Refining

Purpose and definition

Refineries are designed to manufacture marketable petroleum products from import streams of a variety of crude oils.

Refineries transform crude oil via an appropriate number of different processes into marketable petroleum products in programmed quantities and qualities for onward dispatch by sea, inland waterways, rail, road and product pipeline to the consuming markets.

The manufacturing of petroleum products entails a range of physical and chemical processes that are utilised to optimise yields of the most valuable products.

The Refinery Industry has two main tasks: -

- Fractionating crude oils through distillation to separate them out into products of varying density and volatility.
- Purifying and enhancing each fraction through physical and chemical treatment

The refining industry continues in a constant state of flux with adaptions to satisfy changing product demand, competitive influences and refining margins.

Refinery Processes

The six basic refining processes are as follows; -

- **Separation**: This is achieved by raising temperature of the input crude supply in pipes that pass through a furnace heated to circa 360°C. This vaporises individual fractions of the crude feed which then condense and separate out on trays within the column according to the varying boiling points and densities petroleum products. This process is known as simple distillation (topping and hydroskimming). In addition the application of a vacuum enables the products to vaporise at lower temperatures, which is known as vacuum distillation.

- **Reforming**: This process changes the configuration of individual molecules as in catalytic reforming and isomerisation. This process is commonly used in the final stages of gasoline production.

- **Treating**: This process uses catalysts, electrolysis and hydrogen to chemically remove contamination such as salts, nickel, vanadium, sulphur and nitrogen oxides. Examples of treatment processes include: hydrogenating, hydrofining, hydrodesulphurisation).

- **Cracking**: This process breaks down large hydrocarbon molecules into smaller ones in the presence of a catalyst. A catalyst is used to speed up the rate of reaction. The catalysts (example: alumina) can be recycled numerous times. Chemical reactions utilising catalysts can be used in the presence of hydrogen or steam (examples: catalytic cracking, hydrocracking). Alternatively with the application of very high temperatures heat alone breaks down large hydrocarbon molecules. This process is known as thermal cracking. A common process used in European refineries is known as visbreaking.
- **Coking**: Residues, the carbon-rich heavy ends of the refinery process are ‘cooked’ at high temperatures (600°C) to produce lighter products such as gasoil and naphtha.

- **Deep Conversion**: Combines carbon extraction with the addition of hydrogen. This process is designed to convert the heaviest fractions (refinery residue or bottoms) into lighter and marketable products. Process includes coking, residue catalytic cracking and de-asphalting.

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**Refinery Configuration**

Refineries are classified according to the number of processes available for transforming crude into petroleum products.

Simple refineries are designed to distil crude oil into a limited range and yield and products. They are referred to as topping or hydroskimming plants. Topping is the most basic distillation process. Hydroskimming involves distillation in the presence of hydrogen.

Complex refineries involve a combination of interrelated processes to produce a broader range of refined products. They commonly utilise thermal and catalytic cracking that enables deeper conversion of the crude oil feedstock into higher yields of more valuable and marketable products.

All refineries have a design distillation capacity also known as nameplate capacity. This capacity specifies the volume of crude per day or year then can be processed in a crude distillation unit at the maximum utilisation of the plant. Downstream of the crude distillation unit is an array of processing plants that can further enhance the yield of certain petroleum products. The processes include catalytic cracking, hydrocracking,
visbreaking (thermal cracking) and coking. This commonly referred to as charge capacity.

**Flexibility in Refining Crude Oil**

The ability of a refinery to vary its production of output (known as the product slate) varies as to the amount of processing plant available.

Simple hydroskimming refineries are relatively inflexible and give fixed yields of products that are dependant on the crude import specification

- Gases: Methane, Ethane and Natural gas liquids
- Light Distillates: Gasoline, Naphtha
- Middle Distillates: Gas oil, diesel, kerosene
- Heavy Products and Residue: Heavy fuel oil, bitumen, coke

However, refineries that have more processing plant are able to vary yields and improve profitability by focussing on the higher value products.

The most sophisticated and complex refineries can handle a very wide range of crude oils and blends to deliver the highest value of output products that are driven by market demand.

The trend in the past 20 years has been away from fuel oils and bunkers and towards gasoline, naphtha, jet kerosene and diesel/gasoil. Consequently, European refineries have concentrated on delivering the highest yields of the middle distillate fraction that include diesel, gas oils and jet kerosene and reduce the amount of loss-making fuel oils and residues. Hydrocracking and coking plants are designed to convert fuel oils and heavy residues into middle distillates.

