An ExxonMobil white paper

Market Insights on the Crude-to-Chemicals Trend: Refining the Product Slate

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Summary

The refinery product slate has evolved over time from the early days of lamp oil and kerosene to modern day transportation fuels including gasoline, diesel, and jet fuel. In more recent times, chemical plant facilities were co-located adjacent to crude oil refineries to upgrade some refinery streams into higher value chemicals products. The typical product split between fuels and chemicals for traditional medium conversion fuels refineries has been about 95% fuels to 5% chemicals.

Today there is an emerging trend that is significantly changing the refining complex product slate. Crude oil refining investments are shifting aggressively from an emphasis on transportation fuels to higher margin chemicals products. With this focus, each component of the petrochemical complex is evaluated for its potential to contribute to increased production of the desired chemical product slate. Meanwhile, environmental regulations continue to become more onerous, affecting suitability of technologies and configuration choices. As a result, the technologies and the process configurations chosen for a modern refinery/chemical complex must evolve to meet these emerging challenges.

Since vacuum resid can be a significant fraction (~30 to 40%) of the complex feed when processing heavy crudes, it follows that resid conversion technology selection is an important factor in maximizing economic chemicals production and meeting evolving environmental standards. Resid conversion processes convert low value fuel oil to higher value products. However, resid upgrading consumes significant amounts of energy and can substantially increase the total complex investment. Additionally, some resid conversion processes can produce large quantities of waste material such as spent catalyst, waste pitch, or undesirable by-products such as high-sulfur petroleum coke.

FLEXICOKING™ technology is a unique fluidized bed resid upgrading process that can be an excellent fit for Crude-to-Chemicals plants to convert resid streams to chemical feedstocks while optimizing capital investment, energy input and minimizing environmental impacts. FLEXICOKING technology is capable of running a wide range of difficult-to-process heavy oils while converting them to fuel gas, naphtha, and gas oils that are suitable for processing to aromatics and olefin based chemicals.

This paper focuses on two main themes:

1. An overview of the drivers creating the shift in the Crude-to-Chemicals market:
    a. Growing worldwide chemicals demand
    b. New environmental regulations
2. Considerations and benefits of integrating FLEXICOKING technology into a state-of-the-art, world scale, Crude-to-Chemicals plant. This will be illustrated using results of an actual study comparing FLEXICOKING technology vs. an alternative resid conversion option that includes a catalytic resid hydroprocessing (HDP) unit combined with a Delayed Coker (DC) and a Partial Oxidation (POX) unit.

The study results show FLEXICOKING technology offers lower capital investment, lower operating cost, and lower environmental emissions with a better economic fit to the chemicals run plan.

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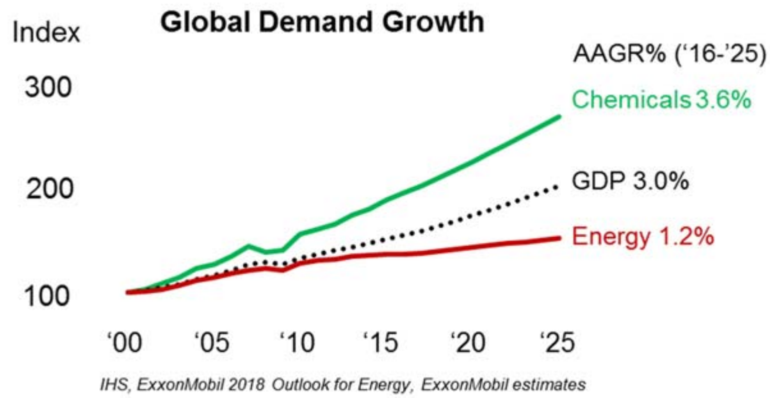
Crude-to-Chemicals - Market Drivers

Growing Worldwide Chemical Demand

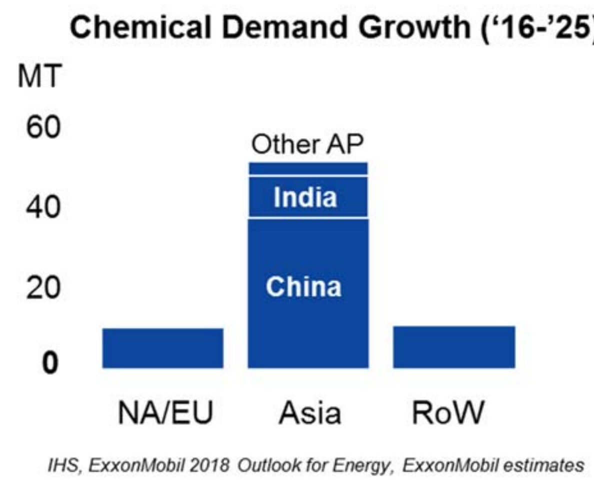
A growing world population, combined with an increasing standard of living is the engine driving demand for Chemicals.

As shown in Figure 1, chemicals demand continues to outpace both energy and GDP.



Chemicals demand growth is especially strong in emerging regions including China and India. Polyethylene (PE), Polypropylene (PE) and Paraxylene (PX) demand trends are shown in Figure 2.

This strong demand has led to a number of new refining/chemicals investments.



China

In China, more than a dozen world-class, multibillion dollar Crude-to-Chemicals complexes have been announced in the past few years and at least six of those are currently in construction. Each complex has crude runs in the 200-400kB/D range and produce between 2 to 5 MTA of paraxylene (PX). Some of these complexes also add Steam Crackers for production of 1-2 MTA of ethylene and other olefins and derivatives. The "General Themes" of these mega projects include: maximize chemicals and derivatives, minimize fuels (diesel and Fuel Oils) and use commercially demonstrated, proven technology.

In addition to the market demand noted above, there are other factors contributing to the drive for new petrochemical plants in China. China plans to increase domestic production and reduce dependence on foreign imported petrochemicals. China tax policy also favors chemicals vs. fuels and recently they have made crude import licenses available to private companies. These policy changes have allowed the rise of independent companies vs. National Oil Companies (NOC's). Also worthy of mention is the goal of some private firms to diversify investment portfolios in petrochemicals. The government is also looking to reduce environmental concerns and increase employment by replacing smaller, older facilities with new modern, efficient manufacturing plants. China's National Development and Reform Commission (NDRC) encourages integration of the small "teapot" refineries to increase profitability and make them more environmentally friendly. Finally, the recent “One Belt, One Road” initiative has incentivized companies to expand operations reaching new markets and driving growth.

