

# IEA Petrochemical Scenarios for 2030-2050: Energy Technology Perspectives

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## **Introduction**

The 2050 outlook for energy demand and the challenges it creates from a supply side CO<sub>2</sub> emissions are mandating a thorough review of the technology alternatives to achieve a sustainable path. This had led to the International Energy Agency initiative on Energy Technology Perspectives (IEA 2006a).

The industry provides significant opportunities for a reduction in energy demand and CO<sub>2</sub> emissions. This can be achieved through a variety of measures and technology advances in equipment and materials. The chemicals and petrochemicals industry is the third largest source of CO<sub>2</sub> emissions after the iron and steel and cement industries and accounts for 30 % of the final energy use (IEA 2006b and IEA 2006c).

From an energy use and emissions management standpoint, the petrochemical industry has challenges, as several thousands of products are generated in variable amounts. Part is accounted for by feedstocks (naphta, ethane). Generated products (plastics, solvents) lock-in the carbon from those feedstocks; additionally, this locked-in energy can be recovered when the product (plastic) waste is incinerated, with generation of additional emissions. A full life-cycle analysis of all chemical and petrochemical products is beyond the scope of the current work. However it is a fact that increased plastic usage can lead to a more efficient energy use in sectors such as transport.

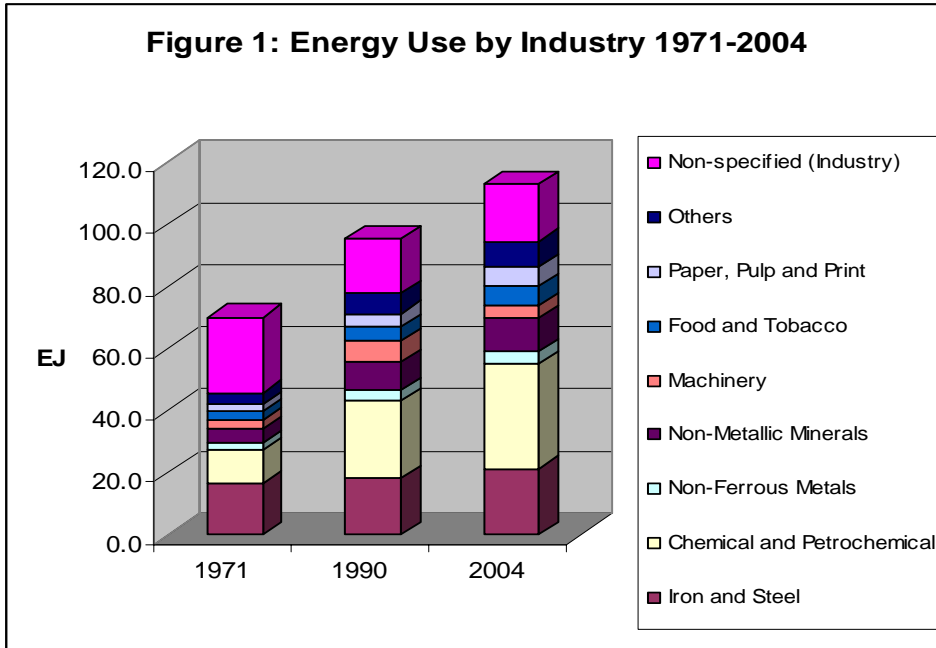
Due to the increase in energy costs, and the industrial growth patterns in the Asia Pacific and Middle East, the petrochemical sector is undergoing radical changes from a supply and feedstock standpoint. Projections of technology impact on energy use need to account for such a shift.

Amongst the scenarios that will impact the energy balance and CO<sub>2</sub> emissions, waste treatment and use of biomass and generation of biopolymers have the potential to contribute significantly to a reduction. New feedstocks are being considered as an alternative to fossil fuels. Despite a limited amount of biomass production today, cost decrease may drive a shift towards them.

## **Industrial and Petrochemical Energy Use and CO<sub>2</sub> Emissions**

In 2004, out of a total primary energy supply of 445 EJ, a third is accounted for industry use (IEA 2006a). Total direct CO<sub>2</sub> emissions from the industry in 2003 amounted to 5.3 Gt or 22 % of the total, excluding the upstream emissions from the production of electricity, or downstream emissions from the waste treatment of synthetic organic products.