**The Classic Market Model**

The classical market model was one of an oil company’s control of an integrated supply chain from ‘well-to-wheels’. Companies historically had upstream/downstream ownership. Equity crude oil supplied the company refineries that were in turn supplied the fuel retail outlets all of which were company-owned.

**De-Integration**

The classic market model no longer exists. Large integrated IOCs have re-engineered the business process so that the various segments are stand-alone business units, operating as profit/loss centres.

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\(^1\) Global Refinery Report, *Oil and Gas Journal*, 22\(^{nd}\) December 2008
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Refinery Economics

Refinery economics involve a combination of interrelated manufacturing processes. Refinery processes range from simple hydroskimming distillation with some hydrotreating and reforming through to complex refining which involves cracking and deep conversion of the crude oil feedstock.

Analysing refinery economics must take into account the co-production of products such as naphtha, jet kerosene and fuel oils in addition to gasoline, diesel and the low sulphur heating gas oils. A further complicating factor is that some of the large plants have
synergistic opportunities such as co-located petrochemical plants, power generation and/or onsite CHP units.

Refining performance is improved by consideration of the following factors:

- The ability to process crude oil into high-volume marketable products and generating high yields of those products.
- Selection of the crude feedstock from which the refinery can generate the highest product price differential or crack.
- Optimising the selection of crude, timing of throughput, and matching the product slate to market demand. This is achieved through forward planning and the use of linear programming.
- Tight control of both fixed and variable operating costs.
- High utilisation (uptime) rates.

The **refining margin** is the difference in value between the products manufactured by a refinery and the value of the crude oil used to produce them. Refining margins will thus vary from refinery to refinery and depend on the price and characteristics of the crude used. Refinery margins are the oil industry’s key performance indicator of downstream returns. Refinery margins gauge profitability based on the co-production of the product slate based on specific refinery configuration, location of the refinery and the type/specification of the crude oil feedstock.

Margins are influenced by refinery configuration (simple or complex), the running of a variety of crude types and the range of products.

Over recent years complex refineries (those with the ability to crack fuel oil and convert heavy residue) have achieved consistently higher refining margins than simple hydroskimming refineries. The key players have invested extremely large sums in refining upgrades—desulphurisation, hydrocracking and deep conversion.

Refining margins have fluctuated substantially over time. The drivers of refining margin are as follows:-

- Overcapacity and declining demand (a serious issue in the mid-1980s-1990s)
- Economic climate affecting product demand. Particularly relevant in the current economic downturn
- Product oversupply that can reduce prices and hence margins
- External competition from other refineries and trade flows into the EU
- The light/heavy differential. This is the differential price between light sweet crude oils and heavy sour varieties. If the differential narrows the complex refineries become less profitable.

This study has used refining margins as reported by the International Energy Agency’s Oil Market Report. Published monthly this report analyses the refinery margins for both simple and complex refineries in the Northwest Europe and Mediterranean regions.

The IEA methodology relies on their own modelling programmes together with external inputs from other experts in the field including Purvin & Gertz, FACTS and EMC.
The margins are calculated on a ‘full cash-cost’ basis, taking into account changes in fixed costs associated with refinery operation, such as wages, together with variable costs of buying and processing crude oil into its constituent products. The calculations have also been adjusted to take account of regulatory, environmental and product specification changes over the years.

The comprehensive nature of the refining margin calculation means they incorporate a wide range of product output, together with credit/debit adjustments (such as fuel oil sulphur content, octane adjustments etc., where appropriate, due to single crude optimisation analysis) and a broad range of inputs. The resulting margin can provide several barometers for the markets. The refinery margin provides a proxy barometer of the net return to a refinery, and therefore possible investment trends. The overall margin reflects the baseload return to a refinery optimised for running a specific crude. It does not represent the return through processing a marginal barrel and cannot, therefore, be used to directly infer the marginal price differentials among grades or possible operating rates (although the impact of refinery shutdowns for maintenance is often a more significant factor that can mask the effect of changes in economics). However, a comparison of the differences in returns between crudes processed and through different processing technologies will provide a guide to the likely demand trend for sweet and sour crudes, therefore contributing to the understanding of some of the factors affecting regional refinery throughput levels. Not only is the margin designed to provide a barometer of refinery returns in various regions, but also the trend these margins follow such as their rate of change.

**Key areas for Refinery Investments**

- **Increasing desulphurisation** of refined products to meet road fuel standards (Euro V and VI) and the move towards lower sulphur levels in jet fuels and marine bunkers. Desulphurisation relies on treating the refined stream with hydrogen that removed sulphur via chemical reactions. EU desulphurisation units are now capable of treating >10 million barrels/day.