India

Trends in India have many thematic parallels with China. India is quickly becoming one of the largest global economies. There is a very large population which is transitioning into a middle class standard of living. With that move, there is a greater demand for packaged goods, small appliances, and eventually individual transportation. All of these require chemicals or plastics. India uses fewer chemicals per capita than many other countries so there is a significant potential for growth and polyolefin demands could double in the coming years. These trends were apparent at the 21st Reverse Trade Mission (RTM) meeting, themed “Refining to Petrochemicals – The Way Ahead”, and by the recent formation of the Ratnagiri Refinery and Petrochemical Limited (RRPCL) joint-venture to build a Crude-to-Chemicals complex on the west coast.

The forecast demand growth in transportation will also require additional fuels, lubricants, and roads. In addition to the consumer demand, there is a need to create jobs especially for the growing group of young people coming into the workforce in the future. The government is working to help foster progress in both of these areas with the “Make in India” initiative. Its goal is to manufacture goods and services to meet the needs of its people. Investments are planned in automotive, IT, biotechnology, infrastructure, and most importantly refining and petrochemicals.

New Environmental Regulations

There are new environmental regulations expected to impact refinery economics and contribute to reduced demand for traditional refinery fuels products. This will generate increased incentive for run plan optimization to shift to a more chemicals-centric operation to add value. Examples of these new laws or mandates include:

1. Bunker fuel sulfur reduction
2. Proposed restrictions on burning of petroleum coke (PETCOKE)

International Marine Organizations (IMO) Sulfur Reduction

In 2016, the IMO passed a regulation reducing the maximum sulfur specification for marine fuel from 3.5wt% down to 0.5wt% sulfur. This is a very large reduction that will go into effect in 2020 and will significantly reduce the demand for high sulfur fuel oil and incentivize many high-sulfur crude refineries to modify their run plans. There are several options – some of which include investments in resid desulfurization facilities to produce Low Sulfur Fuel Oil (LSFO) or resid conversion facilities to produce lighter liquid products. Adding new conversion units opens up new opportunities for refineries to transition to increased chemicals production and increased margins.

Possible Restrictions on Petroleum Coke (PETCOKE)

PETCOKE is produced from the coking processes which converts resid to naphtha, gas oil, and solid coke. The Delayed Coking process is the most common process for resid coking. Coke produced by Delayed Coking can have a yield of ~25 to 35% of the total feed. The coke yield is a strong function of the Conradson Carbon Residue (CCR) content of the feed. Fuels PETCOKE is typically high in sulfur (~6 to 8 wt. %) and has been used primarily in the production of cement or for production of electrical power as a low cost fuel source.

In the last few years, countries such as China and India have seen government regulators debate the need to limit the sulfur level of imported PETCOKE to reduce the environmental emissions resulting from burning the coke. A possible ban on imported coke has also been discussed as heavy metals, SOx, and NOx emissions can be similar to coal.

The trend of new and more stringent environmental regulations will only continue and could have a significant impact on the value and dispositions for PETCOKE in the future.

FLEXICOKING™ technology is an alternative to Delayed Coking which essentially eliminates PETCOKE. FLEXICOKING technology upgrades resid while minimizing coke production and PETCOKE handling and consumption concerns. In addition, it provides significant environmental benefits. FLEXICOKING technology is an integrated fluidized bed and coke gasification process that minimizes coke yield and coke sulfur content by converting the coke to clean burning fuel gas ("flexigas").

The next section of the paper will provide a more in-depth discussion of refinery configuration alternatives and resid processing considerations from an actual project currently in progress. In addition, FLEXICOKING process advantages will be highlighted including maximizing product values, minimizing CAPEX and minimizing OPEX.

State of the Art, World-Class Crude-to-Chemicals Plant

Traditional Refinery vs. Crude-to-Chemicals Complex

The traditional refinery configuration generally maximized fuels production and chemicals were typically limited to opportunistic removal of aromatics compounds for benzene, toluene and xylene sales. (See Figure 3). Given the increasing global demand for chemicals products, fast approaching tighter environmental regulations, and a high cost of energy, the traditional refinery run plan as shown in Figure 3, will need to change to remain profitable.

The key factors for an integrated Crude-to-Chemicals run plan include:

1. Maximum conversion of feedstocks into light chemicals and minimization of fuels products
2. Feed and product (material balance) flexibility to adjust with changing market drivers
3. Energy optimization (fuel and power) to reliably and economically meet the needs for high severity, high conversion process demands
4. Environmental capability to meet stricter emissions laws
5. Configuration optimization to meet CAPEX and OPEX goals

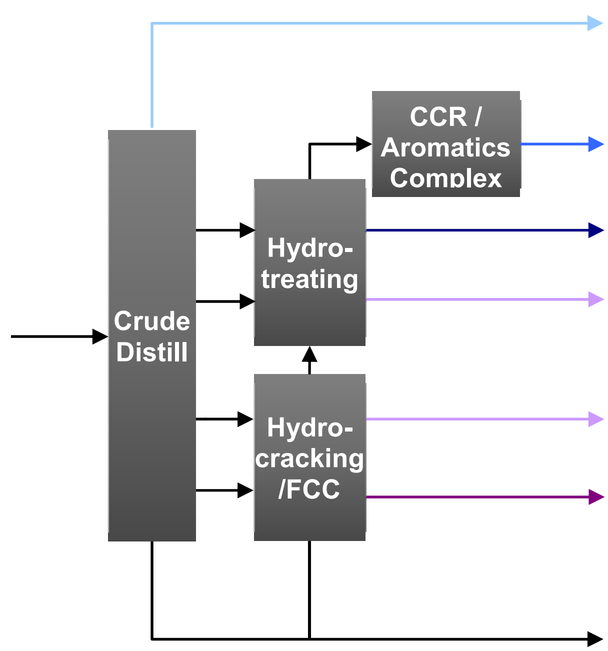


Figure 3. Traditional Fuels, Medium Conversion Refinery Run Plan

The major changes for a chemicals focused run plan require a step change increase in conversion of gas oils and resid to light liquids by adding additional process units.