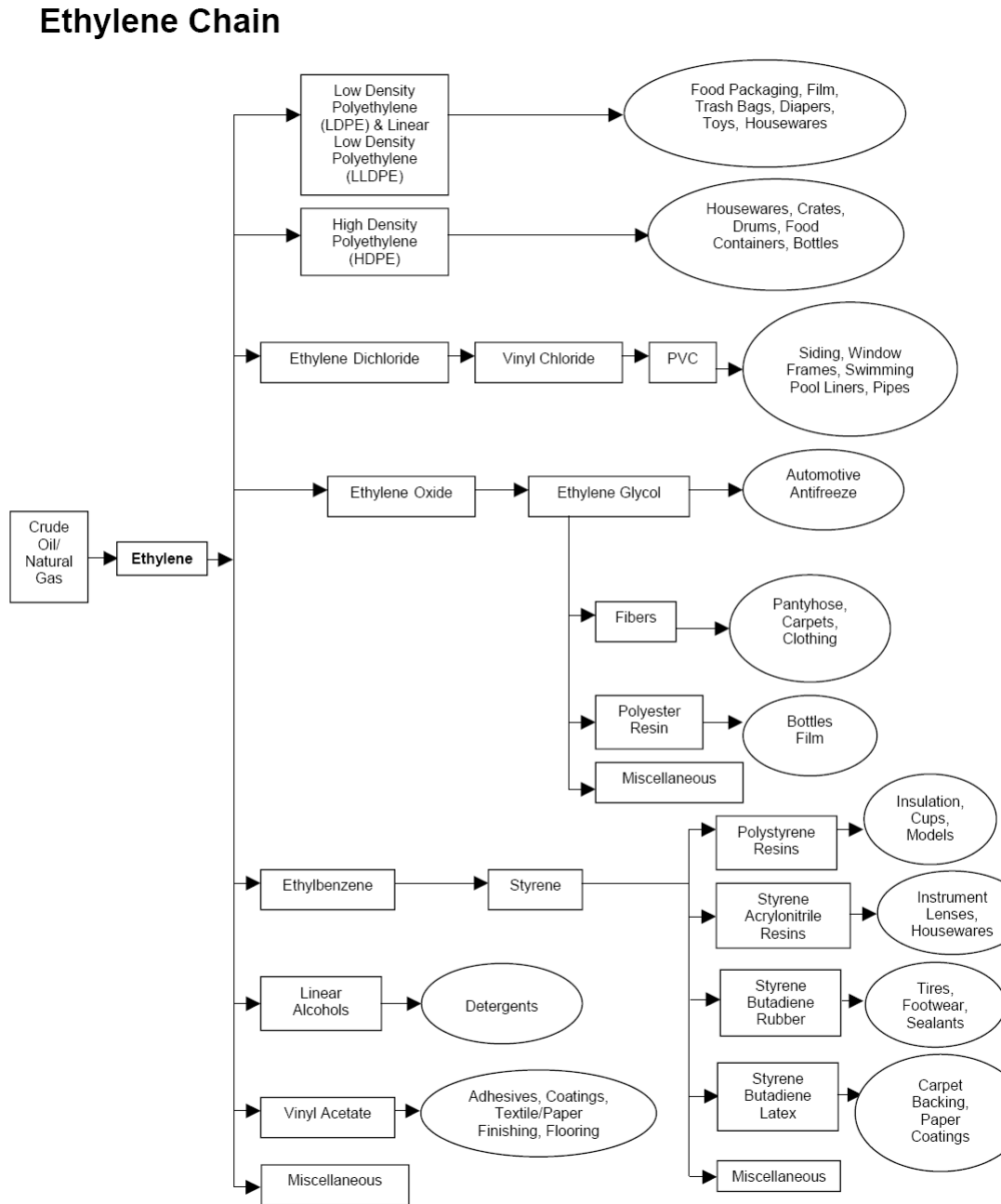
The share of the chemical and petrochemical sector has increased from 1971 to 2004 and represents 30 % of the energy use in the industry (Figure 1). More than half of the total energy is associated with the use of oil and gas feedstocks. The chemical and petrochemical industry accounts for 18% of the direct industrial CO<sub>2</sub> emissions (excluding electricity production) (IEA, 2006a).



Source: IEA Statistics

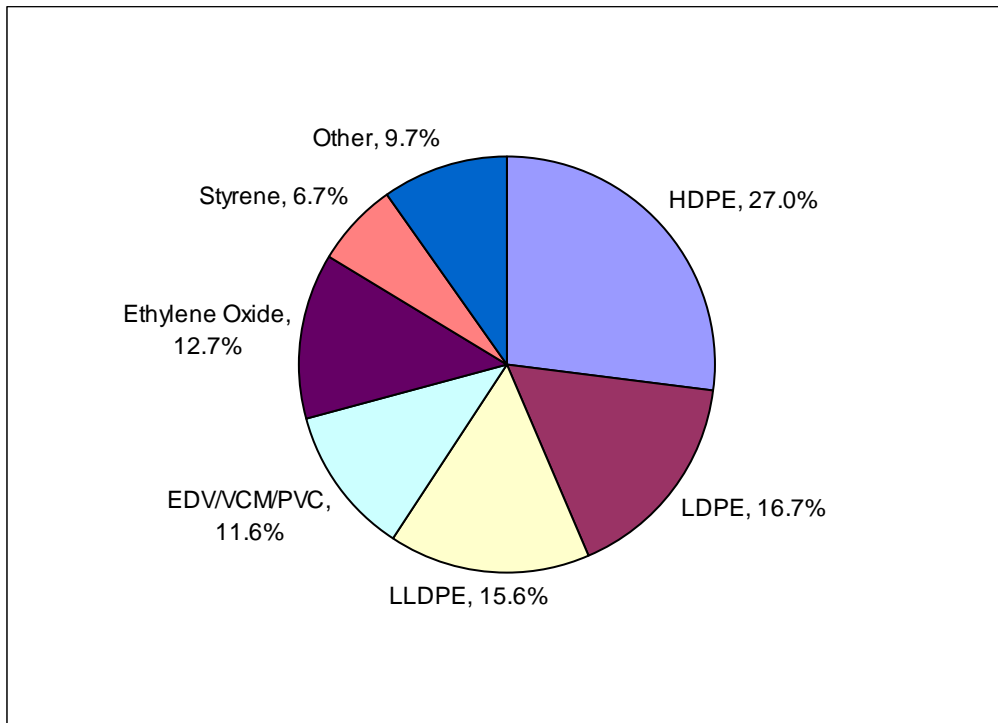
The petrochemical sector produces a wide range of products. Ethylene is the most important one, in terms of production volume. Ethylene is produced via steamcracking of gas and oil feedstocks. Ethylene is an intermediate. It is converted into a range of solid and liquid products with a wide range of applications. Figure 3 provides a breakdown of ethylene derivative market shares. Polyethylene (High Density Polyethylene HDPE, Low Density polyethylene LDPE and Linear Low Density Polyethylene (LLDPE) accounts for 59.3% of the total ethylene market.

