Quantitative Modelling of Industrial Biotechnology and Renewable Chemicals

Final report

Final Report to
Department of Business, Enterprise and Regulatory Reform

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1 Executive summary

The application of biotechnology to the chemical and chemistry-using sectors, or Industrial Biotechnology (IB), could represent an important market for the UK. The sector offers attractive opportunities for growth; nationally in terms of manufacturing, and internationally it terms of maximising home developed knowledge and expertise. However, parts of the sector depend crucially on the availability of land to grow biomass, and technology breakthroughs to ensure feedstock and production costs that are comparable to current petrochemical alternatives.

To properly appreciate what determines a successful bio-chemical industry we have distinguished six different IB chemical categories, i.e. three production platforms, used for the manufacture of low volume and high-volume chemicals, respectively:

Categories of chemicals used for the assessment

Production method	Dedicated single compound production	Biofuel-derived	*In planta*
Description	Production of chemicals using (modified) enzymes [biocatalysis] and (GM'd) whole cells [fermentation]	Production of chemically useful products, as a byproduct of biofuel production	Production of chemicals through (GM'd) crops or algae, and extracting these after harvesting
Feedstock	Various, high-value, glucose, sucrose	Low-cost sugars, vegetable oils	Arable crops
Biotech type	Red, White	White	Green
Low volume example chemicals (Specialty & fine chemicals)	A1 Penicillins, amino acids, S-chloropropionic acid (Avecia UK), PHA, Stereospecific alcohols	B1 Protein-based plastics	C1 PHA (commodity form)
High volume example chemicals (Commodities & platform chemicals*)	A2 Acrylamide (from acrylonitrile) Citric acid, LA/PLA, Glycerol/1,3-propandiol, isoprene (Genencor)	B2 Ethanol, butanol, 1,3-propandiol (from glycerol)	C2 Rubber, MMA, Acrylamid from cyanophycin

*Platform chemicals, defined as chemicals of which the primary use is to transform them into multiple different chemicals

Such a categorization has not previously been applied in the field but is crucial to appreciate the different drivers affecting the industry's development. The expected path of each category was assessed quantitatively under four viable future scenarios.

Main findings

Future market growth potential

A growing industrial biotechnology-based chemical industry is taking shape in the world, offering attractive opportunities for the UK and its industries; 2007 chemical industry Industrial Biotechnology sales in the UK are estimated at around £1.8 billion, or less than 5% of total chemical and pharmaceutical industry sales.

Under different scenarios, UK IB chemical sales are projected to grow between 5% and 11% per annum, up to at least £4.4 billion and at most to £11.8 billion in 2025, which would be equivalent to between 7% and 17% of total UK chemical industry sales. While UK IB-manufacturing opportunities may remain comparatively modest for the foreseeable future, a strong position in this knowledge-intensive industry would allow UK-based companies to increase their market share of the much larger global market: Global IB sales are estimated at £35-£53 billion (3-4% of global chemical industry sales), which under different scenarios are expected to grow to £150-360 billion in 2025.

High value, low volume chemicals

For the UK, a growth of the sales of high value, low volume chemicals direct production or *in planta* has been shown to occur in all four scenarios, implying that a favourable research environment and technology development in this area now could create substantial market opportunities in the future:

- Direct production has proven to be successful in the past few decades and could further increase IB production through support for incremental technology development
- The potential for sales of *in planta* derived chemicals is surprisingly high; while it relies on the technology development and public acceptance of GM crops, the UK industry could take a strong position in this area based on its capabilities in nature-derived chemicals (such as vegetable oils) and chemical formulation, and a strong customer base for such products

Biofuel-derived chemicals

Until 2025, sales of chemicals derived from biofuel production appear to be comparatively modest even under favourable scenarios. Sales of such chemicals are expected to develop independently from government interventions, if and when a viable biofuel industry forms. The market is most attractive when production of biofuels and their feedstocks are competitive with, or preferably more cost-effective than crude oil-derived fuels *and* when competition between biofuel and food/feed crops is avoided.

A chemical industry that relies on biofuel production for raw materials is structurally different from the current petrochemical industry. While the latter is based on the scale and efficiency of the oil refining industry, the former could be significantly smaller and more distributed in order to cost-efficiently source biomass from surrounding lands unless significant feedstock imports are involved. The same, incidentally, will be valid for *in planta* production.

Low value, high volume chemicals

For low-value chemicals derived through *in planta* and direct production, sales have been shown in the present analysis to be strongly reliant on the future price of oil. This reliance makes the production of these IB chemicals an area of uncertainty in terms of market opportunities for *in planta* in particular.

Conclusions

This analysis shows that there are significant opportunities for the UK and that action may be taken to further improve the attractiveness of the UK for IB-related companies and institutes to develop and commercialise new ideas, products and processes. For most of the chemical groups the limitation is on technology development and, for high volume chemicals, on oil prices. While financial incentives will have limited effect in many markets, governments can facilitate by improving the climate to do business.

In particular, there should be action to stimulate the development of a knowledge industry on which *in planta* and direct production can thrive. This includes enhancing technology development rates and mitigating risks to high tech projects allowing a rapid exploitation of new products produced by GM, fermentation and biocatalysis. Emphasis should be placed on addressing key concerns about such GM technology, i.e. avoiding unwanted diffusion of genetic material in the environment, and long-term stability of the modified crops.

High volume, low value chemicals produced through direct production or *in planta* will occur when industry is able to produce chemicals cost efficiently and there is a sufficiently high oil price. While some developments are anticipated to take place in this area, there would appear to be little benefit in specific government interventions for these categories of chemicals beyond stimulating those mentioned above for the low volume categories.

