 35 refineries. Total U.S. coke production for 1999 was 96,200 tons; therefore, these 35 refineries represent over 98 percent of production. Based on total crude capacity, this coke production is equivalent to 12.5 tons per thousand barrels. The feed to the cokers was 1.6 million barrels per day (MMBPD) to give an average coke yield of about 57 tons per thousand barrels feed. Table 2 also identifies the hydrogen plant capacities for the refineries.

## The Future U.S. Refinery Situation

In order to estimate the U.S. refinery situation in the year 2010 it was necessary to make some assumptions. These are summarized in Table 3. It was assumed that demand for petroleum will continue to increase at a rate of 1.2 percent per annum to 2010. This assumption is taken from the Energy Information Administration's Annual Energy outlook for 1999.[2]

Further, it was assumed that by 2010 all gasoline and diesel produced by U.S. refineries will have a sulfur content of less than 30 ppm. This results from the Tier 2 regulations. Desulfurization of gasoline and diesel to these low levels will require extensive hydrotreating of both catalytic cracker feed and product and of distillates. Mitretek has developed a refinery simulation model that estimates the hydrogen required and the costs of this desulfurization. Based on the results of this simple refinery model, it is estimated that an average 150,000 barrel per day (BPD) refinery currently producing gasoline and diesel with average sulfur contents of 350 ppm and 500 ppm, respectively, will require an additional 38 million standard cubic feet per day (MMSCFD) of hydrogen to produce gasoline and diesel with a sulfur content of less than 30 ppm. This is equivalent 0.25 MMSCFD per 1000 BPD of refining capacity.

For California the situation with respect to hydrogen is different. California is already producing gasoline that is low in sulfur under the Phase 2 gasoline regulations (CaRFG2). This CaRFG2 program was adopted in 1991 and implemented in March 1996. It places limits on sulfur, T50 and T90, olefins, Reid vapor pressure, benzene, aromatics, and oxygen content. CaRFG2 has an average sulfur content of 30 ppm and a cap of 80 ppm. In addition, California has strict regulations for diesel fuel which were implemented in October 1993. These require refiners either to limit aromatic content to 10 volume percent or to have equivalent formulations certified as meeting the emissions standards. The effect of this is to

## Table 1. U.S. Refineries with Coking Units of 1,000 TPD or Greater

| Company | Location | BPD Crude | BPD Coking | TPD Coke | MMSCFD Hydrogen |
|---|---|---|---|---|---|
| **California** | | | | | |
| ARCO | Carson | 255,000 | 57,000 | 2,600 | 105 |
| Chevron | El Segundo | 260,000 | 64,000 | 3,800 | 122 |
| Equilon | Wilmington | 90,250 | 37,800 | 2,000 | 36 |
| | Bakersfield | 61,750 | 19,440 | 1,200 | 25 |
| | Martinez | 153,900 | 44,100 | 1,300 | 101 |
| Exxon | Benicia | 129,500 | 25,500 | 1,000 | 110 |
| Mobile | Torrance | 130,000 | 50,200 | 3,300 | 140 |
| TOSCO | Wilmington | 125,000 | 48,000 | 2,200 | 100 |
| San Francisco | Avon | 271,000 | 84,000 | 3,900 | 190 |
| Ultra Mar | Wilmington | 100,000 | 22,000 | 1,200 | --- |
| **Delaware** | | | | | |
| Motiva | Delaware City | 140,000 | 49,000 | 2,000 | 67 |
| **Illinois** | | | | | |
| CITGO | Lemont | 145,350 | 25,100 | 2,000 | 11 |
| Marathon | Robinson | 192,000 | 27,100 | 1,500 | 25 |
| Mobil | Joliet | 231,700 | 47,700 | 3,300 | --- |
| **Indiana** | | | | | |
| Amoco | Whiting | 410,000 | 34,200 | 1,860 | 30 |
| **Louisiana** | | | | | |
| CITGO | Lake Charles | 304,000 | 84,600 | 4,200 | --- |
| CONOCO | Westlake | 231,100 | 64,100 | 3,750 | 100 |
| Exxon | Baton Rouge | 473,000 | 102,000 | 5,400 | 18 |
| Mobil | Chalmette | 184,100 | 33,800 | 2,400 | --- |
| Motiva | Norco | 225,000 | 25,500 | 1,100 | 65 |
| TransAm | Norco | 200,000 | 75,000 | 4,500 | --- |
| **Minnesota** | | | | | |
| Koch | Rosemount | 280,000 | 70,000 | 4,400 | 90 |
| **Mississippi** | | | | | |
| Chevron | Pascagoula | 295,000 | 71,000 | 4,500 | 205 |
| **New Jersey** | | | | | |
| Valero | Paulsboro | 155,000 | 23,200 | 1,400 | 11 |
| **Oklahoma** | | | | | |
| CONOCO | Ponca City | 168,000 | 21,800 | 1,000 | 10 |
| **Texas** | | | | | |
| AMOCO | Texas City | 437,000 | 40,400 | 2,850 | 202 |
| CITGO | Corpus Christi | 130,000 | 36,000 | 2,400 | --- |
| Clark | Port Arthur | 225,000 | 37,500 | 2,100 | --- |
| Coastal | Corpus Christi | 100,000 | 17,000 | 1,100 | 39 |
| Lyondell-CITGO | Houston | 263,055 | 87,300 | 5,500 | --- |
| Mobil | Beaumont | 335,000 | 41,600 | 2,580 | 54 |
| Motiva | Port Arthur | 235,000 | 49,500 | 3,500 | --- |
| Shell | Deer Park | 274,200 | 59,100 | 4,100 | 111 |
| **Washington** | | | | | |
| ARCO | Ferndale | 202,000 | 51,000 | 2,800 | 81 |
| Equilon | Anacortes | 144,900 | 24,100 | 1,450 | --- |
| | | **7,557,000** | **1,651,000** | **94,580** | |

generally reduce sulfur levels compared to the federal diesel standard of 500 ppm. Because of these regulations it is assumed that California refiners will require considerably less hydrogen to produce gasoline and diesel with less than 30 ppm sulfur. In this analysis it is assumed that California refineries will only need one third as much hydrogen as refiners in the rest of the country, that is 0.0825 MMSCFD per 1000 BPD.