- **Hydrocracking.** This refining process enables the yield to be focused in high demand products diesel and jet fuel. Specifically hydro cracking units that can convert the undesirable heavy fuel oils into desirable diesel and jet fuel by the application of catalytic cracking in the presence of hydrogen under pressure.

- **Deep Conversion.** Under conditions of simple refining heavy crudes yield a higher percentage of carbon-rich residues at heavy fuel oil residues. Those heavy-end yields can be altered by the application of catalytic cracking, thermal cracking (predominantly visbreaking) and coking.

The main current and future refinery investments are focused on hydrocracking, and deeper conversion designed to give higher yield of the more valuable middle distillate fraction. This is achieved by converting low value fuel oil into higher value middle distillates, such as gas oil and jet-kerosene.
Refining definitions

The Refining Margin The difference in value between the products produced by a refinery and the value of the crude oil used to produce them. Refining margins will thus vary from refinery to refinery and depend on the price and characteristics of the crude used.

Crack Spread- Weighted average of the price of a refined product minus the price of crude oil

Net refinery margins are defined as the gross product worth (GPW) – the multiplication of the spot price for each refined product by its percentage share in the yield of the total barrel of crude – less the feedstock costs (crude oil and other feedstock); less running expenses (variable and fixed costs).

Gross product Worth (GPW) - A method of calculating the value of a particular crude oil type that is based on the value of refined products derived from that crude oil. GPW depends on prevailing product prices and the refining process; simple or complex.

Refinery Gate Value of a crude source is calculated by subtracting refining costs from the gross product worth.

Netback Value: Refinery gate value minus freight costs

Netback Margin: Netback value minus crude price. Netback margins indicate the incentive to refine additional specified crude into more refined products.

NWE- Northwest Europe. Product prices in this area

ARA Amsterdam/Rotterdam/Antwerp product prices in those coastal refining areas of the Netherlands and Belgium
Characterisation of the Petrochemical Business

The products of the petrochemical industry are predominantly commodities, which is to say that their pricing is primarily a function of producer competition rather than of their value-in-use to the consumer. The business is global and highly competitive. Its profitability for the long-established producers has declined markedly over the decades. This is an industry that has progressed remarkably quickly from its inception and high returns in the 1940s and 1950s to its maturity and much more modest returns in the 1990s. Evidence of this transformation is provided by the recent withdrawals of BP and Shell from their previous substantial involvements in the industry.

As with all commodity businesses, it is highly cyclical, its profitability being primarily determined by the supply/demand balances. Indeed in recent times China’s import demand has been the dominant factor determining the pricing of the major traded products.

Again as with all commodities, cost competitiveness is critical and in this regard feedstock costs are central. In general crude oil-derived feedstocks are associated with poor to moderate profitability, and gas-derived feedstocks are associated with moderate to good profitability. Producers based on feedstocks derived from stranded gas are particularly advantaged and understandably long-established producers have pursued joint-ventures in such opportunities (eg Shell and ExxonMobil in Saudi Arabia).

Demand growth rates in the developed markets are now low at around GDP growth rates. The real growth of the business is now very largely in the developing markets, notably China and India. It is in the developing areas that future petrochemical investment will largely be concentrated.

The industry is technologically mature with process improvements now being largely incremental. While further major technological breakthroughs are unlikely, one area does have real potential and that is the conversion of methane to olefins. A breakthrough here would transform the feedstock foundation of the industry, given the substantially larger world resources of natural gas than crude oil.

The challenge for the developed market producers will be to live with their relatively high feedstock costs, labour costs and plant cost, and the tight and costly environmental regulations. While striving to minimise production costs they will need to emphasise customer care and support, to differentiate their products where possible, notably with “tailored” grades of polymers (plastics, fibres, synthetic rubbers and resins) and to shift towards products less susceptible to competition from low-cost producers (e.g. speciality polymers such as polycarbonates).

The export producers based on feedstocks derived from stranded gas will concentrate on large outputs of a limited number of commodity product grades sold essentially on price
alone, customer support being minimal. They have the potential to expand their production internationally, acquiring plant in the developed markets or investing in new plan in the developing markets, so as to participate in the business in both modes: export producer of commodities and local producer of differentiated products. This approach has already been exhibited by SABIC’s (Saudi Arabia) acquisition of the bulk petrochemicals business of DSM (Netherlands).

The developing market producers will have higher feedstock and energy costs than the export producers but closer proximity to and relations with their customers. Their labour and plant costs will be fully competitive and they can integrate downstream into the production of packaging, fibres, etc.