Stimulating the development of a UK biofuel industry should be a strategic decision based on whether the UK wants to decrease dependency on foreign sources of oil and/or be less vulnerable in periods of high oil prices. Associated chemical production may be expected to take place independently once a sizable biofuel industry emerges, as has happened in the early 1900s from oil refining.

If biofuel developments are to be supported, the UK should prefer to stimulate breakthrough technologies that do not compete with food production and that address the national disadvantages based on geographical location, e.g. technology based on off-shore algae which are not tied to the UK's location and which would draw upon off-shore capabilities already available.

Market scenarios and underlying drivers

The scenarios illustrate how the IB market in the UK may develop over the period to 2025 and beyond. To do this we identified clearly distinguishable, singular movements in the wider environment with a high, direct and/or indirect impact on the UK divided by:

- *Drivers, which* are developments that have high impacts on IB production, with high uncertainty about the outcomes including oil/naphtha price, bio-feedstock prices, technology breakthroughs (further broken down by *in planta,* lignocellulosic and direct production processes)
- *Trends, which* are developments with medium to high impact, but rather high certainty of direction such as financial incentives, market demand for chemicals, development of high volume biomass conversion, changes in arable land, economic prosperity and consumer interest in product attributes

Drivers were then quantified using end-points (e.g. for oil price, in real terms a low value of 50 USD/bbl and high value of 150 USD/bbl were assigned). By looking at the correlations between each end-point, it was possible to construct four logically consistent and representative scenarios. These scenarios were primarily based on either high/low differential between feedstock prices and high/low levels of technology breakthrough. The scenario development was supported by information on other trends. By definition none of the scenarios is more or less likely to occur than the other. Rather, they provide insight for users in those actions or positions that would be more or less successful in each alternative future. From this, strategies with higher success rates can be derived. The scenarios used for this assignment are summarised in the table below.

Descriptions of scenarios

Name	Description of Scenario
Stuck	The focus for growth is in fine and speciality chemicals; fluctuations in oil and food crops prices mean that the biofuel technology breakthroughs are absent. Biofuels production is seen to compete with other land uses
Knock On Wood	There is an initial boom in cellulosic ethanol technology due to technology breakthroughs and high oil prices. The long term growth then levels off due to competition with food and reduced availability of alternative low-cost feedstocks from the UK or internationally The secondary bio-chemical industry remains focused on smaller scale biocatalysis and fermentation opportunities which continue to grow based on successful technology development
Green Bloom	The ability to exploit feedstocks which do not compete with arable crops results in the development of a thriving bio-chemical industry akin to the petrochemical boom of the early 1900s. At the same time IB is increasingly important for specialty and fine chemicals due to ongoing technology development
Electrified	Despite IB technology breakthroughs, a sustained drop in demand for crude oil makes industrial biotechnology only competitive for low volume/high value chemicals

Model structure and results

The model uses current estimates of market size projected to 2025 based on several key parameters. As accurate data is not available, Arthur D. Little has estimated current market sizes based on literature survey, comparative analysis, and interviews. On this basis, world market size of IB in 2007 was estimated at £35-£53 billion, of which approximately £1.8 billion may be attributed to the UK, (£0.4 billion for base and commodity chemicals; £1.4 billion for fine and speciality chemicals).

In order to get order-of-magnitude sizes of the future market under each scenario, each of the chemical categories is modelled separately:

- For low volume/direct production (A1 category), assuming a continuation of technology developments in the past 10-20 years, the model tracks technological development through time (moving from approximately 6.2% share of overall chemical sales to 12.5% between now and 2025)

- For high volume/direct production (A2 category), market size is still a function of technological breakthrough. However, the incentive to undertake this research is such that it is stronger when there is a relatively high oil price compared to bio-feedstock prices, meaning that higher breakthrough rates occur when alternative IB chemicals can be produced at a sufficiently lower cost than the traditional chemical. We therefore model the production cost of a representative IB chemical and compare this with relative price of a traditional alternative, with higher breakthrough rates occurring when the relative cost of IB is sufficiently lower than the price of traditional chemicals. This higher breakthrough rate (capped at 5%) represents a maximum share of overall chemical sales that this category can expect to achieve, and is based upon similar levels of penetration achieved by the A1 category in the first few decades of its development
- For biofuel-derived chemicals (B1 and B2) we start by modelling the production of biofuels. Where it is more cost-effective to produce the biofuel then the production of biofuel-derived chemicals will occur, otherwise it will not. The volume that is produced is assumed to be a function of future transport fuel demand, set at approximately 10% of total UK demand in 2025. This represents an upper limit. If there are, for example, limitations on feedstock availability or biorefinery capacity then this will cap the volume produced. Related to the total transport fuel demand, we have assumed that 1.6% to 4% equivalent of the total biomass used for biofuels will be valorized to chemicals (depending on feedstock)
- For chemicals produced *in planta* (C1 and C2) we estimate the costs of producing chemicals. When the cost of producing the IB chemical alternative is sufficiently lower (by at least 15%) than the price of the traditional chemical then there is sufficient incentive to undertake the R&D necessary to allow its manufacture. Additionally, given that to-date no examples of GM *in planta*-derived chemicals exist, within the 15-year timescale the model assumes a maximum penetration of 4% for low volume chemicals, and 2% for high volume chemicals

To quantify the market for IB in 2025, the model provides results for the totals of four scenarios for global and UK market values, UK production volume and CO_2 savings. These are summarised in the table below.