**Table 2. Coking Capacity by State**

| State | #Refin | | Pet Coke TPD | Crude MBPD | HydReq MMSCFD | NGEquiv MMSCFD | MWRef* Reqd |
|---|---|---|---|---|---|---|---|
| **California** | 10 | NERC | 22,549 | 1,577 | 923 | 390 | 686 |
| **Delaware** | 1 | WSCC | 1,984 | 140 | 67 | 28 | 61 |
| **Illinois** | 3 | MACC | 6,852 | 569 | 36 | 15 | 247 |
| **Indiana** | 1 | MAIN | 1,863 | 410 | 30 | 13 | 178 |
| **Louisiana** | 6 | ECAR | 21,445 | 1,617 | 183 | 77 | 703 |
| **Minnesota** | 1 | SERC | 4,409 | 280 | 90 | 38 | 122 |
| **Mississippi** | 1 | MAPP | 4,501 | 295 | 205 | 87 | 128 |
| **New Jersey** | 1 | SERC | 1,383 | 155 | 11 | 5 | 67 |
| **Oklahoma** | 1 | MACC | 1,102 | 168 | 10 | 4 | 73 |
| **Texas** | 8 | SPP | 24,236 | 1,999 | 398 | 168 | 869 |
| **Washington** | 2 | ERCOT | 4,255 | 347 | 81 | 34 | 151 |
| **Totals** | 35 | WSCC | 94,580 | 7,557 | 2,034 | 860 | 3,286 |

*Megawatt (MW) of electric power required by the refineries.

With respect to power consumption in refineries, it is assumed that a 230,000 BPD refinery will consume, on average, 100 MW of power. It is assumed that future coke will be unchanged from current coke needs on a per barrel of coker feed basis.

With respect to the capital costs of installed facilities, it is estimated that a plant to gasify pet coke to produce power will cost \$1200 per kilowatt, a coke to Fischer-Tropsch fuels plant will cost \$43,000 per daily barrel, and a plant to produce hydrogen from coke will cost \$1800 per 1000 standard cubic feet per day (SCFD).

To estimate the economic impacts in this analysis it is necessary to assign values to both electric power and to hydrogen. It is assumed that the value of electricity is determined by the cost of producing it from an advanced natural gas combined cycle (NGCC) plant, which is estimated to have an installed capital cost of \$494.5 per kilowatt and a heat rate of 6,396 Btu/kWh. Based on these estimates, the required selling price of the electricity is by the following equation:

Electricity, \$/kWh = 0.0064*NG cost, \$/MMBtu + 0.0116

For hydrogen, the value is assumed to be equal to the cost of producing hydrogen from new steam reforming facilities. It is estimated that a new hydrogen plant to produce 60 MMSCFD of hydrogen will cost $90 million. Based on this the required selling price of hydrogen is given by:

Hydrogen cost, $/MSCF = 0.45*NG cost, $/MMBtu + 0.76

For example, if NG were $2.75/MMBtu, then hydrogen would be $2/MSCF.

**Table 3. Assumptions Regarding Situation in 2010**

- Petroleum demand will increase 1.2% per annum (EIA, AEO '99)
- By 2010, less than 30 ppm sulfur gasoline and diesel will be required
- 38 MMSCFD additional $H_2$ will be required for a 150,000 BPD refinery (0.25 MMSCFD/1000 BPD)
- For California, 0.0825 MMSCFD/1000 BPD of additional hydrogen will be required
- Refinery power consumption will be 100 MW for a 230,000 BPD refinery
- Coke production per barrel of coker feed will remain unchanged
- Estimated capital costs
  - Plant to produce power from Pet coke to power $1200/kW
  - Plant to produce F-T liquids from Pet coke, $43,000 BPD
  - Plant to produce hydrogen from Pet coke, to $1800/1000 SCFD hydrogen
- Inter-related price structure
  - Power cost, $kWh = .0064 NG + 0.0116
  - New hydrogen cost, $/MSCF = 0.45 NG + 0.76
  - NG = natural gas cost, $/MMBtu

Table 4 summarizes the situation in 2010 as a result of the above assumptions. In 2010, 40 refineries are estimated to produce sufficient pet coke to warrant installation of pet coke gasification facilities. Because of the increase in petroleum consumption by 2010, coke production is estimated to be over 116,000 tons per day. Hydrogen demand in these refineries is estimated to increase to about 4.4 BSCFD compared to just over 2 BSCFD in 1999.

**Table 4. Summary of Situation in 2010**

| State | #Refin | NERC | Pet Coke TPD | Crude MBPD | HydReq MMSCFD | NGEquiv MMSCFD | MWRef Reqd |
|---|---|---|---|---|---|---|---|
| **California** | 10 | WSCC | 25,710 | 1,798 | 1,201 | 508 | 782 |
| **Delaware** | 1 | MACC | 2,262 | 160 | 116 | 49 | 69 |
| **Illinois** | 3 | MAIN | 7,813 | 649 | 203 | 86 | 282 |
| **Indiana** | 1 | ECAR | 2,124 | 467 | 151 | 64 | 203 |
| **Kansas** | 2 | SPP | 3,545 | 250 | 69 | 29 | 109 |
| **Louisiana** | 7 | SERC | 27,851 | 2,100 | 763 | 323 | 913 |
| **Minnesota** | 1 | MAPP | 5,027 | 319 | 182 | 77 | 139 |
| **Mississippi** | 1 | SERC | 5,132 | 336 | 318 | 134 | 146 |
| **New Jersey** | 1 | MACC | 1,577 | 177 | 57 | 24 | 77 |
| **Ohio** | 2 | ECAR | 2,075 | 356 | 124 | 52 | 155 |
| **Oklahoma** | 1 | SPP | 1,257 | 192 | 59 | 25 | 83 |
| **Texas** | 8 | ERCOT | 27,635 | 2,279 | 1,024 | 433 | 991 |
| **Washington** | 2 | WSCC | 4,852 | 396 | 191 | 81 | 172 |
| **Totals** | **40** | | **116,861** | **9,479** | **4,458** | **1,886** | **4,121** |

## Macroscopic Economic Analysis of U.S. Refineries

Figure 1 shows simple schematics of the petroleum coke and natural gas conversion technologies considered in this analysis. More details of the pet coke facilities are given later when these technologies are analyzed on a single plant basis. These simple schematics show

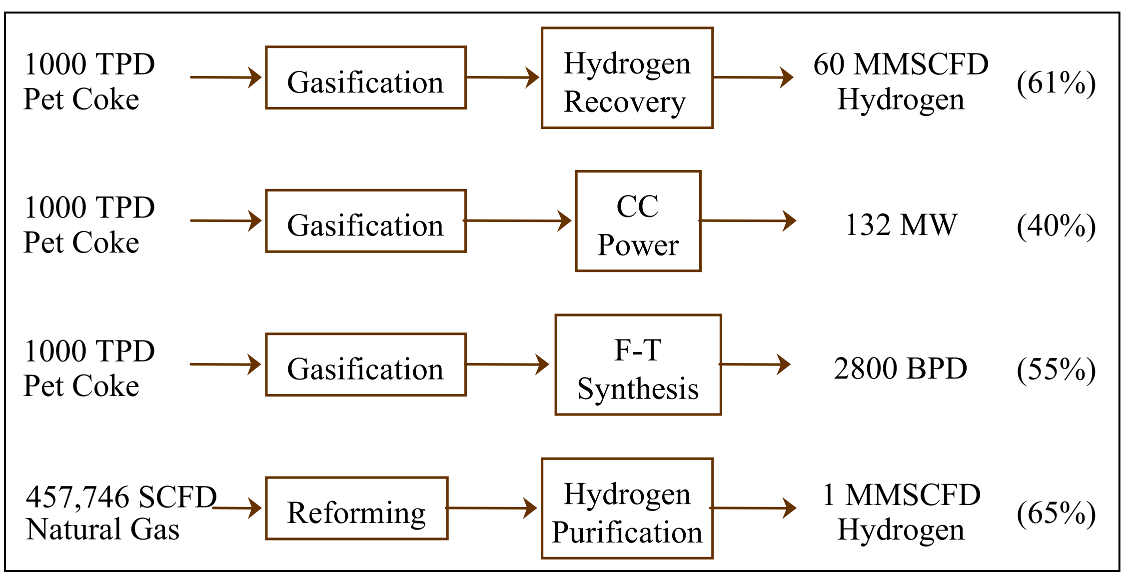


**Figure 1. Conversion Processes**

the quantities of hydrogen, power, and F-T liquids produced from 1000 TPD of pet coke. Also shown is the quantity of natural gas required to produce 1 MMSCFD of hydrogen from steam reforming.

