Biochemical Opportunities in the United Kingdom

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A project report from NNFCC

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The National Non-Food Crops Centre

Building sustainable supply chains

- NNFCC, the UK's single independent authority on renewable materials and technology
- Helping get products to market by building and strengthening supply chains
- Supporting decision makers with comprehensive information resources from all sectors

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ABOUT THIS DOCUMENT

The work presented in this document was funded by Defra, project managed by NNFCC and conducted by Nexant ChemSystems.

This document begins with a foreword by NNFCC, followed by the executive summary of a comprehensive study on the potential for production of bio-based chemicals from renewable resources in the UK.

The detailed study was conducted in 2007-2008 and a summary report 'Biochemical Opportunities in the United Kingdom' (March 2008) is presented here; additional supporting information and full screening data are available from NNFCC on request.

This study along with other new work co-ordinated by NNFCC will help shape the UK strategy for renewable materials.

For further details, to comment on the study, or if you have any interest in this area of NNFCC activity, please contact Dr Adrian Higson, NNFCC Technology Transfer Manager for chemicals (email address a.higson@nnfcc.co.uk, telephone +44(0)1904 435182).

FOREWORD

The UK chemical and downstream chemical-using industries form an important sector of UK manufacturing. The sustainability, both economic and environmental is and should be an area of importance for both UK industry and its academic base. The production of chemicals from renewable raw materials can bring a range of environmental and social advantages. Life cycle analysis has shown that chemical production from renewable feedstocks using biotechnology can reduce fossil energy requirements and mitigate greenhouse gas emissions. The use of renewable raw materials coupled with benign process chemistry has the potential to improve the public perception of the industry and create new markets for agriculture.

The production of bio-based chemicals, whist still a niche operation in terms of global chemical production, is demonstrating double digit growth. Enabled by the rapid advances in industrial biotechnology and the 4-fold increase in the price of crude oil over recent years, the number of bio-based chemicals within the sights of commercial producers is increasing. With the narrowing of cost differences between petrochemical and agricultural raw materials and processes, the potential of these bio-based chemicals to penetrate new markets is being realised.

Though it will improve the sustainability of the industry, the development of biotechnology or the use of renewable raw materials will not transform the fundamentals of the industry. Chemicals will still be prepared in large volumes to maximise economies of scale and, in turn, these items will move down the value chain through transformation to fine and specialty chemicals and finally consumer end products.

It is unsurprising, therefore, that the first impacts of renewable materials have been felt in the bulk chemical sector, with ongoing activity by major producers such as

DuPont, Dow, Solvay and others. As these operations increase in number and scale, bio-based chemicals will be increasingly available for downstream conversion, presenting new opportunities for industrial biotechnology development. Lactic acid based polymers are produced in the tens of thousands of tonnes for packaging applications, and the production of polyethylenes from ethanol in volumes of hundreds of thousands of tonnes will soon become reality. Away from fermentation, the increased availability of glycerol in the market is providing new opportunities. Solvay has developed a process for epichlorohydrin production from glycerol, turning on its head the old paradigm of glycerol production via epichlorohydrin. Propylene glycol is another major target for glycerol conversion with at least seven research programmes underway including Dow Chemicals, Ashland/Cargill and Huntsman.

The manipulation of microbes to allow the cost competitive commercial production of chemicals has been demonstrated by DuPont and Genencor. Their process for production of 1,3-propanediol relies on a microbe expressing genes from several different microorganisms to give the required productivity. Similar approaches are being developed for a range of chemicals. Succinic acid is the focus of a joint venture between DSM and Roquette, while 3-hydroxypropionic acid has drawn the attention of Cargill and Novozymes. These targets and others are now the focus of global research activity at academic institutions and within industry. Reviewing current activity, it is clear that developments are targeted at current or potential large scale polymers markets. This is understandable as the research and development effort required can be considerable, and therefore the security offered by large end product markets is desirable.

The UK needs to develop its technology base (academic and industrial) to allow it to capitalise on these new opportunities in bio-based chemical production. These opportunities may lie in manufacturing but could also be realised through technology development and licensing or through joint ventures.

The UK has initiated a number of activities to develop this area. The Bioscience for Business KTN-led Integrated Biorefinery Technologies Innovative will ensure a close working relationship between industry and academia. The special interest group ‘FROPTOP’, run jointly by the Bioscience for Business KTN, Royal Society Chemistry and Chemistry Innovation KTN, can serve to highlight the opportunities from downstream processing of bio-based chemicals. Suschem United Kingdom will allow close cooperation between the existing chemical industry and developments in Industrial Biotechnology. The National Non-Food Crops Centre (NNFCC) will continue to promote the opportunities for renewable raw materials in the chemical sector to industry, agriculture and the public. Centres such as the National Industrial Biotechnology Facility in Wilton and the Centre of Excellence for Biocatalysis, Biotransformations and Biocatalytic Manufacture (CoEBio3) in Manchester can provide a focus for activity. It is suggested that focussing on a small number of bio-based chemicals through focussed funding calls such as the ‘glycerol challenge’ would allow the development of fundamental technology and science, while providing the opportunity for greater collaboration between groups working on different aspects of science. This will in turn allow greater insight into the challenges faced within a particular process stream and, therefore, increase the rate of science and technology advancement.

Developing new processes for bio-based chemicals is a multidisciplinary activity requiring the attention of biotechnologists, chemists and engineers. Within these disciplines the number of fields is considerable; when coupled with the number of potential of bio-based chemicals and transformations the area becomes extremely complicated and difficult to co-ordinate. This complexity can be addressed somewhat by reducing the number of potential targets to a smaller group of bio-based chemicals. These preferred targets should offer the best opportunity for technical and market development for the UK.

With this in mind, the NNFCC commissioned the chemicals consultancy company 'Nexant ChemSystems' to analyse a range of bulk and specialty chemical production streams for their potential as UK targets for bio-based chemical development. Through this study the NNFCC is building the UK's information base and wishes to stimulate the UK's research and development efforts in the field of bio-based chemicals.

EXECUTIVE SUMMARY OF THE REPORT

Today, the United Kingdom petrochemical industry is not a sector of the economy showing tremendous growth. In recent years major industry players have rationalised and spun off non-core businesses to international industry players, e.g., SABIC, as well as private equity. Many of the traditional household names such as ICI are no more although their businesses still exist in some form under new ownership.

The UK petrochemical industry suffers from generally high energy costs, high raw material costs and high labour costs compared to different parts of the world, notably the Middle East with its access to low cost natural gas and China with access to favourable investment costs and low labour costs. However, the United Kingdom does have wealth of technology development capability, skills and scientific endeavour, particularly in the biotransformation sector. The challenge is finding the right process to fit the circumstances of the United Kingdom.

With this in mind, the NNFCC commissioned the chemicals consultancy company 'Nexant ChemSystems' to analyse a range of bulk and specialty chemical production streams for their potential as UK targets for bio-based chemical development. The initial targets were drawn from previous studies performed by the US Department of Energy and the BREW project. Using the results of these studies allowed the rapid selection of 48 targets from over 300 potential chemicals.

Using 'Nexant' methodology, each of the production streams were assessed for both market attractiveness and technical attractiveness. The study considered the market within the time frame of 2020. Market attractiveness addresses two fundamental questions: 1) Is there a growing market for the renewable chemical of interest? 2) Could 'UK plc' compete in the market place and a make a realistic return on its investment? To answer these questions each production stream was scored on a number of factors:

1) Potential markets
    - Local
    - European
    - Global
2) Profitability of target chemicals with respect to their current markets and the complexity of production
3) The competitive intensity of a given market (i.e. number of current producers and ease of entry into the market for a new producer)
4) Partnering requirements for technology, infrastructure or market access.
5) Opportunity for downstream development (e.g. polymer formulation processing).

The market attractiveness of any chemical opportunity can only be realised through cost effective production. Thus, the 'technical attractiveness' of each process was assessed and scored on a by number of technical feasibility factors:

1) The status of commercial development
2) The level of capital investment that would be required
3) The ability to build a world-scale unit to maximize competiveness
4) The complexity of the proposed chemical process
5) Access to the required process technology
6) Environmental considerations during production beyond normal chemical manufacture.

These individual factors were scored on a weighted basis and summed to give a market and a technology attractiveness score. The scores for each individual process were then normalised to give relative results for the 48 chemicals assessed.

The top 11 chemical streams with positive market and technology attractiveness relative to the total sample are listed below:

1) Propylene glycol produced from glycerine
2) γ-butyrolactone (GBL) produced from glucose via succinic acid
3) Linear low density polyethylene (LLDPE) from bioethanol-derived ethylene
4) High density polyethylene (HDPE) produced from bioethanol-derived ethylene
5) Tetrahydrofuran (THF) from glucose via succinic acid
6) THF from glucose via fumaric acid
7) Fumaric acid from glucose
8) 3-hydroxypropionic acid (3-HP) from glucose
9) Methyl methacrylate (MMA) using a ‘Plants as Plants’ approach
10) Polyhydroxyalkanoates using a ‘Plants as Plants’ approach
11) Lactic acid from glucose and conversion to polylactide

Chemicals which appeared attractive to the UK for bio-based development included linear low density polyethylene (LLDPE) and high density polyethylene (HDPE), succinic/fumaric acid and their conversion to 1,4-butanediol/tetrahydrofuran/γ-butyrolactone, 3-hydroxypropionic acid and conversion to acrylic acid, downstream applications for polylactic acid, methyl methacrylate and polyhydroxyalkanoates using green biotechnology, and propylene glycol and its downstream applications.

After consultation with the NNFCC, four of the top chemical process streams were taken forward for more detailed examination.

Bioethylene production with a combined LLDPE /HDPE facility

Europe is a multi-million ton polyethylene market. For wheat prices in the range of £80 per ton in the UK, a green polyethylene process could be cost competitive at the high oil prices observed today.

Integrated succinic or fumaric acid production with 1,4-butanediol (BDO), tetrahydrofuran (THF) and γ-butyrolactone (GBL)

In addition to the large markets offered by BDO/THF conversion, fumaric and succinic acid are platform chemicals which could give rise to lots of spin off UK business opportunities. In the UK, the dextrose solution price needs to be below €200 per ton to make a bio-1,4-BDO process competitive at $70 per bbl crude oil price. Opportunities exist to access higher value products such as N-methyl-2-pyrrolidone, through the butanediol chain.

3-Hydroxypropionic acid (3-HP) to acrylic acid

A major outlet for 3-HP is the acrylic acid market. In addition to this large market the production of 3-HP could give rise to lots of spin off UK business opportunities. 3-HP is a new product and could foster new applications development. Indications are that a biotransformation process can be competitive a crude oil price greater than $70 per bbl with a sugar-syrup price below €200 per ton

Methyl methacrylate and polyhydroxyalkanoates via the Metabolix "Plants as Plants" approach

The European market for MMA is around 686 000 tons and growing in line with average GDP. Methyl methacrylate could be produced based on the Metabolix "Plants as Plants" approach, where genetically modified switchgrass actually generates the product *in planta*. This could give rise to new science and R&D linked to agriculture.

It should be remembered that the screening process looks at relative chemical attractiveness and does not comment on the absolute economic potential of a single chemical stream. Each of these applications has its own merits in serving the development of biotechnology in the UK and can be considered as platforms for development of directed research strategies for biotechnology, chemistry and engineering programmes.

Biochemical Opportunities in the United Kingdom
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Contents

1 Introduction

1.1 Project Overview

The National Non-Food Crops Centre ("NNFCC") has engaged Nexant to provide a focused analysis of renewable chemical opportunities in the United Kingdom. The project is in part being undertaken to gain a better understanding of the opportunities for the United Kingdom to integrate renewable feedstocks into its chemical manufacturing base.

Nexant's analysis will be used to advance research and development programmes in both academia and industry.

Today, the United Kingdom's petrochemical industry is not a sector of the economy showing tremendous growth. In more recent years major industry players have rationalised and spun off non-core businesses to international industry players, e.g., SABIC, as well as private equity. Many of the traditional household names such as ICI are no more, although their businesses still exist in some form under new ownership.

The UK petrochemical industry suffers from generally high energy costs, high raw material costs and high labour costs compared to different parts of the world, notably the Middle East with its access to low cost natural gas and China with access to favourable investment costs and low labour costs.

However, the United Kingdom does have a wealth of technology development capability, skills and scientific endeavour, particularly in the biotransformation sector. This is positive, but Government and industry support is also necessary.

Unlike biofuels, there is currently virtually no legislative driver for biochemical process development. However, the examples of France, Italy and Belgium, who have policies encouraging the use of degradable plastic bags, show how incentives could stimulate the bio-based chemicals sector. Given a sustained high oil price and acknowledgement of the need for environmentally acceptable chemicals production, renewable chemicals could emerge in the United Kingdom.

The challenge is finding a process that fits the United Kingdom's market situation, renewable feedstocks, and technology, while attracting appropriate Government and industry support. For this purpose Nexant has carried out a screening analysis from a market and technical perspective to indicate candidate processes for further and more detailed investigation.

1.2 Chemical Products and Manufacturing Approaches Considered

Nexant has considered a broad range of commodity chemical products together with fine and performance chemicals[1] (Table 1). These reflect the findings of a number of major Government-sponsored (European Union and United States Department of Energy) initiatives.

[1] **Commodity Chemicals**
Characterised by large scale, typically > 100 000 tons per year, generally high capital investment, Euros 100s of millions, cyclical margins, modest investment returns, and specification many companies can meet.
Speciality Chemicals
Characterised by products or systems that employ "value in use" pricing generally and require close consumer and supplier interaction in applications development, backed up by strong research and development.
Fine Chemicals
Characterised by small scale, typically < 10 000 tons per year, generally high price, >Euros 10 per kilogramme, products with very high specification needs backed up by strong research and development activity.

The list is by no means exhaustive, but covers a broad range of possibilities. Each exploits a renewable feedstock base and potentially generates new derivative opportunities, whilst stimulating further research and development activities in the United Kingdom across academia and industry.

Table 1 List of target molecules

1	Ethylene ex ethanol	**17**	Acrylic acid ex glucose via 3-HPA	**33**	Acetoin
2	LLDPE ex bio-ethylene	**18**	Acrylamide ex glucose via 3-HPA	**34**	Threonine
3	LLDE ex bio-ethylene	**19**	Malonic Acid ex glucose via PDO	**35**	MMA - Plants as Plants
4	HDPE ex bio-ethylene	**20**	Isoprene monomer ex-glucose	**36**	Polyhydroxyalkanoates
5	EO/MEG ex bio-ethylene	**21**	Succinic Acid ex-glucose	**37**	Itaconic Acid
6	Alpha Olefins ex bio-ethylene	**22**	BDO ex glucose via Succinic Acid	**38**	Furfural (THF intermediate)
7	VCM/PVC ex bio-ethylene	**23**	THF ex glucose via Succinic Acid	**39**	Levulinic Acid
8	Biobutanol/acetone	**24**	GBL ex glucose via Succinic Acid	**40**	Glutamic acid
9	Cyclohexanone ex Lysine	**25**	PTMEG ex Bio-THF	**41**	Xylose and derivatives
10	1,3-propanediol/PTT ex glycerine	**26**	Fumaric Acid ex-glucose	**42**	Citric Acid
11	Propylene glycol ex glycerine	**27**	BDO ex glucose via Fumaric Acid	**43**	Lysine
12	Acrylic acid ex glycerine	**28**	THF ex glucose via Fumaric Acid	**44**	Methionine
13	Acrylic acid ex lactic acid	**29**	GBL ex glucose via Fumaric Acid	**45**	Glucaric acid
14	Lactic acid/polylactide ex glucose	**30**	Malic Acid ex glucose via Succinic Acid	**46**	Sorbitol
15	Lactate esters ex glucose	**31**	Aspartic acid	**47**	Adipic Acid
16	3-Hydroxypropionic acid ex glucose	**32**	3-Hydroxy-butyrolactone	**48**	Isopropanol.

1.3 Screening approach

1.3.1 Overview

For each of the 48 chemical product manufacturing options considered, Nexant has considered a number of factors that will influence both '*market attractiveness'* and 'technical feasibility' of the particular product, which will in turn influence its ranking with respect to the screening analysis.

In reality the analysis attempts to answer two major questions:

Is there a growing market for the renewable chemical product "United Kingdom plc" wants to manufacture?

and ***Can "United Kingdom plc" compete in the market and make a realistic return on its investment?***

In effect, is this a good business to be in from a United Kingdom perspective?

The factors considered by Nexant in this analysis are described in more detail below.

1.3.2 Market Attractiveness Factors

Local Market in United Kingdom
It would be advantageous for any of the projects considered if the United Kingdom itself had a growing market.

As an example methylmethacrylate ("MMA") is already produced in the United Kingdom, so there is a growing local market albeit at GDP-related rates.

European Market
Given the potential size and proximity of the European mainland market to the United Kingdom, the ability of United Kingdom plc to sell its product in Europe could have a marked impact on the financials of the project.

Global Market
Away from its domestic market and Europe, the wider global market, particularly Asia, is also likely to be a future possible geography and should be considered.

Profitability
This is an estimate of how profitable the industry is today, further reinforcing the idea of whether this is a good business to participate in. Given the complexity of the processes and the integration considered the projects must be profitable and show reasonable returns.

Competitive Intensity
This is analysis of the regional competition and the ability of United Kingdom plc to enter the market. The market could be highly concentrated with a few producers with large market shares and a protected market position. Conversely the market could have a number of producers with relatively small market shares.

Competitive intensity relates to ease of market entry for UK plc and has impact on business profitability.

Partnering Requirements
For some products it will be possible to license a technology, build the plant and enter the market. However, some processes may require joint ventures, either to gain technology access or improve market access.

Opportunities for Downstream Development
New projects for the manufacture of new chemical products could provide a platform for further downstream industry development.

Examples include, in the case of MMA, the further development of downstream polymer compounding activities and possibly glazing industries, etc.

It is important to note that information varies enormously across the product groups. Nexant has aimed, where possible to provide the same level of detail across the various product options. This has not always been the case. Indeed some products are not yet products of commerce and are only under embryonic development.

1.3.3 Technical Feasibility Factors

Commercial Development
It is important to understand whether a technology has been licensed or is it developmental. In the latter case what stage of development has been reached? This topic is therefore a measure of technology risk and time to market.

Capital Investment
Capital investments could vary enormously depending on the complexity of a biochemical complex from less than $200 million to over $500 million. The higher the capital investment implies a higher risk.

Ability to build a World-scale Unit
In order to maximise competitiveness, any plant or process needs to be built at world-scale.

Technology Complexity
Some chemical processes require highly specialised skills to operate successfully and reliably. Related to this question is the issue of maintenance practices and costs therein.

Technology Access
Can the technology be freely licensed from one or more suppliers? For example, in the case of citric acid, there are a number of licensors capable of building world-scale plants. In the case of lysine there are very few. The greater the source of reliable technology that can be licensed the lower the technical risk.

Environmental Considerations
Does the process carry significant environmental risks at parity to typical normal limits? It is anticipated that in most cases a biochemical process should be much more benign provided biohazard controls are in place.

2 Overview of selected chemicals

2.1 Ethylene

In 2006 global ethylene consumption amounted to 109 million tons. 60 percent of global ethylene consumption was for the production of polyethylene in the three main forms of low density (LDPE), linear low density (LLDPE) and high density (HDPE).

Uses (global 2006)
HDPE (27%), LDPE (17%), LLDPE (16%), Ethylene oxide (14%), EDC (12%), Styrene (7%), Alpha Olefins (2%), VAM (1%), Others (4%)

Ethylene is mainly produced by the steam cracking of paraffinic liquids like naphtha and natural gas liquids like ethane, propane and butane. These are refined products or streams derived from associated and raw natural gas processing.

In regions like China, coal is being exploited as an ethylene feedstock via gasification to syngas with subsequent conversion to methanol which in turn is used to manufacture ethylene and propylene via catalytic technologies.

More recently, high crude oil price has prompted reconsideration of ethanol conversion to ethylene where low cost ethanol is available, e.g. in Brazil.

Global ethylene demand over the next decade is forecast to remain close to the trend level of 4.5 percent per year.

Ethylene itself is very expensive to ship and so trade is mainly in ethylene derivatives such as the polyethylenes and ethylene glycol. Aside from areas such as the United State’s Gulf Coast and North-West Europe, which have ethylene pipeline networks, most ethylene is consumed at plants adjacent to the steam crackers.

West European Ethylene Demand
West European total consumption in 2006 was 21.8 million tons.

Uses (Western Europe 2006)
HDPE (22%), LDPE (22%), EDC (14%), LLDPE (13%), Ethylene oxide (10%), Styrene (7%), Alpha olefins (3%), Others (9%)

Ethylene demand growth in Western Europe is expected to be significantly below historical growth rates. This is a result of an increasing proportion of major derivatives such as polyethylene and mono-ethylene glycol (MEG) being imported from the Middle East.

De-bottlenecking of steam crackers has added considerably to West European ethylene capacity over the past few years. The bulk of capacity additions continue to come through expansion of existing facilities.

United Kingdom Ethylene Demand
Total ethylene production capacity in the UK was 2.9 million tons per year in 2006. UK ethylene demand was approx. 1.8 million tons in 2006 based on average requirements to meet its derivative platform. Currently there is an excess of ethylene and this is exported from Wilton to mainland Europe.

Uses (UK 2006)
LAO (30%), LLDPE (16%), Ethylene oxide (13%), LDPE (10%), HDPE (9%), VCM (7%), VAM (4%), EDC (4%), Styrene (1%), Others (6%)

2.2 Linear Low Density Polyethylene (LLDPE)

The largest end use sector for LLDPE is packaging, largely served through film. In such applications LLDPE is typically blended with LDPE to allow down-gauging and improve product quality whilst maintaining processability.

Total global LLDPE demand was 18.4 million in 2006.

LLDPE maintained its position as the fastest growing polyolefin, with consumption growing at an estimated 6.9 percent in 2006.

The trend of LLDPE displacing LDPE could accelerate with the commercialization of easy processing LLDPE.

LLDPE consumption growth remains well above GDP growth, although this is expected to decline closer to GDP growth levels as substitution for LDPE is completed and certain application areas mature.

Global LLDPE Supply
LLDPE capacity expansion is fairly evenly distributed between the regions. Capacity additions will be highest in the Middle East and Asia, but capacity will also increase in the more mature regions. Western Europe is forecast to become a major importer of LLDPE, primarily from the Middle East.

West European LLDPE Consumption
LLDPE growth rates are expected to be significantly above GDP growth projections. The long term growth forecast is around 4.2 percent per year, driven in the main by the polymer’s successful penetration of the LDPE market.

West European LLDPE Supply
Total capacity in Western Europe was 3 801 thousand tons in 2006 with a LLDPE demand of 3.5 million tonnes.

Capacity additions in Western Europe are expected to be moderate, limited by feedstock availability, and the more attractive investment opportunities in areas with lower labour and/or feedstock costs.

Investment is expected to focus on improving competitiveness rather than expansion. Capacity increases will be limited by the options for economical expansions of olefins production.

United Kingdom LLDPE Market

Total LLDPE capacity in the United Kingdom was 320 thousand tons per year in 2006. LLDPE supply is expected to remain at the current level for the short term at least. The United Kingdom consumes around 600 000 tons of LLDPE with around 300 000 tons of imports. The UK’s sole producer Ineos exports around 150 000 tons.

2.3 Low Density Polyethylene

Global LDPE demand was 18.3 million tons in 2006.
LDPE growth remains the lowest of all polyolefins, due to ongoing substitution by LLDPE and the maturity of many LDPE applications.

Global LDPE growth in 2006 was 2.7 percent while LLDPE achieved 6.9 percent, giving a combined LDPE/LLDPE growth of 4.8 percent.

Uses (global 2006)
Film (64%), Extrusion coating (11%), Other extrusion (10%), Injection moulding (6%), Blow moulding (3%), Others 6%

LDPE Supply and Demand
LDPE capacity is concentrated in the developed regions such as Western Europe and the United States. Total capacity in these regions is expected to remain flat, while capacity will continue to develop in the Middle East and Asia.

West European LDPE demand was 4.5 million tons 2006. West European LDPE demand growth remains small but positive in medium term. Long term growth will contract as a result of LLDPE penetration.

2.4 High Density Polyethylene

Global HDPE consumption totalled 29.6 million tons in 2006. Global HDPE demand growth increased 5.1 percent in 2006 compared to 2005.

Uses (global 2006)
Blow moulding (28%), Film (26%), Injection moulding (19%), Pipe and conduit (14%), Fibre (5%), Other extrusion (4%), Rotomoulding (1%), Others (3%)

HDPE growth during the next few years is projected to be higher due to the reverse substitution for polypropylene in the injection moulding sector. Essentially all moulders now have two sets of moulds so switching from one polymer to the other can be rapidly accomplished.

Bimodal HDPE continues to be a focus for much of this growth based upon an expanding product performance envelope and the potential for single gas phase reactor production which would have a lower capital and production cost.

The Asia-Pacific region will show strongest demand growth at over 6.1 percent per year. Developed economies will show growth in line with average GDP at circa 3.0 percent.