**Figure 2: The Ethylene Chain (American Chemistry Association)**

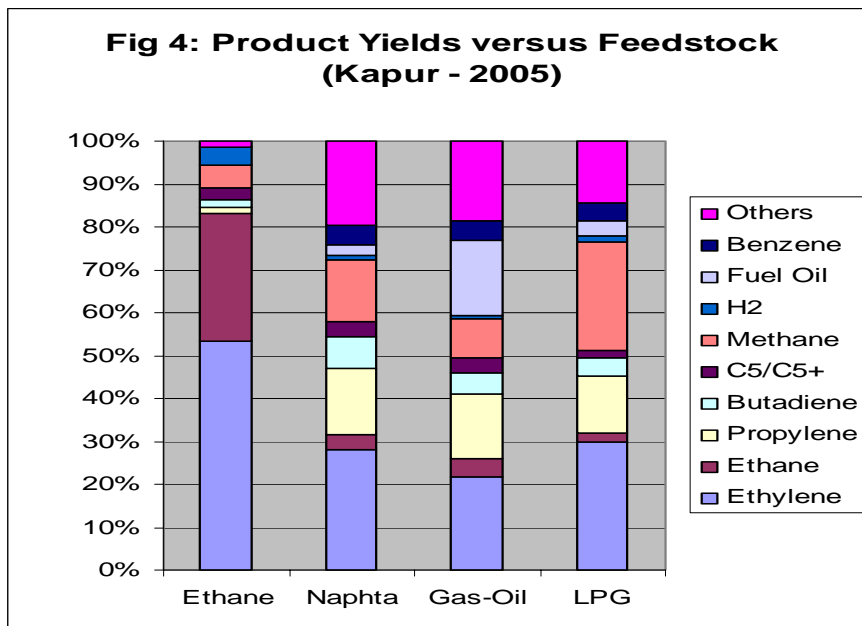


While the petrochemical sector is quite complex for the number of products that it generates (e.g. Figure 2), the key process in the industry is steam-cracking of ethane, and refinery products. There are about 256 crackers in operation (OGJ – 2006). These crackers produce a mix of high-value chemical products: ethylene, propylene, butadiene and aromatics (a mixture of benzene, toluene and xylenes). Moreover hydrogen, methane and oil fractions by-products are also generated (Figure 3).

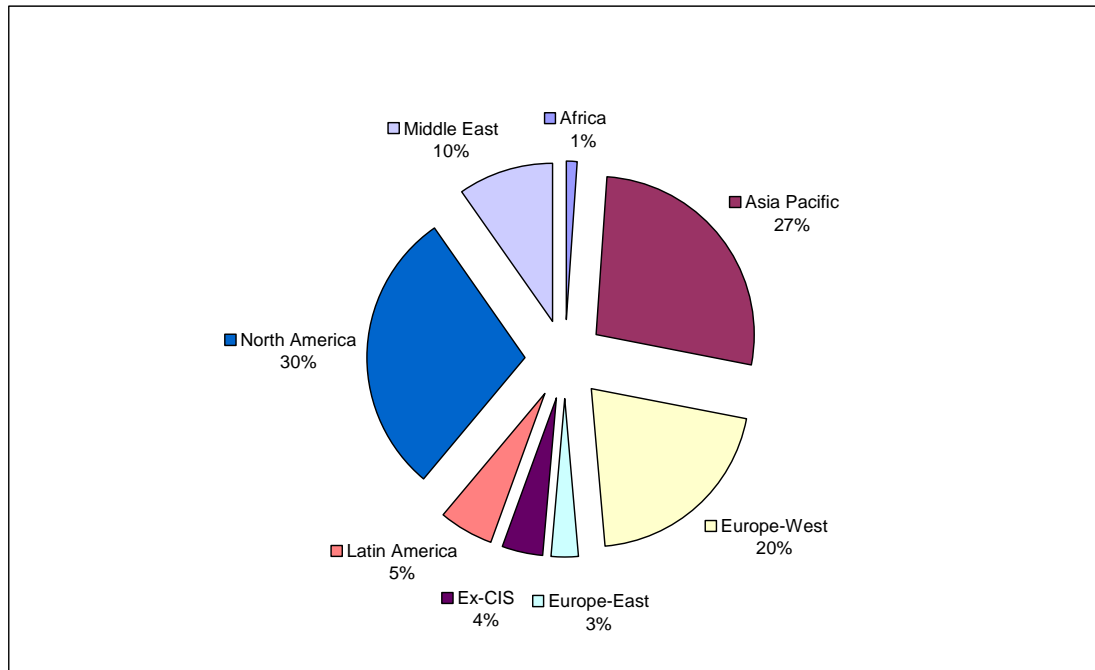
**Figure 3: Global Ethylene Demand by Derivative, 2005 (Nexant, 2005)**