Table 5 shows the baseline assumptions used in the macroscopic economic analysis. Capital costs of pet coke conversion facilities are shown based on an input of 1000 TPD of coke. In this macroscopic approach, it is assumed that operating and maintenance (O&M) costs are 4 percent of capital. Pet coke is assumed to be valued at $5 per ton. The reference world oil price (WOP) is taken from the EIA estimate to be $21.30/bbl in 2010. Because of the high quality of the F-T product, it is assumed to command a $5/bbl premium value over the WOP. The value for electric power and for hydrogen is given by the equations listed in Table 3.

Figure 2 shows the results of the macroscopic analysis for all of the U.S. refineries. The payback period in years, defined as the total capital divided by the total revenue minus the total operations cost, is shown plotted against the natural gas price for several combinations of products from the pet coke. As Figure 2 shows, the shortest payback periods are those where hydrogen is one of the products.

**Table 5. Baseline Assumptions**

| **Capital Costs** | **Capital Cost $MM** | **Capacity TPD Coke Feed** | **Capacity** | |
|---|---|---|---|---|
| **Pet Coke to Hydrogen** | 110 | 1000 | 60 | MMSFD |
| **Pet Coke to Power** | 158 | 1000 | 132 | MW |
| **Pet Coke to F-T** | 120 | 1000 | 2800 | BPD |
| **Natural Gas to Hydrogen** | 90 | | 60 | MMSCFD |
| **O&M Costs** | 4% of capital cost | | | |
| **Pet Coke** | $5/ton | | | |
| **World Oil Price** | $21.30/bbl | (Reference EIA) in 2010 | | |
| **F-T Premium** | $5/bbl | | | |

As an example of the methodology, let us examine the combination with the shortest payback, hydrogen and power. In this case, it is assumed that the refineries construct pet coke to hydrogen facilities so that all of the required hydrogen for the refineries is produced from coke. Coke in excess of that required for refinery hydrogen is then used to produce power. When the refineries produce hydrogen from coke, they avoid purchasing natural gas for steam reformer hydrogen, and they also avoid the cost of new steam reformers. New steam reformer hydrogen would have been necessary, because in 2010 the refiners require additional hydrogen to produce low sulfur fuels. These avoided costs, in effect, represent revenue for the coke to hydrogen facilities, and this increases with the price of natural gas. This translates into shorter payback periods as natural gas price increases as shown in Figure 2.

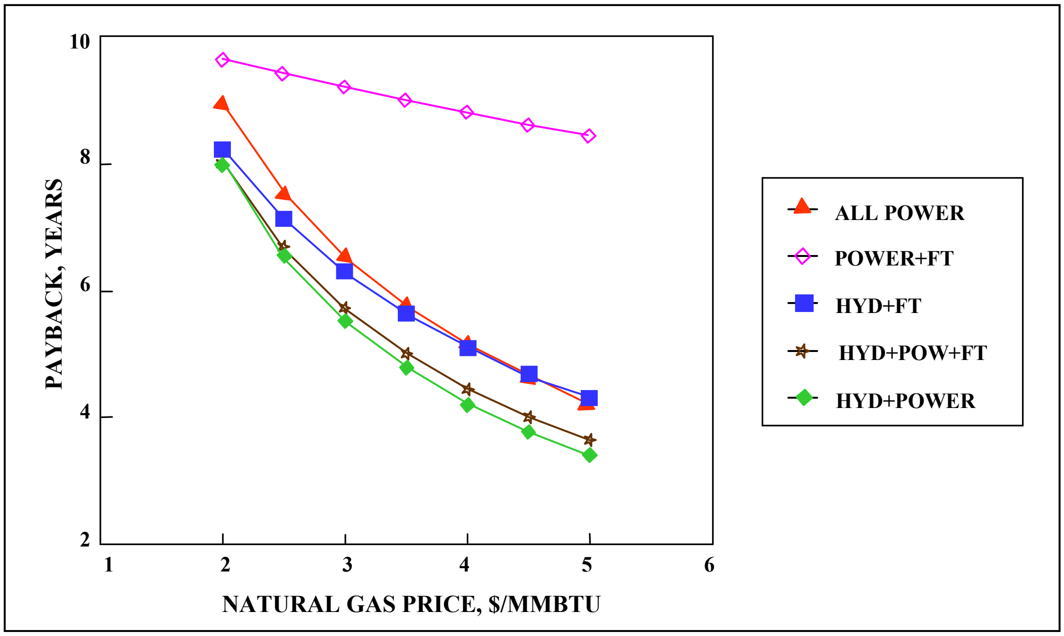


**Figure 2. Payback Period Versus Natural Gas Price for Pet Coke Gasification (Ref WOP $21.30/BBL)**

Coke in excess of that required for hydrogen is used to produce power. Power in excess of refinery requirements is sold to the grid. Revenue comes from not having to purchase power for the refinery and from power sales to the grid. Again, these revenues increase as the price of natural gas increases.

The other cases shown in Figure 2 are treated in a similar manner. A few of the refineries produce enough coke to make three products: hydrogen, power, and F-T fuels. This combination also gives a short payback period. Production of only power from the coke does not show quite as short a payback as cases coproducing hydrogen except at high natural gas prices. The combination of coproducing power and F-T fuels shows a longer payback period and would not represent a preferred configuration for a refiner based on this macroscopic analysis of all refineries unless the WOP were high.

Payback periods of below 5 years are generally considered to be reasonable economic investments. Therefore, using pet coke as a feed to produce combinations of hydrogen and power would appear to be worth considering, especially if the price of natural gas is above $3/MMBtu.

This macroscopic economic analysis also investigated sensitivities to the WOP, to the value of the pet coke, and to the capital investment of the pet coke conversion facilities. Figure 3 shows the results of this analysis for the high EIA WOP of $27.33/bbl in 2010. The major effect is on the payback period for the power and F-T case. Those configurations not coproducing high quality F-T fuels are unaffected. For those configurations coproducing F-T fuels, the payback periods are generally shortened by between six months to a year.