Figure 4 shows a high conversion, maximum chemicals configuration. A FLEXICOKING™ unit is added to convert vacuum resid to coker naphtha and gas oils. The coker liquids are fed to the hydrocracker. Light gases from the FLEXICOKER would be combined into the FCC gas plant. To maximize chemicals production, light paraffins are processed in a dehydrogenation plant for propylene and butylene production. An aromatics plant produces benzene, toluene and mixed xylenes or para-xylene to meet local market needs. Naphtha and light gas oils are fed to a steam cracker for production of ethylene and higher olefins. In this scheme, a lube unit is added which allows for processing of unconverted oil from a low conversion hydrocracker to be processed into high quality lubricant base oils for additional margin uplift above transportation fuels.

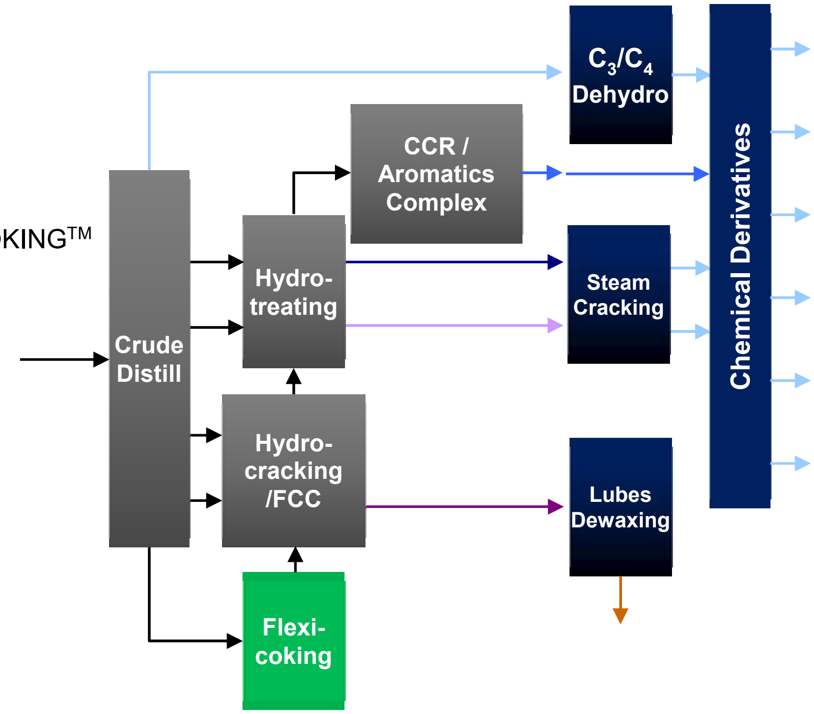


Figure 4. Crude-to-Chemicals Run Plan

The change in the product balance from fuels to chemicals and lubes is shown in Figure 5. This shows the traditional refinery total chemicals products are only in the range of ~5 to 20% depending on the level of aromatics and olefins recovery for chemical sales. However, with this potential Crude-to-Chemicals configuration, the chemicals production can increase to as much as 40 to 50%.

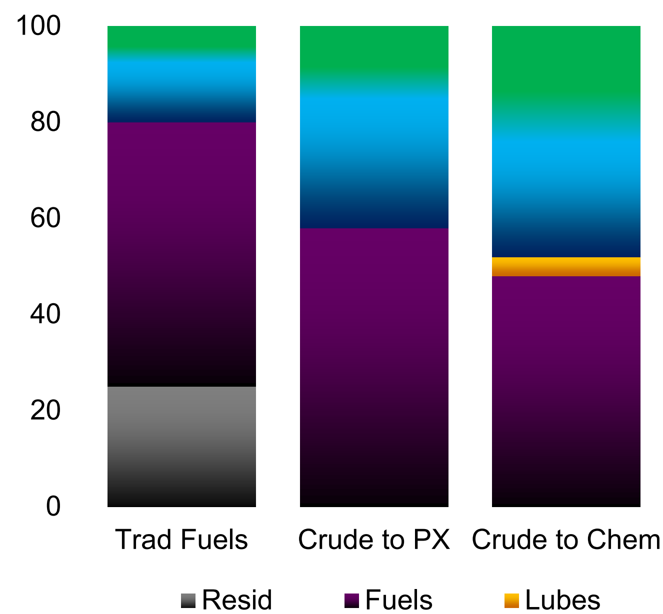


Figure 5. Shift in Product Mix from Traditional Fuels Refinery to Crude to PX (aromatics) and then full shift to Crude-to-Chemicals Run Plan

There are a number of technology alternatives for each of these processing steps. However, the vacuum resid conversion technology is critical to managing a range of important parameters affecting the configuration. These factors include investment cost, feed flexibility, energy management, hydrogen consumption, cost and disposition of unconverted pitch and tar, cost of fresh catalysts and disposition of spent catalysts, and the environmental impacts of the overall complex.

Resid Conversion Alternatives

Resid materials are high boiling hydrocarbons that are not suitable for clean transportation fuels, chemicals or lubes unless they can be converted to lighter more hydrogen rich hydrocarbons. There are two basic approaches to processing these feed stocks to more valuable, lighter products. These are referred to as hydrogen addition or carbon rejection processes.

Hydrogen addition processes operate at high pressure and depend upon catalysis and hydrogen gas to achieve the desired reactions which simultaneously crack and hydrogenate the large resid molecules. These heavy feedstocks generally cause catalyst deactivation at a significant rate due to presence of hetero atoms and metals, requiring high fresh catalyst make-up rates. Hydrogenation is indiscriminate and the resultant high hydrogen demand can be expensive at locations where hydrogen is costly. These processes also produce a bottoms stream that is very poor quality and can be difficult to dispose of in a cost-effective manner.