Global HDPE Supply
The current slate of new projects under development in the Middle East will see the region develop a significant share of global HDPE capacity by 2010.

Large scale capacity additions are also underway in Asia, to serve the rapid growth for HDPE in the buoyant manufacturing sectors of the region.

Capacity additions in Western Europe are forecast at lower levels, due to the expected abundant availability of exports from the Middle East.

West European HDPE Consumption
The long term growth rate of HDPE is expected to be ~2.1 percent due to the trend to reduce polymer consumption downstream caused by high polymer prices.

More finished products imported from China will also adversely affect resin demand.

West European HDPE Consumption
Total capacity in 2006: 4828 thousand tons. Capacity additions in Western Europe are expected to be moderate, limited by feedstock availability, and the more attractive investment opportunities in areas with lower labour and/or feedstock costs.

Investment is expected to focus on improving competitiveness rather than expansion. Capacity increases will be limited by the options for economical expansions of olefins production.

Western Europe imports of commodity HDPE from the Middle East and exports of higher value added grades to Asia.

2.5 Ethylene Oxide and Mono Ethylene Glycol

Ethylene oxide (EO) is an important industrial chemical mainly used for the production of ethylene glycol and other chemicals. In 2006 about 75 percent of the 18.2 million tons of global EO production was used in the production of monoethylene glycol (MEG).

The major non-MEG outlet for EO is the production alcohol ethoxylates for sophisticated detergent. EO is also used as a sterilant for foods and medical supplies. EO is sometimes used as the fuel component of a fuel-air explosive.

MEG is predominantly consumed in the production of polyester polymers (polyethylene terephthalate, or PET) which is in turn used in fibres, films, moulding applications and other speciality outlets.

MEG capacity has increased by 6.3 percent to 18.7 million tons in 2006. World total consumption of MEG is 17.3 million tons in 2006. As a result, the capacity utilization is approx. 89 percent globally.

Currently, the 10 largest producers of MEG worldwide represent 53 percent of world capacity.

Global Ethylene Oxide Consumption and Supply
Most growth in EO consumption will be in the Middle East, which will almost exclusively be for MEG production. Consumption of EO in North America and Europe will be broadly stable, as declining use for MEG production is offset by growth in other applications.

As EO is not transported, the pattern of production is the same as that for consumption.

Global Monoethylene Glycol Consumption and Supply
The concentration of the PET industry in Asia Pacific has generated very high growth rates for MEG, such that the region now accounts for 67 percent of the global market.

Despite the considerable competitive disadvantage versus Middle Eastern producers, Asian companies continue to pursue new MEG projects. This is partly due to the high prices and margins resulting from the prolonged period of high MEG operating rates. Aside from this, MEG provides some diversification from polyethylene in new cracker projects.

Capacity additions in the Middle East will be around one million tons per year between 2008 and 2011, as major new plants come online. The plants under construction in Saudi Arabia and Iran are significantly larger than any built previously (between 650 000 and 1 000 000 tons per year).

The United Kingdom MEG and EO Market
MEG is mainly used for polyester production for bottle grade and a limited amount for fibres and speciality polymers. The major consumer of EO is Shell for the production alcohol ethoxylates and detergent intermediates.

2.6 Linear Alpha Olefins (LAO)

The alpha olefin business is very complex. A LAO plant provides a distribution of products to supply a wide range of very different markets.

The light components such as butene-1, hexene-1 and octene-1 are consumed in the production of polyethylene. Decene-1 is principally used to manufacture polyalpha-olefins (PAO) for the production of high performance lubricants.

Higher alpha olefins are consumed in the production of detergent alcohols for subsequent ethoxylation, sulphonation, etc. Certain fractions, namely hexadecene-1 (C16) and octadecene-1 (C18), are used to manufacture high value lube oil additives, oilfield chemicals and paper sizing agents.

Higher fractions still, i.e. greater than eicosene (C20+) are used to manufacture various speciality chemicals and speciality waxes. LIO fractions are unique to Shell and are consumed mainly in detergent applications.

LAO Supply and Demand
The global demand for linear alpha olefins (LAO) is estimated to have reached over 4.5 million tons in 2006.

Demand is focused on LLDPE which dominates, accounting for about 35 percent of total demand consuming butene-1, octene-1 and hexene-1.

North America accounted for 49 percent of the demand for LAO globally in 2006. However, out to 2020, Asian demand is expected to grow by around seven percent per annum and by 2020 is projected to make up 16 percent of total global demand at a total of 1.2 million tons across all fractions. In contrast, North American growth is forecast at around two percent per year, giving a projected consumption of 2.6 million tons of LAO by 2020.

European demand for linear alpha olefins (LAO) is estimated to have reached over 900 000 tons in 2006. In the United Kingdom Shell is the major LAO consumer with its integrated detergent alcohols plant located at Stanlow. Ineos and other polymer producers consume a small amount of hexene-1 and butene-1.

The remainder of the market is small and highly fragmented.

2.7 Vinyl Chloride Monomer and Polyvinyl Chloride

Almost all VCM produced is used to manufacture PVC. Other applications, such as chlorinated solvents and polyvinylidene chloride, consume very little VCM. Consumption of VCM is therefore directly linked to regional production of PVC.

In 2007 the global total consumption of VCM was 36 million tons, with more than 99 percent consumed in the production of PVC.

PVC is one of most important products of the chemical industry in terms of the revenue it generates. PVC is used in a variety of applications, with its major uses in the construction (~50 percent) and automotive industries. There are claims that PVC production has negative effects on the natural environment and human health. Nonetheless it is still widely used.

Other applications of PVC as a hard plastic include vinyl siding, magnetic stripe cards, window profiles, pipelines, plumping, and conduit fixtures. In its softer and more flexible form made by the addition of plasticizers, PVC is used to produce phthalates, that are used in clothing and upholstery, flexible hoses and tubing, flooring, roofing membranes, and electrical cable insulation.

VCM Supply

Little investment over the past decade has resulted in the current tight VCM market.

The proportion of VCM produced from acetylene globally has increased from six percent in 2000 to 17 percent in 2006, and is expected to reach 18 percent by 2008. Nearly all of China's new PVC capacity is back integrated and enormous amounts of new acetylene-based VCM capacity are expected in line with PVC.

Until recently, the Middle East has had limited investment in vinyls in comparison to capacity for other ethylene derivatives such as polyethylene and mono ethylene glycol production. In the longer term, however, the region is expected to develop more capacity with exports aimed at Europe and Asia.

Little to no new capacity is expected in Western Europe except for some possible replacement capacity or de-bottleneck of existing plants.

West European VCM Supply

Total VCM capacity in Europe was circa 6.7 million tons per year in 2006. West European producers continue to invest in expansions and process improvement to enhance the competitiveness of the installed capacity base.

VCM capacity in United Kingdom is 300 thousand tons per year operated by Ineos Vinyls (formerly ICI) in Runcorn.

PVC Supply, Demand and Trade

PVC Consumption

Vinyls producers throughout the chain are currently enjoying high margins despite the high underlying power and feedstock costs. High global economic growth and particularly strong construction/reconstruction activity in certain areas is driving high consumption levels and high global operating rates.

Global PVC consumption growth is expected to average just under four percent through 2015. Asia's growth, driven by large populations in China and India, is expected to lead the world.

West European PVC Consumption

PVC demand growth has declined in recent years as economic growth in Western Europe has averaged only two percent over 2005-6. The PVC/VCM/EDC business continues to be driven by the activity of the construction sector in particular with its heavy reliance on pipe and construction associated profiles.

Environmental issues still figure largely in the vinyls story. The banning by the European Commission of phthalate plasticisers in teething toys for children under five reflected on PVC and emphasised the vulnerability of some flexible applications.

The market is divided between mainly rigid construction applications such as pipes, fittings, profiles and sheet, and flexible applications such as wire and cable, coatings, films and tubes. The construction sector dominates the market, and its volatility relative to GDP growth is a major factor in the balance of supply and demand at any time.

Packaging is the second largest end use sector (albeit a third of the size of construction) but this has declined over the last decade as a number of end users have switched from PVC to "greener" alternatives. As an example, PET has replaced PVC in many bottle applications. Initially this substitution was on the basis of environmental issues and aesthetics but the change is also motivated by processing advantages.

Improvements in design and production techniques have allowed a continued decrease in the quantity of PVC resin used in many applications. The effect has been to limit PVC growth despite growth in the end-use sectors themselves.

Uses (West European 2006)
Non extrusion coating (56%), Film and sheet (18%), Injection moulding (5%), Blow moulding (5%), Extrusion coating (4%), Rotomoulding (2%), Others (10%)

PVC Supply
Little investment has resulted in sharply higher operating rates throughout the chain. Poor margins, higher energy costs, and environmental concerns have limited new capacity.

Over the next few years, huge amounts of new vinyls capacity will be built in China, much of it using acetylene-based technology.

The Middle East has limited PVC capacity but new capacity, due onstream from 2010, will lead to exports aimed at Europe and Asia.

Little new capacity is expected in Western Europe except for some possible replacement capacity and expansions in the longer term.

The United Kingdom produced 470 000 tons of PVC in 2006. The three existing producers are EVC, Ineos Vinyls, and Hydro Polymers.

2.8 Biobutanol

n-Butanol consumption amounted to 2.8 million tons in 2006. Primary current uses of n-butanol are butyl acrylate and methacrylate esters, accounting for about 46 percent of the total n-butanol demand.

Uses (global 2006)
Acrylates (46%), glycol ethers (25%), Butyl acetate (15%), Solvent (7%), Phthalates (2%), Others (5%)

The drivers for butyl acrylate and methacrylate esters are emulsified and solution polymers used in latex surface coatings and enamels and lacquers. These water-based systems, which are heavily dependent on construction and remodelling/maintenance activities have benefited in recent years from the trend away from solvent-born coating systems.

Bio-butanol is being considered as a new generation biofuel as it is not as corrosive as ethanol, and can be shipped through existing fuel pipelines, while ethanol must be transported via rail, barge or truck.

Consumption of n-butanol is forecast to grow at an average rate of 2.1 percent per year between 2006 and 2020. Growth is relatively moderate in all regions except Asia, where consumption continues to grow and outpace local supply.

Western Europe n-Butanol Market

In 2006 Western Europe consumed about 700 000 tons of n-butanol. By 2011, Western Europe demand for n-butanol is expected to reach 786 000 tons per year.

In Western Europe the combined volume of n-butanol for use in acrylates and acetates accounts for 56 percent of total demand. Butyl acrylate and methacrylate esters have exhibited good growth potential, primarily on the back of demand for latex paint from a growing housing industry in Europe.

The second largest use is for butyl acetate followed by use as a solvent and for production of butyl glycol ethers. Small volumes are also used for production of butyl plasticizers, amino resins and butylamines.

2.9 Cyclohexanone

The global demand for cyclohexanone is estimated to be about 6.2 million tons per year in 2006, the majority (97-98 percent) of which is captively used in the production of adipic acid and caprolactam. Therefore, unlike cyclohexane which is widely traded worldwide, there is only a small amount of cyclohexanone traded in the world's market.

Caprolactam and adipic acid are consumed in the production of nylon 6, nylon 6,6 and other specialty chemicals.

Industrial solvent, oil extractant, paint and vanish remover, dry cleaning material, solid fuels and insecticide are other miscellaneous end users of cyclohexanone.

BASF is the world leader of adipic acid and caprolactam.

Small volumes of cyclohexanone are traded between regions. DSM at Geleen is known to sell the product in Asia. There are also tactical inter-country movements in the Asia-Pacific region.

2.10 1,3-Propanediol

1,3-Propanediol (PDO) or trimethyl glycol (TMG) as it is otherwise known is a relatively low volume chemical with a global production of 130 000 tons per year. It is mainly used (80%) to make the new polyester polytrimethylene terephthalate (PPT). This PTT product is being developed for the carpet fibre sector and marketed by Shell Chemical Company under the tradename Corterra™ and by DuPont under the trade names Sorona™ and Cerenol™.

The world PTT market has been growing rapidly since 2001 at 50 percent growth rate. In 2006 the world production capacity for PTT is approx. 125 000 tons per year. End use applications of PDO can be found in cosmetics, laminates, adhesives, paints, powder, inks, and UV-cured coatings. It can also be used as a solvent and as a coolant, and as co-monomer in the manufacture of other polymers and co-polymers.

Although 1,3-propanediol is a simple organic chemical, unlike other glycols it has historically been a high priced speciality. The high cost and limited availability has restricted its commercial use but developments in technology are reducing costs and opening up new markets.

A proprietary process, developed by Shell Chemicals in 2004, combined with the economics of a world-scale production unit in Canada, allows PDO to be produced cost-efficiently and priced competitively with similar compounds. PDO has now become a viable industrial chemical intermediate. Currently, the plant capacity is 73 000 tons per year of PDO per year.

DuPont and Tate & Lyle have also developed a new process to use corn to produce 1,3-propanediol. This new product, Bio-PDO™, is a key ingredient in the production of DuPont Sorona™, the newest DuPont polymer for clothing, carpeting, plastics and many other possible uses. Another portion of Bio-PDO™ will be used to produce DuPont's new line of polyols called Cerenol™. The DuPont plant has a capacity of 45 000 tons of PDO.

Growth
Because of the processes developed by Shell Chemicals and DuPont and Tate & Lyle there will be a rapid growth of this market.

Annual growth rate is estimated at 5.5 percent.

Potential 1,3-Propanediol Derivatives

Thermoplastic Polyurethanes (TPUs)
These materials find widespread use in adhesive and transportation sectors as well in the production of sportwear, e.g. ski boots.

Polybutylene Terephthalate (PBT)
PBT is mainly consumed in the automotive and electronic sectors. By 2005 tri-regional (US, WE, Japan) demand was estimated at about 376 000 tons with an average annual growth rate of 5 percent.

Copolyester Ethers (COPEs)
Copolyester ethers are high performance elastomers mainly used mainly in automotive applications. They can be produced in the same unit as PBT but require the additional component polytetramethylene ether glycol (PTMEG) made from THF.

Tri-regional demand rose to 99 000 tons in 2005 with a global average annual grow rate of 7.6 percent. In Western Europe, however, the annual growth rate is lower, at 6.6 percent.

2.11 Propylene Glycol

Propylene glycol consumption totalled 1.6 million tons in 2006.

Propylene glycols (PGs) are mainly used in the production of unsaturated polyester resins (UPRs) which are used in surface coatings and glass fibre reinforced resins for applications in the construction, marine and transportation industries. The second largest use is as a substitute for ethylene glycol in antifreeze and heat transfer fluids (functional chemicals).

Other applications include plasticisers and hydraulic brake fluids, non-ionic detergents used in the petroleum, sugar refining and paper making industries, preparation of toiletries, antibiotics and liquid washing formulations.

Propylene glycol is also an excellent solvent and finds outlets in printing inks, alkyd resins and as an extractant. It is also widely used as a humectant in the pharmaceutical, cosmetics, animal foodstuffs and tobacco industries.

Uses (global 2006)
Unsaturated polyester resins (26%), Functional fluids (22%), Food/Drug/Cosmetic use (20%), Liquid detergents (16%), Paints and coatings (4%), Tobacco humectants (3%), Others (9%)

There are three main grades of propylene glycol in the market place.

- Industrial grade
- Antifreeze grade
- Pharmacy grade

Propylene Glycol Supply Demand and Trade

The global annual average demand growth rate is projected to be about 3-4 percent to 2015.

The market for propylene glycol is mature in the US and Western Europe and growth is slow due to economic downturn. Moreover UPRs based on phthalic anhydride could potentially face increased competition from dicyclopentadiene-based resins. Demand growth in the US is predicted at 2 percent per year.

China is the main growth area with the expected growth rate of 7 percent throughout 2010 as many investments are under way in Asia. Lyondell is planning a 100 000 tons PG plant in Ningbo, downstream of its cracker project which is due to finish in 2009, in a joint venture project with Zhenhai Refining and Chemical.

In the pharmaceutical, personal care, food and UPR sectors demand has been growing at normal and constant rates despite economic slowdowns. However, some other applications such as de-icing and antifreeze fluid demand is seasonal.

There are a number of companies looking to build PG facilities using glycerine feedstock, as glycerine is becoming increasingly available as a byproduct of biodiesel manufacture. Examples of these are Ashland Chemical and Cargill's joint venture to build a 65 000 tons per year glycerine-based PG plant in Europe, Huntsman's glycerine-based PG facility in Conroe, Texas to start in 2008, and Dow Chemical's commercialization of its glycerine-based PG product called PG Renewable by the end of 2007. Archer Daniels Midland (ADM) also plans to manufacture PG and polyols from agricultural-based feedstocks.

Global Propylene Glycol Supply
The global production of propylene glycol was 1.8 million tons in 2006. The current global supply is tight as PG producers continue to compete with polyurethane producers for propylene oxide feedstock.

Steady demand was seen in Europe in 2005-2006 with supply being also balanced with demand. The supply of dipropylene glycol (DPG) and tripropylene glycol (TPG) however was tight whilst demand was relatively strong.

Dow Chemical and Lyondell are the market leaders with a total production of 1.1 million tons per year, accounting for 58 percent of total global production. Both are back-integrated to their propylene oxide facilities. Plants are currently under construction in China and Japan.

United Kingdom propylene glycol demand was estimated at 46 700 tons in 2006.

Currently there is no PG production in the United Kingdom hence the United Kingdom is a net importer of PG. The United Kingdom imported more than 50 000 tons of PG in 2005 and 2006.

2.12 Acrylic Acid

Acrylic acid, also known as propenoic acid, can be used in both its crude and glacial forms.

The global crude acrylic acid market has reached around 3.9 million tons. As a base case forecast global demand growth lies in the range of average global GDP at around 3.4 percent and the demand for crude acrylic acid will increase to 4.5 million tons by 2015.

Crude acrylic acid (typically 99.7-99.8 percent acrylic acid) can be used directly in the production of commodity and specialty acrylates or purified into its glacial form. It is also likely that some blending of crude and glacial acid may be undertaken for less critical polyacrylic acid applications.

Uses (global 2006)
Glacial acrylic acid (43%), butyl acrylate (30%), ethyl acrylate (9%), methyl acrylate (8%), 2-ethylhexyl acrylate (6%), Others (4%)

Crude acrylic acid demand is dominated by the production of glacial grades to serve its major market, super absorbent polymers (SAP) which account for around 33 percent of global crude acid demand.

Given strong forecast double digit demand growth in Asia, particularly China, demand for crude acrylic acid will outstrip that in developed economies moving from only 21 percent of global demand in 2005 to around 38 percent in 2015.

China has been showing high growth rate for bulk acrylates and acrylic market and this growth will continue at the rate of 8 percent per year. The total capacity is China is about 795 000 tons in 2006, up 112 percent from 374 000 tons in 2005 as several new plants came on stream in 2006.

Global Acrylic Acid Supply
The global crude acrylic acid capacity exceeds 4.2 million tons per year putting global utilization rates quite high at around 90 percent. During the early part of the decade weak demand lead to tactical plant closures. Industry recovery and demand in China has seen a major capacity building programme worldwide.

Downstream integration is more usual than upstream with many producers producing acrylate esters and super absorbent polymers.

BASF is the global leader, with Rohm and Haas as the second biggest producer globally, but the largest in United States. Other major producers include Nippon Shokubai, Mitsubishi Chemical and Dow Chemical.

Inter-regional trade of acrylic acid is expected to remain modest, with more trade in the major derivatives. The expected high rate of capacity addition in China may swing the region towards a small net export position.

Western Europe Acrylic Acid Demand
Demand for crude acrylic acid will reach around 846 000 million tons in 2007. Estimated United Kingdom demand for acrylic acid and its salts was about 24 000 tons in 2006 based on trade statistics. The UK used to make SAP, but this ceased after the BASF fire at Elsemere Port some time ago.

The UK is a major consumer of acrylate esters for coatings. Akzo (formerly ICI) is a major butyl acrylate consumer for paints production.

There are also a number of diaper facilities operated by Kimberly Clarke and Proctor&Gamble as well as private label producers in the UK.

Western Europe Acrylic Acid Supply
Crude acrylic acid capacity in Western Europe stands at around 950 000 tons by the end of 2005. Currently there is no acrylic acid or commodity acrylate plants in the United Kingdom.

2.13 Lactic Acid and Lactate Esters

Lactic acid is an "Alpha-Hydroxy-Acid" (AHA) and therefore competes with a number of products with similar properties, some produced from petrochemical feedstocks and others using biotransformations. Examples of these products are malic acid, citric acid, and glycolic acid.

Global lactic acid demand was around 275 000 tons in 2006 with an average annual growth of 10 percent.

Uses (global 2006)
Polymers (55%), Personal care (17%), Food Industry (15%), Solvent (12%) Others (1%)

The key growth drivers are in the industrial applications segment with the expected high growth of lactic acid based biodegradable polymers polylactic acid (PLA) and lactate solvents. The industrial applications segment, including PLA and new biodegradable solvents such as ethyl lactate and butyl lactate, is growing at 19 percent per year. Polylactic acid alone is growing at 22 percent annually in the same period.

Lactic acid is a product for developed economies primarily, despite recent capacity increases in China and India. The current global market is dominated by North America and Western Europe where lifestyle and personal finance enable consumers to choose products such as fortified foods, high quality foodstuffs and beverages, etc.

However, from a demographic perspective, improvements in living standards over the longer term in developing economies could give rise to very significant increases in lactic acid demand in the food industry sector. At the same time, demand in lactic acid is reduced in the developed areas as consumers call for natural foods without artificial preservatives.

Western Europe Consumption
In the year 2006 the Western Europe consumed in the region of 33 000 tons of lactic acid with a market dominated by personal care and food industry sectors. Together, these applications account for around 75 percent of demand.

Many top players are seeking to move production facilities to the growing market in Asia as a result of the high production cost and price pressure in recent years. Historically Western Europe has been a net exporter of lactic acid. Net exports in the 15 000 to 20 000 tons per year range are usual. The building of the lactic capacity at Blair, Nebraska to support the needs of polylactide and ester production could result in a shift in trade patterns but it is expected that Western Europe will remain an exporter albeit at a reduced level.

Lactate Esters Overview
Lactate esters can be consumed in a variety of industrial and consumer applications where it functions as a "green" solvent as they are non-toxic and biodegradable. The end uses for lactate ester solvent include specialty coatings, inks, cleaners, and straight use cleaning. Lactate esters can also serve as the chemical building block for industrial production of polymers and other commodity chemicals.

Despite their huge potential, the use of lactate esters has been limited due to the high costs of production.

The current solvent market is estimated at about 3.6 to 4.5 million tons per year, and is offered at prices from $US 1 800 to $US 3 400 per ton. The selling prices for ethyl lactate have ranged from $US 3 000 to $US 4 000 per ton, but processing advances could drive the price as low as $US 2 000 to $US 1 700 per ton.

2.14 3-Hydroxypropionic Acid

3-Hydroxypropionic Acid (3-HP), like lactic acid and succinic acid, is an important chemical building block that can be converted to a number of value added chemicals such as 1,3-propanediol, acrylic acid and esters, malonic acid, acrylamide and hydroxyamides, acrylonitrile, and ethyl ethoxy propionate (EEP).

Currently there is no commercial-scale production of 3-HP from petrochemical feedstock but the derivatives of 3-HP are produced in petrochemical process.

Cargill has developed a biobased pathway to convert dextrose into 3-HP and claimed that the microbial route is less expensive than the conventional petroleum process. Therefore it is anticipated that the commercialisation of the bio-based process will provide an economically viable alternative to many chemicals products that are currently produced from non-renewable feedstock.

Glycerine can also be used as a feedstock for 3-HP production.

2.15 Acrylamide

Acrylamide is primarily used in the synthesis of polyacrylamides which are used as water-soluble thickeners.

These find their applications in wastewater treatment, gel electrophoresis (SDS-PAGE), papermaking, ore processing, and in the manufacture of permanent press fabrics.

Smaller amount of acrylamide is used in the manufacture of dyes and as comonomers in styrene-butadiene latex, acrylic resins, and many others.

Global Acrylamide Market

Consumption
In 2006 the global acrylamide business was worth approx. $US 2.0 billion and the total consumption was about 475 000 tons, at the market price of $US 3 520 to $US 3 720 per ton.

In US, Western Europe and Japan, wastewater treatment application dominates acrylamide consumption (about 56 percent of total consumption), followed by the paper industry (24 percent).

The worldwide acrylamide demand in wastewater treatment application is growing at about 3.5 percent.

The paper application growth is about 4.5 percent per year in Europe whereas slow growth is experienced in US and Japan.

The fastest growth area is the enhanced oil recovery (EOR) application sector with China being the world's largest consumer in this application. In the US, consumption was low before 2004 due to the drop in crude oil prices. However, interest in EOR applications has recovered due to oil price increases in 2004-2005 and demand in this application is expected to increase significantly in the next few years.

Overall, the global growth rate for acrylamide is approx. 3.8 percent. In the next 5 years, China acrylamide demand is forecast to grow at about 7-10 percent, while US and Japan will grow at a much slower rate. Europe and the rest of the world will grow moderately at a good rate.