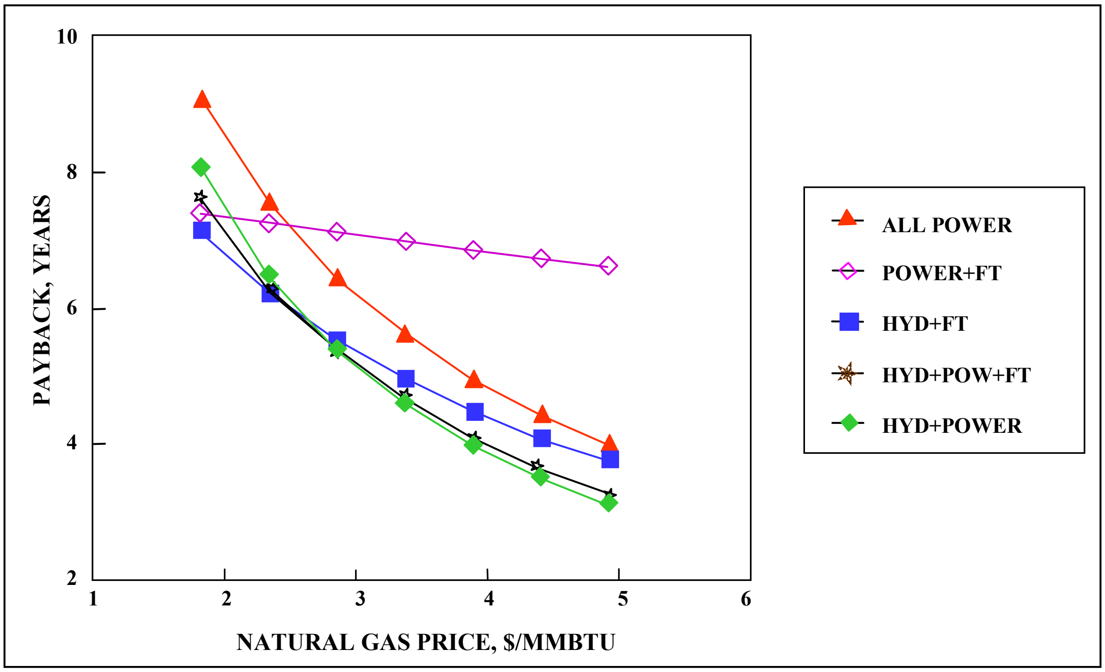


**Figure 3. Payback Period Versus Natural Gas Price for Pet Coke Gasification (High WOP $27.33/BBL)**

Figure 4 examines the impact of a negative value pet coke. If coke becomes even higher in sulfur content in the future as crude oil quality deteriorates, it may become more difficult to dispose of without penalty. If pet coke were minus $10/ton, then Figure 4 shows that the payback periods are shorter by almost two years in some cases. Many of these options would be attractive at natural gas prices lower than $3/MMBtu.

Figure 5 examines the case for higher capital investment for the pet coke conversion facilities. If capital were 25 percent higher than the base case, payback periods would obviously be longer. Pet coke to hydrogen would cost $138 million instead of $110 million for a 1000 TPD plant. Payback would be increased from one and a half to three years, depending on natural gas price and configuration. The most favorable projects do not realize a 5-year payback period until natural gas prices are in excess of $4/MMBtu.

This macroscopic analysis of U.S. refineries indicates that pet coke should become an ideal feedstock for gasification to produce combinations of refinery hydrogen, electric power, and, in certain cases, F-T liquids. With what we believe to be reasonable estimates of capital investment for pet coke conversion facilities, payback periods of about 5 years could be expected for certain configurations of product slate, depending on the future price of natural gas.

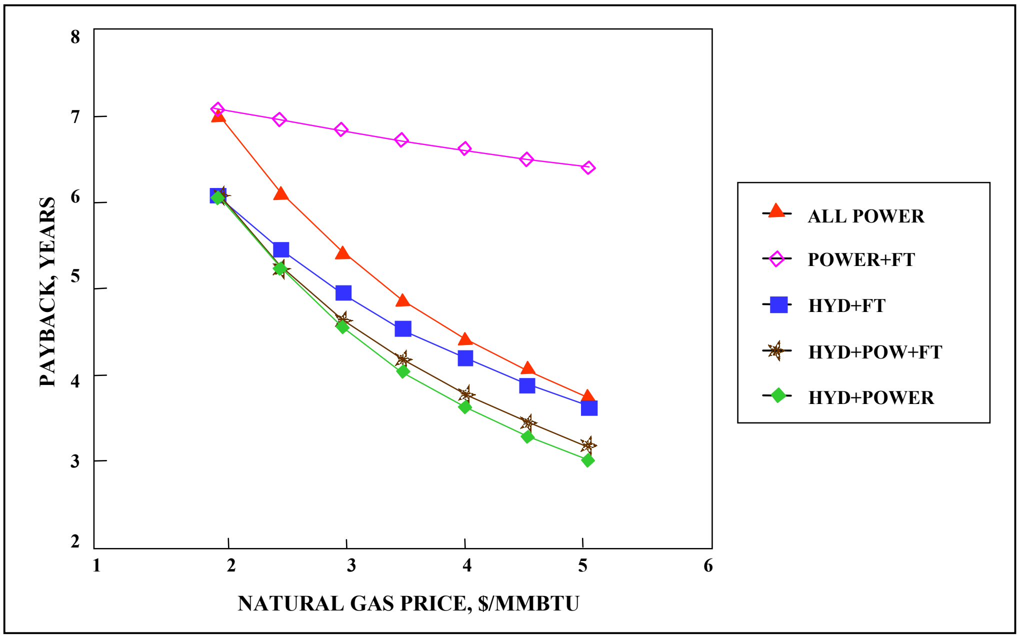


**Figure 4. Payback Period Versus Natural Gas Price for Pet Coke Gasification (Ref WOP \$21.30/BBL, Pet Coke -\$10/Ton)**