Summary of results for scenarios (2008 real terms)

Summary of results	Stuck (oil price at 100 USD/bbl)	Knock On Wood (oil price at 150 USD/bbl)	Green Bloom (oil price at 150 USD/bbl)	Electrified (oil price at 50 USD/bbl)
Global IB market value (billion £)[1]	150	346	360	220
UK IB market value (billion £)[2]	4.4	11.4	11.8	6.2
UK IB production (million tonnes)	0.8	1.9	2.2	0.5
CO_2 savings[3] (million tonnes CO_2 p.a.)	2.0	4.7	5.2	1.4

Source: Arthur D. Little; Note 1: This does not include the global market for biofuels which could be over £150bn. Note 2: This does not include the wider biofuel market which could range from less than £1bn to over £7bn for the UK. Note 3: If calculated based on the production volumes for the UK the model is using in this study, CO_2 savings from bioethanol production would be between 1.3 and 10 million tonnes of CO_2 and savings from biodiesel production would be between 3.0 and 9.7 million tonnes

The highest market value is achieved in the Green Bloom scenario with a UK market of £11.8 billion and 2.2 million tonnes of chemicals produced. Beyond 2025, it is expected that this market will continue to grow at a similar rate; further growth would be associated with chemical production requiring minimal use of land.

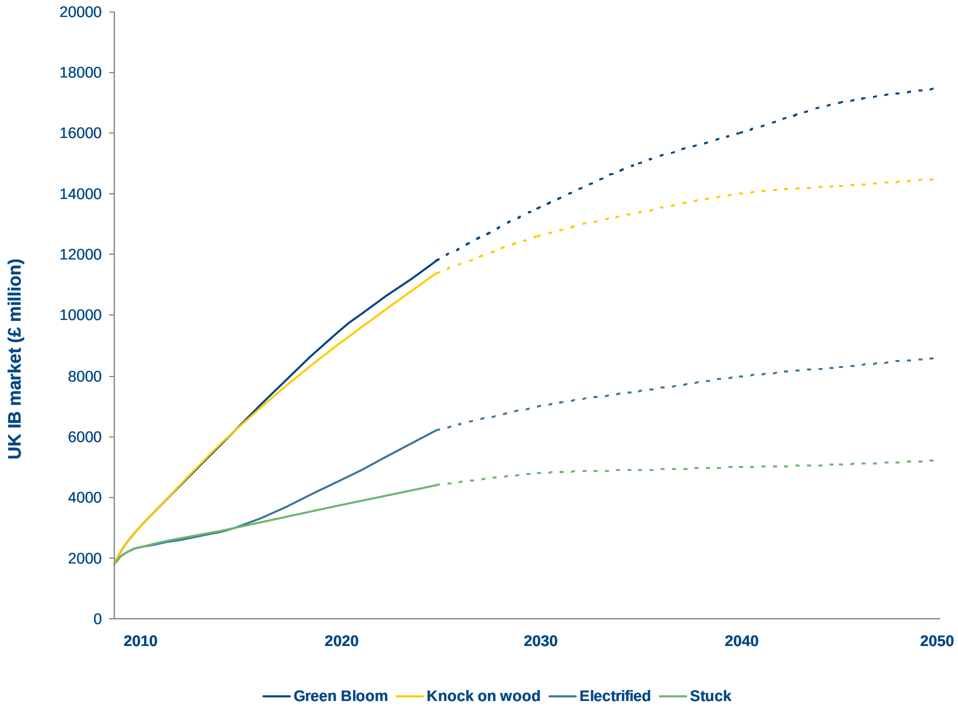
The differences between the Green Bloom and Knock On Wood scenarios are due to the absence of breakthroughs in algal technologies and limitations to land use for lignocellulosic feedstocks linked to competition with food and feed for the Knock On Wood scenario. Under the Knock On Wood scenario, it is expected that the market will level off after 2025 as low-cost feedstock sources in the UK would have been exhausted; however international markets could continue to grow.

In comparison, under the Electrified scenario the volume of chemicals produced is the lowest of all the scenarios primarily due to low oil prices. While the rate of market growth could be higher between 2015 and 2020, it will level off after 2025 due to a low price differential between bio-feedstocks and traditional feedstocks.

The Stuck scenario has the lowest market value at £4.4 billion. A lack of technology breakthroughs forces the biofuels industry to remain dependent on arable crops where there is strong competition with food and feed. Volatile oil prices further prevent long-term investments restraining the growth of IB.

It is anticipated that the slow growth rate would continue beyond 2025 reflecting ongoing breakthroughs in low volume/high value products. Future trajectories for each scenario are presented in the graph below.