**Fig 4: Product Yields versus Feedstock (Kapur - 2005)**



**Figure 5: Steam Crackers Distribution**

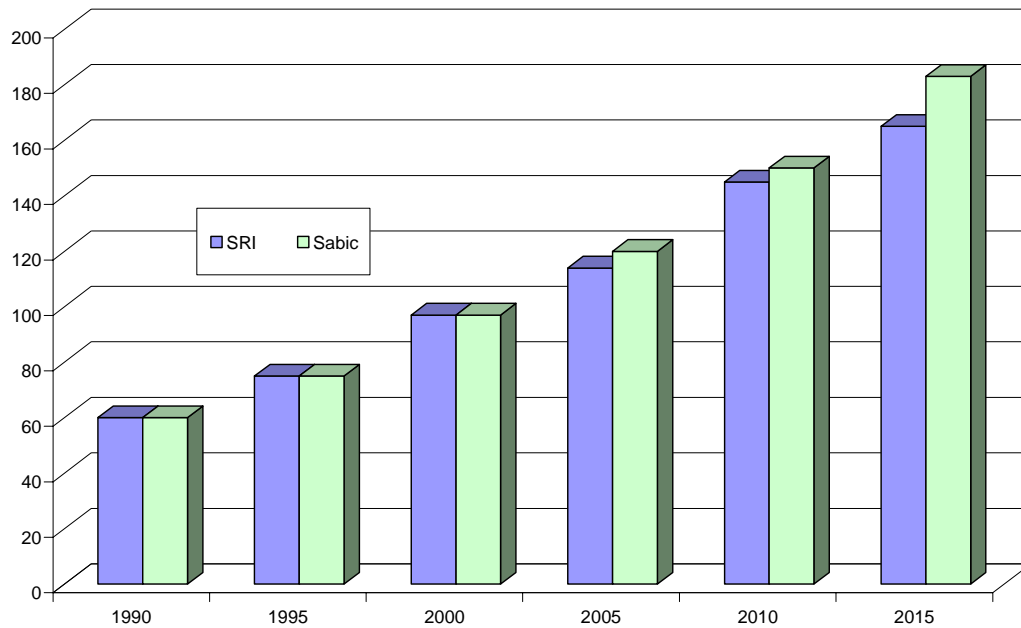


Source: Oil and Gas Journal, 2006

Total world ethylene production capacity amounted to 116 Mt in 2006 (OGJ, 2006). The 3 major markets by volume (Figure 5) were North America (30 %), Asia-Pacific (27 %) and Western Europe (20 %). While capacity has doubled over the 15 year spanning 1990-2005, predictions of ethylene supply and demand over the 2006-2015 (SRI, 2005; SABIC, not dated) show a significant growth in demand in the Asia-Pacific region, and a build-up of capacity in the Middle East spurred by favourable energy supply conditions.

In contrast, in Western Europe, half of the crackers are over 30 years old, and the last new cracker was BASF's Antwerp plant, constructed in 1994. Figure 6 shows the worldwide trend over the 1990-2015 period.

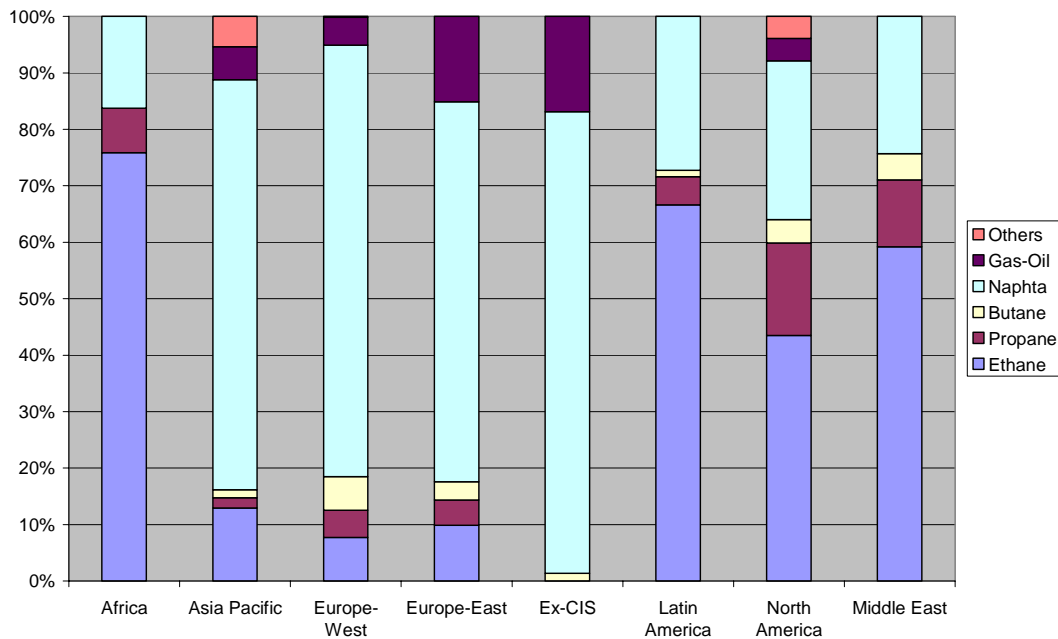
**Figure 6: Ethylene Production Trends and Projections 1990 – 2015**



Source: SRI Consulting and SABIC

Naphtha cracking represents about 45% of world ethylene production capacity, ethane cracking 35%, LPG 12%, gas oil 5% and others 3%. Figure 7 shows the feedstock distribution by geographic area, with a marked difference between the Asia-Pacific & Western Europe vs. the North American plants.

**Figure 7: Ethylene Plants by Feedstock and Region**



Source: Oil and Gas Journal, 2006

In the coming years the share of ethane cracking will grow as new capacity comes on-stream in the Middle East.

## CO<sub>2</sub> Emissions

Several references discuss the estimation of CO<sub>2</sub> emissions in the production of intermediates (Mathews-2001, APME -2004, Joosten-2001, Neelis-2003). Steam cracking emissions were in the P70 range of 1.5-2.5 tonne CO<sub>2</sub>/tonne ethylene and 0.7-1.3 tonne CO<sub>2</sub>/tonne HV Chemicals.

The Non-Energy Emission Accounting Tables (NEAT) model was used by Neelis et al. (2006b) for a more accurate account of the CO<sub>2</sub> emissions associated with non-energy use (feedstock use) of fossil fuels. A carbon mass balance was developed, equating the total input of fossil fuels in equivalents of carbon to the sum of the total outputs (plastics also in equivalents of carbon) and the production losses. Model validation was obtained for a number of countries such as Germany, Japan, Korea, the Netherlands and the UK (Patel et al. 2005). The NEAT analysis has revealed shortcomings in energy and CO<sub>2</sub> emission accounting for petrochemicals in a number of countries that have resulted in important adjustments in the energy statistics and emissions accounting guidelines.