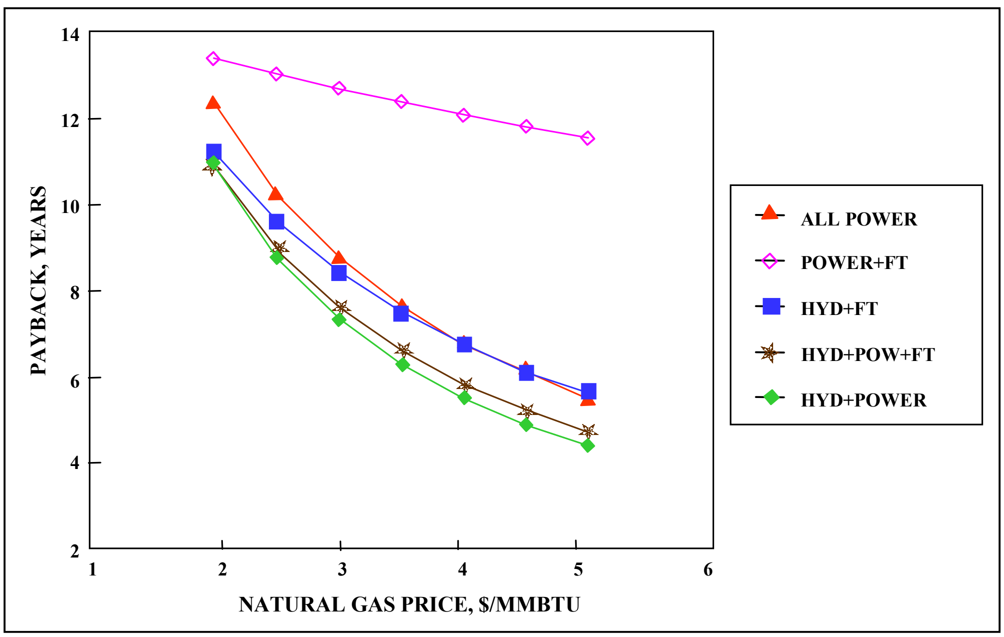


**Figure 5. Payback Period Versus Natural Gas Price for Pet Coke Gasification (Ref WOP \$21.30/BBL, 1.25 Times Capital)**

## Single Plant Analysis at A Typical U.S. Refinery

This analysis considers the case of a single pet coke conversion facility located at a generic refinery. The plant gasifies 2,700 tons per day of pet coke in a single train of a Texaco, oxygen-blown gasifier. Pet coke is assumed to cost $5 per ton. The hydrogen required for this generic refinery is assumed to be 60 MMSCFD, and electric power required is assumed to be 100 MW. The value of the hydrogen and electric power produced is given by the equations shown in Table 3.

The configurations analyzed are summarized in Table 6 and Figure 6. The primary conversion process is the gasification of the pet coke to a raw synthesis gas. The overall raw syngas efficiency is 75 percent, that is 75 percent of the heating value of the pet coke on an HHV basis is available in the raw syngas. For the power production configuration, the raw syngas is cleaned using an acid gas removal (AGR) system, and the clean gas is sent to a combined cycle power block, consisting of a gas turbine, a heat recovery steam generator (HRSG), and a steam turbine. From an input of 2700 tons per day of pet coke, the net power produced (after parasitic plant power for air separation) is 374 MW, equivalent to an overall efficiency of 41.7 percent on a HHV basis.

**Table 6. Configuration Summary for Single Refinery Analysis**

| Product | Capital Cost $MM | Power MW | Liquids BPD | Hydrogen MMSCFD | Efficiency (% HHV) |
|---|---|---|---|---|---|
| Power | 464 | 374 | 0 | 0 | 41.7 |
| F-T/Power | 382 | 88 | 5,847 | 0 | 51.8 |
| Hydrogen/Power | 434 | 238 | 0 | 60 | 53.5 |
| F-T/Hydrogen/Power | 373 | 35 | 3,739 | 60 | 58.0 |

For the configuration that produces both power and F-T liquid transportation fuels, the raw syngas is cleaned in an AGR system and polished to ultra-low sulfur levels and then sent to a slurry-phase F-T process. The F-T process is operated in a once-through mode and, after liquid product separation, the tail gas containing unconverted gas, light hydrocarbons and carbon dioxide is used as fuel to superheat the steam produced in gasification and synthesis. This superheated steam is then fed to a steam turbine for power production. This configuration is used in this case because of the size of the single train facility. In this configuration 2,700 TPD of pet coke can produce 88 MW of electric power and 5,800 BPD of essentially naphtha and diesel boiling range liquid fuels. The liquid products are a combination of straight run material and hydrocrackate resulting from the cracking of the F-T wax. The overall plant efficiency is 51.8 percent HHV. If the plant was larger and more syngas was available after the F-T process, the F-T tailgas could be fed directly to a gas turbine.