UK IB market values for scenarios until 2050

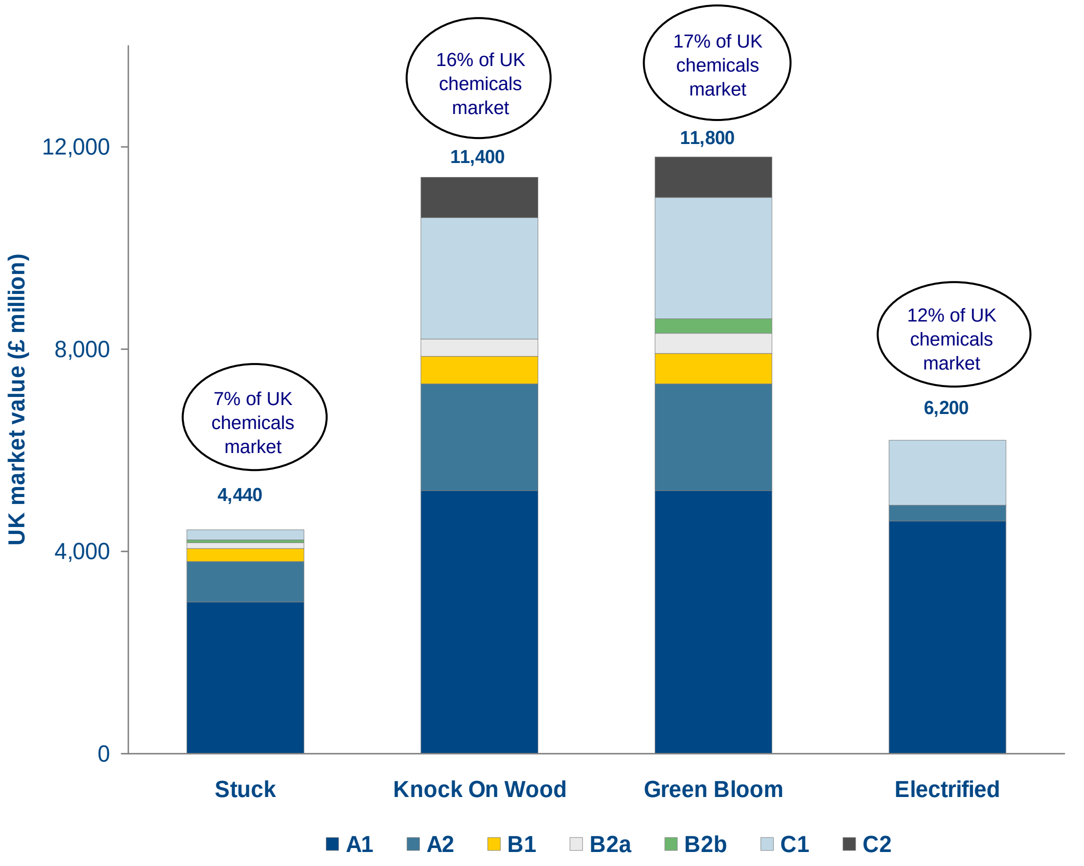


Source: Arthur D. Little. Note: Baseline for the UK IB market value for 2009 is based on estimates for the market in 2007 (see Table 2).

UK market values for 2025 are also compared in the figure below showing also the split between chemical categories. An overall conclusion is that market opportunities for biofuel-derived chemicals are limited in all scenarios as producing biofuels in the UK remains comparatively expensive. However, there are niche markets for all biofuel-derived chemicals in three of the four scenarios. Where technology breakthroughs occur through the use of lignocellulosic materials, bioethanol-derived chemicals (B1 and B2a) are more attractive compared with biodiesel-derived products (B2b). Biodiesel derivatives become more competitive when algal feedstocks can be exploited (as in the Green Bloom scenario).

High value chemicals produced *in planta* (C1) and chemicals produced through dedicated production (A1 and A2) represent the largest market values in all scenarios. As the technology and processes for dedicated production are more advanced, continuous, incremental technology developments are important in developing these markets; the production of these chemicals is less affected by changes in feedstock prices.

UK market values for 2025 split by scenario and chemicals categories (2008 price level)



Source: Arthur D. Little

Lower value and high volume products produced through dedicated production (A2) are more dependent on both feedstock prices and technology breakthroughs, but the market will be attractive as long as there is a clear cost differential between traditional and bio-based feedstock prices. High value chemicals produced *in planta* (C1) are relatively competitive when feedstock availability is not limited.

Low value and high volume products produced *in planta* (C2) are attractive when significant technology breakthroughs are achieved and in scenarios with high oil prices. Relatively high production costs restrain the required scale-up for high volume production and due to the high volumes of feedstocks needed, competition with food and feed is likely where feedstock availability is limited.

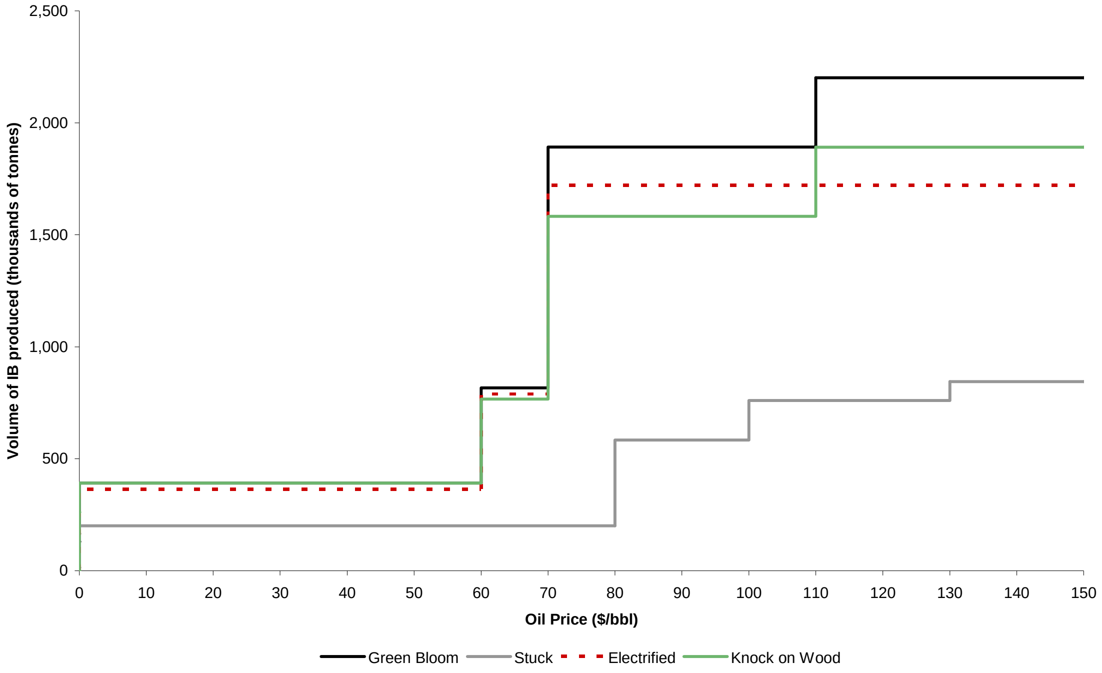
Furthermore, significant breakthroughs in lignocellulosic and algal feedstocks (and especially off-shore cultivation of the latter) would decrease these land use requirements and help avoid competition with food.