Carbon rejection processes generally refer to thermal coking processes which operate at low pressure (less than 0.4 MPa-g or ~60psig) and utilize thermal cracking reactions to achieve the desired conversion of the high boiling molecules. Thermal cracking reactions refer to several types of reactions including cracking, condensation, polymerization and isomerization. This chemistry results in a redistribution of hydrogen in the feed to yield lighter liquid products with higher hydrogen-carbon ratios and a byproduct solid coke with low hydrogen-carbon ratio. Typical commercial coking processes include delayed coking, fluid coking, and ExxonMobil's trademarked FLEXICOKING™ technology**.** FLEXICOKING technology is differentiated by the integrated steam/air gasification of the coke making it essentially a coke less Coker.

The remaining portion of the paper will focus on the technical and economic considerations for the selection of resid conversion technology based on a real project. The paper is intended to highlight the benefits of integrating FLEXICOKING technology into state-of-the-art, world scale Crude-to-Chemicals plant versus a commonly proposed alternative. Specifically, FLEXICOKING technology will be compared with a configuration that incorporates high pressure catalytic resid hydroprocessing (HDP), Delayed Coking (DC) of unconverted pitch from the HDP unit and gasification of the PETCOKE from the DC unit. Coke gasification in this case will be via a partial oxidation (POx) slagging gasifier, a water gas shift reactor and gas clean up processing to produce hydrogen, synthesis gas and an H2S stream. The POX unit will process coal and coke to provide hydrogen for the new HDP unit. The combination of technologies will be referred to as HDP+DC+POX. The solid ash, high metals purge stream from the POX unit is assumed to be sold for cement production.

First we will start with a brief process description of FLEXICOKING technology.

FLEXICOKING™ Process Description

The FLEXICOKING process is a low pressure process that integrates fluid bed thermal coking with a fluid bed steam and air coke gasification. The feed is converted to high value full-range liquid products, conventional fuel gas and a CO / H_2 based fuel gas referred to as "flexigas." Process heat for the thermal conversion and gasification steps is provided by partial oxidation of carbonaceous coke formed in the coking reactor. Most of the coke is gasified with air and steam via partial oxidation and water gas shift reactions. The resulting synthesis gas is desulfurized with a proprietary amine absorption process. The significant volume of clean flexigas can be used in refinery fired equipment in place of refinery fuel gas and natural gas, or for power generation or for other energy needs.

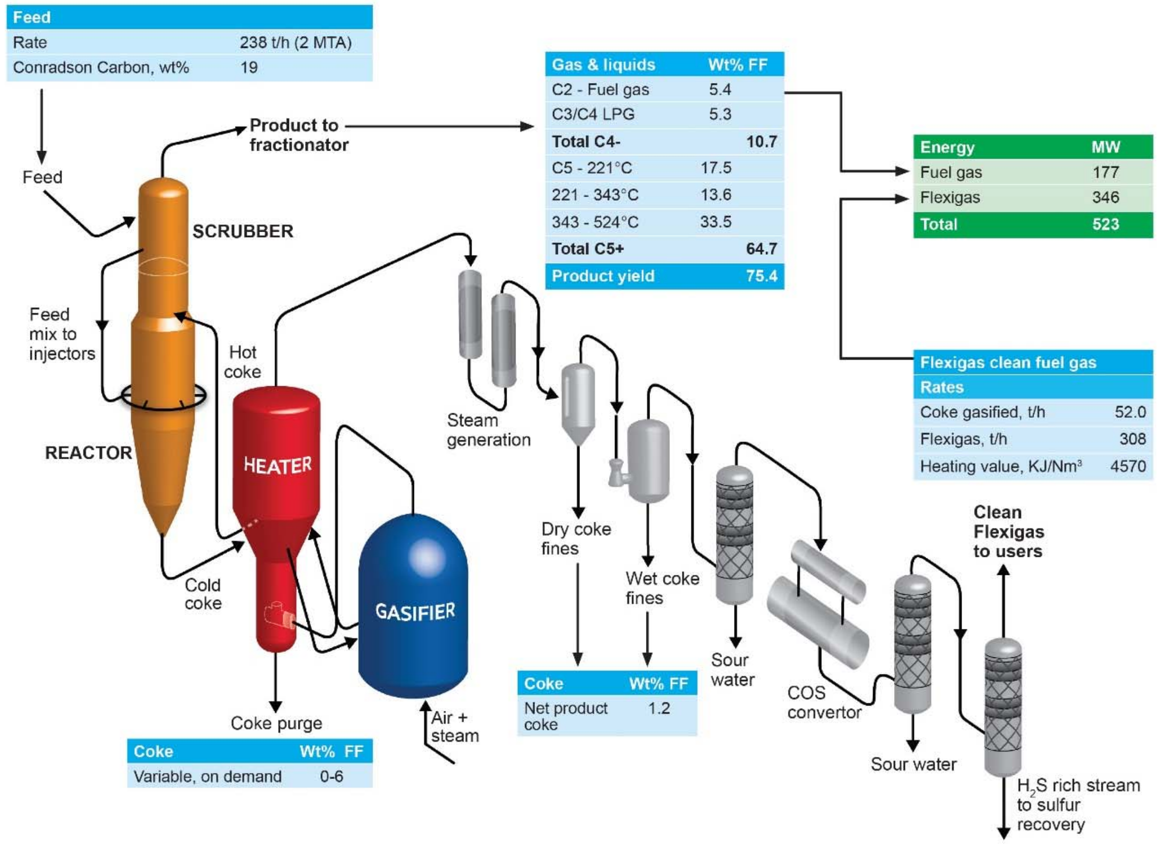


Figure 6. FLEXICOKING^{TM} Technology Products and Energy Balance

The FLEXICOKING^{TM} process can gasify ~95 to 97% of the coke to produce a clean flexigas. In this example, the combined fuel gas and flexigas energy output exceeds 500MW (thermal). A small purge stream of coke is used to remove metals. This high metals, low sulfur material is particularly attractive for cement production.

Resid Upgrading Study for Maximum Chemicals Production

To compare the resid conversion alternatives, i.e. FLEXICOKING technology vs. HDP+DC+POX, a detailed study was completed for an actual Crude-to-Chemicals complex evaluating all key parameters.