Most polyacrylamide ("PAM") producers are captive in acrylamide but not in its feedstock acrylonitrile. PAM is sold in various forms from emulsions, solutions, solids and so-called Mannich products.

Production
About 93 percent of the world's acrylamide capacity is located in China, US, Western Europe and Japan.

In 2002 the top three producers account for about 51 percent of the world acrylamide production. The major producers of acrylamide are Ciba Specialties, Cytec Industries (sold their water treatment and acrylamide business to Kemira in 2007), ONDEO Nalco, and S.N.F. Floerger.

The market of acrylamide is oversupplied, however not much rationalization is taking place as the majority of acrylamide production is captive to polyacrylamides production.

Acrylonitrile feedstock supply is more or less stable in price which results in a stable acrylamide market and acrylamide price.

Globalization of the acrylamide business is taking place, as producers tend to build production facilities nearer to their consumers and in lower-cost regions.

2.16 Malonic Acid

Malonic acid is used in organic synthesis, in anodization of aluminium as an electrolyte additive, or in adhesive composition.

Malonic acid can also be used to produce 1,3-propanediol (PDO) and subsequently polymer polytrimethylene terephthalate (PTT).

The most important derivatives of malonic acid are dimethyl and diethyl malonate, methyl and ethyl cyanoacetate, cyanoacetic acid, and malononitrile.

2.17 Isoprene Monomer

High-purity isoprene (also known as 2-methyl-1,3-butadiene), is used as a monomer for the production of rubbers and elastomers such as polyisoprene, styrene based block copolymers e.g. styrene-isoprene-styrene ("SIS") and butyl rubber. A small volume of isoprene are used as an intermediate for specialty chemicals such as pharmaceuticals, flavorings and perfumes, and epoxy hardeners.

Uses (global 2006)
Isoprene rubber (71%), SIS/SEPS (21%), Butyl rubber (4%), Others (4%)

The isoprene market today is dominated by polyisoprene, but this is limited to the Former Soviet Union (FSU). Outside the FSU, the major isoprene end-use today is in the production of styrene block copolymers (SBCs) and this will spur future demand growth for isoprene.

About 21 percent of total isoprene demand is taken by SBC production for making hot melt adhesives, polymer compounds, etc. Major SIS/SEPS producers include Dexco, Kraton Polymers, Kuraray and Polimeri Europa.

Although the butyl rubber market is large, isoprene consumption per ton of rubber is very small and so accounts for only around four percent of total demand.

Most isoprene production is consumed in the country of origin. Eastern Europe, North America (mainly the United States) and Japan are the major producers and consumers of isoprene, and account for around 90 percent of global total.

The UK has a very small and virtually static isoprene market.

2.18 Succinic Acid

Succinic acid is a commercially important chemical and the current world market is estimated at 16 000 ton per year.

Succinic acid is mainly used as sweetener in food and beverages, as feedstock for some fermentation processes and for (bio)chemical non-food valorisation. However because of the costly production process its potential is still underexploited. The current market price of succinic acid is about $US 2 000 – 3 000 per ton.

Succinic acid is also a key platform chemical to produce many other chemicals such as butanediol, tetrahydrofuran, γ-butyrolactone, adipic acid, succinate ester solvents, 2-pyrrolidone, succinimide, maleic anhydride, and polybutylene succinate. Therefore the market for succinic acid could rapidly increase to large volumes on an integrated basis.

Most succinic acid is manufactured from maleic anhydride in on-purpose facilities.

Other key growth driver is the progress made in the development of the microbial fermentation process to produce bio-based succinic acid that has significantly lower cost than the conventional petrochemical process.

2.19 1,4- Butanediol

BDO is used almost exclusively as an intermediate to synthesize other chemicals and polymers.

Uses (global 2006)
THF (34%), PBT (31%), GBL (15%), TPU (12%), COPE (4%) Others (4%)

The global consumption of BDO was approx. 915 000 tons in 2006 and is growing at 6 percent per year. High growth is partially influenced by new investments for BDO and derivatives in China.

The BDO value chain is sub-divided into three based on BDO uses itself, the THF value chain and the GBL value chain.

GBL represents the specialty segment of the business serving as an intermediate in NMP productions as well as 2-pyrrolidone for pharmaceuticals and the monomer n-vinyl-2-pyrrolidone (NVP) for polyvinyl pyrrolidone (PVP) homopolymers and copolymers.

On the THF side, PTMEG is the most important derivative as this supplies the strongly growing spandex fibre industry, however this industry turned round in 2005 due to huge overcapacity and operating rates average at 72 percent.

BDO for PBT is mostly a merchant market with the exception of Western Europe. BDO for GBL market is highly captive. Growth in demand for BDO for THF and GBL will only show modest growth as new investments in BDO, e.g., via Davy technology, will co-produce these intermediates. That is not to say that in countries like China where new investments in acetylene-based processes are underway THF will be made from BDO. Indeed even in the United States in recent years, Penn Chemical closed its furfural THF plants in favor of investing in BDO dehydration.

Global consumption by regions
United States (40%), Western Europe (30%), East Asia (19%), Japan (19%), ROW (2%).

The United States and Europe will remain the largest BDO consuming regions, accounting for 67 percent of the global total of 1.26 million tons in 2015.

In Western Europe the BDO growth rate is about 4 percent per year while in Asia growth will be about 8-9 percent per year. In China the spandex industry is expected to grow at a minimum 10 percent per year and world PBT demand growth is anticipated to be at 7 percent per year.

West European Demand

An estimated 274 500 tons of BDO were consumed in the Western Europe in 2006.

Currently the United Kingdom does not have any major BDO and derivatives facilities. Small amounts are consumed in polyurethanes and speciality polymers. Demand is less than 5 000 tons.

2.20 Tetrahydrofuran

The global THF consumption was around 342 000 tons in 2006 dominated by PTMEG production which accounted for 80 percent of total demand.

THF demand will grow at around 5.5 percent per year to reach approx. 0.55 million tons by 2015. Growth could be higher depending on PTMEG/spandex developments.

Global capacity is around 448 000 tons per year in 2005 with a global average utilization of 72 percent. Operating rates however, are likely to remain at modest levels given major investments, e.g. BASF at Caojing, China, until PTMEG demand catches up with supply.

West European Market
In 2006 the West European demand for THF was around 92 000 tons clearly dominated by PTMEG. The West European market is growing at around 2.7 to 3.4 percent per year.

2.21 Gamma Butyrolactone

The production of N-methyl-2-Pyrrolidone is the main outlet for GBL in the world as a whole and in Europe.

Global consumption amounted to 114 000 tons in 2006.

Uses (global, 2006)
NMP (61%), Other pyrrolidones (16%), Butanediol (8%), Pharmaceuticals (5%), Foundry resins (4%), Herbicides (3%), Others (3%)

West European consumption by End-Use

The size of GBL market in Western Europe will reach around 30 000 tons by the end of this year.

Overall demand growth will be around 4.4 percent per year to 2015 assuming Lyondell goes ahead with its proposed GBL/NMP investment in the 2010/11 timeframe.

2.22 Polytetramethylene Ether glycol (PTMEG)

Polytetramethylene ether glycol (PTMEG), derived from tetrahydrofuran (THF), is a key ingredient in the production of a variety of elastomeric products and is also used in copolyester ether production.
The global consumption of PTMEG in 2006 is amounted to about 276 000 tons.

Uses (global 2006)
Spandex fibres (40%), Thermoplastic polyurethanes (32%), Copolyester ethers (21%), Others (7%)

By 2015 the global PTMEG demand may reach approx. 438 000 tons. This represents a short-term average growth of about 8 percent per year, and about 6 percent over the longer term.

Spandex applications will be the future key PTMEG growth driver. Total spandex production is growing at about 3 percent per year.

PTMEG is found mainly in the advanced economies as it is a performance product. The US dominates global demand, followed by Western Europe.

Global PTMEG Consumption by region (2006)
US (36%), Western Europe (26%), East Asia (24%), Japan (13%), Latin America (1%)

Global PTMEG Production
The world’s total capacity is about 330 000 per year. Nameplate capacity could reach 500 000 tons per year by 2015. DuPont is the largest producer followed by BASF, who has production facilities in each major market.

Global PTMEG Production Capacity by Region (2006)
US (34%), Western Europe (30%), Japan (19%), East Asia (17%)

The average global utilization rate is about 82 percent and will continue to rise.

PTMEG Demand in Western Europe
About 71 700 tons of PTMEG was consumed in Western Europe in 2006. About 58 percent of the total demand was accounted for by thermoplastic polyurethanes and 20 percent was accounted for by spandex.

Demand for PTMEG in Western Europe is forecast to rise to 107 500 tons by 2015 with average annual growth of the order of 4.6 percent.

The market is highly merchant with only DuPont and BASF being the captive consumers of PTMEG.

2.23 Fumaric Acid

Fumaric acid, the trans-isomer of maleic acid, can be produced commercially on-purpose from maleic anhydride or recovered as a by-product of phthalic anhydride manufacture. Technically maleic anhydride is first converted to maleic acid and then isomerised to fumaric acid.

Uses (global 2006)
Food and beverages (40%), Rosin paper sizes, Unsaturated polyester resins and alkyd resins (46%).

Fumaric acid also has a number of smaller volume uses in pharmaceuticals, polymer applications, and also diverse applications like lubricants and adhesives.

Because of its double bond and two carboxylic groups, fumaric acid can be converted to several interesting derivatives comparable to succinic acid: tetrahydrofuran (THF), 1,4-butanediol (BDO), γ-butyrolactone (GBL), L-aspartic acid, L-alanine, and succinic acid.

Global demand for fumaric acid was approx. 130 000 tons in 2006, with Western Europe consuming around 53 000 tons.

Demands for fumaric acid in food, beverages and confections are strong. However, because of its stronger acidity fumaric acid is only used in small quantities and the market cannot grow at the same level as other acidulants such as citric acid or DL-malic acid.

Historical growth rate of fumaric market is about 3 percent per year.

Global Capacity and Competition
The world capacity of fumaric acid is approx. 203 000 per year. Global utilization rate was 64 percent in 2006.

Lonza PI is market leader in the production of fumaric acid (37%), followed by Bartek (25%), SISAS (13%) and other (25%).

2.24 Malic Acid

Malic acid is used as additive in yoghurt, preserving agent in wine and fruit juice, and is also applied in the pharmaceutical industry to produce tablets and syrups.

Uses (global, 2006)
Beverages (51%), Food (42%), Industrial applications (7%)

The global demand for malic acid in 2006 was 55 000 tons. Asia and North America consumed about 72 percent of malic acid, while Europe takes up 19 percent.

In 2006 the global capacity was estimated at about 81 000 tons with an average utilization rate of 68 percent.

2.25 Aspartic Acid

The majority of L-aspartic acid is used in the production of aspartame, a low-calorific sweetener. This acidic amino acid is also used as a nutrition supplement in soft drinks, and as a component in medicines. It can be used as a biochemical agent, and an intermediate in organic synthesis.

The demand growth for aspartic acid has waned in recent years as the demand for its key use aspartame has also declined due to intense competition in the sweetener market.

The global demand growth rate for aspartic acid is therefore expected to be modest, at around 2-3 percent each year. Annual growth in US is expected to be at the lower end of the spectrum, at 2 percent. In Western Europe growth will be slightly higher, at 3.5 percent annually.

However, the global growth rate is expected to be rejuvenated as new aspartic acid-based sweeteners are introduced to the market such as Neotame.

While the food market has traditionally been the main market for aspartic acid, there are promising industrial applications for aspartic acid in the production of biodegradable specialty polymers. These biodegradable polymers could have substantial long-term potential to replace other polymers such as polyacrylic acid and polycarboxylates.

2.26 3-Hydroxy-Butyrolactone

3-Hydroxy-Butyrolactone (3-HBL) is an important C4 intermediate for the production of various high value pharmaceutical products, for example, the anti-obesity drug Orlistat (marketed by Roche as Xenical and by GSK as alli™ over the counter).

It can also be converted to l-carnitine which is a naturally occurring vitamin used to treat several medical problems, and as a food and drink nutritional supplement.

3-HBL can be converted to 3-hydroxy tetrahydrofuran, 3-aminotetrahydrofuran, acrylate lactone and other specialty chemicals.

2.27 Acetoin

The global market for acetoin is circa 12 000 tons and growing at sub-GDP levels except in China. The market is now centred on the Far East.

Acetoin is mainly used as food flavouring agent and a fragrance.

Acetoin can find applications in many food products such as baked goods, breakfast cereals, candy, cottage cheese, margarine, dairy desserts, and puddings. However, it is largely used in butter.

Global supply is highly fragmented. The leading supplier is BASF in the West, but capacity is proprietary. In China there are at least five producers exploiting biotransformation chemistry for acetoin production. These companies include Puyang Organics and Shanghai Kaixin.

2.28 Threonine

Threonine is an essential amino acid that promotes normal growth by helping to maintain the proper protein balance in the body.

Threonine has a global market of around 45 000 tons mainly serving the animal feed industry. Strong growth is forecast at around 4.5 percent per year.

Major producers include Degussa (now Evonik), Ajinomoto, and ADM.

Current pricing of threonine is $50 per kilo for pharmaceutical use and $9.8 per kilo for animal feed use.

Europe has a market of 18 000 tons but growth is in line with average GDP. The UK has an estimated market of around 3500 tons.

2.29 Methacrylic Acid / Methyl Methacrylate

Methacrylic acid (MAA) and its esters (methacrylates) are mainly used as monomers or comonomers in a variety of polymers with a broad spectrum of applications.

Uses (global, 2006)
Acrylic sheet (35%), Surface coating (20%), Molding compounds (19%), Impact modifiers (12%), Emulsion polymers (7%), Mineral filled sheet (5%), Others (2%)

Global MMA demand is estimated at 2.75 million tons in 2006. The market average annual growth rate was above 5 percent within the last 10 years and growth has been about 6.5 percent in the last 5 years with Asia demand growing at 10 percent in this period.

Methacrylic esters, with methyl methacrylate (MMA) being the most important product, can be made into acrylic sheets and molding resins which find commercial applications in signs, displays, glazing compounds, lighting fixtures, building panels, automotive components, plumbing fixtures, and appliances.

Salts of poly(methacrylic acid) can serve as basis for water-soluble thickeners and detergent additives. Other higher methacrylate polymers are useful in the manufacture of oil additives, inks and coatings, and binders for xerography.

The largest application is in the production of transparent extruded PMMA sheets, which are sold widely under various trade names such as Plexi-glass. The production of these sheets is a mature commodity business with relatively low margins, and is restricted to large scale operators, often the MMA producers themselves.

Demand is evenly spread between the major regions.

Europe (30%), North America (29%), East Asia/Oceania (21%), Japan (17%), Latin America (2%), Other (1%)

Main markets in the West are more mature (coatings, glazing, molding compounds for automotive applications), and demand in the west will therefore grow more slowly than in Asia.

Demand growth in Asia as a whole is projected to be around 7-8 percent per year for the period 2005-2008.

European MMA Market
The European MMA market has grown by 5 percent per year in average for the last 5 years with key drivers being in the applications for the construction industry.

There has been no expansion in Europe since 2003 due to historical overcapacity in the region. The MMA industry in Europe is operating at an utilization rate of above 95 percent.

The UK is a major MMA market with Lucite, one of the leading global producers, operating a major complex near Teesside based on the acetone cyanohydrin process. The company also has a number of PMMA production sites including Darwin in Lancashire.

Major Players in the Methylmethacrylate Business
MMA is produced by comparatively few producers worldwide. Total capacity amounts to 3.1 million tons.

Lucite (24%), Degussa (15%), R&H (15%), Mitsubishi Rayon (9%), Arkema (6%), Asahi (5%), Others (26%)

2.30 Polyhydroxyalkanoates

Polyhydroxyalkanoates (PHAs) are a family of natural polymers that can be produced via fermentation from sugar or lipids. PHAs can be combined with other polymers, enzymes, or inorganics to produce copolymers of different properties, e.g. thermoplastics or elastomers. The applications of PHAs therefore can go from blow-molded products such as shampoo bottles or disposable trays, to elastomeric materials that can be used for hot melt adhesives or pressure sensitive adhesives.

Other potential uses of PHAs are non-woven fabrics, films and fibres, and latex coatings. They can also serve as the basis for some specialty chemicals such as solvents, polyurethane intermediates and sufactant precursors.

PHAs are highly desirable materials due to their biodegradability and independence from petrochemicals.

Bio-based PHAs are currently widely applied in the medical and pharmaceutical industries due to their biodegradability, but offered at very high prices. More commercial processes will be coming on stream to produce PHAs for use as packaging material and molded goods.

Market Dynamics
Every year the consumption of polymers having similar properties to PHAs amounts to approximately 13.6 million tons.

Because the costs of production of PHAs are still too high for them to become competitive with commodity plastic materials, the use of PHAs has been limited to medical applications.

It is expected (by some companies) that the biodegradable packaging material market will grow at about 20 percent per year.

On the supply side, ADM will build a 50 000 tons per year PHA plant in Clinton, Iowa in a joint venture with Metabolix. The plant will produce bioplastics that can find applications in coated paper, film, and molded goods.

This year P&G has sold the rights to its PHA technology to Meredian. Meredian plans to start the construction of a 272 000 tons PHA plant in 2008 in Clinton, Iowa to supply for the packaging market.

In Japan, Kaneka is working on a type of PHA called PHBH.

2.31 Itaconic Acid

Itaconic acid is consumed in the manufacture of synthetic latexes where its function is to improve emulsion stability and adhesion. It is also used in polymeric fibre blends to add toughness and abrasion resistance.

The global demand for itaconic acid is estimated at about 10 000 – 15 000 tons per year.

Itaconic acid is also used as comonomer in resins and in the manufacture of synthetic fibres, coatings, adhesives, thickeners and binders. The paper-coating and carpet-backing industries are the primary users of the acid.

Itaconic acid may also serve as a substitute for petrochemical-based acrylic or methacrylic acid.
Some other itaconic acid derivatives are used in medicine, cosmetics, lubricants, and herbicides. Polyitaconic acid is a superabsorbent.

The production of itaconic acid from petroleum is expensive therefore its use has been limited by high market price.

Itaconic acid can be fermented from starch derived glucose and sucrose. The fermentative production route offers potential for a lower cost route and use could be expanded in plastics and paints for the housing and automotive sectors.

2.32 Furfural

The majority of world furfural production is used in the production of furfuryl alcohol, which accounts for 60-70 percent of total furfural output. World production of furfuryl alcohol is approx. 120-180 thousand tons per year, with China representing about half of the total production.

Other uses of furfural are:
- Extractant for aromatics in the refining of lubricating oils, diesel fuels and vegetable oils.
- Purification solvent for C4 and C5 hydrocarbons
- Reactive solvent and wetting agent
- Nematicide and fungicide
- Furfural can replace other pesticides that have more harmful effect on the environment.

Furfural is also an important chemical for the production of a number of derivatives including furan, tetrahydrofurfuryl alcohol, furfurylamine, tetrahydrofurfurylamine and furoic acid.

Furfural Supply and Demand
The global annual demand for furfural is estimated at about 200 000 - 210 000 tons, with furfuryl alcohol consuming about 120 000 - 130 000 tons per year.

Currently there are several significant product applications of furfural under development which could double or triple the current world demand for furfural by 2012. These applications include agrochemicals, clean fuels/biofuels, timber treatment, and PLA performance plastics.

The world largest single producer is Central Romana Corporation with their 35 000 tons per year in the Dominican Republic which operates at near 100 percent capacity.

2.33 Levulinic Acid

Levulinic acid is applied in the manufacture of nylons, synthetic rubbers, plastics and pharmaceuticals. It is also used to produce other industrial commodity chemicals such as methyltetrahydrofuran (MTHF), valerolactone, and levulinate esters. The end use applications of levulinic acid could range from fuel oxygenates, solvents, flavouring agents to polymers, plasticizers and herbicides etc.

Levulinic acid is also consumed in cigarettes to increase nicotine delivery and bind nicotine to neural receptors.

The production of levulinic acid is expensive; hence it is currently a relatively small market specialty chemical.

The Le Calorie plant built in 2006 in Caserta, Italy is the world's first commercial levulinic acid plant. This facility is expected to produce 3 000 tons per year of levulinic acid.

Levulinic acid is one of the top twelve value added chemicals from biomass (hemicellulose) identified by US DOE and its potential is still to be further exploited.

2.34 Glutamic Acid

Glutamic acid is used the medical/pharmaceutical industries, food industry and chemical synthesis.

Glutamic acid is also consumed as a chemical intermediate to manufacture amino acid compounds which are converted to drugs, polymers and other chemical products.

The global demand for glutamic acid is about 1.7 million tons per year with demand from China taking up aprox. 1.1 million tons per year. The demand for monosodium glutamate (MSG) is about 1.2 million tons and China MSG demand is about 0.5 million tons.

2.35 Xylose and Derivatives

Xylose has a number of medical uses and industrial uses. In veterinary applications, xylose is used in malabsorption tests.

In industrial applications, xylose is used to produce a number of derivatives such as furfural, 1,2,4-butanetriol, xylitol, xylaric and xylonic acid, polyesters, ethylene and propylene glycol, levulinic acid, and other fermentation products.

Xylitol is an important outlet of xylose as it is a popular sweetener for the food and pharmaceutical industries.

Xylitol is currently produced on an industrial scale from wood sources such as white birches; however production costs are still high and there are environmental impacts associated with the use of wood resources.

Advanced development in the microbial route for xylitol production could yield a lower production cost process with higher profitability.

The market for xylitol is estimated to be about $US 144.6 million in 2006 and is growing at over 8 percent per year. Key drivers for growth are increased use of xylitol in dental care and diabetic products as consumers become more conscious about health and weight.

In 2007 xylose supply is poor because of the new environmental regulations introduced by the Chinese government regarding xylose production plant effluent limits. Xylose production is water intensive; therefore the producers have to operate below their maximum capacity to be able to meet the new wastewater directive.

2.36 Citric Acid

Citric acid is primarily used as a flavouring and preservative agent in food and beverages, especially in soft drinks.

Uses (global 2006)
Beverages (50%), Food (18%), Detergent and soaps (17%), Pharmaceuticals and cosmetics (8%), Industrial uses (7%)

The global demand for citric acid is 1.3-1.4 million tons in 2005.

The global average annual growth rate in the 2001-2005 period was around 3.5-4.5 percent with China around 6-7 percent.

Chinese plants supply 50 percent of world citric acid market, whereas both the US and Europe account for approximately 18 percent of total world supply each. The three regions account for a combined 65-70 percent of global consumption.

Citric acid market continues to feel pressure from high production costs and intense competition from Chinese producers.

In the United Kingdom, Tate & Lyle closed its 25 000 tons citric acid plant in Selby, Yorkshire in March this year due to continuing price pressures and market overcapacity.

2.37 Methionine and Lysine

Methionine, lysine and threonine are three of the four major amino acids in animal feeds. The remaining amino acid is tryptophan.

Methionine and lysine have been produced on a commercial scale and been dominant in the amino acids market for several years. Threonine and tryptophan are not yet produced on a large scale but are experiencing high growth.

Methionine Supply and Demand
Over 90 percent of methionine and lysine demand is for poultry feed alone, the remainder for swine and cows.

Population growth and increasing consumption of meat products are the key drivers of demand.

Global Methionine Demand
Methionine global consumption reached 600 000 tons in 2006 (CAGR 02-06: 7 percent). 2006-12 CAGR is expected to be 5 percent.

The Chinese market is the major growth area. It is anticipated to grow at a compound annual growth rate of 7 percent, increasing its share of the global market demand to ~15 percent by 2012.

European demand is circa 120 000 tons and met by local supply, mainly Adisseo and Evonik (ex Degussa). United Kingdom demand is circa 25 000 tons.

Global Methionine Supply/Demand Balance
Global capacity in 2006 reached 783 000 tons with utilization rate of 77 percent. This low utilization rates seen between 2005-2007 were due to over 150 000 tons per year capacity addition during this period. Operating rates are expected to increase to 96 percent in 2012 as demand catches up with capacity additions.

The methionine market is dominated by 3 major players.
Evonik (Degussa) (30%), Novus (29%), China Bluestar (23%), Sumitomo (11%), Nippon Sod (4%), Orgsynthese (3%)

Global Lysine Supply
China accounts for the largest share of the world's lysine demand, about 20 percent, followed the US with 17 percent. China is also the largest lysine producer with about 35 percent of the world total supply.

World lysine consumption is forecast to grow at an average annual rate of 5-5.7 percent in the 2005-2010 period.

Global Bio-Chem Technology Group in China is the world's largest lysine manufacturers with a 100 000 tons lysine plant (75 000 tons expansion in 2005) and a 140 000 tons per year protein lysine (65-70 percent concentration) plant.

2.38 Glucaric Acid

Glucaric acid is used to make calcium D-glucarate for use as a health supplement.

Glucarate esters are also used in coatings, particularly those which are water soluble. Dow Halterman produces glucarate esters.

Glucaric acid is produced in very small quantities as a by-product from adipic acid production. Invista at Wilton produces a concentrate of succinic acid and glucaric acid. Dow Haltermann buys this stream, purifies it and makes esters.