Model sensitivities

Whether chemicals are produced using traditional or bio-chemical routes, feedstock costs are the most important driver of their market attractiveness and a key risk for the development of the IB markets. For the purposes of this study, the key factor is the relative cost competitiveness of bio-based feedstocks with traditional feedstock prices, namely crude oil and naphtha prices.

By adjusting the oil price, we have identified tipping points at which bio-based chemicals become attractive compared with their petro-chemical counter parts. These tipping points, presented in the figure below, vary by scenarios, where different oil prices have been used.

Impact of changes in oil price to volume of IB products produced by scenario



Source: Arthur D. Little analysis

With current bio-based feedstock prices, the new market potential of IB will not be fully realised when the oil price falls below $60 per barrel for any of the scenarios.

The risk associated with changes to oil prices is significant and not readily mitigated. By maintaining or increasing efforts to develop low volume chemicals (such as A1 and C1), the UK could avoid excessive exposure to oil price volatility. While reducing bio-feedstock prices can be important in some cases, it is unlikely to counteract a scenario where oil prices are low.

The chemical industry in the UK accounts for just over 4% of emissions out of a total level of UK emissions of 636 million tonnes in 2007. Even when embedded carbon[1] is considered (as in this study), the overall proportion of national CO_2 savings is not high. However, IB can play a role in reducing emissions within the sector.

There are numerous mechanisms used by governments to reduce emissions, such as the use of a carbon price through markets (e.g. Emissions Trading Scheme). The analysis shows, however, that carbon prices do not cause chemical production to become unattractive under the Stuck, Green Bloom and Knock On Wood scenarios[2] as oil prices are already high; further carbon prices would only raise the cost of production of traditional chemicals even further and make it less attractive than IB production. However, when the oil price is low (i.e. $50/bbl as in the Electrified scenario), a price of carbon between £30 and £70 per tonne of CO_2 would increasingly encourage IB production.

[1] Total carbon emitted along the value chain, from extraction/harvest of raw materials, all along to and including company operations

[2] Note: Under carbon prices above £300/tonne, chemicals within the C2 category could be produced in the Stuck scenario

2 Introduction

2.1 Background

On behalf of the established Industrial Biotechnology Innovation and Growth Team (IB-IGT), the Department for Business, Enterprise and Regulatory Reform (BERR) commissioned Arthur D. Little to identify and quantify future market growth opportunities and challenges in Industrial Biotechnology (IB). This project builds on existing work conducted by IB-IGT over the past year.

IB-IGT aims to deliver a strategic action plan that is aligned with other related policy initiatives to encourage and increase the use of industrial biotechnology in the chemicals sector (and thereby improve the profitability and sustainability of the sector). Under the guidance of an industry-led Steering Group, three working groups have been established: the Technology & Manufacturing Working Group, the Finance/Investment Working Group and the Policy Measures Working Group. These groups focus on improving the capabilities of the sector and identifying relevant issues within their own remits.

The IB-IGT has identified opportunities and barriers for IB and recommended what mechanisms could help achieve and overcome them. The three main work strands focused on technology, finance and policy. Initial findings and recommendations have emerged and these have been validated with stakeholders and will eventually feed into the final strategic action plan that is to be published in Q2 2009.

This particular study focuses on quantifying how identified drivers and forces and the use of policy levers could affect the sector over the next 15 years and beyond under four different future scenarios. The model allows for testing of propositions to support the previous work carried out by IB-IGT.

2.2 Objectives

The overall aim of this work is to model a series of robust scenarios that map the interaction of a range of drivers which will influence the development of IB and renewable chemicals in the UK. The model and outcomes of this work will help policy makers compare different levers and options with regards to their potential impacts on the scale of opportunities and challenges and hence their ability to help achieve higher up-take of IB in the medium and long term.

2.3 Scope

Timeframe

As this study considers the medium and long term markets, IB scenarios are modelled up to 2025; this timeframe is sufficiently long-term to represent emerging technologies and to an extent, can be supported by the available data and IB technology assessments (e.g. the Technology Horizon Scan prepared by Bioscience for Business Knowledge Transfer Network). Extrapolations extending up to 2050 are also discussed through testing results by adjusting key variables in the model supported by commentary and caveats.

Chemicals considered

The focus for the analysis is for chemicals derived from industrial biotechnology based on renewable feedstocks. Importantly, for this analysis we have distinguished between six different IB chemical categories, i.e. three production platforms, used for the manufacture of low volume and high volume chemicals, respectively (Figure 1). Such breakdown has not been previously applied in any IB market assessments and therefore represents a novel approach in the understanding of the future IB market. The analysis will consider representative groups of chemicals defined by possible technologies and market opportunities:

- Fine and specialty chemicals have been grouped together to avoid confusion around the terminology and definitions. Most of the drivers will influence both groups in a similar fashion
- The speciality/fine chemicals and platform chemicals have been broken down into further groups reflecting the range of production methods that are likely to be affected by a different set of drivers

Figure 1: Categories of chemicals used for the assessment

Production method	Dedicated single compound production	Biofuel-derived	*In planta*
Description	Production of chemicals using (modified) enzymes [biocatalysis] and (GM'd) whole cells [fermentation]	Production of chemically useful products, as a byproduct of biofuel production	Production of chemicals through (GM'd) crops or algae, and extracting these after harvesting
Feedstock	Various, high-value, glucose, sucrose	Low-cost sugars, vegetable oils	Arable crops
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High volume example chemicals (Commodities & platform chemicals*)	A2 Acrylamide (from acrylonitrile) Citric acid, LA/PLA, Glycerol/1,3-propandiol, isoprene (Genencor)	B2 Ethanol, butanol, 1,3-propandiol (from glycerol)	C2 Rubber, MMA, Acrylamid from cyanophycin