The study basis was as follows:

- Arab Heavy crude capacity of 20 MTA with all cases aimed to maximize chemicals production (i.e. the feedstock for PX and olefins), while transportation fuels are produced as by-products.
- All cases include a CCR/Aromatics plant to produce PX and a Steam Cracker to produce olefins.
- The comparison includes the following:
    - Material balance (feeds and products)
    - Energy balance
    - Hydrogen balance
    - Investments
    - Operating costs
    - Environmental impact (key emissions)
- Two resid conversion process run plans have been evaluated in detail
    - FLEXICOKING technology
    - Resid HDP + Delayed Coking + POx technologies

Comparison of Resid Conversion Run Plans

A simplified run plan for each technology option is shown in Figure 7.

In the run plan diagram on the left (FLEXICOKER Configuration), the crude is processed in the atmospheric distillation unit (ADU) and the atmospheric resid is processed in the vacuum distillation unit (VDU). The Vac Resid is processed in a FLEXICOKING™ unit and the liquid products are treated in the naphtha hydrofining (NHF), distillate hydrocracking (HCK) and gasoil hydrocracking units (HCK). The FLEXICOKER coke is gasified in the FLEXICOING™ process using air and steam to produce flexigas that is completely utilized within the petrochemical complex.

In the run plan diagram on the right (Resid HDP/Delayed Coker/POx Configuration), the crude is processed in the atmospheric distillation unit (ADU) and the atmospheric resid is processed in the vacuum distillation unit (VDU). The Vac Resid is processed in a high pressure, Resid Hydroprocessing Unit (HPD) unit and the lighter liquid products are treated in the naphtha hydrofining (NHF), distillate hydrocracking (HCK) and gasoil hydrocracking units (HCK). The unconverted bottoms stream is sent to a Delayed Coker (DC) and the liquid products from the DC are co-processed with the HPD products. The coke produced from the DC is combined with imported coal and sent to a POx Unit to produce hydrogen. In this run plan, the Resid Hydroprocessing unit and related HF+HCK units have much higher hydrogen consumptions vs. the FLEXICOKING technology run plan. In addition, the POx syngas must be further processed in a Pressure Swing Adsorption (PSA) Unit to produce a high purity hydrogen stream for the Resid HDP unit. Also note that importing coal was necessary to generate all the H2 needed for the hydroprocessing step. This run plan also included all the related hardware necessary (such as coal import facilities and air separation plant) to support the primary processing units.

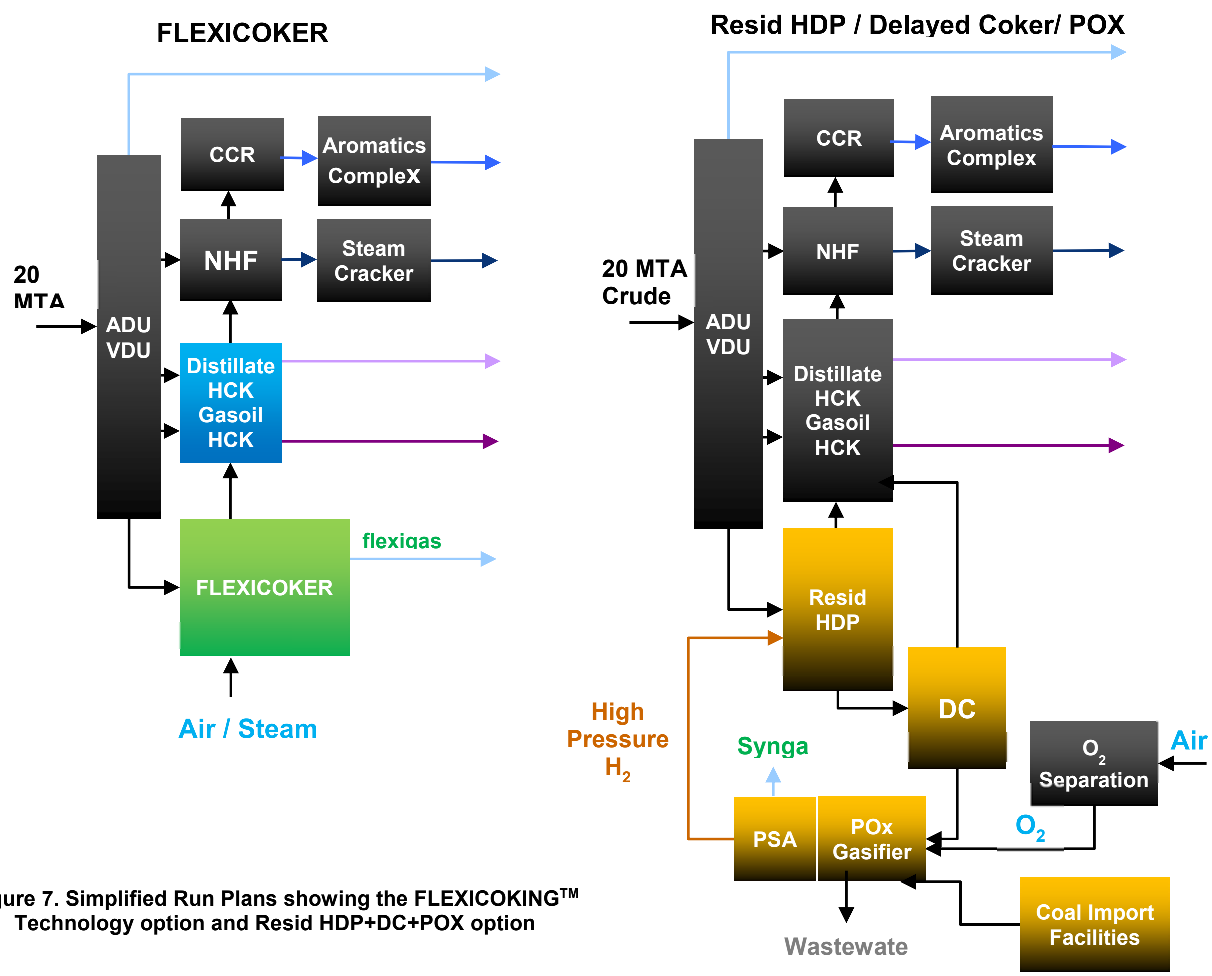


Figure 7. Simplified Run Plans showing the FLEXICOKING™ Technology option and Resid HDP+DC+POX option

In comparing the two run plans, they both produce the same amount of aromatics and olefins plant feeds to meet the chemicals product targets. However, the FLEXICOKER configuration is much simpler and streamlined since it has significantly fewer process units and less equipment. In addition, the hydrogen balance for the FLEXICOKING™ technology run plan can be satisfied using all the hydrogen produced from the CCR and Steam Cracker along with hydrogen recovery from hydrotreating purge streams. Lastly, the FLEXICOKER flexigas makes an excellent clean fuel gas that can be utilized in the process heaters and boilers or used to generate power. Additional details on the hydrogen and energy balances, as well as, the capital and operating expense estimates are provided later in the paper.