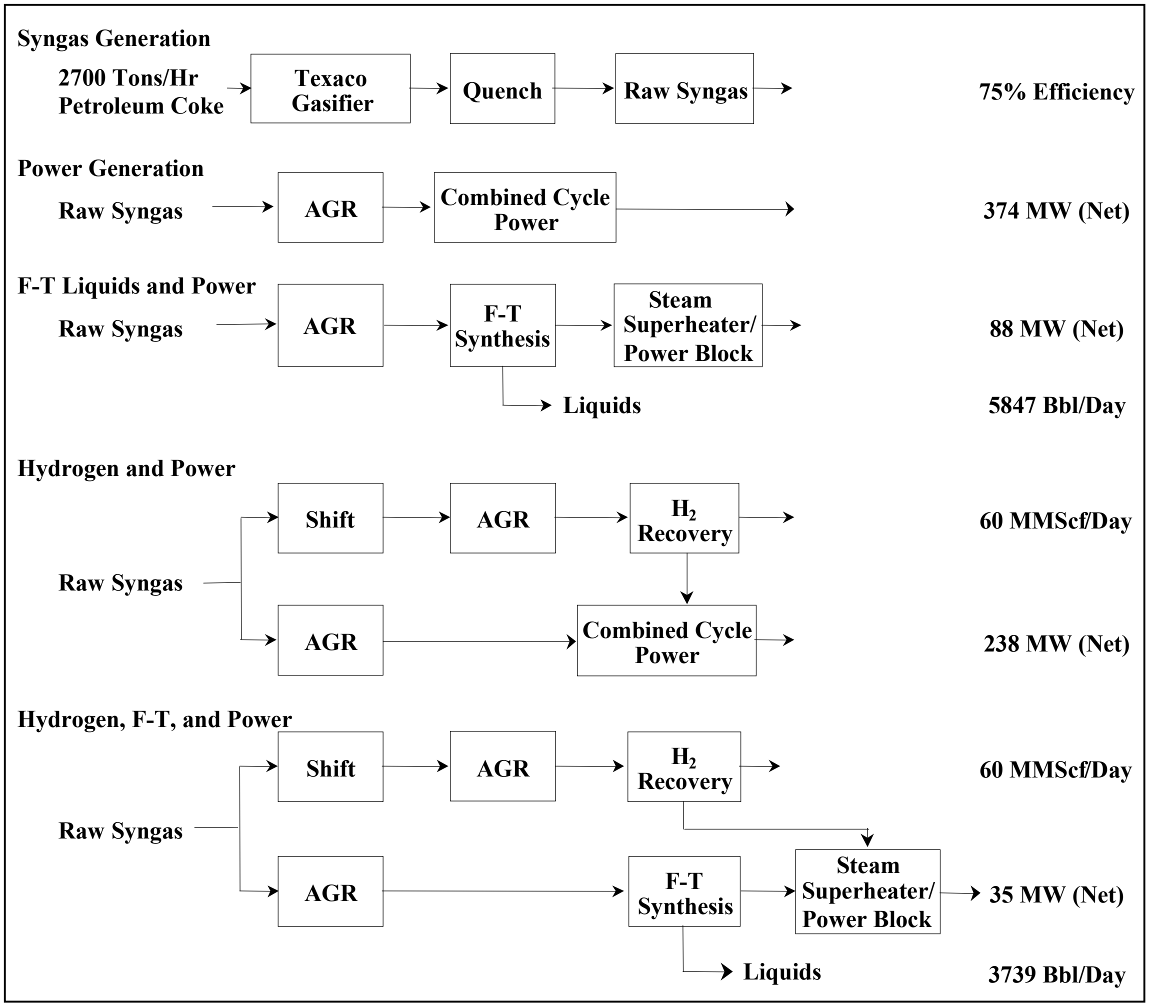


**Figure 6. Single Refinery Coke Gasification Configurations**

For the configuration that produces both power and hydrogen, the raw syngas is split into two steams. One of these streams is shifted using raw gas shift and the shifted gas is cleaned and sent to PSA units for recovery of hydrogen. The other stream is cleaned in an AGR unit and sent to a combined cycle power block that includes a gas turbine, HRSG, and steam turbine. This configuration produces the required 60 MMSCFD of hydrogen for the refinery and 238 net MW of power. Overall efficiency for this configuration is 53.5 percent HHV.

The final configuration investigated in this analysis is a combined facility that produces the refinery hydrogen requirement, F-T liquid fuels, and electric power. In this configuration, the raw syngas stream is split, and one of the streams is used to produce hydrogen as described above. The other stream is cleaned and sent to a slurry F-T reactor in a once through mode of operation. The liquid product is separated, the wax is hydrocracked, and the F-T tail gas is used to fire a superheater to superheat the available steam for feed to a small steam turbine for power production. This configuration produces 60 MMSCFD of hydrogen, 3,700 BPD of F-T fuels, and 35 MW of power. Overall efficiency is 58 percent HHV.

**Economic Analysis of Single Plants**

In the macroscopic analysis described above, payback period was used as a method of determining the relative viability of a configuration. This was because in the macroscopic approach no detailed capital or operating costs was developed. However, for the single plant analysis, detailed capital and operating costs for the various configurations were developed. This made it possible to perform detailed discounted cash flow analyses to determine the actual return on equity (ROE) that would be realized for the various configurations. Because of the 25-year plant life assumption, it was necessary to use estimates of oil prices for the entire life of the plant. The same EIA estimates were used for WOP as were used in the macroscopic analysis, except that in the single plant cases the WOP at 2020 is quoted instead of at 2010. Beyond 2020, a linear extrapolation was used.

The financial assumptions used in this single plant analysis are given in Table 7. These were used to calculate the return on equity (ROE) for these plant configurations as a function of natural gas price for various world oil price (WOP) scenarios. Details of the capital and operating costs of the various plant configurations are given in Appendix A.

**Table 7. Financial Assumptions for Single Refinery**

- 25 Year Plant Life
- 67/33 Debt Equity Financing
- 8% Interest, 16 Year Term
- 3% Inflation
- 16 Year DDB Depreciation
- 40% Combined State and Federal Tax Rate

Figure 7 shows the ROE plotted against the natural gas price for the EIA reference WOP. F-T liquids were assumed to command a premium value over crude oil of $5 per barrel. ROEs of about 15 percent can be realized for configurations producing hydrogen + power and F-T + hydrogen + power for natural gas prices of about $3/MMBtu. The all power configuration will realize a ROE of about 15 percent for gas prices above $3.50/MMBtu. At this reference WOP, the configuration producing power and F-T liquids can only realize a ROE of about 10 percent over this range of natural gas prices. At the high WOP (Figure 8) the F-T + power configuration will realize a 15 percent ROE. Even at the low WOP, those configurations coproducing hydrogen still yield a good ROE (see Figure 9).