This global industry will continue to develop and expand. However, its profitability will continue to be highly variable and for the smaller regional producers in the developed markets such as Europe particularly pressured.
Notes:
Adding Value: Petrochemicals

The Petrochemicals Industry

The Petrochemical industry utilises various streams of petroleum compounds in the supply chain to develop petrochemical products for a wide range of uses. Some examples include plastics, detergents, paints and fibres.

Petroleum Refineries produce a number of streams that can be used directly as petrochemical feedstocks (for example, naphtha)

In many cases these feedstocks are retained on the refinery complex to be used in petrochemical plants. They therefore have the advantage of being co-located with refinery operations and the potential for added-value for the range of petrochemical products.

The petrochemical business is cyclical. Prices and growth vary according to changes in production capacity economic activity and supply/demand balances. After sustained growth in the 1980s petrochemical supply/demand balances slumped during the economic recessions in the early 1990s and recovered to pre-recession levels in the late 1990s.

History and Background

The Petrochemical Industry produces predominantly organic chemicals (i.e. those based on carbon). Their production was originally based on coal.

The industry was born out of the growing availability from the mid 20th century of cheap hydrocarbon feedstocks (oil and gas-derived) and eventually supplanted the coal-based industry.

The industry took on strategic significance during World War II with the development of products such as synthetic rubber and nylon.

From the middle of the 20th Century major growth occurred in the OECD economies. Significant advances in polymer chemistry led to a boom with rapid growth in plastics and fibres.

Terminology

Refinery Feedstocks - Products or a combination of products derived from crude oil destined for further processing in the refining industry other than blending. They are transformed into one or more components and/or finished products. This definition covers naphtha imported for refinery intake and naphtha returned from the petrochemical process to the refining process.
Naphtha - Light or medium oil distilling between 30°C and 210°C, for which there is no official definition, but which does not meet the standards laid down for motor spirit. The properties depend upon consumer specification. The Carbon:Hydrogen ratio is usually 84:14 or 84:16, with a very low sulphur content. Naphtha may be further blended or mixed with other materials to make high-grade motor gasoline or jet fuel, or may be used as a raw material for manufactured gas. Naphtha is sometimes used as input to feedstocks to make various kinds of chemical products, or may be used as a solvent.

Petrochemical Processes:

Cracking

The cracking process is the cornerstone of petrochemical manufacture. Cracking involves a reduction in the size of the organic molecules in the feedstock. As an example naphtha can be cracked to yield light olefins such as ethylene and propylene.

Steam Cracking

Steam-cracking is applied to feedstocks ranging from ethane to gasoil and is the primary process used.

Cracking is the source of olefins (ethylene, propylene and butadiene) the core base chemicals of the petrochemical industry.

Olefins are also produced as byproducts in the oil refining processes catalytic cracking and thermal cracking, the primary purpose of which is to convert heavy cuts into more valuable lighter products.

Thermal Cracking

Heat is use to break up the large molecules into smaller ones. The cracker is a complex unit designed with tubular coils and naphtha entering the furnace tubes heated to 700-800°C with a short residence time. The mixture of gasses from the furnace are separated and promptly cooled and pressurised as products such as ethylene and propylene.

Catalytic Cracking

Catalysts are chemical agents that speed up the rate of chemical reactions. In catalytic cracking these agents enhance the breaking up of large molecules ("cracking").

Polymerisation

A chemical process to involve the agglomeration of numerous monomer molecules into a long molecular chains is known as polymerisation. Polymerisation lies at the
heart of the production of a range of plastics from monomers such as ethylene and propylene.

During the 1960s, commercial production of new types of plastics commenced, and were based on base petroleum feedstock. High-density polyethylene and specialised products such as polycarbonate are produced from simple organic molecules, the monomers.

**Example Base Chemicals and Their Derivatives**

**Ethylene**

Ethylene is one of the primary base chemical. It is used in the manufacture of polyethylene, PVC and polystyrene plastics, antifreeze, and polyester fibres. It is obtained by cracking naphtha, ethane or liquefied petroleum gas.

**Propylene**

Propylene is a primary product used in the manufacture of polypropylene and polyurethane plastics, acrylic fibres and industrial solvents. It is obtained by cracking naphtha, and liquefied petroleum gas or as a by-product from cat cracking.

**Butadiene**

A highly reactive base chemical that is used to produce synthetic rubber. Butadiene is also an intermediate for certain paints, plastics and nylon.