2.39 Sorbitol

Sorbitol is also known as D-glucitol and is predominantly used in the personal care and food and beverage industries.

Uses (global, 2006)
Personal care (36%), Food (31%), Vitamin C (13%), Detergents (10%), Pharmaceuticals (7%), Other (3%)

Total demand amounted to 1.1 million tons in 2006.

Western Europe Sorbitol Market
Demand for sorbitol in Western Europe is about 334 000 tons per year in 2006, with an average growth rate of 4.2 percent per year in the 2005-2010 period. This growth rate in Western Europe and in the US is higher than the global average due to increased consumer demand for lower calorie and non-carbohydrate sweet products. The Western Europe total demand may reach 394 000 tons in 2010.

Western Europe exports considerable quantities of sorbitol to all regions. Operating rates are relatively high, about 91 percent in 2005, although it is difficult to account for production in multipurpose complexes.

2.40 Adipic Acid

The major use of adipic acid is to produce nylon-6,6. The market for nylon-6,6 is predominantly in fibres and engineering resins.

Uses (global 2006)
Nylon 6,6 resin (32%), Nylon 6,6 fibre (26%), Polyester polyols (25%), Platiciser (5%), Other (12%)

In many of its applications nylon 6,6 is in competition with nylon 6, which is made from caprolactam. However, nylon 6,6 has some distinctive properties such as higher temperature resistance and higher strength that permit it to retain a share of higher value application in spite of its higher cost.

The global adipic acid market was approx. 2.57 million tons in 2006. The consumption of adipic acid in the developed countries accounts for about 76 percent of the global market.

The global average growth rate is forecast to be around 6 percent per year to 2010 with Asia Pacific growing at 12 percent per year.

Western Europe Adipic Acid Demand
Western Europe total demand for adipic acid is projected to increase from 856 000 tons in 2006 to 915 000 tons in 2010.

Growth is forecast at around 4.2 percent per year rate in the 2007-2010 period.

2.41 Isopropanol

Apart from some specialised intermediate applications, isopropanol (IPA) is used principally as an oxygenated solvent and mainly consumed in the printing inks and coatings sectors. These two sectors together account for 50 percent of total global demand.

Uses (global 2006)
Chemicals (27%), Printing Inks (25%), Coatings (19%), Solvent (13%), Other (16%)

The global IPA market was around 2.1 million tons in 2006 dominated by the coatings and printing inks sectors. The business remains focused in developed economies, but China is becoming an important growth market.

Looking ahead the global market is growing at 2.5 percent per year on average, i.e., below average GDP.

The IPA market is highly concentrated with the four top producers holding 75 percent of market share.

West European Isopropanol Demand
The IPA market in Western Europe reached approx. 611 000 tons in 2006. Looking ahead the average annual demand growth will be of the order of 1.8 percent.

Historically the operating rate for isopropanol production has been severely dependent on acetone. This has led to large fluctuations in supply and demand. Recent plant closures should help to raise operating rates, but the market will remain a structural importer.

Both types of processes require that the isopropyl alcohol to be separated from water and other by-products by azeotropic distillation.

3 Screening Analysis

3.1 Introduction

Nexant has applied a screening methodology to identify the key candidates for further examination.

Nexant has considered each of the target 48 products from a commercial perspective, covering:

- The market opportunity in the United Kingdom
- The market opportunity in Europe
- The global market opportunity
- Industry profitability
- Competitive intensity
- The need or otherwise for partnerships
- The opportunity for downstream developments.

In addition each target product has been examined from a technical perspective, covering:

- Commercial experience in product technology licensing
- Likely level of capital investment
- Is a worldscale plant feasible?
- Complexity of the process
- Ability to license technology
- Environmental aspects.

Each of the above the factors is provided with a weighting. Each product is scored against specific criteria, which when multiplied by the weighting factor provides a market-screening score and a technical feasibility score.

3.2 Screening Results

The weighting approach used for the target 48 products has been applied by Nexant is several similar situations (Figure 1). Market factors, for example, use hard numbers related to growth with respect to GDP. Softer issues are measured and scored in a more subjective manner. Technical screening also combines harder directly quantifiable factors and softer more judgment-based factors.

The normalised screening factor totals are provided (Table 2). These figures are expressed in matrix form (Figure 2). The target products of interest appear in the top right sector of the figure with highest normalised scores in respect of market attractiveness and technical feasibility.

Figure 1 Screening Process Diagram

Configuration No				1
Option Description	Ethylene ex Ethanol based first and second generation processes			
Plants	Bioethanol plant integrated with bio-ethylene			
Market Attractiveness		**Weight**	**Score**	**Rank**
Local Market	1.8 million tons in 2006. Growth will remains flat over next 5 years. Currently export 1 million tons per year but will export less after LDPE plant start up in 2008.	20%	50%	10%
European Market	21.8 million tons in 2006 growing at 0.5 percent over next 5 years Europe is net exporter of almost al derivatives except LDPE.	15%	50%	8%
Global Market	109 million tons in 2006, growth in line with economic activities, at 4.5 percent per year. Asia is growing the most rapidly. Trade is limited due to high freight cost.	10%	75%	8%
Profitability	Return on investment about 12-14 percent. Profitability reduces due to new Middle East capacity. Returns are not sufficient for new investment unless there is integration or cash cost advantage.	25%	25%	6%
Competitive Intensity	Four major producers control the market who also have with different downstream activities. Merchant market is non-existent.	10%	50%	5%
Partnerships	No entry barrier as long as new entrants also have downstream porfolio. Possible to enter on biomass platform but projects still need to include a derivative.	10%	75%	8%
Downstream Developments	Growth in UK is limited for ethylene. Potential market for 'green' olefin derivatives provided suitable legislation is in place.	10%	100%	10%
Market Attractiveness Score		**100%**		**54%**
Technology Attractiveness				
Commercial Experience	Major commodity petrochemical, well-known technology. Large number of commercial-scale plants worldwide Two biomass plants (200 and 350 ktons) coming on line in 2011 in Brazil. No fermentation route from ethanol to ethylene	20%	100%	20%
Capital Investment	A 775 kton greenfield NGLs or Naphtha steam cracker costs € 1 billion. € 600 million if using ethane feedstock. Dow and Crystalsev's 350 kton biomass plant requires $US 1 billion capital investment	25%	100%	25%
World-scale Plant	Large number of world-scale plant existing. New major investment is a 1.3 million ton ethane to ethylene plant in Saudi Arabia in 20 Require 200 000 hectares for wheat plantation for a 300 kton biomass to ethylene plant in the UK	20%	100%	20%
Complexity	Fermentation of wheat to ethanol is a well-established process Wheat to ethylene is a simple 2 step process (fermentation and dehydration) with 99+% yield	5%	75%	4%
Technology Access	Technology is available from a number of providers, e.g. SABIC, Chematur (Sweden).	25%	75%	19%
Environmental	Ethylene production from coal emits significant amount of CO2 No significant environmental risk from the biomass process (however ethanol and ethylene form explosive mixtures with air).	5%	75%	4%
Technology Attractiveness Score		**100%**		**91%**

Case	Market Score	Technology Score
1	54	91
2	74	85
3	43	91
4	68	85
5	45	85
6	49	79
7	43	83
8	60	73
9	58	46
10	54	60
11	63	68
12	58	66
13	58	50
14	80	70

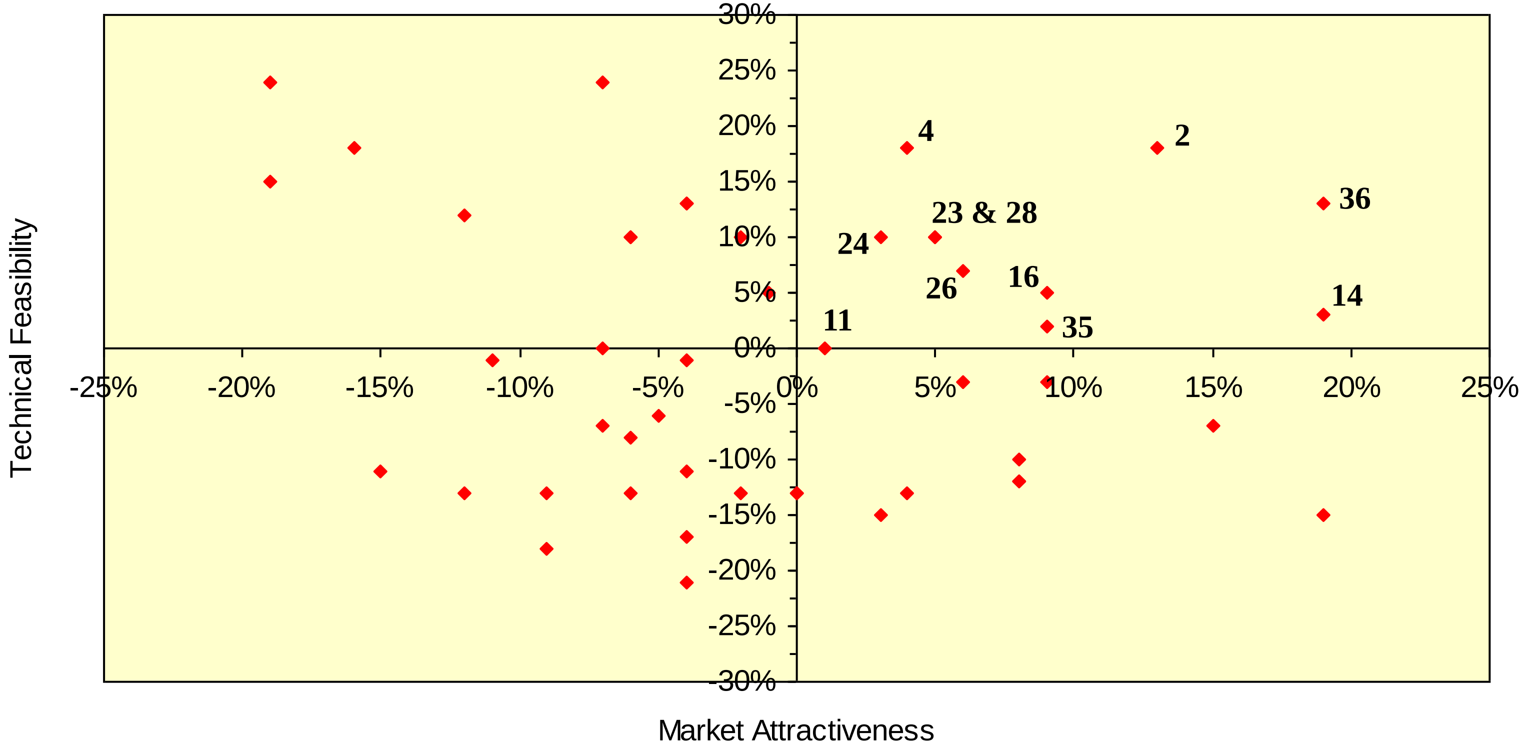
Normalised Market Score	Normalised Technology Score
-7	24
13	18
-19	24
4	18
-16	18
-12	12
-19	15
-1	5
-4	-21
-7	-7
1	0
-4	-1
-4	-17
19	3

Table 2 Screening Process - Results for All Target Products

	Normalised Scores			Normalised Scores			Normalised Scores	
	Market Attractiveness	Technical Feasibility		Market Attractiveness	Technical Feasibility		Market Attractiveness	Technical Feasibility
1 Ethylene ex ethanol	-0.07	0.24	17 Acrylic acid ex glucose via 3-HPA	-0.04	0.13	33 Acetoin	-0.09	-0.13
2 LLDPE ex bio-ethylene	0.13	0.18	18 Acrylamide ex glucose via 3-HPA	0.15	-0.07	34 Threonine	0.19	-0.15
3 LLDE ex bio-ethylene	-0.19	0.24	19 Malonic Acid ex glucose via PDO	-0.11	-0.01	35 MMA - Plants as Plants	0.09	0.02
4 HDPE ex bio-ethylene	0.04	0.18	20 Isoprene monomer ex-glucose	-0.06	-0.08	36 Polyhydroxyalkanoates	0.19	0.13
5 EO/MEG ex bio-ethylene	-0.16	0.18	21 Succinic Acid ex-glucose	0.08	-0.1	37 Itaconic Acid	-0.02	-0.13
6 Alpha Olefins ex bio-ethylene	-0.12	0.12	22 BDO ex glucose via Succinic Acid	-0.06	0.1	38 Furfural (THF intermediate)	-0.06	-0.13
7 VCM/PVC ex bio-ethylene	-0.19	0.15	23 THF ex glucose via Succinic Acid	0.05	0.1	39 Levulinic Acid	0.04	-0.13
8 Biobutanol/acetone	-0.01	0.05	24 GBL ex glucose via Succinic Acid	0.03	0.1	40 Glutamic acid	-0.12	-0.13
9 Cyclohexanone ex Lysine	-0.04	-0.21	25 PTMEG ex Bio-THF	0.09	-0.03	41 Xylose and derivatives	0	-0.13
10 1,3-propanediol/PTT ex glycerine	-0.07	-0.07	26 Fumaric Acid ex-glucose	0.06	0.07	42 Citric Acid	-0.07	0
11 Propylene glycol ex glycerine	0.01	0	27 BDO ex glucose via Fumaric Acid	-0.06	0.1	43 Lysine	0.08	-0.12
12 Acrylic acid ex glycerine	-0.04	-0.01	28 THF ex glucose via Fumaric Acid	0.05	0.1	44 Methionine	0.08	-0.12
13 Acrylic acid ex lactic acid	-0.04	-0.17	29 GBL ex glucose via Fumaric Acid	-0.02	0.1	45 Glucaric acid	-0.05	-0.06
14 Lactic acid/polylactide ex glucose	0.19	0.03	30 Malic Acid ex glucose via Succinic Acid	0.03	-0.15	46 Sorbitol	-0.04	0.13
15 Lactate esters ex glucose	0.06	-0.03	31 Aspartic acid	-0.09	-0.18	47 Adipic Acid	-0.04	-0.11
16 3-Hydroxypropionic acid ex glucose	0.09	0.05	32 3-Hydroxy-butyrolactone	0	-0.13	48 Isopropanol.	-0.15	-0.11

Figure 2 Screening Matrix Diagram

(normalised scale)



The 11 chemical process streams identified as top performers within the target list, with respect to market and technical attractiveness for the UK, are listed below.

1. Propylene glycol produced from glycerine
2. γ -butyrolactone (GBL) produced from glucose via succinic acid
3. Linear low density polyethylene (LLDPE) from bioethanol-derived ethylene
4. High density polyethylene (HDPE) produced from bioethanol-derived ethylene
5. Tetrahydrofuran(THF) from glucose via succinic acid
6. THF from glucose via fumaric acid
7. Fumaric acid from glucose
8. 3-hydroxypropionic acid (3-HP) from glucose
9. Methyl methacrylate (MMA) using a 'Plants as Plants' approach
10. Polyhydroxyalkanoates using a 'Plants as Plants' approach
11. Lactic acid from glucose and conversion to polylactide

The most attractive products can be grouped for further review in light of potential future R&D activities. These groups are:

1. Bio-ethylene with a combined LLDPE or HDPE facility
2. Integrated fumaric acid (succinic acid) with butanediol/THF and GBL
3. 3-Hydroxypropionic acid and acrylic acid prodcution
4. Biopolymers
5. Propylene glycol
6. Methyl methacrylate and polyhydroxyalkanoates via the Metabolix "Plants as Plants" approach

Each application has its own merits in serving the development of biotechnology in the United Kingdom. At this stage both acrylic acid and biopolymers are worth more detailed analysis within limits of confidentiality given Nexant current activities with other clients.

After consultation with the NNFCC, four of the top performers from a commercial and technical standpoint were taken forward for more detailed examination. The scope of the phase two analysis is comprehensive, covering market, pricing, technology and development opportunities.

The analysis covers market opportunity in the United Kingdom and export potential including: market structure; dynamics and future supply; market segmentation and demand growth; identification of potential customers and specification needs. Cost competitiveness versus existing petrochemical-based producers is considered for low, medium and high cases subject to Nexant ranges:

High oil scenario:	Average \$65.6 per barrel (2008-2030)
Medium oil scenario:	Average \$45.6 per barrel (2008-2030)
Low oil scenario:	Average \$29.8 per barrel (2008-2030)

The analysis looks at product pricing and drivers and gives technology description and configuration of a suitable complex.

Initial development roadmaps are introduced including: partnership identification and requirements; initial concepts for supportive legislative frameworks and potential preliminary commercialisation strategy.

4 Green Polyethylene Derived from Bioethanol

4.1 Linear Low Density Polyethylene (LLDPE)

4.1.1 LLDPE trade in the UK

Ineos owns the UK's only LLDPE manufacturing plant in Grangemouth which has a nameplate capacity of 320 000 tons per year, representing 10 percent of total Western Europe capacity.

Ineos manufactures hexene-1 based grades. Such grades are more sophisticated products for mainly non-commodity applications. C6-LLDPE films perform much better than C4-based films for example.

The commodity LLDPE market requires mainly C4-LLDPE grades and these are imported. Ineos manufactures C4 grades in Germany and imports them to UK customers. SABIC too imports from Saudi Arabia into the UK.

All high performance C8-LLDPE grades are imported from Dow in the Netherlands and Spain.

4.1.2 Supply/Demand Trade Balance

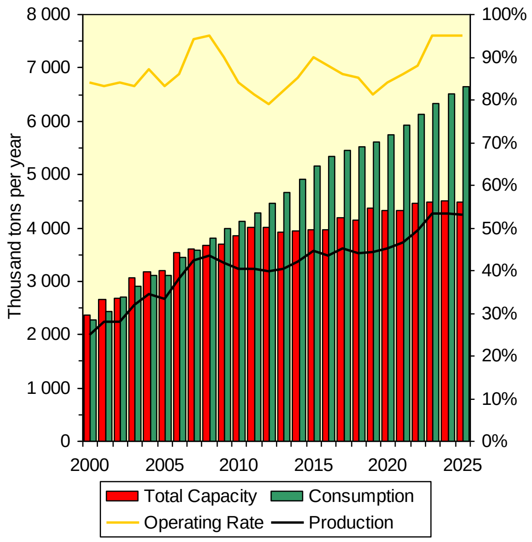
Western Europe is set to become an increasingly large importer of LLDPE as a result of fairly static domestic production capacity and large-scale developments in the Middle East. In the near term however, strong consumption growth in 2006/07 after a slow 2005 will keep markets tight and lead to high average operating rates (Figure 3).

The impact on Western Europe of new LLDPE and HDPE capacity in the Middle East and Asia between 2008 and 2010 will be dramatic and unprecedented. Production is expected to decline taking operating rates down to the mid-80 percents and production capacity will be rationalised. Some swing to HDPE is anticipated but Western Europe will bear much of the impact of the massive capacity build, importing nearly one million tons per year by 2010 and one and a half million by 2015.

In the longer term, West European producers are expected to maintain fairly high operating rates, benefiting from the regions net import status as demand continues to grow strongly. West European producers are likely to further develop higher value added grades to avoid competition with low cost Middle Eastern commodity grades.

Figure 3 LLDPE Supply, Demand, Trade Balance in WE

(Thousand tons per year)



4.1.3 Prices in Western Europe

LLDPE price presented here are based on the annual average spot markets prices for butene-1 commodity grade resin on a delivered North-West Europe basis.

LLDPE prices in Western Europe are generally set by free negotiation between the major producers and convertors. Prices will settle at a balance between the value of the resin to convertors on the demand side, and the costs of production on the supply side.

Major producers with a strong influence in negotiating LLDPE prices include Dow, Borealis and Polimeri Europa.

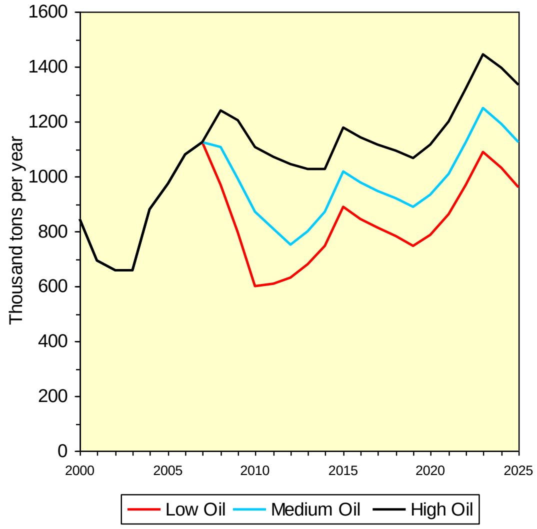
LLDPE prices are forecast by balancing the projected production costs (dominated by ethylene monomer feedstock cost), and projected margins against the need for continued competitiveness with other grades (most notably LDPE) and supply in other regional markets (Figure 4).

The following issues are typically some of the most important drivers of pricing settlements:

- Production economics for LLDPE (most notably ethylene feedstock costs)
- The price of competing polymers (most notably LDPE)
- The supply/demand balance for LLDPE
- Prices for LLDPE in other regions, and projected trade flows
- Profitability of upstream steam crackers
- Profitability of convertors and plastics processors

Figure 4 LLDPE Prices in Western Europe

(current US dollars per ton)



4.1.4 Partnership Identification and Requirements

The successful development of a world scale polyethylene business in the UK requires four key elements to be in place:

- competitive ethylene feedstock
- an effective route to the (local) polyethylene market
- access to competitive polyethylene technology
- finance for the project.

These elements can be provided by the PE producers or by partners, which may or may not take an active role in the project.

Based upon the key requirements above, it can be seen that there are a number of different types of partner: feedstock partner, technology licensor, marketing partner, and equity investor.

The LLDPE market is concentrated in the film sector and is continuing to penetrate traditional LDPE applications.

To successfully compete against the only LLDPE producer in the UK, Ineos, and to achieve the level of exports that would be required to sell out a world scale plant, it is likely that a marketing partner would be needed to help market access within the UK and Europe.

A differentiated LLDPE strategy concentrating on high alpha olefin grades may provide an advantage. This will achieve higher added value, and enable a new entrant to avoid competing directly against the commodity C4 grades entering Western Europe from the Middle East.

A differentiated strategy however requires additional support from the licensing/marketing partner to provide the level of technical service expected, and to access a much more widely spread market.

4.2 High Density Polyethylene (HDPE)

4.2.1 HDPE trade in the UK

The UK is now a net importer of HDPE as the product is no longer manufactured here since Ineos closed its facility in Grangemouth.

The UK imports approx. 500 000 tons of HDPE per year, mainly from Belgium and the Netherlands. Whilst European countries supply the UK market, substantial volumes are imported from Saudi Arabia as well as finished products from China.

Future consumption is expected to follow regional trends, growing at a rate of about 2 percent per year.

With the Ineos closure, the UK's imports of HDPE will significantly increase in 2008. Imports could reach 790 000 tons by 2015.

4.2.2 HDPE Capacity in WE

Total HDPE nameplate capacity in WE was 4.783 million tons in 2006 and is expected to slightly reduce to 4.745 million tons by 2015 due to plant closure and limited capacity additions.

Basell will replace the HDPE facility at Munchsmunster that exploded at the end of 2005. The new plant will have a capacity of 150 000 tons per year, planned to start-up in 2009. To ensure adequate ethylene supply for the plant, Basell has acquired Ruhr Oel's cracker in Munchsmunster.

Borealis' 108 000 tons per year facility at Bamble closed at the end of October 2006 as a result of increased competition.

SABIC Europe is to build a new 250 000 tons per year HDPE unit at Gelsenkirchen, with start-up expected at the end of 2008. One of the two currently operating lines at Gelsenkirchen will close once this new unit comes onstream.

Ineos closed its 185 000 tons per year HDPE plant at Grangemouth, UK by the end of 2007 due to poor economic conditions. However, HDPE capacity at Lillo, Antwerp will be increased by 200 000 tons per year in 2009.

Capacity additions in Western Europe are expected to be moderate, limited by feedstock availability, and the more attractive investment opportunities in areas with lower labour and/or feedstock costs. Investment is expected to focus on improving competitiveness rather than expansion. Capacity increases will be limited by the options for economical expansions of olefins production.

4.2.3 HDPE Supply/Demand Trade Balance

HDPE net trade remained low in 2007 as a result of high global operating rates, allowing WE to be more or less self-sufficient in HDPE. WE imports commodity HDPE from the Middle East and exports higher value added grades to Asia.

In the medium term, the region is expected to become a major net importer, primarily from the Middle East.

4.2.4 HDPE Price Basis and Valuation Mechanisms

HDPE is the strongest grade of polyethylene, enabling its use in a more diverse range of applications than the film applications that dominate consumption of other grades. Many alternative grades of HDPE resin are sold, with different additives included in the resin mix to optimise resin properties to the requirements of specific end use sectors.

In Western Europe, most HDPE prices are settled by free negotiation between major producers and convertors. The biggest producers in the European market, with strong influence in setting prices include INEOS, Total Petrochemicals and Basell.

Factors that are frequently included in the negotiation of price settlements include:

- production economics for HDPE (most notably ethylene feedstock costs)
- the price of competing polymers (most notably polypropylene, and LLDPE)
- the supply/demand balance for HDPE
- prices for HDPE in other regions, and projected trade flows
- profitability of upstream steam crackers
- profitability of convertors and plastics processors.