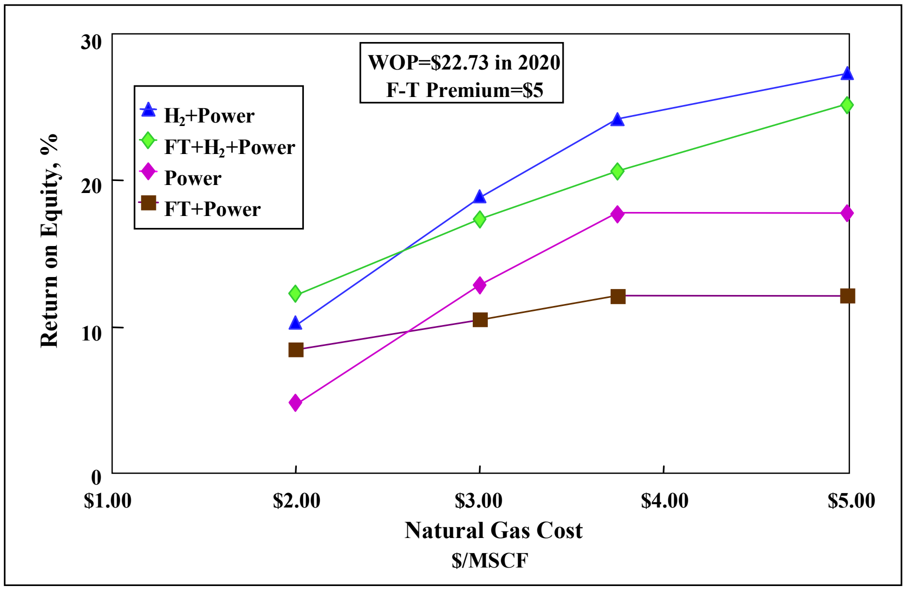


**Figure 7. Return on Equity Versus Gas Price for Reference World Oil Price**

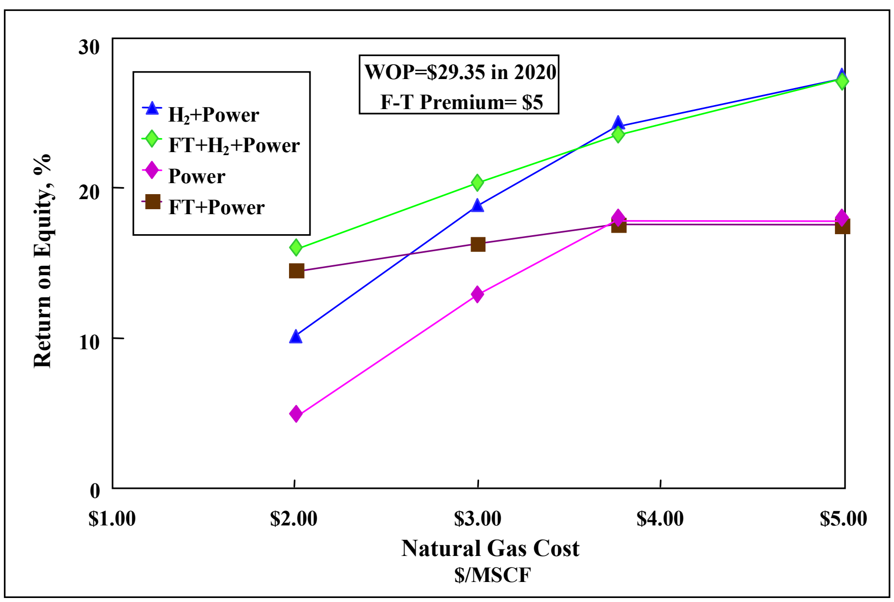


**Figure 8. Return on Equity Versus Gas Price for High World Oil Price**

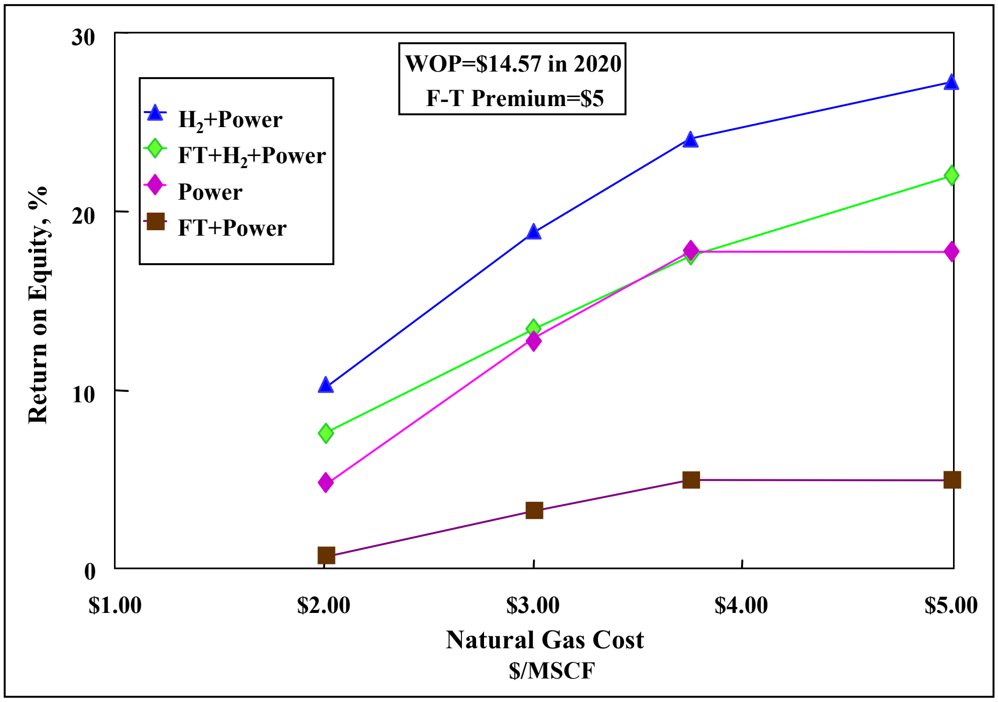


**Figure 9. Return on Equity Versus Gas Price for Low World Oil Price**

Figure 10 shows the ROE plotted against the WOP assuming that there is a fixed relationship between the WOP and natural gas price. It is assumed that the natural gas price in $/MMBtu is equal to 0.13 times the WOP in $/Bbl. Thus, if the WOP is $25 per barrel, then natural gas would be $3.25/MMBtu. This analysis shows that for a WOP of $25/Bbl, all of the pet coke conversion configurations would realize an ROE of 15 percent or greater.

## Conclusions

This analysis has investigated the potential for pet coke conversion to produce a combination of products including hydrogen, electric power, and F-T liquid fuels at U.S. refineries. Both macroscopic and single plant analyses were used to assess the potential economic and technical impact of these conversions. With the Environmental Protection Agency Tier 2 regulations pending, refineries will require additional hydrogen to hydrotreat and hydrocrack feeds to produce gasoline and diesel fuels with less than 30 ppm of sulfur. This analysis indicates that pet coke would be an ideal feedstock for hydrogen production, especially if natural gas prices are $3/MMBtu or higher. Many refineries produce sufficient pet coke to allow configurations where both hydrogen and power or F-T liquids are produced. Many of these options look economically viable when gas prices are above $3/MMBtu. Coproducing ultra-clean F-T liquids as blending stocks for ultra-low sulfur fuels production could also be a viable option for refiners in the future if the WOP remains in the range of $25-$30/bbl. Thus, pet coke that is often of poor quality and low value can become an important feedstock for a refiner to produce not only his own hydrogen and power needs, but also F-T blending stocks and power for export. Figure 11 summarizes the major conclusions resulting from this study.

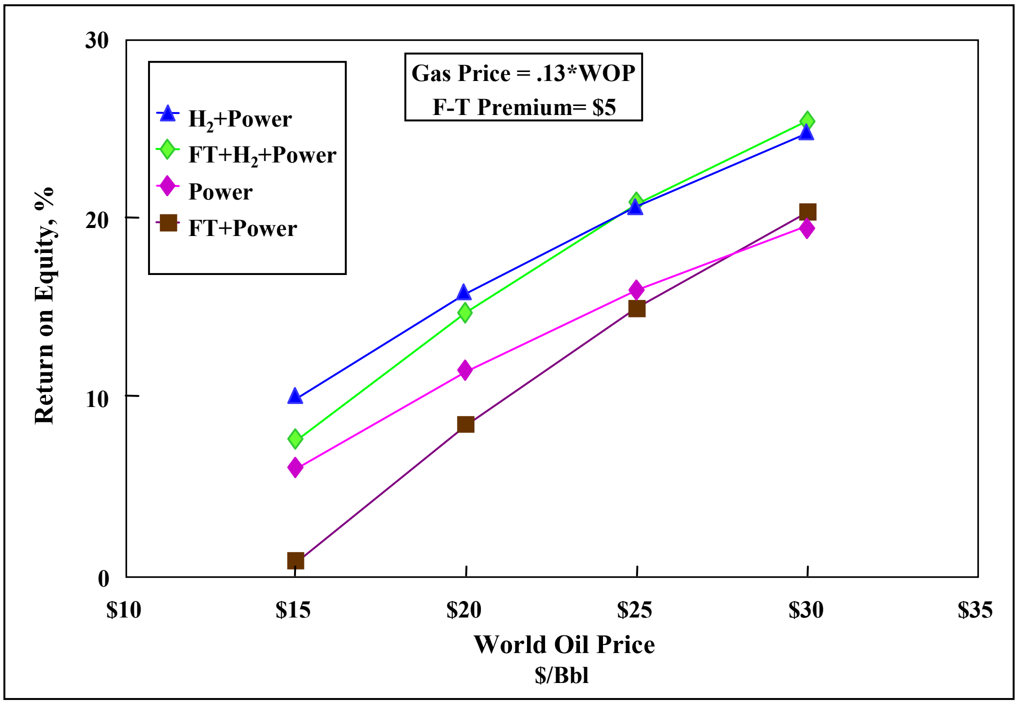


**Figure 10. Return on Equity Versus WOP for Gas Price Proportional to World Oil Price**

- With Tier 2 and other more stringent fuel specifications, refinery requirements for additional hydrogen will be substantial
- Petroleum coke is an ideal feedstock for hydrogen production
- Coproduction options producing hydrogen, power, and Fischer-Tropsch liquids are promising configurations
- Payback periods about 3-5 years can be achieved for several of these configurations for natural gas prices above $3/MMBtu
- ROEs of 15% and higher could be realized for $H_2$ coproduction options for natural gas prices at $3/MMBtu and above

**Figure 11. Conclusions**

## List of References


1. Oil and Gas Journal, December 20, 1999.

2. Energy Information Administration Annual Energy Outlook 1999 With projections to 2020, DOE/EIA-0383(99), December 1998.