**Synthesis Gas –“Syngas”**

Methane is the primary constituent of natural gas. In most cases it comprises >90% of the gas reserves. It can be utilised in the formation of syngas- a mixture of carbon monoxide and hydrogen.

As an intermediate product Syngas provides the essential building block for a range of end-products that include ammonia, urea, methanol, waxes and light liquid petroleum-based products.

Two chemical processes are used in the formation of syngas- steam reforming and partial oxidation.

Processes to form Syngas

In any process to form syngas it is vital to eliminate sulphur from the natural gas feedstock.
Steam Reforming. The natural gas feed is de-sulphurised and mixed with excess steam. Nickel–based catalysts are utilised to speed up reaction times. The temperature is kept at ~700°C, and the reaction is strongly endothermic. Two chemical reactions occur that produce carbon monoxide/dioxide and hydrogen.

\[
\begin{align*}
\text{CH}_4 + \text{H}_2\text{O} & \quad \text{CO} + 2\text{H}_2 \\
\text{CO} + \text{H}_2\text{O} & \quad \text{CO}_2 + \text{H}_2
\end{align*}
\]

Partial Oxidation Syngas can also be produced by partial oxidation of the natural gas feedstock. The reaction can be summarised by the equation:-

\[
\text{CH}_4 + \frac{1}{2}\text{O}_2 \quad \text{CO} + 2\text{H}_2
\]

**Ammonia and Derivatives**

Increased demand for global food production led to a rapidly increasing demand for fertilisers based on nitrogen particularly in the 1970s and 1980s.

Large-scale plants are built on sites close to the giant gas reserves capable of providing the economy of scale required in ammonia projects.

Global consumption of ammonia is ~120 million tonnes/pa.

Ammonia is used as a refrigerant and in the manufacture of explosives. Ammonia is an intermediate product in the manufacture of urea.

**Industrial**

- Urea-based synthetic
- Resins, fibres
- Explosives

**Fertilisers**

- Urea
- Ammonium Nitrates
- Ammonium Phosphates
- Ammonium Sulphate
- Direct Application

**Ammonia and Urea**

Urea is an important fertiliser and intermediate product in the manufacture of products such as urea-formaldehyde resins and melamine. It is derived by combining ammonia with carbon dioxide. The reaction is:-

\[
2\text{NH}_3 + \text{CO}_2 \quad (\text{NH}_2)_2\text{CO} + \text{H}_2\text{O} \\
\text{UREA}
\]
<table>
<thead>
<tr>
<th>Sector</th>
<th>Percent Use</th>
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<td>14</td>
</tr>
<tr>
<td>Fertilisers</td>
<td>86</td>
</tr>
</tbody>
</table>

In the conversion of natural gas to syngas as a feedstock for ammonia production, carbon dioxide is produced as a by-product that can then be used as a source for urea production.

Approximately one tonne of ammonia produces 1.6 tonnes of urea.

**Methanol**

Methanol, or methyl alcohol (CH$_3$OH), is used in the production of formaldehyde, acetic acid and MTBE; a blending agent in the improvement in performance of gasoline.

Methanol is produced from syngas in reactor vessels at temperatures between 250-270$^\circ$C and pressures of ~100bars, and using copper catalysts.

The reactions are:-

\[
\begin{align*}
\text{CO} + 2\text{H}_2 & \rightarrow \text{CH}_3\text{OH} \\
\text{CO}_2 + 3\text{H}_2 & \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}
\end{align*}
\]

Water and other impurities are removed by distillation.

**Petrochemical Trends and Developing Markets**

The shifts in raw material supply and the balance between solid fuel, crude oil and natural gas.

Projected increased demand for petrochemical products

The impact of new environmental legislation. Example: Kyoto Protocol

The emergence of natural gas as a source of supply for petrochemical processes.

The monetising of stranded gas.

The challenge of diverse crude oil supply.

The emergence of developing economies such as China and India, with both increased demand and supply to the petrochemical market.
New and developing petrochemical processes and technologies Example: deep catalytic cracking.

Increased in synergy in refining and petrochemical operations located on same sites Petrochemical plants to concentrate on niche markets and products

**Challenges in the Petrochemical Industry**

Feedstock cost is a key element in establishing a competitive position. The highly cyclical market has led to intense price competition.

Petrochemical products are not produced in significant enough volumes to influence oil or gas prices. They are typically dependent on lower-valued streams in the oil refinery or natural gas plant.

Key shifts in feedstock supply, notably the growth of gas liquids production, coupled with new technologies and cost synergies has led to a rejuvenated industry that is able to process feedstocks across the spectrum from methane to residual heavy oil.