Comparison of Material Balances Impacts for Resid Conversion Run Plans

A summary of key differences between the two material balance cases is shown in Figure 8.

On the feed side, the crude rates are identical but, as was mentioned earlier, coal imports are required to produce the additional hydrogen needed for the Resid HDP/DC/POx case.

On the products side, there are several differences to note. First is that the FLEXICOKING technology case produces the same amount of gasoline but slightly less sales naphtha. In this case, the sales naphtha has a relatively low value and if needed, can be easily purchased from the local market. Not shown in this table, but worth noting, are the impacts on the energy balance from excess syngas from the POx unit (since only a portion of the syngas is hydrogen and the remainder is fuel gas) and the clean flexigas from the FLEXICOKING technology case. The energy balance is highlighted later in the paper.

Feeds (Unit is KTA)	***Resid HDP / DC / POX***	***FLEXICOKER***	***Production Changes***	***Remark***
Crude	*20,000*	*20,000*	*0*	*No change*
Coal	*2,050*	*0*	*-2,050*	*FXK eliminates coal to POX*
Liquid Products (Unit is KTA)	***Resid HDP / DC / POX***	***FLEXICOKER***	***Production Changes***	***Remark***
PX to Sales	*4,000*	*4,000*	*0*	*No change*
Olefins to Sales	*Base*	*Base*	*0*	*No change*
Refined naphtha/ Gasoline	*4,740*	*3,150*	*-1,590*	*FXK reduces light naphtha sales keeps CCR full*

Figure 8. Material Balance Impacts Comparison of HDP+DC+POX vs FLEXICOKING™ Technology Run Plans

Comparison of Hydrogen Balances

The amount of hydrogen needed for the FLEXICOKING™ technology case is ~38% lower than the Resid HDP case. The hydrogen balances for both cases are shown in Figure 9. This is typical for FLEXICOKING technology since hydrogen is used much more efficiently and selectively on only the high value products. The Resid HDP case shows the POx unit hydrogen production about equal to the Resid HDP consumption. The Resid HDP, which operates at very high pressure, has a much higher hydrogen consumption since it hydrofines over the full range of resid molecules including the very low value unconverted bottoms. The Resid HDP bottoms are further processed in the Delayed Coker with a significant portion of the DC feed converted to coke.

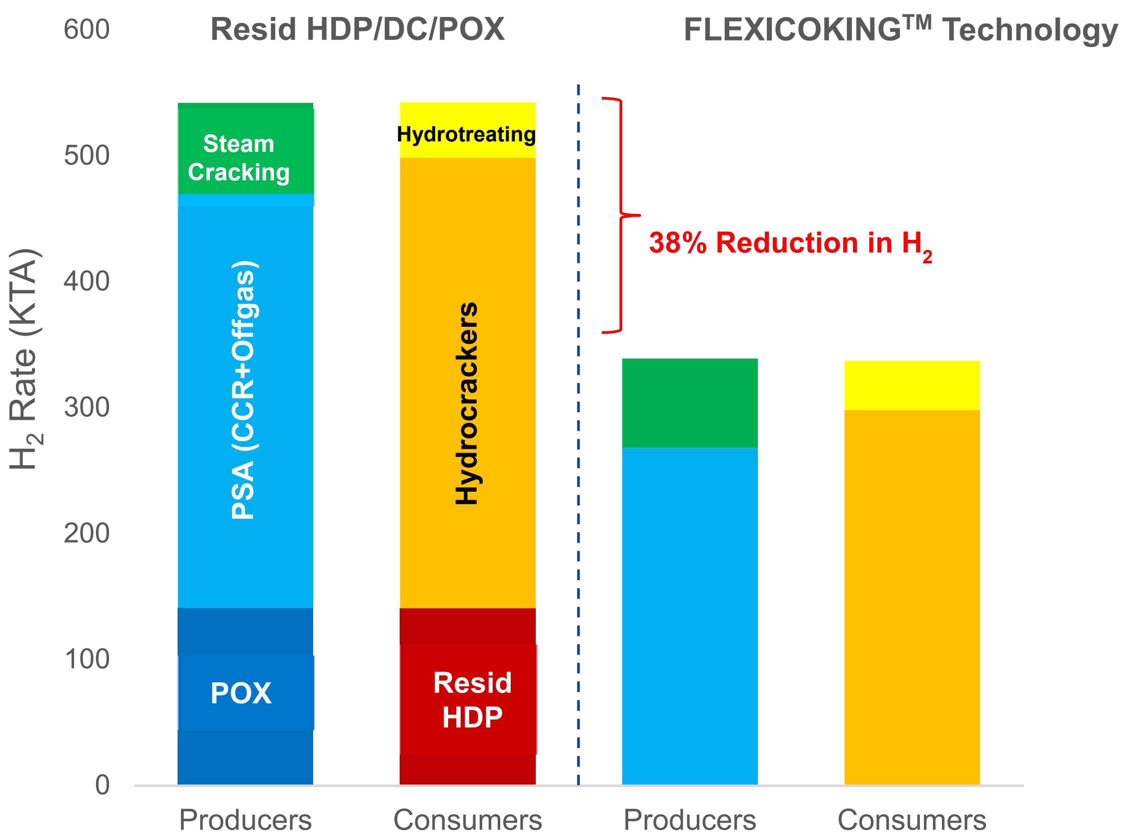


Figure 9. Hydrogen Balance

Comparison of Energy Balances

The Energy Balance is shown in Figure 10. The overall energy consumption for the two cases is similar however, the FLEXICOKING™ technology case provides a significant amount of energy in the form of clean flexigas which can be used to back out high cost natural gas imports, and/or generate steam/power for use by the petrochemical complex. This is a large advantage since no imported coal is required which results in significant environmental benefits for FLEXICOKING technology.