# APPENDIX A

# Capital and Operating Cost Summaries

## IGCC Power Generation

374 MW

| Construction Cost | $MM(1999) |
|---|---|
| Coke Handling | $5 |
| Gasification/Quench/Clean | $83 |
| Air Separation | $69 |
| Sulfur Polishing | $0 |
| F-T Synthesis | $0 |
| Hydrogen Removal | $0 |
| Refining | $0 |
| Heat Rec/Power Gen | $174 |
| Balance of Plant | $47 |
| TOTAL | $377 |

| Capital Cost | $MM(1999) |
|---|---|
| Construction | $377 |
| Home Office 8.4% | $32 |
| Fee 2% | $8 |
| Contingency 5% | $21 |
| TOTAL PLANT COST | $437 |
| Start-up Costs | $23 |
| Working Capital | $3 |
| TOTAL NON-DEPRECIABLE CAPITAL | $27 |
| TOTAL CAPITAL REQUIRED | $464 |

| Operating Costs | | | $MM(1999) |
|---|---|---|---|
| | | $5 /ton AR | 4.2 |
| Consumables | | | 0.5 |
| Labor/Overhead | | | 7.7 |
| Administrative Labor | | | 1.2 |
| Local Taxes & Ins. @ | | 2.00% | 8.7 |
| Other | | | 11.2 |
| GROSS OPERATING COST | | | 33.5 |
| Sulfur, | @ | 80 /ton | 2.8 |
| Ammonia, | @ | 150 /ton | 0.0 |
| TOTAL BY-PRODUCT CREDITS | | | 2.8 |
| NET OPERATING COSTS | | | 30.6 |



## Fischer-Tropsch Synthesis/Power Generation

5,847 Bbls /Day 88 MW

| Construction Cost | $MM(1999) |
|---|---|
| Coke Handling | $5 |
| Gasification/Quench/Clean | $83 |
| Air Separation | $69 |
| Sulfur Polishing | $4 |
| F-T Synthesis | $14 |
| Hydrogen Removal | $0 |
| Refining | $10 |
| Power | $87 |
| Balance of Plant | $40 |
| TOTAL | $310 |

| Capital Cost | $MM(1999) |
|---|---|
| Construction | $310 |
| Home Office 8.4% | $26 |
| Fee 2% | $6 |
| Contingency 5% | $17 |
| TOTAL PLANT COST | $360 |
| Start-up Costs | $19 |
| Working Capital | $3 |
| TOTAL NON-DEPRECIABLE CAPITAL | $22 |
| TOTAL CAPITAL REQUIRED | $382 |

| Operating Costs | | | $MM(1999) |
|---|---|---|---|
| Coke, | @ | $5 /ton AR | 4.2 |
| Consumables | | | 1.6 |
| Labor/Overhead | | | 7.7 |
| Administrative Labor | | | 1.2 |
| Local Taxes & Ins. @ | | 2.00% | 7.2 |
| Other | | | 9.3 |
| GROSS OPERATING COST | | | 31.2 |
| Sulfur, | @ | 80 /ton | 2.8 |
| Ammonia, | @ | 150 /ton | 0.0 |
| TOTAL BY-PRODUCT CREDITS | | | 2.8 |
| NET OPERATING COSTS | | | 28.4 |

# Capital and Operating Cost Summaries (Concluded)

## Hydrogen Production/Power

60 MMScf/Day 238 MW

| Construction Cost | $MM(1999) | Capital Cost | $MM(1999) | Operating Costs | | | $MM(1999) |
|---|---|---|---|---|---|---|---|
| Coke Handling | $5 | Construction | $353 | Coke, | @ | $5 /ton AR | 4.2 |
| Gasification/Quench/Clean | $82 | Home Office 8.4% | $30 | Consumables | | | 1.6 |
| Air Separation | $69 | Fee 2% | $7 | Labor/Overhead | | | 7.7 |
| Sulfur Polishing | $0 | Contingency 5% | $19 | Administrative Labor | | | 1.2 |
| F-T Synthesis | $0 | TOTAL PLANT COST | $409 | Local Taxes & Ins. | @ | 2.00% | 8.2 |
| Hydrogen Recovery | $14 | Start-up Costs | $22 | Other | | | 10.4 |
| Refining | $0 | Working Capital | $3 | GROSS OPERATING COST | | | 33.3 |
| Power | $133 | TOTAL NON-DEPRECIABLE CAPITAL | $25 | Sulfur, | @ | 80 /ton | 2.8 |
| Balance of Plant | $50 | TOTAL CAPITAL REQUIRED | $434 | Ammonia, | @ | 150 /ton | 0.0 |
| TOTAL | $353 | | | TOTAL BY-PRODUCT CREDITS | | | 2.8 |
| | | | | NET OPERATING COSTS | | | 30.5 |

## Fischer-Tropsch Synthesis/Hydrogen/Power

3,739 Bbls/Day 60 MMScf/Day 35 MW

| Construction Cost | $MM(1999) | Capital Cost | $MM(1999) | Operating Costs | | | $MM(1999) |
|---|---|---|---|---|---|---|---|
| Coke Handling | $5 | Construction | $303 | Coke, | @ | $5 /ton AR | 4.2 |
| Gasification/Quench/Clean | $83 | Home Office 8.4% | $25 | Consumables | | | 1.6 |
| Air Separation | $69 | Fee 2% | $6 | Labor/Overhead | | | 6.5 |
| Shift | $9 | Contingency 5% | $0 | Administrative Labor | | | 1.1 |
| F-T Synthesis | $12 | TOTAL PLANT COST | $335 | Local Taxes & Ins. | @ | 2.00% | 7.0 |
| Hydrogen Recovery | $15 | Start-up Costs | $19 | Other | | | 9.1 |
| Refining | $7 | Working Capital | $3 | GROSS OPERATING COST | | | 29.5 |
| Heat Rec/Power Gen | $68 | TOTAL NON-DEPRECIABLE CAPITAL | $22 | Sulfur, | @ | 80 /ton | 2.8 |
| Balance of Plant | $36 | TOTAL CAPITAL REQUIRED | $373 | Ammonia, | @ | 150 /ton | 0.0 |
| TOTAL | $303 | | | TOTAL BY-PRODUCT CREDITS | | | 2.8 |
| | | | | NET OPERATING COSTS | | | 26.7 |