*Platform chemicals, defined as chemicals of which the primary use is to transform them into multiple different chemicals

The choice of chemical categories is based on the following rationale:

- Chemicals within the same category should be influenced by similar set of drivers
- The focus is on the primary product of the process (i.e. further derivatives are not explicitly analysed)
- The categorisation recognises that there is an overlap between some categories, for example, 1,3-propandiol can also be produced both by a biofuel-derived production method and a dedicated single compound production
- Fatty acids and other chemicals directly extracted from crude vegetable oils (e.g. rape seed oils) are excluded as key process is mechanical rather than relying on IB

Furthermore, a number of IB-related activities are excluded in line with the scope of this assignment including:

- "Red biotechnology" that uses biotechnology to manufacture pharmaceutically active compounds; white biocatalysis methodologies are included
- Biofuels *used as a fuel*; the analysis *does* consider the use of chemicals such as ethanol or butanol that could be used as part of an IB process. It will also consider the roles of drivers such as financial incentives available for biofuels
- Products produced by thermo-chemical pathways – e.g. gasification or pyrolysis; products derived from syngas and further transformation using IB would not be considered

Geographical scope

The analysis of the selected chemicals focuses on the UK market, but within the global context. Policy options available need to be analysed at the national level, yet the UK market will be influenced by external market forces (for example regarding sourcing feedstocks) and these need to be considered.

While a number of feedstocks which would be produced in other countries have been considered, (e.g. sugar cane in Brazil, maize in USA for bioethanol, soya beans in USA for biodiesel, palm oil in Asia for biodiesel), the model focuses on UK IB production and market opportunities.

2.4 Approach

Our overall approach consisted of four phases and is illustrated in Figure 2. Following agreement of scope and review of findings from IB-IGT's previous work, an outline of the model-structure and scenarios were developed. We then developed the information for the underlying drivers for the scenarios including a series of interviews with IB-IGT and other experts (Section 3.1). The third step involved confirming the scenarios and building the model. The final step involved developing outputs from the model and testing for specific sensitivities (Chapter 4).

Figure 2: Approach for quantitative modelling of IB

1 Confirm scope	2 Assessment of drivers	3 Confirm scenarios and build model	4 Analysis and reporting
1.1 Kick-off meeting to confirm scope, workplan, and deliverables 1.2 Interpret outputs of workshop, also drawing on our evidence base 1.3 Develop outline model structure and scenario-structure 1.4 Select shortlist of chemical streams for further analysis 1.5 Internal workshop to: – Validate model structure – Review outline scenarios	2.1 Validation of existing drivers 2.2 Source data for quantifiable drivers 2.3 Review key gaps, uncertainties and key assumptions 2.4 Review meeting to discuss data quality	3.1 Develop and confirm scenarios with IB -IGT based on specific quantified endpoints 3.2 Build economic model based on model structure and data from Step 2 3.3 Presentation of key scenarios including forecasting until 2050	4.1 Determine likelihood of given scenarios and impacts on industry/ economy 4.2 Identify levers and actions which will enable the realisation of future market opportunities 4.3 Workshop to review sensitivity of model to use of specific levers and identify key priorities for IB-IGT 4.4 Production of report and final version of model

2.5 Structure of this report

This report is organised into five sections:

- Section 1 provides the executive summary of the report
- Section 2 includes the introduction including background for this study, objectives, the scope of this study and the approach used
- Section 3 presents the main findings and conclusions
- Section 4 provides details on the scenarios themselves
- Section 5 includes an overview of the model and gives details on the results for each scenario
- Section 6 discusses the key risks and opportunities for the UK IB market

3 Main findings and conclusions

The application of biotechnology to the chemical and chemistry-using sectors, or Industrial Biotechnology (IB), could represent an important market for the UK. The sector offers attractive opportunities for growth; nationally in terms of manufacturing, and internationally it terms of maximising home developed knowledge and expertise. However, parts of the sector depend crucially on the availability of land to grow biomass, and technology breakthroughs to ensure feedstock and production costs that are comparable to current petrochemical alternatives.

Crucial differences exist between low-volume, high value chemicals – that are found to have generally good prospects – compared to high volume, low value chemicals where competition from incumbent chemicals at low oil prices is an important barrier.

The low volume, high value chemicals through direct production or in planta technologies have the potential to grow under each of the scenarios assessed. Those produced through direct production methods represent a range of 45% to75% of total UK IB market values under different scenarios, while the market value out of the total UK IB market for low volume *in planta* chemicals range between 5% to 21%. The key drivers vary between the two categories:

- The key driver for direct production is continuous incremental technology development for this platform; this technology has proven itself to be successful and cost-effective in the past few decades and can be developed even further
- The potential for *in planta* is surprisingly large; the key drivers for *in planta* technology breakthroughs are further advances in genetic modification of plants through research, development and demonstration, and public acceptance of GM crops to produce useful materials and food

For both of these categories, market size is not primarily driven by the difference between bio-based feedstock prices and oil prices. Further development of these markets should be enhanced as it is low risk based on development of proven technology and drawing on a good customer base in the UK. Key areas which could influence future direct or *in planta* production of low volume, high value chemicals include:

- Developing an industrial biotechnology cluster to enhance technology development rates involving both the research community and the companies exploiting the R&D
- For low volume, high value direct production, mitigating risks to high-tech IB projects allowing a rapid exploitation of new products produced by fermentation and biocatalysis. This would include measures such as pilot plants

- Similarly for high value, low volume *in planta* production, there are opportunities to extend existing capabilities in specialty oils and other compounds. This includes supporting R&D for GM chemicals and mitigating risks to high-tech IB projects. Emphasis should be placed on addressing key concerns about such GM technology, i.e. avoiding unwanted diffusion of genetic material in the environment, and long-term stability of the modified crops

Extension into high volume, low value chemicals can primarily be achieved when a bio-chemical industry is developed in close association with a biofuels industry. This should be a strategic decision to the UK after 2025 based on whether the UK wants to decrease dependency on foreign sources of oil and/or be less vulnerable in periods of high oil prices.