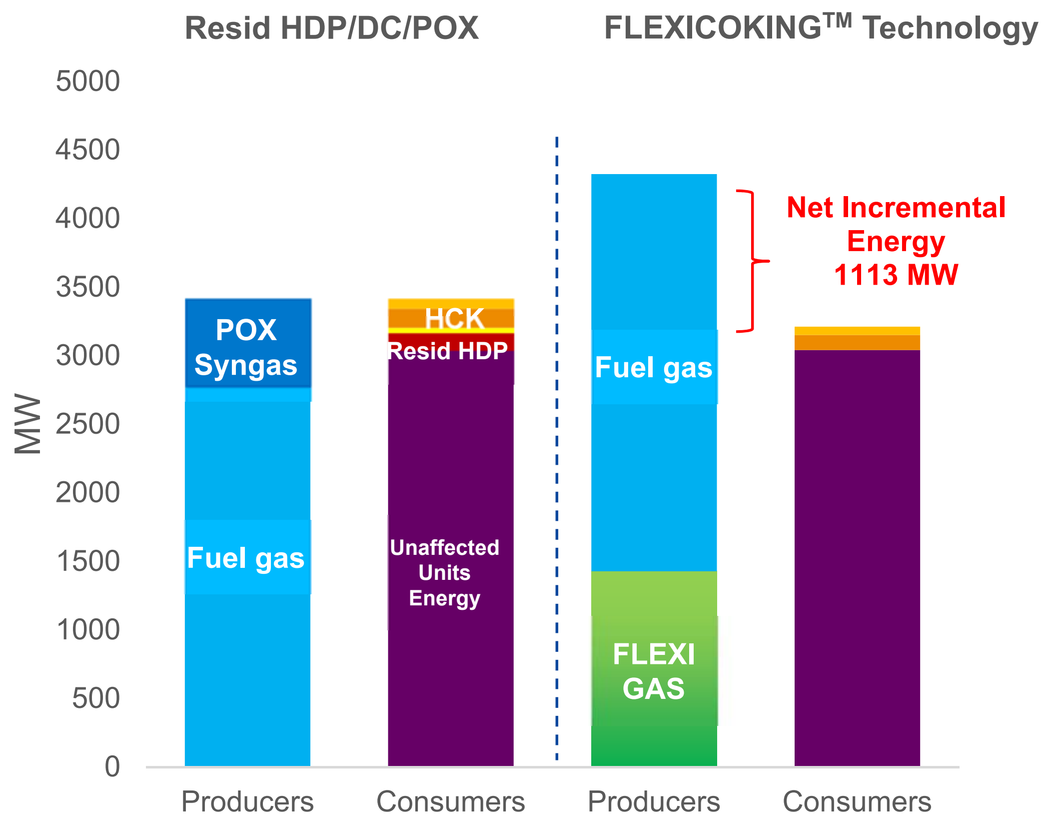


Figure 10. Energy Balance

Comparison of Investment Costs

The total project investment costs are shown in Figure 11 and have been developed using ExxonMobil's standard cost estimating practices for screening quality estimates. These estimates include all onsite and offsite project costs but exclude owner's costs such as escalation and contingency. Consistent with the run plans, the simpler FLEXICOKING™ process flow plan, with smaller hydrocrackers units, has much lower capital investment. No air separation plant is needed since the FLEXICOKER uses steam/air for gasification. This approach results in a lower flame temperature in the FLEXICOKING process Gasifier allowing the use of low cost carbon steel for all major vessels. A coke gasification level of 97% also eliminates the need for large coke handling facilities and reduces plot space requirements. The overall costs for the high pressure Resid HDP, the Delayed Coker and POx units are ~$3B USD higher providing a significant economic advantage for the FLEXICOKING technology case.

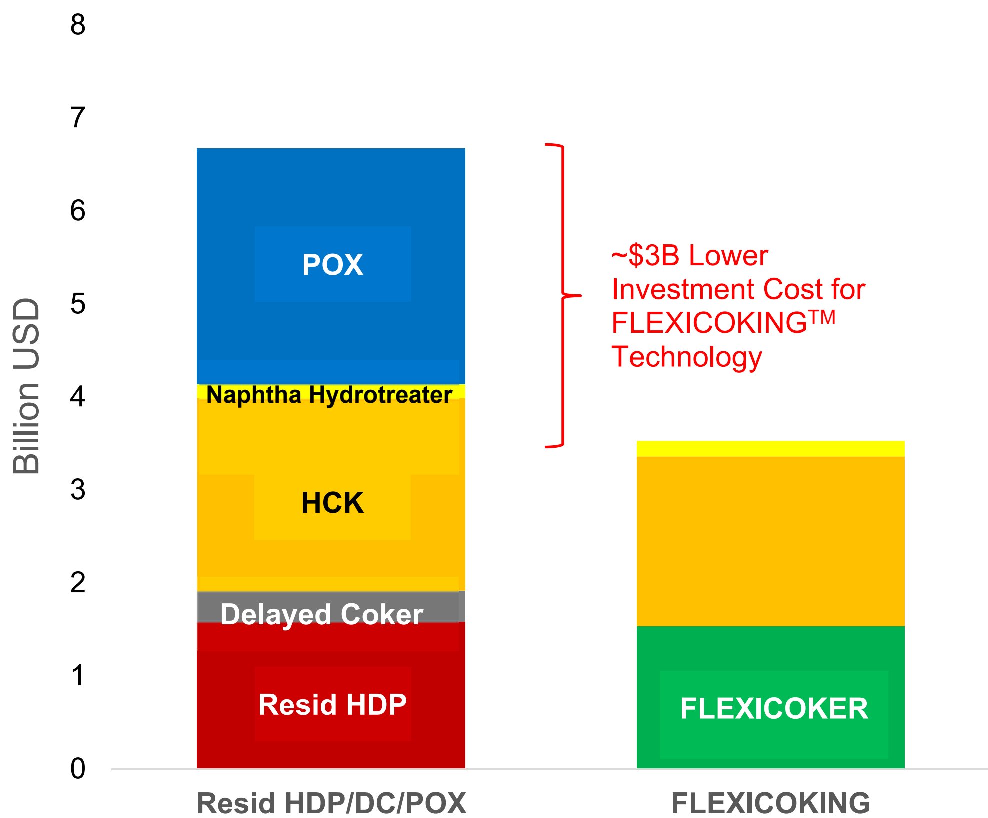


Figure 11. Investment Comparison

Comparison of Operating Costs

There are several key differences in operating costs comparing the two options:

- FLEXICOKING™ technology avoids costly, continuous hydrogenation catalyst replacement (~$60M/year) which is required for the High Pressure, resid HDP Unit
- The FLEXICOKING process run plan has a simpler configuration with fewer operating units and has a reduced utilities consumption and lower manpower requirements.
- FLEXICOKING technology eliminates the POx Unit and related coal handling facilities which results in lower maintenance costs, less hazardous waste disposal cost and lower water treatment cost.

Comparison of Environmental Emissions

The comparison of environmental emissions for each case is shown in Figure 12. There are two key advantages for the FLEXICOKING technology case by eliminating the POx unit and coal imports:

- Reduction of sulfur, slag and ash from coal gasification
- Elimination of incremental 3.7 MTA of CO2 emissions from coal

As a method of curtailing Greenhouse Gas (GHG) emissions, some governments are considering a CO2 tax on manufacturing facilities. These potential future costs should be considered as a sensitivity in the economic analysis. As an example, at $15/T of CO2, the FLEXICOKING technology option could potentially save ~$55M USD /year as a result of reduced emissions.

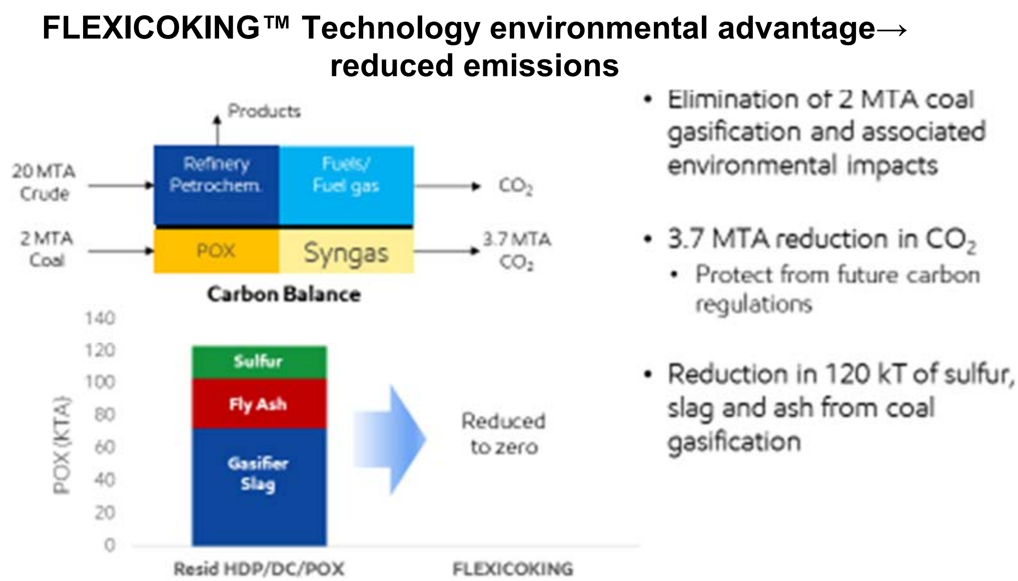


Figure 12. Comparison of Emissions

FLEXICOKING^{TM} Technology Advantages in Crude-to-Chemicals

The previous comparisons have covered the Material, Energy and Hydrogen Balances and other important considerations including investments and operating costs. The overall net economic advantage of FLEXICOKING technology results in about $1.6B USD of NPV8 (net present value @ 8% discounted cash flow rate) improvement over the Resid hydroprocessing case. A summary list of the advantages of FLEXICOKING technology in a Crude-to-Chemicals project are shown in Figure 13.

FLEXICOKING^{TM} Technology - excellent fit for Crude-to-Chemicals

• Simplification of site run plan	+ Eliminates 3 large process units
• Reduction in investment	+ $3.2B capital savings
• Full utilization of available H_2 without additional facilities	+ $120M/yr. savings with elimination of coal imports
• Produces clean, sweet flexigas fuel gas	+ $430M/yr. energy credit
• Reduction in operating costs	+ $60M/yr. catalyst cost reduction
• Vac Resid CCR flexibility	+ Crude purchasing flexibility
• Reduction in environmental emissions	+ Potential $55M/yr. carbon tax avoidance
• Maximizes site economics and profitability	+ $1.6B NPV8 project improvement

Figure 13. Advantages for FLEXICOKING^{TM} Technology in Crude-to-Chemicals Run Plan

Conclusion and Summary

The Crude-to-Chemicals trend is driven by market supply/demand with higher margin chemicals derivatives yielding improved profitability vs. traditional transportation fuels refineries. This trend combined with the global drive towards lower environmental emissions significantly favors FLEXICOING as the resid conversion technology of choice. FLEXICOKING technology is proven and reliable with 40+ years of commercial applications and a combined operating capacity exceeding 200 KBD. Unlike delayed coking that is a batch operation that swings coke drums in and out of service every day, FLEXICOKING process is a continuous operation. It is a flexible unit that is capable of handling a variety of heavy feeds of high CCR, sulfur, and metals. The coke is converted to a clean fuel gas that can be used to fire furnaces and boilers and back out expensive natural gas imports. As illustrated in the case study presented in this paper, comparing FLEXICOKING technology to the Resid HDP/Delayed Coker/POx configuration, FLEXICOKING technology has significant economic and environmental advantages by utilizing an integrated steam-air gasification design with low cost carbon steel construction, resulting in lower-capital investment. Combined with lower SOx, NOx, particulate, and hydrocarbon emissions, FLEXICOKING technology is an excellent fit for a Crude-to-Chemicals run plan.