## Technologies for Energy Efficiency

Earlier studies (Phylipsen et al. 2002) have indicated a potential reduction in energy intensity of 20% by using state of the art technologies (regional variations of plant characteristics would account for higher figures).

From a technology standpoint, more than a third of the world ethylene capacity uses Lummus technology (SRT Furnace / short residence time pyrolysis), one third is based on Stone & Webster (USC-Ultra Selective Coil design) technology and one third on KBR technology (SCORE-Selective Cracking Optimum Recovery). Linde and Technip also provide steam crackers. The designs are similar, based on ExxonMobil's steam cracking process (developed in the early 1940's) there are variations in the furnace design, and in the operating conditions. Energy consumptions from state of the art naphtha steam cracking technologies for the different suppliers have been shown to be comparable (CEFIC 2000, DTI-2006).

**Table 1: Process energy use for steam cracking**

Feedstock	GJ/tonne ethylene	GJ/ tonne HVC
Ethane	15-25	12.5-21
Naphtha	25-40	14-22
Gas Oil	40-50	18-23

Source: Ren et al (2005) and Meyers (2005)

Energy can represent up to 25% of production cost. Hence specific energy consumption is a key evaluation factor in comparing ethylene technologies (Bowen, 2005).

The largest energy component is heat use in cracking, which is essentially fixed. Hence the area for greatest energy savings is the recovery section (Bowen, 2005). The majority of energy in an ethylene plant is consumed in the cracking heaters to provide the heat of reaction and the sensible/latent heat to bring the reactants to the desired reaction temperature of 750 – 900 °C.

Heat of cracking depends on feedstock and conversion. Ethane cracking can require up to 5.6 GJ/t high value chemicals (HVC). Naphtha heat of cracking levels at maximum practical severity is about 3.1 GJ/t HVC, based on (Bowen, 2005). The difference is accounted for by the higher heating value of the ethane cracking product mix. Given cracking heater furnace efficiencies of 92%, the cracking furnace energy need is 6.1 and 3.4 GJ/t HVC, respectively.

The reaction energy accounts for about 22% of the total energy needs of a naphtha cracker (Matthews, 2001).

The heat in the cracked effluents is recovered in so-called transfer line exchangers (TLEs) that reduce the temperature to 350 to 450 °C. This heat is used to generate very high pressure steam (about 125 bar). For gas crackers, cracked gas is further cooled to nearly 200 °C in secondary TLEs. For liquid-feed crackers, this is achieved by direct quench with quench oil. This generates low-temperature steam. This is followed by water quenching of the gaseous fraction. The gaseous fraction is subsequently compressed to 32-37 bar in a four-or five stage centrifugal compressor that is usually driven by high pressure steam from the TLEs<sup>1</sup>. The product separation section consists of several distillation columns: a demethanizer, deethanizer, depropanizer and debutanizer. The C2 fraction is further split into ethane (that is recycled to the cracking furnaces) and ethylene. The C3 fraction is split into propane and propylene.

Early naphtha crackers consumed about 38 GJ/t ethylene (about 20 GJ/t HVC). In the 1970s the ethylene industry went through an extensive redesign of its flowsheet and lowered the specific energy requirements by 40- to 50 %. The thermal efficiency of cracking heaters improved to about 92% (Kapur, 2005). The latest furnaces with combustion air preheat and with stack gas residual heat use for feedstock preheat can achieve 96% efficiency (Bowen, 2005). In the 80s the energy consumption was reduced to 31 GJ/t ethylene (15 GJ/t HVC). For ethylene crackers, a typical value today is 20 GJ/t ethylene (also 15 GJ/t HVC).

Crackers typically have a surplus of low-temperature steam that can be used by other petrochemical or refinery processes.

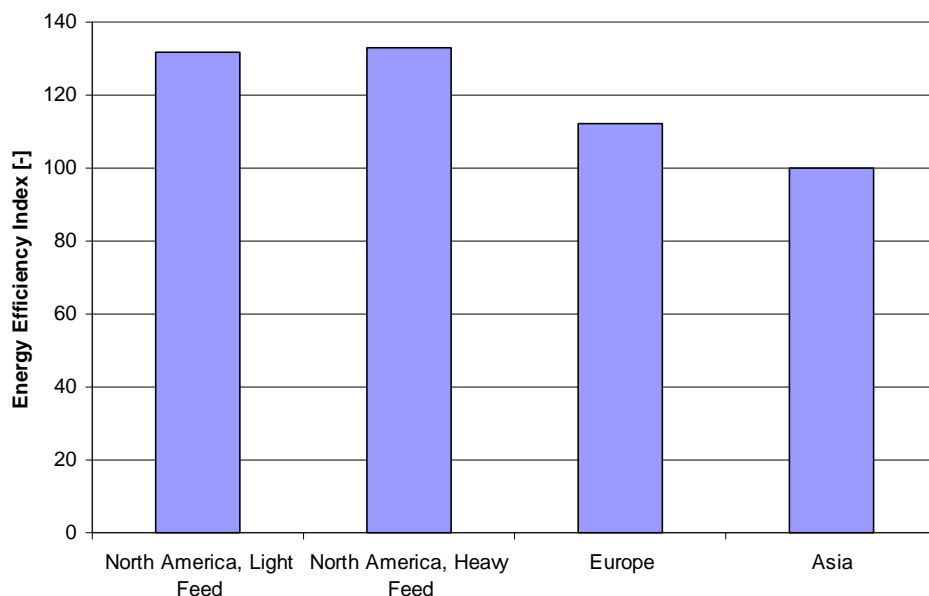
Solomon Associates benchmarks 115 olefin plants, representing 70% of the ethylene-producing capacity worldwide. An analysis has been made of a trend group of 50 olefin plants, half of which are in Europe, 27% in North America and the remaining 23% in other parts of the world. The actual data are confidential, but some regional trends and comparisons are public.