The market is most attractive when production of biofuels and their feedstocks are competitive with, or preferably more cost-effective than crude oil-derived fuels ***and*** when competition between biofuel and food/feed crops is avoided. Comparing the scenarios, the highest potential market value is achieved in the Green Bloom scenario, where the combined total for the biofuel-derived chemicals category reaches £1.3 billion (11% of UK IB market). In general, bioethanol-derived chemicals are more attractive than biodiesel-derived ones.

This could happen, for instance, when non-arable land can be made productive for lignocellulosic ethanol, when sea-borne biorefineries can extract biodiesel from algae, or when waste material from biofuel and chemical production can be used as feed, thus substituting land used to grow e.g. soy for feed. In such cases, an effective "decoupling" between crops and oil can occur, where the demand and price of oil and crops are no longer correlated and biofeedstocks can move to a price level independent of the oil price. These decoupled markets can be developed by support for technology development as well as mitigating risks to the large capital investments that may be required.

Development of these markets could be enhanced further by R&D in lignocellulosic and algal materials or other configurations where competition with food does not exist. It should be noted that, the development of liquid biofuels as a more sustainable alternative for fuel derived from fossil sources is quite attractive from a high-level, macroeconomic point of view. As opposed to e.g. electricity powered transport, biofuels can be readily delivered to the end consumers through the existing downstream infrastructure and capacity built up around petrol and diesel.

The direct production of high volume, low value chemicals through direct production is possible but is highly dependent on the long-term price of oil (and thus naphtha and the bulk petrochemicals derived from it). New, low value IB-derived products may quickly be uncompetitive in a low oil price scenario, compared to the existing, and highly cost optimized petrochemical analogues. ***Some developments in this area are anticipated and additional R&D and incentives could potentially stimulate the growth of this market even further.***

It is most likely that large volume in planta production, would need the use of mandatory targets – making this an area of great uncertainty in terms of any future investment and market opportunities. It is therefore not considered as a priority to the IB IGT.

The big opportunity for the UK is to develop IB knowledge and expertise to be used in the global economy. Compared to the global market for IB, actual production in the UK of IB chemicals for the local or even the export market will remain relatively limited. However, the more interesting opportunity for the UK is not to be the IB manufacturing location of the world (where it will struggle to compete with nations with lower labour costs and/or cheaper biomass sources), but to become the IB knowledge centre of the world.

Further development of these markets can be enhanced by making sure the UK is the prime location to establish IB-related business and institutes, e.g. by establishing one unique area where IB business can come together and benefit from local knowledge and facilities, by offering tax benefits, and offering an attractive place to live for knowledge workers and their families.

4 Scenarios

4.1 Scenario development

To develop the scenarios for 2025, a five-step process was adopted, including:

- Defining the scenario focus including the current IB markets in the UK to place the scenario development exercise in context
- Identifying the key forces, such as feedstock prices and technology among others, which represent broader areas of movement within the scenario focus
- For each force, identify specific drivers and trends with associated potential end-points which could influence the future IB market
- Develop scenarios primarily based on coherent combinations of high impact/high uncertainty drivers
- Quantify markets under each scenario through use of driver end-points within the model (Section 4.2) and test sensitivities of the model

Defining scenario focus

The first step in developing the scenarios involved agreeing a focus for the study. The focus for the scenarios was based on the prior work conducted by the IB-IGT and other background work described above. The focus was agreed to be:

> *"The structure of global Industrial Biotechnology industry for six categories (listed in Figure 1) of chemicals by 2025 and beyond, and impacts on the UK"*

The scenarios are built around this focus through the use of key drivers and trends which inform how the focus may develop over the timeframe considered.

Current market sizes for industrial biotechnology

Determining reasonably accurate sales figures for global Industrial Biotechnology activities is not without challenge. While there are many documents describing the (expected) virtues of the industry and its products, actual figures, particularly at an aggregate national, regional or global level, are scarce. As a result, there is a risk of overstating actual business activity, as often happens in the embryonic phase of a new technology. Probably the most quoted figures are those determined by the consultancy, McKinsey, projecting that white biotechnology would be applied in the production of 10-20% of all chemicals sold by the year 2010[3], i.e. equivalent to € 200-400 billion.

[3] EMBO reports 4, 9, 835–837 (2003); 2

We estimate the size of IB as a share of total chemical sales on 2007 at 3%-4%, or € 50-75 billion. Table 1 below summarizes the most important IB market size estimates available in the open literature, and how these have been arrived at.