HDPE competes with several other polymers in its different end use applications. In many blow moulding and injection moulding applications, HDPE competes directly with polypropylene, with convertors readily able to switch resin to the lowest cost alternative. In the pipe sector, HDPE typically competes with PVC. In the film sector, HDPE competes with other grades of polyethylene films, such as high strength bags and liners. Inter-product competition in sectors where consumers can openly substitute products maintains a close link between HDPE and other polymer prices.

HDPE prices have been forecast by balancing the projected production costs (dominated by ethylene monomer feedstock cost), and projected margins against the need for continued competitiveness with other polymers (including polypropylene, PVC and LLDPE) and supply in other regional markets.

Price forecasts used in this report are the annual averages of injection moulding resin and blow moulding resin traded in spot markets for material delivered into North-West Europe.

4.2.5 HDPE Prices in Western Europe

HDPE (blow moulding) resin has generally traded at a modest premium to injection moulding grade resin. Over the last two decades, the premium has varied between zero and 30 percent, averaging almost seven percent. Projections assume that HDPE blow moulding grade will continue to maintain a steady premium consistent with the historic average.

4.2.6 HDPE Partnership Identification and Requirements

The HDPE market is fragmented, with consumption into a wide variety of end uses (including injection and blow moulding, film, fibre, extrusion, sheet etc.).

To be able to enter this market, a new player will need know how to produce a variety of grades, as well as how to access the market. Here a technology licensor/marketing partner is essential, and the strengths of the specific technology partner chosen will define the grades of product and markets to be targeted.

The addition of a financing partner or the inclusion of financing in the marketing and licensing agreement will provide some commitment to the project, and provide some security to the new LLDPE plant investment.

In view of the current consolidation within the West European polyolefin sector, an equity involvement from current producers is unlikely in Nexant's view. The majority of players within Europe have existing capacity either in the UK or within the Antwerp region with easy access to the UK. Thus an equity holding in an additional facility within the local region is unlikely to fit with current strategies. It however opens the opportunity for investment from equity partners from outside of Europe or from outside of the industry.

Recent trends indicate an increasing involvement within the industry of the private equity sector, where capital can be available for company spin-offs and large investments. For example, the purchase of Vestolit and Vinnolit by Candover/Harris and Advent respectively in 2000.

It is useful to compare the developments within the polystyrene and PVC industries to illustrate the possibilities that could open up in polyolefins. However, in most cases, total assets have been purchased with a view to sale in the not-too-distant future.

4.3 Green ethylene, polyethylene, alpha olefins and polypropylene

Green Ethylene Production

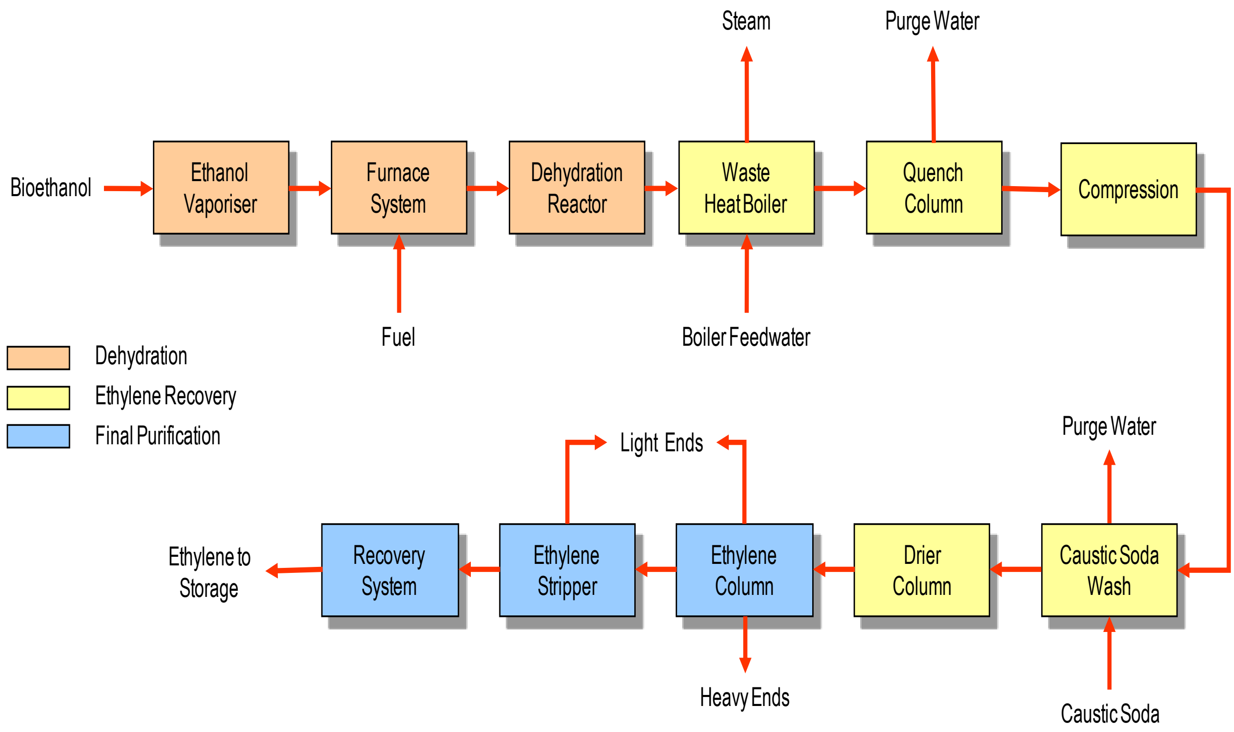
The process for bioethanol conversion is already in commercial operation in India. Dow Chemical and Braskem are looking to build bio-ethylene complexes in Brazil, where favourable bioethanol pricing could be sufficiently low to support such an investment opportunity.

The process is available for license from Chematur Engineering in Sweden and Nexant understands that Scientific Design too has some rights to licensing the process in specific situations.

The process itself employs the catalytic dehydration of ethanol followed by a recovery and purification chain (Figure 5). The process is energy intensive and requires considerable investment in waste water treatment, given the conversion of ethanol into ethylene and water.

The process can be designed to produce either chemical or polymerisation grade ethylene.

Figure 5 Bio-ethylene manufacture process flow diagram



4.3.1 Alpha Olefins and Polyolefins

Subject to the cost competitiveness of bioethylene production, it should be possible to develop a new polyolefin and comonomer complex in the UK. At this stage of commercial development the concept may appear a little far-fetched, but all the processes considered in converting ethanol to polyethylene are in commercial operation today.

Butene-1 and hexene-1 comonomers are produced from ethylene today where favourable economic conditions prevail, e.g., in the Middle East. Octene-1 from ethylene via tetramerisation is still developmental, however a full range alpha olefins plant could provide the octene-1 required for solution polyethylene processes like DOWLEX®, COMPACT® and SCLAIRECH®.

In addition it is possible to convert ethylene into butene-1 and then via hydroisomerisation into butene-2. The TRIOLEFINS® process will convert ethylene and butene-2 into propylene via metathesis. Thus, bioethylene can in effect be used to produce polypropylene.

In the UAE, Borealis converts ethane into polypropylene via steam cracking. A similar approach could work with ethanol.

The capital investment in integrated bioethylene, comonomer and polyethylene would be considerable and likely to be only financially viable in tactical locations under high oil prices. Regions that are both heavily reliant on the imports of petrochemical feedstocks and have access to competitively priced biomass could provide a platform for this form of biopolymer investment.

Ethylene production from bioethanol is a straightforward commercial process involving dehydration and purification

Assuming a fuel blending grade ethanol, around 1.73 tons are needed per ton of polymer grade ethylene. The process is reasonably efficient in mass terms, although the water by-product requires treatment to make it potable. Energy efficiency is key, given it's a dehydration reaction. The process is commercial and available for license from Chematur Engineering in Sweden and Scientific Design.

The agricultural impact of green polyethylene is substantial assuming a first generation ethanol process.

In passing it is worth just a quick examination of the agricultural impact of bio-olefins. On the basis of bioethylene process specifications, a 300 000 tons per year linear low density polyethylene plant would require the following (with captive butene-1 not considered):

- 279 000 tons per year of polymer grade ethylene
- 483 000 tons per year of bioethanol
- 1.64 million tons of feed wheat
- 205 000 hectares of prime wheat yielding land.

On an integrated basis the bioethanol required would be greater than most worldscale operations can produce today, but given that bioethanol plants can be built in multiple trains, technically plants of the size needed are feasible. However, the biomass requirement is enormous. Different grains will still provide yields of similar overall order and for sugar producers the quantities required of beet or sugarcane is still very considerable. Future bioethylene production will most likely need to be linked to second generation bioethanol production to exploit as broad a biomass pool as possible at lowest cost.

In the broader biofuels argument, there is growing concern over the competition for crops between fuel use and food use. This is particularly important with the rising prices of natural oils like palm, rapeseed and soybean oils. A combination of poor harvests and high demand is also pushing up the price of wheat and in turn bread.

4.4 Polyethylene Technology

4.4.1 Linear Low Density Polyethylene (LLDPE)

Overview
Linear low density polyethylene is made by adding a comonomer such as butene-1 to the polymer chain in the polymerisation process. The addition of different comonomers impacts polymer density and hence the properties of the materials produced. The density range of LLDPE goes as low as 0.885 grammes per cubic centimetre.

In addition, catalyst systems such as metallocene also have a strong bearing on the properties and various end-uses for LLDPE.

LLDPE is harder to process than LDPE.

Technologies Available
There are eight technologies licensed today including; Univation Unipol® (Dow ExxonMobil), Innovene® (BP), Evolue® (Mitsui), Lupotech G/Spherilene (Basell), Advanced Sclairtech® (Nova), Compact® (DSM), Borstar® (Borealis). Dow also produces C8-LLDPE using Dowlex® technology but does not license.

Technology Comparison
It is acknowledged in the LLDPE industry that Univation Unipol® technology, BP Innovene® and Basell Lupotech G® are lowest cost in terms of capital investment and operating costs. Dowlex® technology produces premium LLDPE grades of highest value.

Third Party Technologies
None available of any importance.

Capacity by Technology
Of the installed capacity around 61 percent of installed LLDPE is Unipol® (Dow ExxonMobil) technology, 19 percent Innovene® (BP), Spherilene® (Basell), 8 percent Sclair and seven percent others.

Grade Flexibility
Unipol® is the most flexible technology in terms of grade range with butene-1, hexene-1 copolymers as well as the use of new metallocene catalysts to provide new products with enhanced performance. Lower density films can be manufactured with octene-1 LLDPE.

4.4.2 High Density Polyethylene (HDPE)

Overview
High density polyethylene is made in a high pressure polymerisation of ethylene with or without comonomer. The density range goes up to 0.98 grammes/cubic centimetre and above with newer pipe grades.

In addition, catalyst systems such as metallocene also have a strong bearing on the properties and various end-uses for HDPE.

HDPE is harder to process than LDPE but easier than LLDPE.

Technologies Available
There are eight technologies licensed today including; Univation Unipol® (Dow ExxonMobil), Innovene® (BP), CX® (Mitsui), Lupotech G/Hostalen (Basell), Equistar, Borstar® (Borealis).

Technology Comparison
It is acknowledged in the HDPE industry that Univation Unipol® technology. BP Innovene® and Chevron Phillips are lowest cost in terms of capital investment and operating costs.

Third Party Technologies
None available of any importance.

Capacity by Technology
Of the installed capacity around 46 percent of installed HDPE is Unipol® (Dow ExxonMobil) technology, 19 percent Chevron Phillips, 15 percent Innovene® (BP), 11 percent Mitsui and 9 percent others.

Grade Flexibility
Unipol® is the most flexible technology in terms of grade range with butene-1, hexene-1 copolymers.

New Developments
Technologies are constantly improving in terms of scale, production cost, catalysts and grade range. In addition to conventional pipe grades such as hexene-1 PE 100, even denser polyethylenes are under development with higher performance polyethylene economics.

4.5 Ethylene Economics

For a wheat price typical of a balanced to long market, ethylene derived from bioethanol makes green polyethylene competitive with petrochemical derived routes in a high crude oil price world.

Figure 6 provides a view of wheat price required to make a UK ethanol to LLDPE process competitive with petrochemical processes.

The indifference curve back calculates the wheat price to achieve cash cost break even against a petrochemical process using cracker derived ethylene.

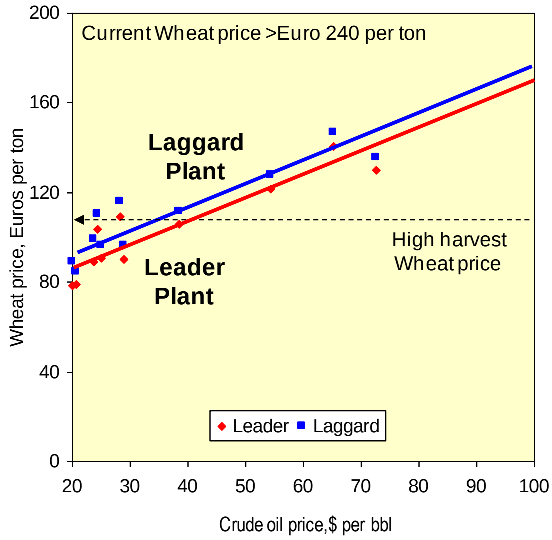
Petrochemical leader and laggard archetype plants represent technoeconomic models for these polymer processes reflecting scale, technology and operations.

In a balanced to long wheat market, pricing could be around £80 per ton to £90 per ton. Current pricing is circa twice this. The figure below suggests that for a balanced wheat market, wheat pricing can support competitive green polyolefin production to crude oil prices as low as $50 per barrel.

This assumes financial factors such as depreciation and internal financing, so indicative costs are only considered at the ex-works level. Adding finance cost will push up the competitiveness range to an oil price world > $70 per barrel. A second generation process could prove even more competitive.

Figure 6 Green Polyethylene Indifference Curve for UK

(First generation process)



4.6 Opportunity Development Issues

Development Roadmap in Outline

The technology to convert biomass into ethanol and ethanol into ethylene is already commercial. Plans are underway in Brazil to produce green polyethylene (Dow and Braskem) and also greener PVC (Solvay). Whilst the UK has an excess of ethylene, albeit reduced when the delayed SABIC LLDPE project finally comes onstream, bioethylene for polymers remains an option for commercial development.

The commercial challenge is building a competitive worldscale integrated bioethanol/ethylene facility in the UK. Such a facility could be linked to the trans-Pennine ethylene pipeline to serve the UK production of polymers, alpha olefins, vinyl acetate and vinyls.

In the case of green polyethylene, it is not a biodegrable product. However, were it to be incinerated it should be classed as a biomass. Therefore there needs to be particular attention paid to the post-consumer value chain. Convenient detection systems would be needed to be able to measure the green polyethylene in any post-consumer waste.

Partnering Issues and Commercialisation Strategy

Although this has already been considered earlier, both the infra-structure and producer companies are already in place to enable this to happen. A more detailed economic and financial analysis is needed, but a bio-ethylene project is feasible today under the right commercial conditions such as off-take agreements, wheat sourcing and cost, etc. Wheat contract price will be a major cost driver that will need more detailed analysis.

Legislation

The trade and mainstream press is replete with articles concerning "plastic bags" in use in retail. The focus of attention for green polyethylene is probably more durables, e.g., hexene-1 based PE 100 for use in urban gas distribution. In this way carbon is actually sequestered, although the life cycle of the products needs more investigation, especially if biomass is being used as a source of fuel for bioethanol dehydration.

Legislation should be targeted positively through incentives in the post consumer value chain to provide credits for energy production from green polyethylene incineration, etc.

5 Methyl Methacrylate Derived from Switchgrass

Methyl methacrylate is primarily used in the production of transparent extruded polymethyl methacrylate sheets, moulding resins, and surface coatings.

Global Consumption
Global consumption of methyl methacrylate (“MMA”) today exceeds 2.5 million metric tons per year, of which more than two million tons (or circa 85 percent) is for MMA polymers: PMMA, often known by the generic name Perspex®.

PMMA is often sold in pure or almost pure forms, but there is also a wide variety of copolymer uses.

The other primary product of this industry is crude methacrylic acid (crude MAA), which is produced by similar technology but often in separate plant units. Production of crude MAA is about 20 percent of the total production of MMA. This crude MAA is first processed into either or both of two other products: butyl methacrylates and "glacial" MAA.

Within the PMMA consumption categories, the largest application is in the production of transparent extruded polymethyl methacrylate (“PMMA”) sheets, which are sold widely under various trade names such as Plexi-glass. The production of these sheets is a mature commodity business with relatively low margin, and is restricted to large scale operators, often the MMA producers themselves.

Surface coatings and molding resins respectively are the next largest consumers of MMA polymers and co-polymers. The market for MMA in surface coatings is also mature, although MMA is favoured in certain water based and powder coatings which are being substituted for solvent-based formulations. Industry surface coating has also been moving toward the high-solids and powder coating, where polyesters are the preferred resin type.

By far the biggest emerging application has been in liquid crystal displays (LCD), where MMA is used in plates that keep light spread evenly across LCD computer and TV screens. The enormous current and projected growth for large LCD screens for home theatre, etc. has been a major driver for MMA expansions, especially in Asia where virtually all the LCD market now concentrates.

MMA is also consumed for the production of the co-polymer methyl methacrylate-butadiene-styrene (“MBS”), which is used as a modifier for PVC.

The use of PMMA as a substrate for DVDs is not now viewed as a major prospect as PC has achieved almost universal acceptance.

European Consumption
European MMA consumption is around 825 000 tons dominated by the cast and extruded PMMA sheet sector.

Consumption of MMA was estimated to total 856 000 tons in 2006 in Europe as a whole, with Western Europe accounting for about 686,000 tons.

MMA demand is expected to grow in West Europe at a rate of about three percent out to 2015, driven by applications for the construction industsry.

The consumption pattern is dominated by the cast and extruded sheet sector, which accounted for about 40 percent of total use. A new and growing automotive use is in the production of high quality acrylic license plates for cars.

The production of various coatings is the next most important end use sector with about 22 percent of total use. The coatings sector, which includes high quality paints, automotive topcoats, lacquers, paper coatings, and leather coatings, is seen as a prime outlet for MMA due to its high UV stability and durability. This sector has shown good growth over the last few years and MMA producers are pushing the use of these high-performance coatings.

Molding resins are the third largest end use accounting for some 20 percent of total consumption. The demand for molding resins is in the production of rear automotive light clusters, electrical appliances, and various small molded products. The production of automotive light clusters is the main sector, accounting for about 33 percent of all molding applications.

Polymer modification accounts for about eight percent of MMA usage. Polymer modifiers are used mainly to improve impact resistance in PVC. Polymer modifiers are now being used at higher rates in PVC due to the increasing use of recyclate. Some MMA is used in other styrene and acrylic resins.

The miscellaneous sector accounts for the balance in consumption equivalent to ten percent of total use, including transesterification products used as lube oil additives, adhesives and ink resins. Other direct uses of MMA include artificial marble, wood/MMA composites, sealants, and dental polymers.

Growth is relatively slow in WE with the main markets becoming more mature (coatings, glazing, molding compounds for automative applications). With the US and WE potentially entering recession, consumption in construction and consumer electronics markets is expected to also slow down.

MMA Market in Western Europe is dominated by five major players

Five producers dominate West European MMA production: Lucite (UK), Rohm (Germany), Arkema (France & Italy), Repsol (Spain), and BASF (Germany). Two small plants are located in the FSU.

Installed capacity in WE totals about 821 thousand tons at the end of 2006.

There has been no expansion in WE since 2003 due to historical overcapacity in the region before that time. Recently supply has become tighter due to stronger demand and limited capacity additions coupled with unplanned shutdowns during 2007.

The latest MMA investment is a 100 000 tons per year MMA plant in Leune, Germany by Quinn Chemicals, planned to come on stream in mid-2009.

Quinn Chemicals intends to mainly focus on supplying MMA to its 2 PMMA operations in Mainz, Germany and Zilina, Slovakia (previously belonged to Barlo Plastics). It will sell any surplus MMA to other customers if available.

All plants (with the exception of the BASF plant that uses ethylene) run on acetone cyanohydrin. The new Quinn Chemicals plant will be based on the new tertiary-butyl-alcohol (“TBA”) technology.

Europe is experiencing supply tightness due to little capacity expansion. Europe has turned from a net exporter of MMA with about 5 000 tons of exports in 2000, into a net importer of about 33 000 tons in 2006.

With only one planned new plant for Europe (Quinn, Germany, 2009), Europe is expected to remain tight in MMA for the coming years, and as the plants in Europe age, some smaller of plants may be forced out business in the 2010-2011 time period. However, no assumptions have been made regarding this in this analysis.

Lucite’s Alpha 2 plant, if it does come on-stream in the Middle East, could then be an obvious source of MMA for Europe as a whole.

The MMA industry in Europe is operating at utilization rate of above 90 percent in recent years (Figure 7). Operating rate may drop in 2009 when the new Quinn Chemicals’ plant starts its production but is expected to rise as supply becomes tight again.

5.1 UK Supply Demand Balance

MMA consumption in the UK is estimated at 150 000 tons per year in 2007.

The UK is a major European MMA supplier with Lucite, one of the leading global producers, operating a major complex near Teesside based on the acetone cyanohydrin process (Figure 8). Total MMA capacity in the UK is 230 000 tons per year, all from the two Lucite plants in Billingham. However, the majority of Lucite MMA consumption is captive.

Currently there is no plans for new MMA investment in the UK up to 2015.

Operating rates at Lucite's plants have been relatively high, above 90 percent since 2000, the UK MMA market having experienced tight supply like the WE MMA situation.

Some minor expansions are expected in response to market conditions.

UK has been a large exporter of MMA in Europe, exporting circa 74 000 tons in 2006.

Figure 7 European MMA Supply/Demand Balance, 2000-2015

(thousand metric tons per year

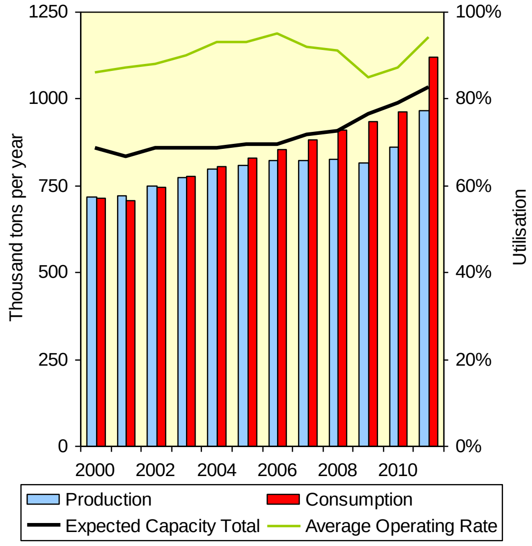
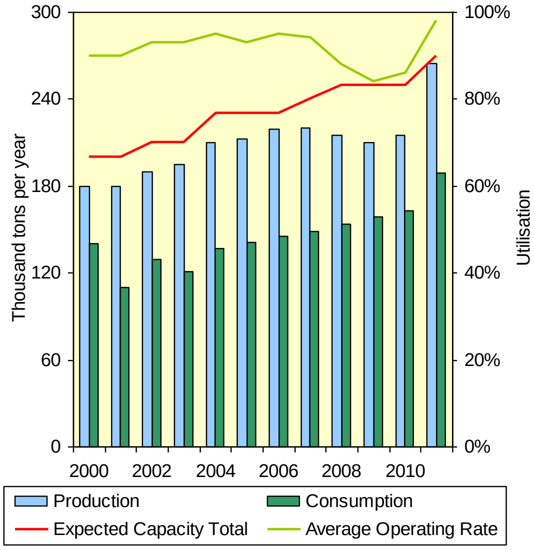


Figure 8 UK MMA Supply Demand Balance, 2000-2015

(thousand metric tons per year)



5.2 Potential Customers and Specifications in UK

UK
Lucite produces PMMA and other end-use products including:
- acrylic sheet
- acrylic blocks/brickettes
- acrylic bars/rod
- moulding resins
- surface coatings

The company's UK PMMA manufacturing site is located in Darwen in Lancashire.

Lucite is also one of the UK's leading acrylic coatings resins suppliers with its Evalcite® brand produced at Newton Aycliffe, UK.

Europe
Producers of PMMA (acrylic glass) in Europe include:
- Altuglas International (Rho, Italy) (Arkema's subsidiary),
- Quinn Plastics (formerly Barlo Plastics) of Quinn Chemicals Group (Mainz, Germany and Zilina, Slovakia),
- Lucite (Rozenburg, the Netherlands).

The total PMMA annual capacity in Europe is circa 115 000 tons and the market is evenly shared between these producers. Most PMMA producers are integrated to MMA production.

Repsol YPF produces cast/extruded sheets in Bronderslev, Denmark and Polivar, Italy.

5.3 Product Pricing and Drivers

In WE MMA prices show strong correlation with methanol, acetone and hydrogen cyanide feedstock prices.