As percentage of the 2003 Olefin Study average energy consumption, North America was 111% of average, Europe was 95% and Asia was 86%. Part of this difference can be attributed to the different feedstock mix. The average ethane cracker in the study consumed 124% of the study average energy consumption, where the average naphtha cracker only consumed 95% of the average (Cagnolatti, 2005). However, even allowing for feed type differences, average energy consumption rates are significantly higher for the North American region, as shown in Figure 8. North American crackers use on average 32% more energy than Asian crackers, and European crackers use on average 12% more energy.

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<sup>1</sup> The only exception are the Total crackers in France that use electricity

**Figure 8 : 2003 Steam cracking energy consumption index per unit of product, corrected for feedstock mix (Cagnolatti, 2005)**



Yield performance performed by 1 percentage point between 1999 and 2003. The energy efficiency of European crackers improved by about 10% during this 4-year period. In North America, the improvement was only 3%. The average number of cogeneration units per plant did not change during this period, but the average size increased by a third. This cogeneration consists of gas turbines that generate part of the heat for the process furnace.

The integration of gas turbines with cracking heaters reduces the specific energy for ethylene production by about 10 to 20 percent of the overall energy requirements for an ethylene plant. The hot off-gas from the gas turbine is used as combustion air for the furnace. Eleven plants designed by Lummus based on the integration concept are operating successfully.

### **Biomass Feedstock and Biopolymers**

Naphta production from biomass feedstock would help reduce emissions, without altering existing petrochemical production infrastructure. Biomass has the advantage of being the only carbon-neutral primary feedstock option. Analysis of technology options for biomass feedstock is discussed in the ETP publication and Ren&Patel (2006). Those options include ethanol-to-ethylene (via dehydrogenation), methanol-to-olefins and Fisher-Tropsch high-temperature upgrading naphta-steam cracking. High fossil-fuel feedstock prices and/or carbon credits would help fast-track the application of biomass products. CO<sub>2</sub> emissions reduction of 10 Mt per year can be achieved in Europe alone by 2010 with policies and support measures in place.

While high production costs of biopolymers had initially stalled their commercialization, new developments in microbial-based polyesters have a potential of applications as early as 2008.

**Table 2: Global Technology Outlook for Biomass Feedstock and Biopolymers (IEA, 2006a)**

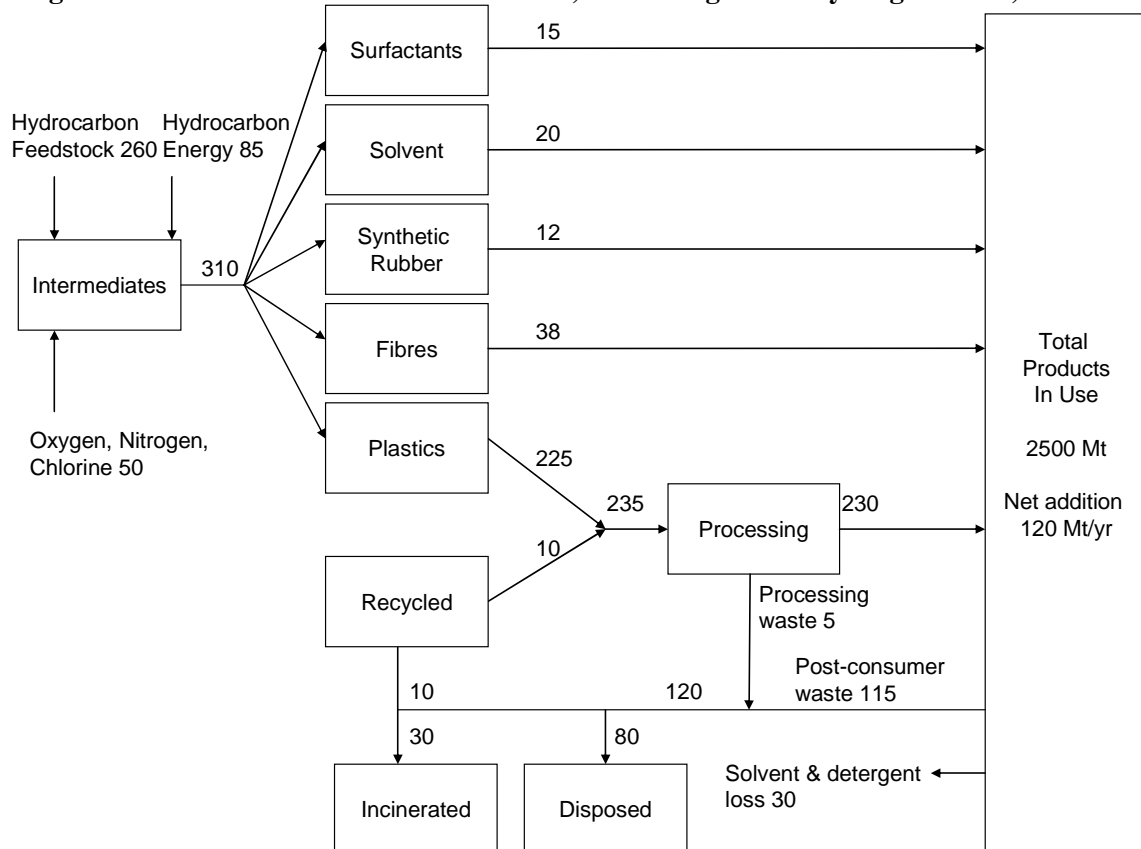
Technology Stage	2003-2015 R&D Demonstration	2015-2030 Demonstration	2030-2050 Demonstration Commercial
Investment Costs (\$/t)	5 000-15 000	2 000-10 000	1 000-5 000
Life-cycle CO <sub>2</sub> reductions	50%	70%	80%
CO <sub>2</sub> reduction (Gt /yr)	0 – 0.05	0.05 – 0.1	0.1 – 0.5