In recent years MMA prices have been influenced by volatile feedstock prices, increased demand and supply tightness (Figure 9). In 2006 and 2007 supply was even more tightened due to the unplanned shutdown of Lucite and Arkema's plants.

Following a tight supply situation, feedstock price has gone up in 2007 but is anticipated to fall in 2008 as the Lucite and Arkema plants start operating again and new capacity comes on stream.

ChemSystems has performed feedstock price forecast, assuming Medium Oil Scenario where oil price averages at $US 45.6 per barrel. It is also assumed that HCN, produced from natural gas and ammonia, is transfered at cash cost to the MMA plant.

Nexant ChemSystems also noted the cyclicality of the industry with the low-point of the next downturn expected in 2010/2011.

MMA price is strongly influenced by its raw materials which are both petrochemical and gas derived (Figure 10). As an example, Lucite in the UK manufactures MMA from on-purpose hydrogen cyanide production with additional acetone cyanohydrin provided as a by-product from the BASF acrylonitrile complex at Seal Sands.

Figure 9 MMA Prices vs Feedstock Prices

(current, US dollars per ton)

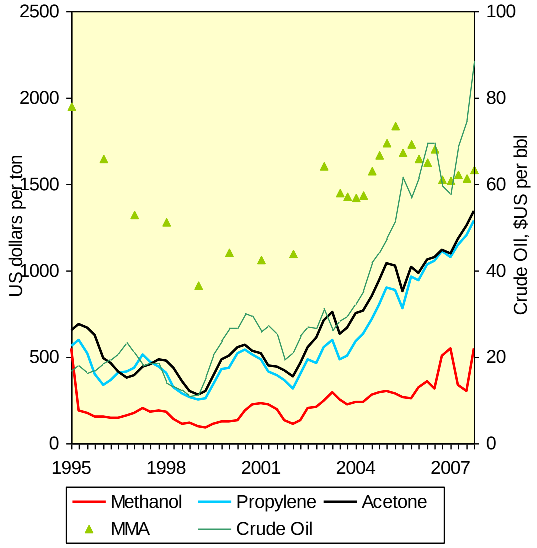


Figure 11 MMA Price Forecasts

(Source: Nexant ChemSystems)

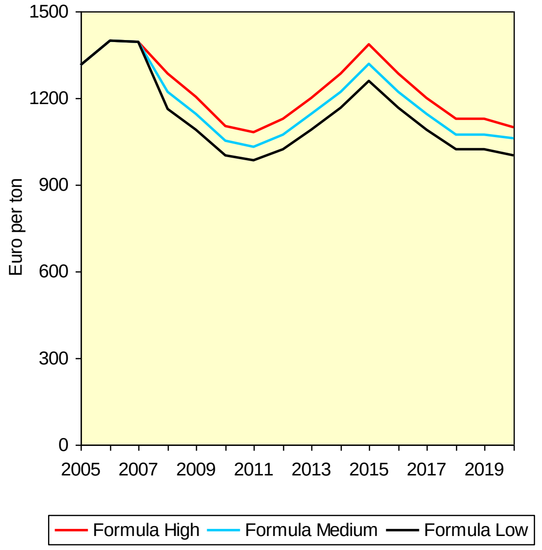
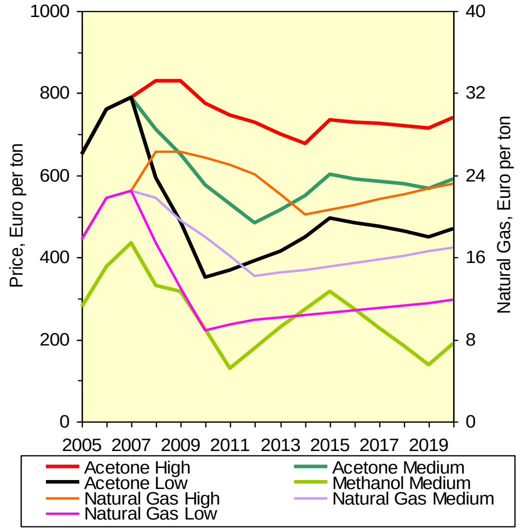


Figure 10 MMA Raw Material Price Forecasts

(Source: Nexant ChemSystems)



5.4 GM Crop Development

Genetically modified crops for chemicals production has accelerated in the United States. There is still a very strong reticence in Europe to such developments.

As long ago as 1997 30 million acres worldwide were planted with genetically modified (GM) crops. Today at least 25 percent of the US soybean harvest is grown from GM seed and China is thought to be growing over ten million acres of GM tobacco and tomatoes. Twenty-three GM crop varieties have reached the stage where strict regulations are no longer required for field testing in the US. As is widely recognized, however, these developments have been vigorously challenged – politically and in the market arena – by environmental and other special interest groups. The challenges are especially strong when GM crops are in or impinge on the human food chain, although genetically modified cotton and non-food oilseeds have also been challenged.

Until the mid 1990s, most commercial transgenic crops were engineered for single gene traits, mostly herbicide tolerance and pest resistance. In 1997, for the first time, crops were marketed with "stacked gene traits", i.e., more than one engineered trait in a single variety. For instance, Garst Seeds (a subsidiary of Advanta) then offered a corn (maize) hybrid that tolerates two different classes of chemical herbicide.

Current and likely future developments include:

- Continued development of herbicide-tolerant, virus- and pest-resistant crops. *Bacillus thuringiensis* (Bt) is a naturally occurring soil bacterium that produces a protein that kills a range of common insects (primarily in the larval [caterpillar] stage) when they ingest it. The Bt gene has been isolated and inserted into crops including corn, soybean, cotton, rapeseed, potato, tobacco, rice and tomato.

- Methods to accelerate traditional plant breeding.

- More fruits and vegetables in which ethylene production is suppressed so that they ripen more slowly. GM avocadoes, bananas, pineapples, mangos and tomatoes are among the ones so developed.

- Modified oils, fats and starches in crops to improve their processing or dietary functionality. New soybeans have been developed with improved protein profiles and reduced levels of indigestible carbohydrates.

- Improved flavor, texture, bio-absorbability, nutritional content and elimination of genes for toxic substances and allergens in foods. For example, rice and rapeseed are being developed with high levels of Vitamin A. Also, isolation of the gene for caffeine production has enabled caffeine-free coffee plants to be grown.

- Identification and manipulation of genes controlling salt tolerance, resistance to drought, flooding, and extreme temperatures (heat and cold), and response to day length (day-neutral crops).

- GM crops that fix nitrogen with greater efficiency, thereby reducing fertiliser needs. GM plants that produce vaccines or therapeutic agents. For example, a diabetes vaccine in tobacco and potato plants is being developed. Some of these materials have been demonstrated to resist degradation in cooking. Edible vaccines in bananas are also in development.

- GM plants for bioremediation, i.e., removing toxic chemicals and agrochemical residues from the soil.

- Better yields of starch, sugar or biomass in commodity crops such as corn, sugar beets, aspen and switchgrass.

5.5 Switchgrass Production Facility for MMA

To date the literature and trade press offers many articles concerning the Metabolix approach. In the case of MMA, Rohm and Haas with Ceres are looking to genetically modify crops like switchgrass for contained MMA production. Given, the volatility and chemical structure of MMA this appears challenging, but genetic engineering could provide a remarkable solution to MMA production compared to the cyanohydrin, C4 and ethylene-based chemistries today.

To address the requirements to produce MMA directly in field crops, and particularly in switchgrass, an integrated agriculture and petrochemical refining approach is needed. As an example Metabolix in the United

States considers a capacity of 50,000 tons per year of polyhydroxyalkanoates (PHAs) produced by extraction from switchgrass to be viable a commercial size that might be typical of such a plant in the future.

A fully-integrated facility with this capacity would need the following elements and resources:

- Switchgrass farming – within a surrounding area of 30 to 50 miles radius or more
- Transportation costs to bring in the harvested switchgrass from the field in bales to storage during mowing season(s), or continuously if storage is primarily on the farms
- Storage facilities, most preferably and likely to be largely on the farms, but also possibly centrally, to accumulate feed for processing during non-harvest times (possibly once, but more likely twice per year)
- Switchgrass drying and grinding immediately before extraction
- Solvent extraction of MMA monomer
- An “energy island”, including a biomass boiler burning extracted switchgrass residue to co-generate steam and power for the facility and power for sale to others (for byproduct revenue credit)

What follows is a simplified discussion of a potential process for switchgrass MMA. Unlike green polyethylene, biomass to acrylic acid, etc., some more focused issues must be considered such as switchgrass storage, biomass energy recovery and transportation.

5.5.1 Extraction processes

Switchgrass Farming

A large range of combinations of land costs, farming costs and yields are possible. In light of UK trials for miscanthus, there are a number of feasible sites around the country that could support an extraction plant with a capacity of 50 000 tons per year MMA. Following a PHA analogy, around 420 000 tons per year of GM switchgrass must be grown within a reasonable farming radius. As an example, the Oak Ridge National Laboratory for the United States Department of Energy (US DOE) estimates that within the United States, there are circa 202 sites that could support plants with 700 000 short tons per year of switchgrass demand, and over one thousand sites that could support plants with 110 000 short tons of demand (these data were developed to estimate the potential for biomass combustion-based electricity generators). Conceptually, there are few differences between energy production facilities and energy production facilities with MMA extraction up front assuming a Nexant/US DOE PHA model.

The UK is not so abundant in trial sites, but these could be developed on the Eastern seaboard exploiting set-aside land.

The estimated farmgate switchgrass prices for these facilities range between €35.00 and € 65 per ton. A somewhat conservative estimate by Iowa State University was about € 74.63 per ton for switchgrass production. This allows for the same methodology, exchange rates, husbandry, etc. Miscanthus production costs are circa £44 per ton in comparison.

In reconciling this diverse information, a benchmark farmgate switchgrass price of € 45 per ton is assumed. This could attract an investor to build in a particular location. With an assumed level of 12 percent extractable MMA in wet switchgrass (per Rohm and Haas targets), this gives a raw material cost of € 380 per ton.

Switchgrass Transportation

Estimated switchgrass transportation costs are about €0.10 per dry ton, up to 50 miles of hauling distances, and up to € 0.20 per dry ton for additional miles. One study in Iowa, adjusted for the UK, on transporting energy crops estimated a somewhat higher cost - €4.15 per wet ton for 30 miles. We assume a cost of € 5.00 wet ton for our model 50 000 tons per year MMA facility. This will bring the switchgrass delivered price to the PHA extraction/energy plant up to € 50 per metric ton. The logistic and other cost uncertainties and the regional price variability are handled by sensitivity cases on plant gate feed costs.

5.5.2 Switchgrass Bulk Handling

The cost of bulk storage of high volume seasonally-harvested biomass materials such as switchgrass is one of the major challenges of developing biomass sources for commodity energy and materials production.

To maximize capital utilization in the processing plant, the seasonal harvest must be stored for continuous processing.

Baling is most likely the best approach to managing and handling this material from the field to the grinding and extraction steps. Baled switchgrass density as given in the literature ranges from 3.0 to 6.0 kg per cubic ft.

The average density depends on the dimensions, moisture content, compaction method, and quality of the switchgrass and the bales. Switchgrass bales must be kept covered but well ventilated if stored in a building. The storage can be primarily at the field locations by the farmers, so that the baled switchgrass would be moved to the processing facility only upon demand, or storage can be primarily at the central facility. Most concepts that have been developed for utilizing switchgrass or similar biomass as an energy crop have featured primarily field storage in bales, by several possible means, including:

- Large (e.g., up to 6'dia.x8' round or 6'x6'x8' "square") or small (3'x3'x4') bales open-stacked on crushed stone foundations, rails, used tires or pallets to reduce ground moisture absorption and damage
- Large bales bagged or shrink wrapped in heavy-duty (3-6 mil) polyethylene film.
- Large bales stacked in pyramids and covered with plastic or plastic/fabric tarpaulins
- Under unframed structures, bubbles, Quonsets, pole-frames, or other minimum cost open-ended structures
- Within framed open-ended buildings.

Since Nexant first reviewed PHA production in the mid 1990s, there have been considerable advances in baling system development. Many combine harvester designs will harvest corn and bale stover.

5.5.3 Switchgrass storage and handling

Central storage, whether of a short-term inventory or seasonal inventory, can be in a number of possible types of structures that are commonly used also for bulk storage of fertilizers, Portland cement clinker, road salt, boxed materials, and other commodity solids.

There are some potential problems with storing biomass, especially switchgrass and similar hay-type materials:

- Depending on its concentration in the biomass, the storage-related costs could be relatively high for the extracted material
- The material is at risk of loss in various ways
    - Fire by spontaneous combustion
    - Attack by insects and other pests and diseases
    - Degradation of the contained MMA over time by oxidation and/or the action of native enzymes
- Baled material is difficult and awkward to put into storage and to retrieve mechanically and automatically
- Hay stored in plastic bags naturally ferments, which is desirable when it is to be used for cattle fodder, and hay that may be exposed to air (i.e., at the surface of unwrapped bales or from holes in the bags) tends to oxidize in a way that makes it less desirable as feed. Hermetically covering the switchgrass in plastic wrap could make it feasible to deliberately treat it with enzymes, organic acids or other low-cost treatments that will render it more easily extractable.

The costs of outdoor field storage of big bales of hay (a proxy for switchgrass) in polyethylene bags was estimated by the Ministry of Agriculture and Food of Ontario to be in the order of €2 per ton per year (ajusted for UK 2007). Light field structures can cost up to about €20 per metric ton per year (assuming 10-year amortization of capital investments). Thus, with 12.5 percent of recoverable MMA per ton in the switchgrass, field storage would add between €16 and €160 per metric ton of MMA.

By analogy to other bulk commodities storage systems, the average capital cost of central storage systems for 220 000 tons of switchgrass (one half-years supply, related to bi-annual harvesting), is estimated to be in the order of €40 million (maybe more in the current EPC environment).

It is likely that any combination of field and central storage for the 440 000 tons per year switchgrass facility will contribute less than €150 per ton to MMA production costs, which costs would be worked into the feed costs, or the central facility capital costs, or shared between both.

This cost uncertainty in the mode and size of storage is handled as a capital cost sensitivity case in Nexant's analysis.

Switchgrass Processing for MMA Recovery
We assume that the capital and operating costs would be roughly the same for solvent extraction of MMA as for solvent extraction of soybean oil (which also includes drying and grinding steps), with adjustments for the higher content of oil in soybeans as a simple parallel model (18.3 percent) compared to potentially extractable MMA in switchgrass (12.07 percent wet basis).

To put the scale in context, this operation would require drying and grinding material that would fill two 15-foot diameter x 40-foot high silos per hour, and processing this through solvent extractors. These types and sizes of silos are commonly seen in agricultural areas in the United States and also in the United Kingdom and this rate of processing agricultural products is not unusual (e.g., up to 4000 tons per day).

Biomass Energy Recovery
We assume dry switchgrass to have a heating value typical of biomass, such as corn stover and sugarcane bagasse, of about 8000 Btu per pound. The heat rate for a cogeneration system is assumed to be 8995 Btu/kWh and the boiler efficiency 85 percent.

The capital cost of this power island is difficult to estimate, but a typical rule of thumb for a biomass thermal generating facility is € 1000/kW installed. In modeling the plants-as-plants extraction complex, we separate the extraction plant from the energy island so as not to bury the costs of one in the other. The net result is that the operating cost of MMA extraction is very low, since it is essentially preparing feed, by grinding and drying, for the energy island based on burning this biomass. It is assumed conservatively, however, that the byproduct fuel has no greater value than the switchgrass feed (without the extracted MMA).

Taking into account the full supply chain costs for GM switchgrass generating 12.0 percent contained MMA, an approximate production cost of as low as €860 per metric ton is possible, this is less than 75 percent of current petrochemical processes.

5.6 Commercialisation Approaches

Development Roadmap in Outline
This is still at the very early stages of development and so discussions of development roadmaps appears superfluous at this stage, given a need for 2-3 years GM development, assuming favourable legislation. Agricultural trials will need around 2 years before development of demonstration and commercial units. This is probably a technology for the 2015 to 2020 timeframe.

Partnering Issues and Commercialisation Strategy
The requirement for partnerships here is enormous given the need for GM skills, agricultural trials, and the building of the supply chain with cooperation from an MMA producer. Lucite is the obvious choice, but both BASF and Degussa have operations in the UK and both companies have a biotechnology capability. The US model is Ceres with Rohm and Haas and a similar approach is needed in the UK. However, this technology is still several years away from commercialisation.

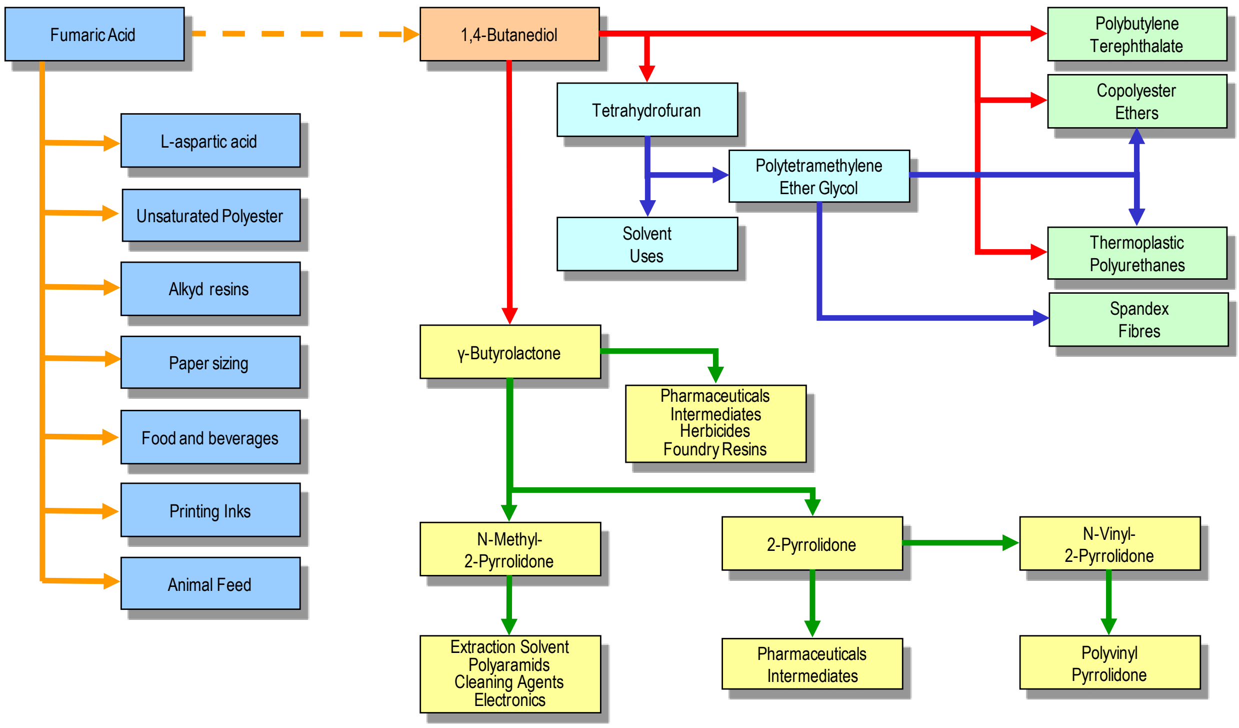
Legislation
The major legislative obstacle is the exploitation of genetically modified crops.

In terms of end use markets, MMA is used in the automotive industry and in the coatings industry. The automotive industry is already looking to increase the use of recycled and renewable materials. Major OEMs in the coatings industry are already looking to exploit more renewables, so it is unlikely that new legislation is needed at this time.

6 Fumaric Acid/Butanediol and Derivatives

Current demand for fumaric acid in Western Europe is relatively low but the new bio-transformation route to BDO can potentially stimulate significantly high growth (Figure 12).

Figure 12 Potential Fumaric acid derivatives chain



In the UK fumaric acid is mainly used in unsaturated polyester resin (UPR) and alkyd resin production. Currently there is no fumaric acid production in the UK. Estimated UPR sales in the UK and Ireland were circa 100 thousand tons in 2007.

UK manufacturers of UPR resins, alkyd resins and polyurethane resins include Deltech (Europe) Ltd, Vil Resins Ltd, Reichhold and Scott Bader Co. Ltd. Other alkyd resins producers in Europe are Eastman Chemicals B.V., the Netherlands and Worlee Chemie GmbH, Germany.

Although these producers manufacture UPR and alkyd resins, some of them do not produce fumaric acid-based resins as fumaric acid is only used where particular properties are needed such as chemical resistance.

Western Europe is one of the major producers of fumaric acid.

The world capacity of fumaric acid was approximately 210 000 tons per year in 2007.

The total fumaric acid capacity in Europe was circa 40 000 tons per year at the end of 2007. Lonza's former subsidiary company Polynt S.p.A is the largest supplier with its 18 000 tons per year plant in Scanzorosciate, Italy. The plant also produces phthalic anhydride, maleic anhydride, malic acid, etc. At the end of 2007, Lonza sold most of its 30 percent stake in Polynt to the Italian company Polimeri Speciali S.r.I.

BASF closed its 12 000 tons per year fumaric acid facility in Feluy, Belgium in Oct 2005.

All European fumaric acid is either made on-purpose from maleic anhydride or as a phthalic anhydride by-product.

6.1 A review of end-uses for 1,4-Butanediol

An estimated 280 000 tons of BDO were consumed in the Western Europe in 2007.

The largest end-use for BDO was to make captive tetrahydrofuran (THF) which accounted for about 30 percent of demand (Figure 13). This is captive to BASF and ISP.

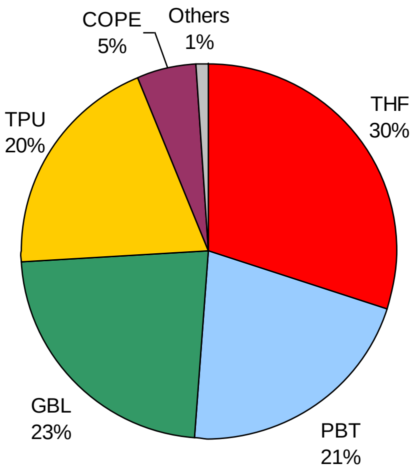
PBT accounted for about 21 percent of total demand. BASF/GE and DuPont have invested heavily in PBT production capacity which has made this sector of the BDO business more captive in recent years. DuPont has no European BDO capacity and is presumably supplied by European producers, maybe via some swap arrangements.

A substantial quantity of Western Europe BDO consumption goes into the production of γ-butyrolactone (GBL) and derivatives. BDO is consumed captively in these applications by BASF.

However, with the acquisition of Eurodiol, BASF gained an alternative method of GBL/THF and BDO production, so the balance of GBL supply in future is up for debate. In the UK small amounts of BDO are consumed in polyurethanes and speciality polymers. Total demand is less than 10 000 tons.

Figure 13 BDO Consumption by End-Use, 2007

(percent)



6.2 1,4-Butanediol market dynamics

6.2.1 Forecast 1,4-Butanediol demand development in Western Europe

BDO demand in Europe is expected to grow at about 3.2 percent per year over the medium term.

Demand may reach 354 000 tons by 2015, driven by consumption in THF, PBT, GBL and thermoplastic polyurethanes.

Total BDO capacity in Western Europe stood around 425 000 tons per year at the end of 2007 (Table 3).

Restructuring has taken place in recent years with BASF closing its 70 000 tons per year BDO plant in Feluy, Belgium (was Eurodiol's till 2001) in 2005 due to the overcapacity pressure coming from Middle East and Asia. BASF also ceased production of BDO derivatives at this site.

Currently the United Kingdom does not have any major BDO and derivatives facility.

Table 3 Western Europe 1,4-Butanediol Capacity, end 2007

(thousand tons per year)

Company	Location	Country	Capacity
BASF	Ludwigshafen	Germany	210
ISP	Marl	Germany	90
Lyondell	Botlek	Netherlands	125
TOTAL			**425**

6.2.2 Supply Demand Balance for 1,4-Butanediol

In 2007 Western Europe was estimated to produce about 323 000 tons of BDO, with net exports of 44 000 tons (Figure 15).

Exports of BDO from Western Europe have declined significantly since 2004 and are expected to continue to drop to about 16 000 tons by 2015 as a result of new plant coming on stream in Middle East and Asia.

Western Europe exports to all regions, although some of these shipments are intra-company movements.

The industry average operating rate has been modest since the start-up of operations of the Eurodiol unit in Feluy in 2001.

A number of BDO plants due to start up in 2007-2008 in Asia has brought the West European operating rate down from its peak in 2006. Average operating rates in WE is like to remain around 80 percent through to 2015.

Figure 14 European Butanediol Demand

(thousand tons per year)

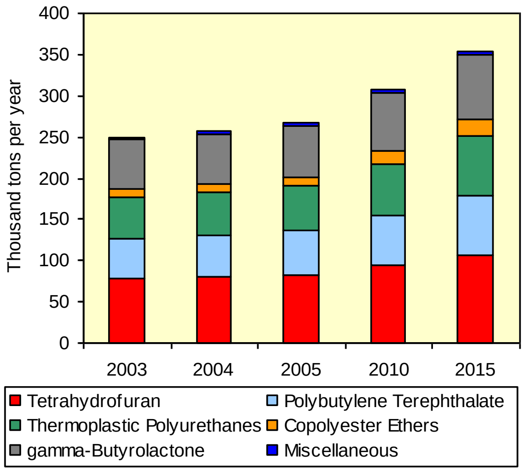
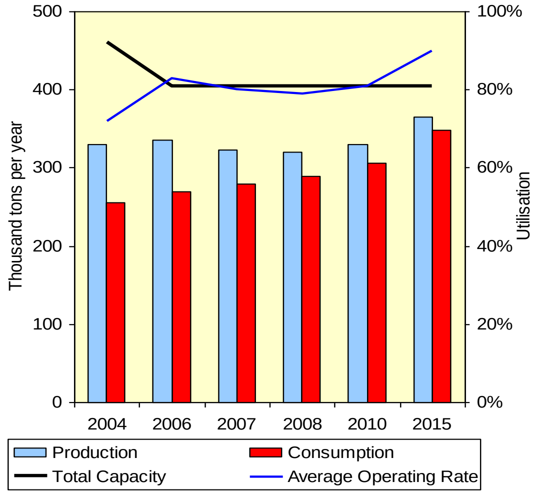


Figure 15 WE BDO Supply/Demand Balance

(thousand tons per year)



6.3 Tetrahydrofuran

Tetrahydrofuran (THF) demand is dominated by PTMEG production for spandex fibres

Whilst a large proportion of THF is consumed in PTMEG production, THF is still used as a solvent and a reaction medium. As a resin solvent, THF is used with PVC, acrylates, and polyurethanes in the following applications: PVC and chlorinated PVC (CPVC) pipe cements; coatings for magnetic tapes; PVC top coatings; polymerisation reactor cleaning; PVC film casting; cellophane coatings; printing inks for plastics.

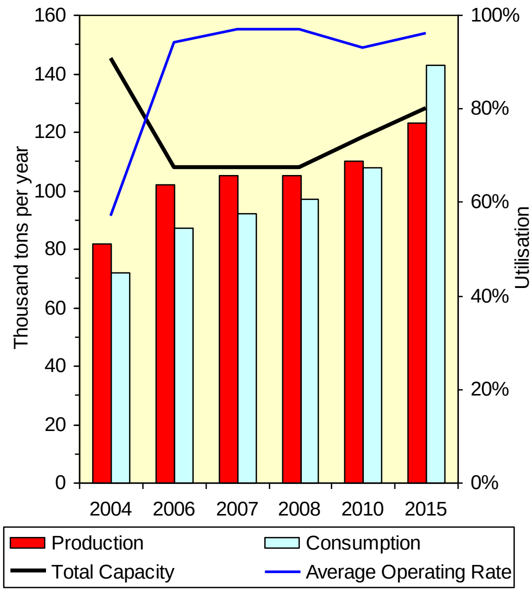
As a reaction medium, THF is often selected because it co-ordinates readily with metals and salts. Thus it is used in the following applications: Grignard reagents; Alkali metals, alkyl and arylalkali metal compounds. In most solvent applications, THF can be used alone, but it is relatively expensive. To offset this high cost, it is often used in mixtures with lower cost, less active solvents. Common cosolvents include methyl ethyl ketone (MEK) and toluene.

Also, by virtue of its relatively low boiling point (66 °C), THF can be easily separated from impurities and economically reclaimed for reuse by distillation. A relatively large volume is handled by solvent reclamation companies that recycle the material and reintroduce it into the market for less critical solvent applications (i.e. paint/lacquer thinners and strippers).

In Western Europe the demand for THF in 2007 was estimated at around 90 000 tons, clearly dominated by PTMEG for spandex fibres, which consumed circa 87 percent of THF produced (Figure 16).

Figure 16 West European THF Supply/Demand Balance

(thousand tons per year)



6.4 N-Methyl-2-Pyrrolidone and γ-Butyrolactone

6.4.1 European market for N-Methyl-2-Pyrrolidone and γ-Butyrolactone

N-Methyl-2-Pyrrolidone
Over the last seven years the West European NMP market has grown at an average rate of 3.3 percent led mainly by general solvent applications. The extraction solvent market for NMP has grown at more modest rates. The NMP market overall should grow to around 23 000 tons this year.

Looking ahead derivatives like polyaramids show strong demand growth on account of security and military use. However, in the general solvents sector growth could be curtailed through continued concern over HSE/toxicity issues. Even so, demand growth roughly in with average GPD is likely.

γ-Butyrolactone
The European GBL market has recovered from the turbulence brought about from SISAS. SISAS manufactured butanediol and NMP from GBL manufactured in its large maleic anhydride to GBL plant.

Assuming Lyondell builds its proposed NMP plant in the medium term then GBL demand growth could reach as high as 4.4 percent per year.

Earlier this year BASF finally closed the SISAS butanediol complex at Feluy including the 84 000 tons per year GBL plant. However, given the recent export statistics showing large volumes of exports to the United States, capacity at Ludwigshafen must have been expanded.

With the SISAS closure pricing has recovered to around $2.1 per kilo for large size customers.

Around 2600 tons of n-methyl-2-pyrrolidone are consumed in extractive distillation processes in Western Europe to produce petrochemicals like acetylene, benzene and butadiene. However, Group I base oil production dominates overall demand for NMP for extraction processes.

6.4.2 GBL and NMP Capacity issues in Europe

γ-Butyrolactone
Today there is only one producer of GBL in Western Europe and that is BASF at Ludwigshafen with around 50 000 tons per year.

In 2002 BASF acquired the Feluy assets of SISAS after its bankruptcy. The SISAS technology manufactured GBL from maleic anhydride and used this as a feedstock for BDO production. SISAS had the world's largest GBL plant with a capacity of around 84 000 tons per year. BASF closed the Feluy BDO complex in Q1 this year.

In 1996 DuPont brought onstream its maleic acid/THF plant in Gijon in Spain. The plant had some flexibility to produce a small GBL side stream with a plant to manufacture NMP as a joint venture with UCB. The transport bed maleic technology never worked satisfactorily and although DuPont tried to run the THF part of the plant with imported maleic anhydride, the plant was finally closed in 2002. The plant has since been dismantled.

Lonza, a major producer of maleic anhydride developed its own process for GBL production, but its Ravenna project never progressed beyond the design phase. Lonza was looking to form a joint venture with Akzo Nobel to develop an NMP project. Akzo Nobel planned to build the NMP plant at its Botlek site in Rotterdam.

Lyondell has recently brought onstream its propylene-oxide supplied BDO plant at Maasvlakte in Rotterdam. The original plan was for integrated GBL and NMP production. The current BDO plant is running at high rates so it is uncertain when or indeed if the development of GBL and NMP projects will continue.

N-Methyl-2-Pyrrolidone

There are two NMP producers in Europe, BASF and Taminco. Both companies also produce speciality pyrrolidones as well as 2-pyrrolidone. Only BASF manufactures polyvinyl pyrrolidone in Europe.

6.5 Fumaric Acid Pricing

Fumaric acid is sold at a small premium to maleic anhydride which is itself related to butane by a factor of around 3.6. Food grade fumaric is priced at an average premium of six percent over technical grade.

BDO Prices have been increasing in recent years to due rising feedstock prices (Figure 17). Both THF and BDO markets have commoditised with highly cyclical pricing compared to fumaric acid (Figure 18/19/20).

Figure 17 Historical European Butane Pricing

(Euro per ton, Medium Oil Scenario)

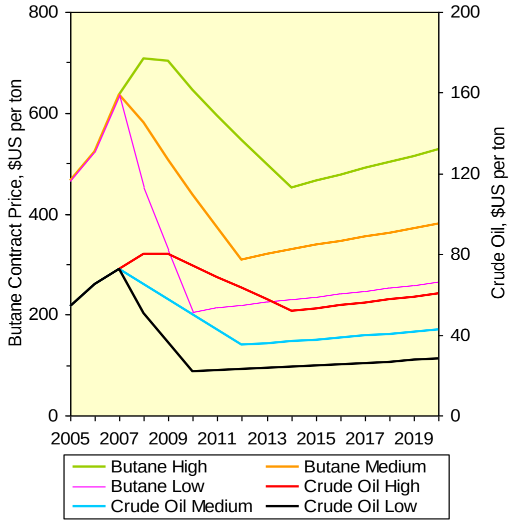


Figure 19 European Butanediol Price Forecast

(Current Euros per ton)

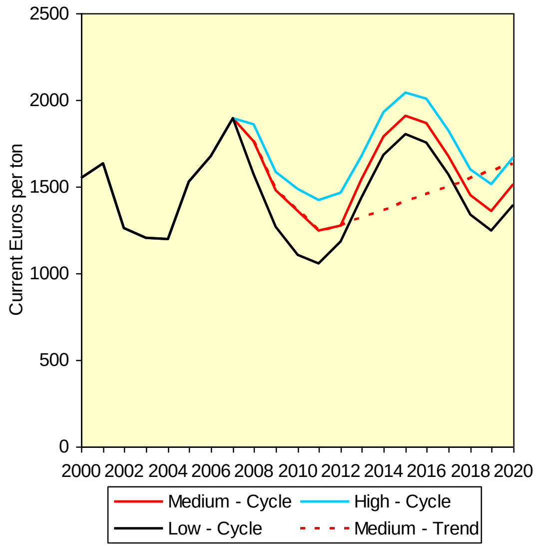


Figure 18 European Fumaric Acid Price Forecasts

(Euro per ton)

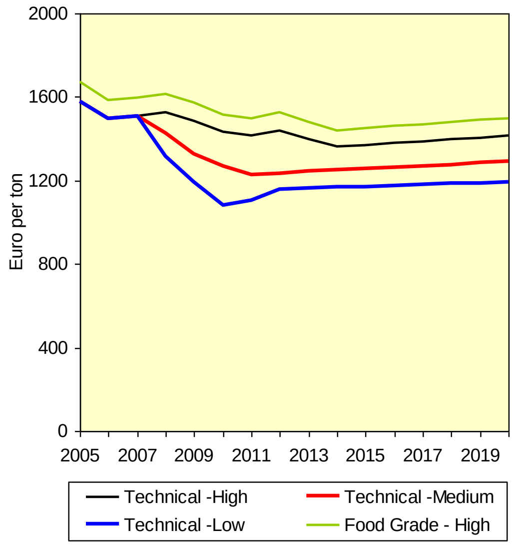
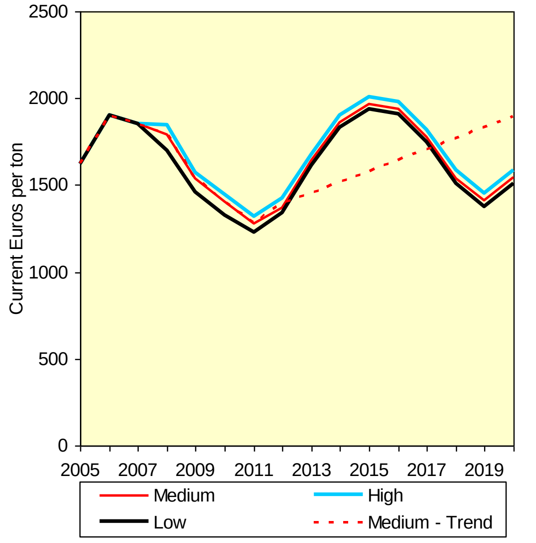


Figure 20 European Tetrahydrofuran Price Forecast

(Current Euros per ton)



6.6 Biotransformation approach to BDO

The biotransformation approach to BDO production involves the production of fumaric or succinic acid as an intermediate in a neutral pH fermentation. Nexant has proposed a design concept based on work undertaken as part of its process evaluation and research planning multiclient programme.

Nexant has developed a preliminary process design for a bio-BDO complex via fumaric acid as the intermediate. The fumaric acid can be sold as a product for its own market. The succinic acid approach is similar but the market opportunity is smaller today, albeit with new applications posisble.

Fumaric acid is produced from dextrose, fed as a 70 percent solution. A genetically modified micro-organism is assumed, operating in a neutral pH environment. The 3-HP is recovered as the calcium salt. To recover fumaric acid acidulation and gypsum recovery is needed. The solubility of fumaric acid makes this relatively straightforward.

The Davy process which currently converts maleic anhydride into BDO can be adapted for fumaric acid. Methanol and hydrogen are needed for this. Fumaric acid is esterified with methanol and then the di-ester is treated to a two stage hydrogenolysis. GBL is first produced and this is then hydrogenated to BDO. Some dehydration occurs to form a THF by-product.

Within reason it is possible to build a plant to make BDO,GBL and THF or 100 percent of each product.

The process has the advantage of being based mostly on adapting commercial processes as bio-fumaric acid can resemble lactic acid as practised by NatureWorks and the conversion to BDO is a clone of the Davy process, which has more than eight licenses at worldscale.

Around 2.0 tons to 2.5 tons of glucose solution are needed per ton of BDO in the current Nexant design. The micro-organism is still proprietary and further generations are under development to improve yields and block fermentation by-product pathways.

Nexant has also developed a sub-neutral pH process (patent pending) which could prove to be an improvement on the neutral approach.

The conversion of fumaric acid into butanediol and co-products can follow a maleic anhydride analogue with esterification with methanol as the first step to produce the dimethyl fumarate ester, followed by hydrogenolysis to GBL, then BDO and/or THF, followed by distillation recovery.

6.7 1,4-Butanediol economics

In order to make an BDO biotransformation process economic the integrated cost of sugar production needs to fall below € 300 per ton on a 100% basis. Brazil shows how competitive the process could be in practice.

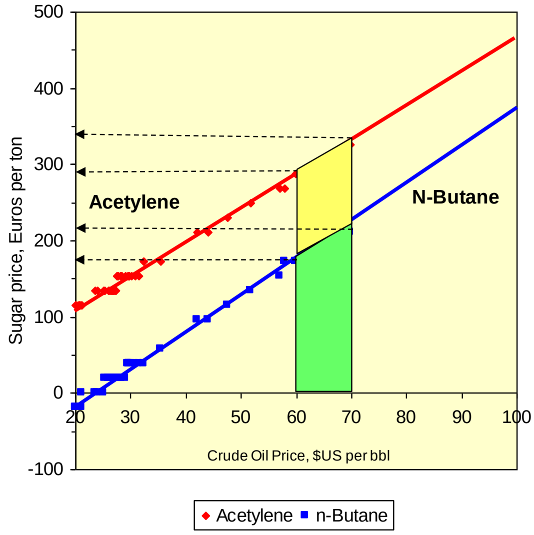
The indifference curve (Figure 21) provides a view of competitiveness for the biotransformation process as a function of oil price and biomass price. The bars indicate the sugar price required for a mid range crude oil price for a UK plant.

The EU refined sugar price even after the recent announced reduction is much higher than average world price.

Assuming an intervention price of circa €650 per ton adjusted for the planned reduction comes to around €450 per ton. This is much higher than Brazil where the effective range of sugar pricing is circa €150 per ton to €200 per ton.

Figure 21 Bio-BDO Indifference Curve for EU

(Assumes Sugar at Intervention Price)



For an EU/UK project to be competitive in a $70 per barrel crude oil price world the effective internal transfer price for a 70% dextrose solution to supply a biotransformation process needs to be less than €200 per ton.

Wet milling of wheat and corn is limited in Europe with most sugar being sugar beet-derived. With a sugar beet price of circa €30 per ton, on an integrated basis it may be possible to support captive fumaric acid and butanediol production.

6.8 Opportunity Development Issues

Development Roadmap in Outline
In the United States and Japan a number of companies are looking at developing processes for BDO derived from biomass. The companies involved include Mitsubishi Chemical and Ajinomoto.

Where UK plc to move in a similar direction several R&D strands must align, namely micro-organism development with fermentation design, fumaric/succinic acid recovery possibly with electrodialysis. Davy Process Technology could collaborate in providing the conversion technology for butanediol and other derivatives. A process like poly-THF may have to be licensed in from China or Korea.

Partnering Issues and Commercialisation Strategy
Partnerships between industry and academia could play a role, but the development should combine an BDO or derivatives producer, ISP, DSM, BASF, Taminco, etc, with biotechnology companies, e.g. Lonza in Slough, and key specialist equipment manufacturers, e.g. for electrodialysis and microfiltration. While the early stages of any collaboration will be technology focused and rightly so, the commercial aspects of the business will soon loom, and bringing on board a major industry player will be key to commercial success.

Legislation
In the case of BDO and derivatives, no new direct legislation is needed. However, there is a case to focus on derivative sectors. As an example, PBT is used extensively in the automotive industry. Major automotive OEMs are already maximising the use of recycled materials in new models. This could be further extended to renewables.

In the case of fibres, spandex is being exploited in many new sectors to provide comfort stretch in suits, male and female functional and leisure apparel. Legislation could be developed focused on renewables in apparel, but more polymers like polyesters, polyamides, etc., need to be manufactured from renewables to offer garment manufacturers a choice of polymer fibres from renewables.

7 3-Hydroxypropionic acid/Acrylic Acid and Derivatives Derived from Glucose

7.1 Acrylic Acid Overview

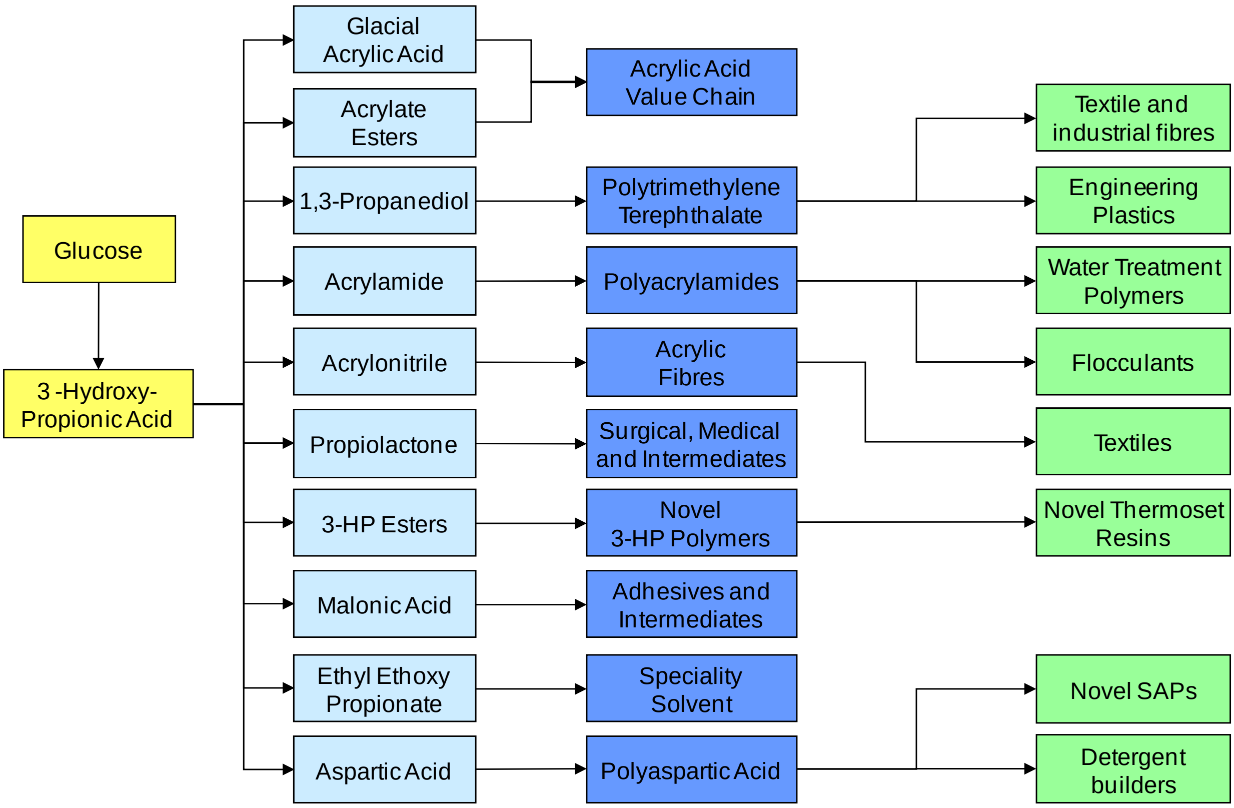
The production of 3-hydroxypropionic acid is focussed on conversion to a number of derivative and in particular acrylic acid (Figure 22).

Based on markets and prices for glacial acrylic acid ("GAA") and acrylate esters, the industry as a whole is worth circa $11.0 billion.

The first step in the process is the production of crude acrylic acid ("CAA") with a market of circa 3.6 million tons.

Average annual growth is in line with average GDP, with the Asia-Pacific region the strongest growth region.

Figure 22 Potential end-use for 3-hydroxypropionic acid



7.2 Major Acrylic Acid Consuming Industries

Superabsorbent Polymers/Diapers
The infant diaper market which forms the major outlet for SAP is a $18 billion industry. The sector is dominated by two major players: Proctor & Gamble and Kimberly-Clark. Some smaller producers exist such as Unicharm, SCA and Kao. Major brands now compete with private label brands. In many parts of the world demand growth is slow. Growth in China and Latin America is strong but coming from a low base. Producers seek to diversify offerings with training pants and adult incontinence products; these too are high growth markets. The removal of fluff pulp from diaper products will also boost SAP demand. Other sanitary products employing SAP include feminine hygiene goods.

Coatings and Dispersions
The coatings business is a $95 billion global industry dominated by Western Europe and North America. In recent years the Asia Pacific region too has become an important market. The industry is replete with different coating systems for wood, metal, automotive finishes, powder coatings, coil coatings, etc. Major producers and hence major buyers of acrylate esters include Akzo Nobel, DuPont, Sherwin Williams, etc.

Adhesives
This $36 billion industry covers many sectors; packaging, construction, transportation tapes, etc. The market is concentrated in developed economies which exhibit only modest growth in line with average GDP. Strong demand growth is forecast for the Asia-Pacific region, notably China. Major players include 3M, Ato-Findley, etc. Many adhesives systems exist such as hot melt, water-based and solvent-based. The latter is out of favour for environmental reasons. Acrylic based systems form about eight percent of total adhesive supply.

7.3 Acrylic acid demand and consumption

Acrylic Acid is primarily used for the production of glacial acrylic acid (Figure 23).

Crude acrylic acid can be used directly in the production of commodity and speciality acrylates or can be purified into its glacial form for the production of polyacrylic acid, super absorbent polymers, etc. It is likely that some blending of crude and glacial acid may be undertaken for less critical polyacrylic acid applications.

Both glacial acrylic acid and acrylates have a diverse number of end-uses. Glacial acrylic acid is mainly used in the production of polyacrylic acid ("PAA"), superabsorbent polymers and detergent applications polymers. Glacial acrylic acid and its PAA polymers/copolymers also find a broad spectrum of applications in various industries such as paper, textile, coatings, personal care, pharmaceuticals, etc.

Commodity acrylates include methyl acrylate, ethyl acrylate, n-butyl acrylate and 2-ethylhexyl acrylate. Some companies also produce isobutyl acrylate in small quantities, but it is usually classified as a speciality acrylate. Acrylates are consumed in a variety of industrial applicatitons such as coatings, adhesives and sealants, textiles and fibres, polymer additives/impact modifiers, film and barrier resin applications, vanishes and polishes, and printing inks, etc.

West European demand growth for acrylic acid is being driven by the SAP market (Figure 24).

Demand for crude acrylic acid in Western Europe reached around 846 000 tons in 2007 and the market recovered from a poor 2001/02. Modest demand growth of 1.6 percent is anticipated in the Nexant *ChemSystems* base case given the emphasis on investments in acrylic acid complexes in East Asia, as indicated by the major development of BASF-YPF in Nanjing, China.

Estimated United Kingdom demand for acrylic acid and its salts was about 24 000 tons in 2006 based on trade statistics.

The UK used to make SAP, but this ceased after the BASF fire at Ellsemere Port some time ago.

The UK is a major consumer of acrylate esters for coatings. Akzo (formerly ICI) is a major butyl acrylate consumer for paints production.

There are also a number of diaper facilities operated by Kimberly Clarke and Proctor & Gamble as well as private label producers in the UK. Ciba Specialty Chemicals in the UK has a major specialty chemical production plant in Bradford, Yorkshire which produces a wide range of specialty chemicals including acrylates and other acrylic acid derivatives for water treatment applications.