**Waste Treatment**

Figure 9 shows the world petrochemical balance. A total of 345 Mt of hydrocarbon (16 EJ) are converted into 310 Mt petrochemicals. With 225 Mt, plastics represent 73 % of the total petrochemical product mix, followed by synthetic fibres (12%), solvents, detergents and synthetic rubber. Energy content is on the order of 30-40 GJ/t of waste. Today, only 10 Mt of plastic waste are recycled (less than 10 % of the waste generated). The general trend is toward more mechanical recycling and energy recovery (municipal waste incinerators).

The general trend seems to be toward more mechanical recycling and energy recovery. The development of back-to-monomer and back-to-feedstock recycling technologies during the 1990s has not resulted in any major applications. But with worldwide plastics consumption running at about 235 Mt per year and assuming an energy content on the order of 30 to 40 GJ/t of waste, the energy saving potential is somewhere between 5 and 8 EJ per year. However increasing product stock and waste quality limitations will reduce this potential by half.

**Figure 9: World Petrochemicals Production, Processing and Recycling Balance, 2004**



Source: Freedonia, 2003; Plastics Europe 2006, Rubber Study, 2006; Industrievereinigung Chemiefaser, 2006

## **Combined Heat and Power (CHP)**

The Petrochemical industry uses significant amounts of steam for its processes. This steam can be generated in boilers or on cogeneration units. Cogeneration units increase the overall efficiency. They are widely applied in certain countries, but not yet in others. Lack of electricity grid access and low feed-in tariffs are reasons for low

High temperature CHP has a potential application in the petrochemical industry: flue gases from a CHP plant are used as a heat source for the furnace. Replacement of existing furnaces is generally required. Different options exist for use of CHP, including in the longer term application of solid-oxide fuel cells (SOFC's).

## **Modelling the Energy Technology Perspectives (ETP)**

In order to bring the world energy sector to a more sustainable path, five Accelerated Technology (ACT) scenarios were considered and modelled. A detailed description of the ACTs is given in the IEA 2006 Energy Technology Perspectives (ETP) publication (IEA, 2006a). The scenarios consider different policies (strong energy efficiency gains in transport, industry and building, increased investment R&D, greater deployment of Carbon Capture and Storage – CCS ...).

The modelling tool used to evaluate the impact of the ACTs is the IEA ETP model, a global 15-region model that allows the analysis of fuel and technology choices. The ETP model belongs to the MARKAL family of bottom-up modelling tools, to provide an optimization of the energy mix required.

Different sectors of the industry were considered: for petrochemicals, most of the energy use considered related to steam cracking of feedstocks to produce chemicals such as ethylene, propylene, butadiene and aromatics, methanol production and aromatics processing.

## **IEA ETP-Reference and ETP-ACT scenarios**

The ETP model has been used to assess future energy use for petrochemicals production and the related CO<sub>2</sub> emissions from production and waste treatment of synthetic organic products. The demand has been calculate as a combination of demand for seven types of plastics, olefins and aromatics derivatives. Assumption is made for the average life span of plastic products to be 10 years, hence a lag of 10 years between the plastic consumption and the waste generation.

It is assumed that petrochemical product demand increases by 160% between 2005 and 2050. The demand growth is identical in the Baseline and ACT scenarios

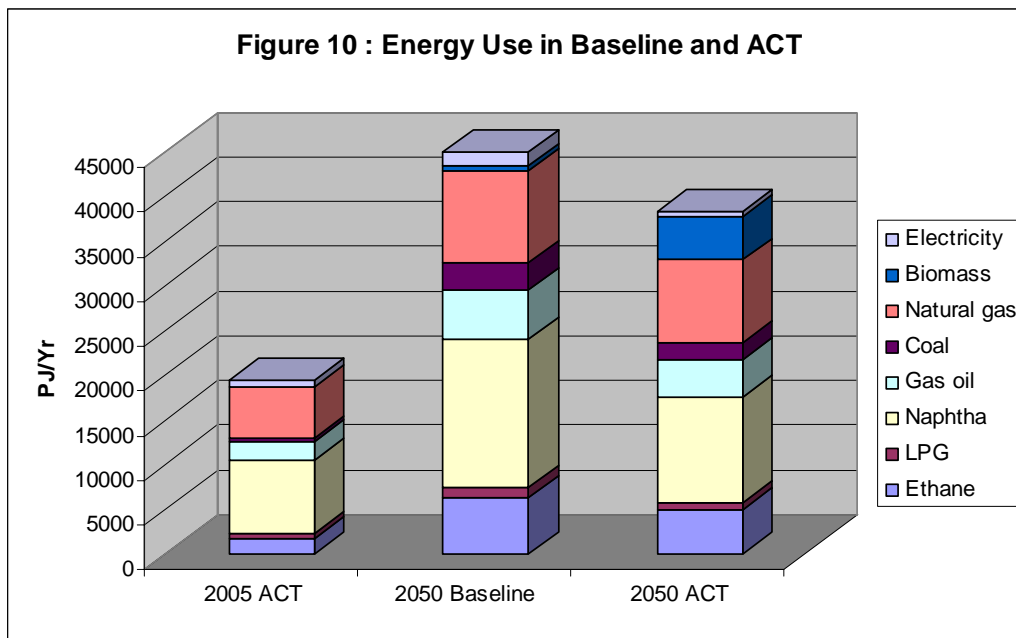
## **Energy Use in the Baseline vs. ACT Scenarios**

There are higher energy efficiency gains in ACT compared to Baseline. The energy use difference is 15 % of the total 45 EJ/yr forecasted.