Figure 23 West European Acrylic Acid Consumption by Derivatives

(thousand tons per year)

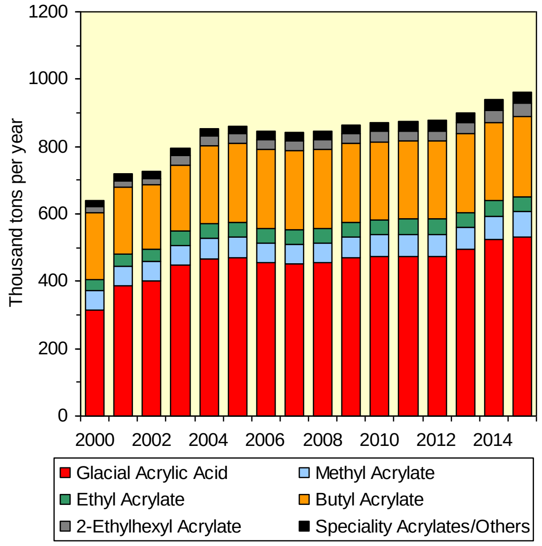
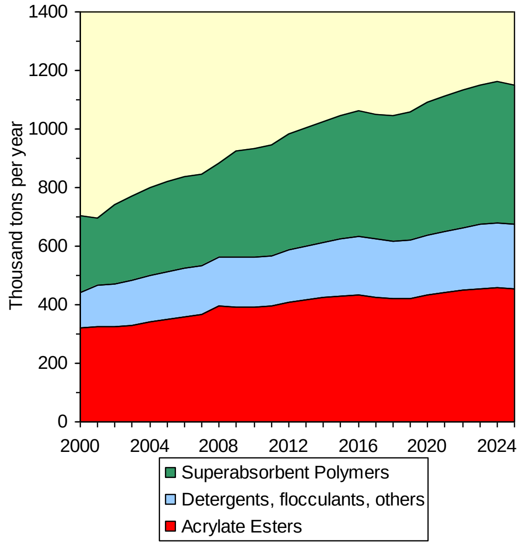


Figure 24 Western Europe Consumption by End Use, 2000-2025

(thousand metric tons per year)



Many capacity additions are taking place in Western Europe despite only modest domestic growth.

Crude acrylic acid capacity in Western Europe stands at around 950 thousand tons by the end of 2005. The last grassroots acrylic acid complex to be built in WE was the Dow Chemical facility at Böhlen (originally a Dow Chemical/Celanese j.v.). This plant provides not only butyl acrylate, but also acrylic acid for Dow Chemical's SAP plant at Rheinmunster (recently acquired by Degussa).

The last major expansion of acrylate capacity was that of the butyl acrylate plant of BASF at Ludwigshafen, Germany.

Despite slow growth, new capacity has been installed in Europe. In 2006, StoHaas expanded its facility at Marl, Germany to 265 000 tons per year. Arkema has increased the capacity of its Moselle plant in France by 15 percent to 276 000 tons per year. BASF will build another 160 000 tons per year plant in Antwerp, Belgium which is due to start production in 2008/09.

Currently there is no acrylic acid or commodity acrylate plants in the United Kingdom. BASF used to operate an SAP facility at Elsmere Port using imported glacial acrylic acid which was destroyed by fire. The plant was never rebuilt. A number of producers of acrylic acid are downstream integrated into not only acrylate esters but also SAPs and coatings. Major SAP consumers however, are not integrated upstream.

7.4 Supply/Demand Balance and Trade

At present, Nexant *ChemSystems* estimates that the West European market is roughly balanced in crude acrylic acid and acrylate esters, but it has exported considerable volumes of glacial acrylic acid (Figure 25).

The structure of the industry in Europe has changed following the various expansions in recent years.

Given the emphasis on expansions in Asia, there is unlikely to be a new grass roots investment in Western Europe, except in unique circumstances, possibly where a local low cost propylene source is available and a joint venture partner with technology willing to invest.

As UK does not have any acrylic acid or acrylate production plants it is a net importer of acrylic acid and acrylates. Imports of acrylic acid and acrylates amount to around 40 000 tons per year and much of this is butyl acrylate for the coating industry (Figure 26).

Imports are mainly from France, Germany, and Belgium, where all European acrylic acid production facilities are located.

Feasibility of the new bio-based acrylic acid investment in the UK will mainly depend on the production cost of the biotransformation process in comparison to that of the traditional propylene-based process. New biotransformation process will have to be cost competitive with imports from both the European mainland and Asia.

Such a facility will need to have a scale of circa 100 000 tons per year, possibly with integrated SAP production to serve the domestic diaper markets and water treatment polymers industry.

Figure 25 WE Crude Acrylic Acid Supply/Demand Balance

(thousand tons per year)

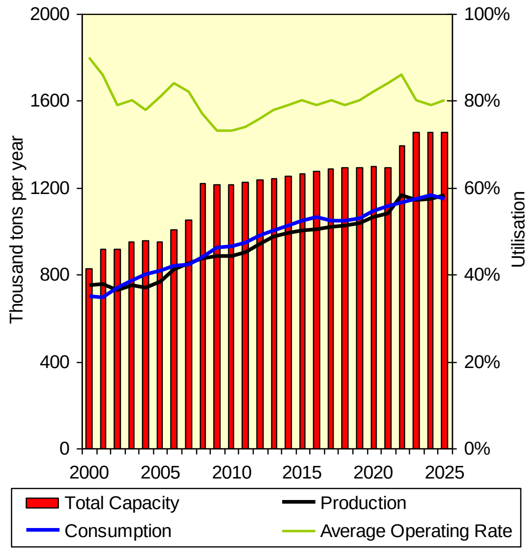
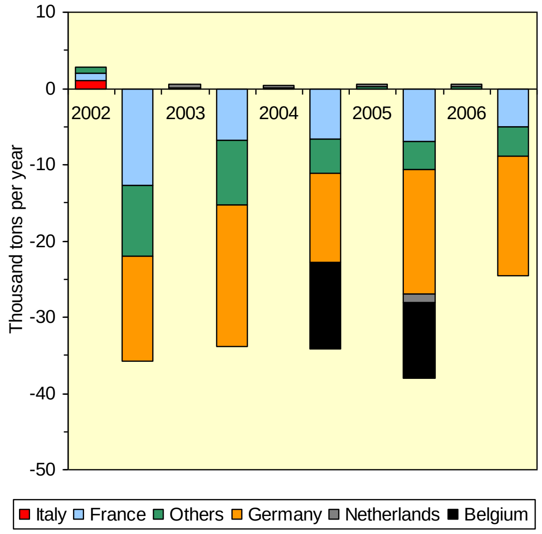


Figure 26 UK Trade of Acrylic Acid and its Salts

(thousand per year)



7.5 Acrylic Acid Pricing and Drivers

Acrylic acid prices have historically seen strong correlation with propylene. However, in times of short supply such as those seen at the end of 2004/beginning 2005, prices have flared up to exceptionally high prices above the trend expected relative to propylene (Figure 27). Acrylic acid prices have since fallen but have still not reached historical levels.

When the market is balanced to long, purchasers can obtain considerable discounts from published list prices of up to 30 percent. However, in short market characteristics such as those seen in 2004/early 2005 these discounts virtually disappear.

The average uplift of glacial acid on propylene is around Euro 576 per ton if the price spike is not considered.

Some product is sold on a formula price related to propylene-based production economics. An approximate formula price is given in Figure 27, indicating that buyers will pay a small premium for supply security in a balanced market, but in a tight market they enjoy a discount.

Acrylic Acid Pricing and Drivers – Forecasts

In the high oil case, the forecast average propylene price in Western Europe will be circa €810 per ton (Figure 28/29), with acrylic in the range of €1510 per ton. This provides good margins for those in the industry.

Figure 27 Acrylic Acid Pricing and Drivers

(Euro per ton)

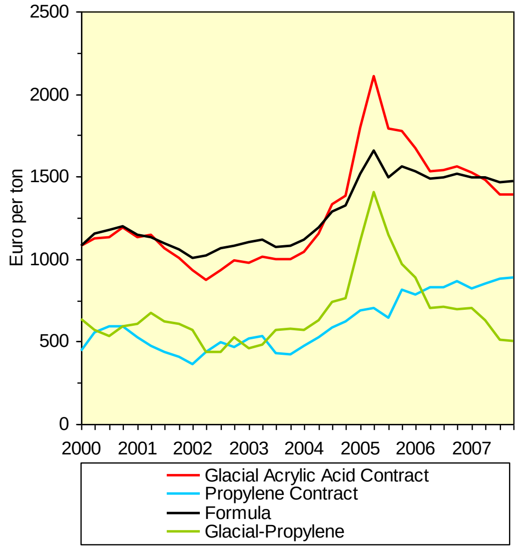


Figure 28 Propylene and Crude Oil Price Forecasts

(Source: Nexant ChemSystems)

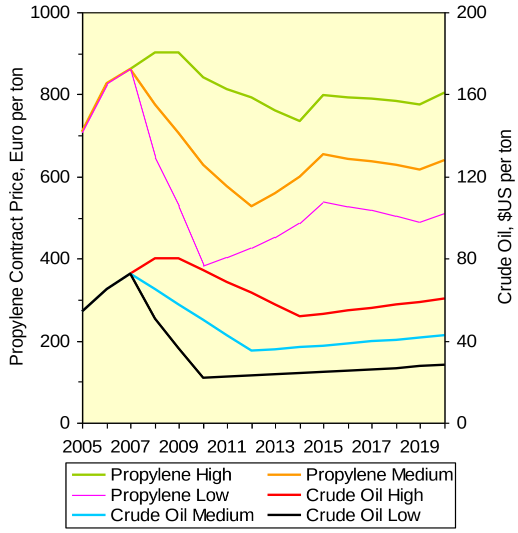
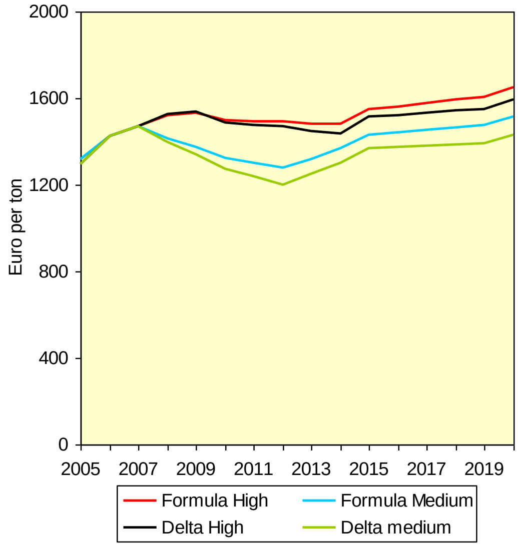


Figure 29 Glacial Acrylic Acid Price Forecasts

(Source: Nexant ChemSystems)



7.6 Biotransformation route to acrylic acid

The biotransformation approach to acrylic acid production proceeds via a 3-hydroxypropionic acid intermediate made in dilute form. This 3-HP is dehydrated to produce an acrylic acid solution which straightforward to refine to glacial grade.

Nexant has developed a preliminary process design for a bio-acrylic acid complex via 3-hydroxypropionic acid as the intermediate. 3-HP could be purified in its own right and sold as new applications develop.

3-HP is produced from dextrose, fed as a 70 percent solution. A genetically modified micro-organism is assumed, operating in a sub neutral pH environment. The 3-HP is recovered as the ammonium salt. A neutral pH process is necessary to recover 3-HP as the calcium salt. 3-HP is recovered from its ammonium salt by salt breaking combined with solvent extraction requiring some expensive solvents like dodecanol. In the calcium salt case, acidulation and gypsum recovery are needed. Either way this is a complex and capital intensive multi-step process. Attempts to simplify the process with the use of techniques such as electrodialysis are being considered.

3-HP can be recovered as a concentrate for purification via distillation. A concentrate in the 30 percent to 50 percent range is fed to a proprietary dehydration reactor with a conventional zeotype catalyst. This produces a dilute acrylic acid stream. The higher the 3-HP concentration, the greater the formation of problematic heavy ends.

The dilute acrylic acid stream is considerably cleaner than that obtained from oxidation processes, with no contained acetic, maleic acids, etc. The separation train removes water and heavy ends under vacuum distillation. As acrylic acid forms an azeotrope with water, toluene is added to break the azeotrope. If sufficient heavy ends are present then a special cracking reactor is deployed to crack heavy ends to recover more acid.

Around 2.5 tons to 3.0 tons of glucose solution are needed per ton of acrylic acid in the current Nexant design. This is not a scale-up risk free process, but most units have been commercially proven, save the fermentation where a new generation of micro-organism is under development.

7.7 Acrylic acid economics

In order to make an acrylic acid biotransformation process economic the integrated cost of sugar production needs to fall below € 300 per ton on a 100% basis. Brazil shows how competitive the process could be in practice.

The indifference curve (Figure 30) provides a view of competitiveness for the biotransformation process as a function of oil price and biomass price.

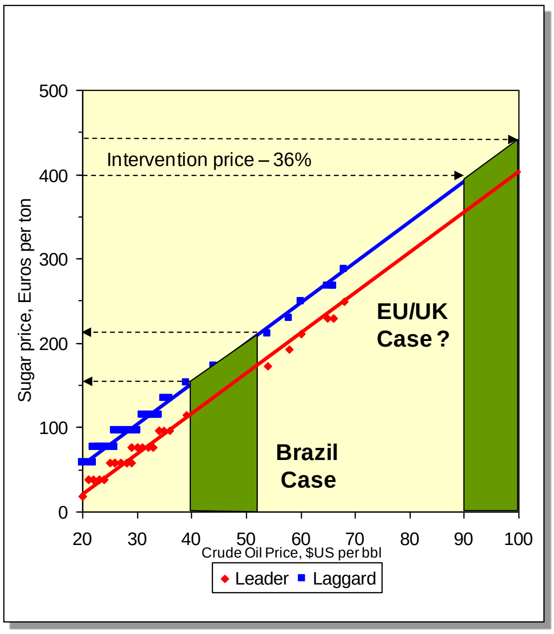
The EU refined sugar price even after the recent announced reduction is much high than average world price.

Assuming an intervention price of circa €650 per ton adjusted for the planned reduction comes to around €450 per ton. This is much higher than Brazil where the effective range of sugar pricing is circa €150 per ton to €200 per ton.

For an EU/UK project to be competitive in a $70 per barrel crude oil price world, the effective internal transfer price for a 70% dextrose solution to supply a biotransformation process needs to be less than €200 per ton.

Figure 30 Acrylic Acid Indifference Curve for EU

(Assumes Sugar at Intervention Price)



Wet milling of wheat and corn is limited in Europe, with most sugar being sugar beet-derived. With a sugar beet price of circa €30 per ton, on an integrated basis it may be possible to support captive acrylic acid production.

7.8 Opportunity Development Issues

Development Roadmap in Outline

Cargill and Novozymes have already announced a joint development programme to commercialise a bio-acrylic acid process.

Were UK plc to move in a similar direction several R&D strands must align, namely micro-organism development with fermentation design, 3-HP recovery, possibly with electrodialysis, and 3-HP dehydration and acrylic acid recovery.

This will require a 1-2 year development programme before a demonstration plant could be commissioned, unless a multi-purpose plant is currently available (or built fit for multi-purpose operation). A year of demonstration trials will provide product for testing as well as proving the process, prior to commercialisation. A world scale plant requires circa 30 months to complete based on existing projects, so a six year development timeline as a minimum is likely for a UK commercial unit.

Partnering Issues and Commercialisation Strategy
Partnerships between industry and academia could play a role, but the development should combine an acrylic acid or derivatives producer, e.g., Degussa, Total, BASF, Proctor & Gamble, etc., with biotechnology companies, e.g., Lonza in Slough, and key specialist equipment manufacturers, e.g., for electrodialysis and micro-filtration. While the early stages of any collaboration will be technology focused and rightly so, the commercial aspects of the business will soon loom, and bringing on board a major industry player will be key to commercial success.

Legislation
Amending legislation regarding products like diapers and coatings in terms of driving through a green agenda is probably not the appropriate action at this time. Companies such as the DIY chains and Walmart are already pushing suppliers to be increasingly green as DIY chains seek to increase the sale of renewable-based goods. This is the stated strategy of certain players.

A switch to branding a new eco-diaper with bio-SAP is a much greater challenge, given the volumes and leading companies concerned. Renewable diapers are available as private label products but their share is very small and performance only modest at best. An incentive-driven approach rewarding the retail chain in exploiting renewable SAP or coatings should be encouraged.

8 Summary

8.1 Ethylene from ethanol

Manufacture of ethylene from ethanol to serve integrated polyolefins production, focused on linear low density polyethylene and high density polyethylene together with ethylene-derived comonomers.

Market Dynamics
Europe is a multi-million ton polyethylene market. The UK too is a large market although commodity LLDPE grade (C4, C8 grades) are imported together with HDPE. Ineos is a major C_6-LLDPE producer for the domestic market and export. In the case of LDPE, new capacity is under construction by SABIC at Wilton, although the project is delayed. Polypropylene is also produced in the UK for the domestic market and export.

Technology Status
The production of ethylene and derivatives is practised at large scale in the UK, although Ineos ceased HDPE production at Grangemouth some time ago. All processes like polyethylene, vinyls, alpha olefins should be able to consume a polymer grade ethylene derived from ethanol.

Biotechnology Developments
All steps in the green polyethylene chain are commercially practiced. For wheat prices in the range of £80 per ton in the UK, a green polyethylene process could be cost competitive at the high oil prices observed today.

There is considerable potential, therefore, for a second generation bioethanol process to provide a dehydration feedstock for olefins production. The technology can be extended to produce propylene as well as ethylene through a series of petrochemical process steps.

Strategic Issues
The process is commercial, but it does require agriculture and petrochemical industry collaboration to provide olefin feedstock to supply the current UK ethylene pipeline system.

On the legal side, attention should be paid to incentivising the post consumer polymer value chain if green polyethylene becomes a mainstream product in the UK.

8.2 Methyl methacrylate

Opportunity for the production of methyl methacrylate based on the metabolix “Plants as Plants” approach, where genetically modified switchgrass actually generates the product *in planta* for seasonal harvesting and extraction.

Market Dynamics
The European market for MMA is around 686 000 tons and growing in line with average GDP. MMA is polymerised and made into sheet, moulding resins, rods, compounds, etc, serving construction, automotive, appliance sectors, etc. Lucite, based in the UK, is a major global industry player. The UK is currently a major MMA manufacturer in Europe and exports product and derivatives into mainland Europe.

Technology Status
In the West, MMA is mainly made from acetone cyanohydrin which is generally derived from the reaction of on-purpose produced hydrogen cyanide and acetone. Hydrogen cyanide is also available as a by-product from acrylonitrile production. BASF also uses ethylene and Lucite is commercialising an ethylene-based process. In the East, isobutylene oxidation is mainly used to manufacture MMA.

Biotechnology Developments

The biotransformation technology is at an embryonic stage of development as switchgrass needs to be manipulated at the genetic level to drive in-site MMA production. Ceres and Rohm and Haas are looking at this in the United States.

Using an analogy of processing soybeans with solvent extraction combined with upstream farming and logistics cost building on the example of the Metabolix PHA approach, an MMA cost of the order of €850 per ton is possible.

Strategic Issues
In terms of a commercialisation strategy, there is a need to bring together a large resource of expertise ranging from GM expertise, agriculture to grow GM crops for chemicals as well as industry parties like Lucite.

On the legal side, the major driver is the need for greater acceptance of GM crops for chemicals production.

8.3 Fumaric Acid, butanediol and derivatives

There are opportunities for the production of fumaric acid, butanediol and derivatives derived from renewable resources serving engineering polymers, speciality fibres and chemical intermediate applications.

Market Dynamics
The European market for BDO is around 300 000 tons and growing in line with average GDP. In comparison, fumaric acid is a fraction of this at circa 30 000 tons. BDO is consumed for THF/PTMEG, PBT and a range of performance polymers as well as speciality solvents. PTMEG is a key component of spandex fibres. Invista consumes PTMEG for Lycra® production at Maydown in Northern Ireland, this is the UK's largest consumer in the BDO value chain.

Technology Status
Fumaric acid is currently derived from maleic anhydride, itself made from n-butane or benzene oxidation. BDO is produced from several chemistries today, e.g. acetylene, propylene oxide, butadiene and n-butane, at scales ranging from 50 000 tons to over 200 000 tons per year.

Biotechnology Developments
A two stage process for acrylic acid is under development converting glucose and other C6 sugars into fumaric acid for subsequent esterification/hdrogenolysis into BDO,THF or GBL. The first step, a fermentation, proceeds at neutral pH with gypsum as the by-product, resembling the current NatureWorks lactic acid production process. The second stage of the process is commercial as Davy offers a similar process using maleic anhydride.

The bio-fumaric and bio-BDO process is competitive at high oil price, with further improvements possible. In the UK, the dextrose solution price to make a bio-BDO process competitive at $70 per bbl crude oil price needs to be below €200 per ton. Some companies are now focusing on Bio-NMP, to access the higher value products in the BDO chain that may support higher feedstock costs.

Strategic Issues
In terms of a commercialisation strategy, there is a need to bring together an upstream company focused on feedstock and possibly a downstream industry player, working together with either a biotech company or affiliates from academia.

On the legal side more incentive to develop fibre products based on renewables would be a step forward. Many BDO derivatives are already used in sectors like automotive where there is increased use of recycling and renewable materials.

8.4 Acrylic Acid from 3-hydroxypropionic acid

There is an opportunity for the production of acrylic acid and derivatives for hygiene applications and the coatings industry made from renewable resources proceeding via 3-hydroxypropionic acid as the preferred intermediate. Indications are that a biotransformation process can be competitive in a high crude oil price world at a sugar-syrup price below €200 per ton.

Market Dynamics
The European market for acrylic acid is around 850 000 tons and growing in line with average GDP. The market is dominated by glacial acid production for SAP manufacture for diapers, hygiene goods, etc. Coatings also consumes large amounts of crude acid for acrylate ester production, of which butyl acrylate for decorative paints dominates. Several companies like Akzo (was ICI) in Slough consume acrylic acid and butyl acrylate for coatings.

Technology Status
Commercially acrylic acid is currently derived from the two stage oxidation of propylene, followed by a quench and recovery system. The oxidation process co-produces energy in the form of high pressure steam for use in integrated downstream processes such as a acrylic esters and superabsorbent polymers.

Biotechnology Developments
A two stage process for acrylic acid is under development converting glucose and other C6 sugars into 3-hydroxypropionic acid for subsequent dehydration into acrylic acid. The first step, a fermentation, proceeds at sub-neutral pH with 3-HP recovered as the ammonium salt. The 3-HP recovery step is currently complex, but simpler approaches are being developed.

The conceptual process can produce acrylic acid in relatively high yield and can be successfully integrated with wet corn milling in the United States or sugarcane processing in Brazil. In such a case the bio-acrylic acid process is competitive at crude oil prices as low as $40 per bbl (Brazil) and $65 per bbl (US). In the UK the dextrose solution price to make a bio-acrylic acid process competitive at $70 per bbl crude oil price needs to be below €200 per ton.

Strategic Issues

In terms of a commercialisation strategy, there are companies like Novozymes and partners seeking to commercialise their process bringing together an upstream feedstock-focused company (Cargill) and an industry player (undisclosed) with potential acrylic acid consumers. A similar approach would be needed in the UK.

On the legal side, more incentives to develop products like renewable diapers from SAP derived from bio-acrylic acid is probably the approach to take given that acrylic acid consumers in the value chain are already looking to increasingly exploit renewables to support branding activities.

8.5 Strategic issues

Strategies for the development of chemicals from renewable resources in the UK need to consider the entire value chain, from agriculture through to finished downstream derivative products. A further issue is the need for government organisations to commit to major research programmes in "White Biotechnology".

Agriculture
As the Rohm and Haas/Ceres case illustrates, there is a case for genetic manipulation of plants to produce selected desirable chemical intermediates. The Metabolix example of polyhydroxyalkanoates (PHAs) derived from switchgrass also demonstrates this is possible, although agriculture must be adapted and planned to service such opportunities.

Fermentation
A number of semi-commercial and commercial large fermentations for chemicals produce acids. In contrast, the micro-organisms facilitating the fermentation are only stable at or near neutral pH levels. Consequently, there is a need for in-situ salt production necessitating increased recovery complexity. There is a need for the study of genes related to pH tolerance in organisms such as *Aspergillus niger*, and the subsequent transfer of these genes into target microorganisms.

Intermediate Recovery Systems
Recovery systems for platform chemicals and intermediates remain far too complex, requiring acidulation in the case of metal salt recovery, e.g., gypsum, or salt splitting with solvent extraction.

There is a place for more sophisticated but reliable separation trains based on electro-dialysis. These can be very effective, but need to be made more robust and capable of large scale operation, whilst keeping capital investment in line with current membrane chloralkali units.

Integrating Petrochemical and Biotransformation Processes
Examples cited here illustrate the integration of petrochemical process to upgrade the platform chemicals and intermediates derived from renewable resources. Further research is needed to develop robust catalysts that can withstand new poisons encountered when processing chemicals derived from renewables. Petro-catalytic and bio-catalytic chemistries should be combined sequentially as part of developing strategies for upgrading renewable to speciality and commodity chemicals.

Sponsorship
Countries like the United States have publicised major development programmes in exploiting renewable resources. Second generation biofuels are a clear example, where the US Department of Energy (DOE) has committed upwards of $0.5 billion to development consortia. Chemicals activities are not as well publicised but still considerable, driven a number of US agencies including the National Renewable Energy Laboratory (NREL). The UK needs to make major financial commitments to industry and academic consortia to push through new developments under the guidance of expert and independent industry professionals to ensure commercial and technical targets are realistically aligned.