- The Autonomous Energy Efficiency Gain (excl. feedstock use) is 1% in Baseline and 1.5% in ACT
- In the Baseline scenario plastics recycling accounts for 11% of total plastics supply (12% of plastic waste arising) in 2050. In the ACT scenario it increases to 26% of the total plastics supply (28% of plastic waste arising). This includes back-to-polymer and back-to-monomer recycling, and it includes post-consumer waste and processing waste.

- Bioplastics account for 1% of the plastics supply in Baseline in 2050, and they account for 4% in ACT.
- Biomass-based solvents, inks, synthetic lubricants etc., account for 3 % of the supply in the Baseline in 2050 vs. 17% in the ACT supply scenario.
- Gas-based CHP accounts for 65 % of the steam supply in the ACT scenario vs. 40 % in the Baseline
- Waste treatment: The Baseline projects that 50 % of the plastic waste goes through waste incinerators, and 50 % in industrial installations, such as cement kilns. The ACT scenario projects a greater amount of waste incineration (two-thirds) in kilns, replacing coal. Also the average electric efficiency of waste incinerators ranges from 20 % in the Baseline to 25 % in the ACT scenario.

Figure 10 shows the energy use projects for the petrochemical sector in Baseline and ACT scenarios. That accounts for more than 65 % of the energy use in the combined chemical/petrochemical sectors, and will represent 5 % of the total estimated energy use. Total energy use increases by 130 % in the Baseline scenario vs. 97 % in the ACT. The lower share of coal and naphtha/gas oil is compensated by an increased share of bio-feedstock and bio-energy.



Source: IEA estimates

### CO<sub>2</sub> emissions projections

The assumption made in the Baseline is that Carbon Capture and Storage (CCS) is not used; in the one of the ACT scenarios, CCS is deployed and 150 Mt of CO<sub>2</sub> is captured and stored. The figure does not include capture in power plants (upstream from the petrochemical operation. Table 3 summarizes the CO<sub>2</sub> emissions under those two scenarios.

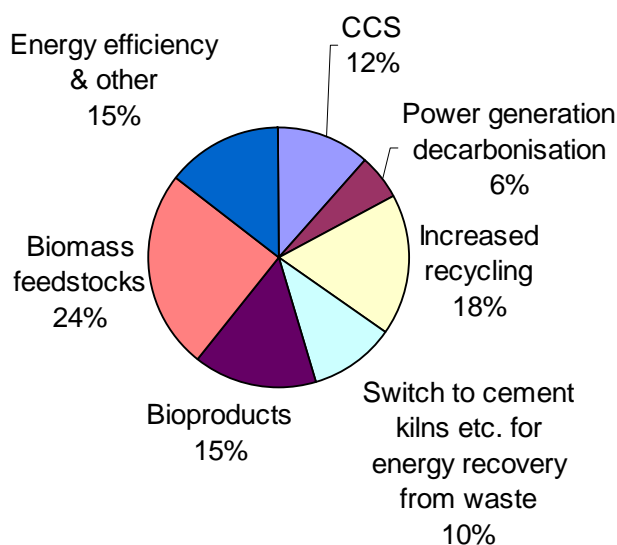
**Table 3: CO<sub>2</sub> Emissions in the Petrochemical Sector (Mt CO<sub>2</sub>/yr)**

	Baseline		ACT
	2005	2050	2050
CCS	0.0	0.0	150.0
Direct	493.9	891.1	224.8
Electricity from grid	151.2	297.2	31.7
Emissions during use	170.0	480.6	434.0
Waste incineration	96.7	428.1	342.0
<b>Total</b>	<b>911.7</b>	<b>2097.0</b>	<b>882.5</b>

Source: IEA

Total direct CO<sub>2</sub> emissions from the petrochemical installations increase by 80% in the Baseline versus a 55% decline in the ACT scenario. The direct emissions from process installations represent less than half of total CO<sub>2</sub> emissions. Including emissions during use and waste treatment and including the emissions related to electricity consumption, total emissions amount to 2.1 Gt CO<sub>2</sub> emissions. This represents a 130% increase, compared to 2005 levels. In the ACT scenarios total emissions decline by 1.2 Gt to 883 Mt. This represents an absolute decline of 3% compared to 2005 levels.

The emission reduction of 1.2 Gt CO<sub>2</sub> represents 5% of the total global emissions reduction in ACT. The most important category is biomass feedstocks and bioproducts, that accounts for 39% of the emission reductions. Increased recycling accounts for 18%, followed by energy efficiency measures, CO<sub>2</sub> capture and storage and enhanced energy recovery from waste, each in the 10-15% range (Figure 11).

**Figure 11: CO<sub>2</sub> Reductions in the petrochemical industry in the ACT scenario, compared to Baseline, 2050**

Source: IEA

## **Conclusions**

The comparison between the 2050 projections for energy usage and CO<sub>2</sub> emissions in the Baseline scenario and the Accelerated Technology indicates a significant potential for reduction in the petrochemical sector. The key contributing factors are biomass feedstock usage, biopolymer production, gas-based CHP and changes in waste treatment (increased recycling and energy recovery). Energy efficiency in production processes and CCS in production processes would contribute 27%. The CO<sub>2</sub> emission intensity can be more than halved with a combination of such technologies. This would result in a decline of 3% in absolute terms in 2050, compared to the 2005 level.

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