Table 1: Comparison of estimates for the global IB market

Source	Year	Share of IB in global chemical sales	Estimated global sales (billion)	Remark
Arthur D. Little, 2009	2007	2.7-4.1%	€ 51-77	Literature survey & comparative analysis; interviews
USITC, 2008[1]	2007	n.a.	USD 30	Based on US industry survey
JRC EU report, 2007[2]	2005	n.a.	€ 13.3	Biopharmaceuticals, vaccines & diagnostics
TVM Capital, 2006[3]	2004	3%	€ 40	Estimates, industry survey
Kircher, 2006[4]	2005	n.a.	€ 50	
McKinsey, 2003[5]	2010	10-20%	USD 200-400	Forecast based on slow and fast market uptake

1. USITC publication 4020, "Industrial Biotechnology: Development and Adoption by the US Chemicals and Biofuel Industries", July 2007; 2. Zika et al., JRC Reference report "Consequences, Opportunities and Challenges of Modern Biotechnology for Europe", 2007. 3. http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/NeoBio/fi/Dokumenttiarkisto/Viestinta_ja_aktivointi/Loppuseminaari_06/7_Wolf.ppt#307,1,Are Industrial Applications in Biotechnology Interesting for Investors?; 4. M Kircher (2006) „White Biotechnology: Ready to partner and invest in" Biotechnology Journal, Vol. 1, Issue 7-8, pgs 787-794; 5. *EMBO reports* **4**, 9, 835–837 (2003)

Our estimate has been derived in large part from what we judge are the most reliable numbers available to date, namely those compiled by the United States International Trade Commission (USITC)[4] using data submitted in response to US International Trade Commission questionnaire. For 2007, this revealed a total of USD 30 billion in bio-based chemical sales, roughly 80% of which can be attributed to pharmaceutical companies. The sales figures include:

- Chemicals derived from biocatalysis and fermentation, ~ 75% of total
- Chemicals produced using renewable resources, ~ 15% of total
- Enzymes and microorganisms, ~ 10% of total

Remarkably, US bio-based chemical sales have registered only very limited growth between 2004 and 2007: just 11.4% or 3.7% per annum, short of the overall US market which grew as much as 25% in the same period.

[4] USITC publication 4020, "Industrial Biotechnology: Development and Adoption by the US Chemicals and Biofuel Industries", July 2007

We have used the USITC numbers to determine a high and low estimate for the total global market as well as sales in Europe and Asia. To do so, chemical industry sales figures were taken from Cefic[5], except for US and Canada which were obtained from C&EN[6]. Sales were determined to constitute 61% of fine and specialty chemicals (pharmaceuticals, specialty and consumer chemicals, specialty plastics[7]) and 39% base and commodity chemicals (base chemicals and commodity plastics).

First, taking into account some further sales in Canada we have determined USD 33 billion as the minimum estimate for the North American IB market size (to be compared to total chemical and pharmaceutical sales in the US and Canada of USD 680 billion in 2007, or 5%). However, if we assume that the USITC did not get a full response from the US industry, and identified only 80% of all activities, then we can arrive at USD 40.3 billion as a high estimate.

Estimates for European and Asian activities were subsequently determined. A high estimate was obtained by applying the high estimate of US market share of IB in pharmaceutical sales (~18%) and in chemical sales (~ 1.7%) to the European pharmaceutical and chemical markets. Asian market size was then determined at a quarter of combined sales, based upon the fact that 80% of IB R&D is done in North America and Europe. A low estimate was obtained by taking the European and Asian high estimates, and discounting it relative to the US for the fact that the US has 75% more products in the pipeline[8].

Given the significantly higher penetration of white biotechnology in the fine and specialty chemicals sector, it was assumed that 80% of all white biotechnology sales are currently attributed to fine and specialty chemicals and 20% to platform and commodity chemicals. On this basis, high and low estimates of the market share of IB have been determined, by region and type of chemical, as shown in Table 2. The high estimate would put the world market size of white biotechnology at around € 77 billion, or 4.1% of global sales. The low estimate yields a market size of just over € 50 billion, or 2.7%. Extrapolating these figures to the UK, and accounting for the fact that UK has a large share of the global pharmaceutical sales, a high estimate of UK IB sales is likely to be in a region of €2.6 billion, or £1.8 billion[9] in 2007.

[5] http://www.cefic.be/en/Statistics.html

[6] C&EN using Department of Commerce data; http://pubs.acs.org/cen/coverstory/86/8627cover.html

[7] www.plasticseurope.org; PU and other non-high-volume plastics constitute 26% of total volume plastics volume; Assume 30% of sales is specialty plastics

[8] Zika et al.: JRC Reference Report, 2007

[9] Exchange rate used: €1 = £0.685

Table 2: Estimates of current market sizes for white biotechnology and traditional chemicals

2007 estimates (€ billion)	World	USA and Canada	Asia	Europe	UK (GBP billion)	Rest of the World
Total chemical sales	**1900**	**486**	**690**	**537**	**38**	**188**
White biotechnology (high estimate)	*77*	*29*	*15*	*33*		*<1.0*
White biotechnology (low estimate)	*51*	*24*	*9*	*19*	*1.8*	*0.0*
Overall % of white biotechnology (high)	*4.1%*	*5.9%*	*2.2%*	*6.1%*		*<0.1%*
Overall % of white biotechnology (low)	*2.7%*	*4.9%*	*1.3%*	*3.5%*	*4.7%*	*0.0%*
Fine/specialty chemicals	**1160**	**296**	**421**	**328**	**23**	**115**
White biotechnology	*41*	*19*	*7.1*	*15*	*1.4*	*0.0*
% of white biotechnology of total fine/specialty chemicals	*3.5%*	*6.4%*	*1.7%*	*4.6%*	*6.1%*	*0.0%*
Base/commodity chemicals	**741**	**189**	**269**	**209**	**15**	**73**
White biotechnology	*10*	*4.7*	*1.8*	*3.8*	*0.36*	*0.0*
% of white biotechnology of total base/commodity chemicals	*1.4%*	*2.5%*	*0.7%*	*1.8%*	*2.4%*	*0.0%*

Note: The values for the different regions do not add up to the World values as the UK figures are in GBP, while the rest are in Euro

Identifying market forces

The future development of the industrial biotechnology market can be described through industry *forces* which are clusters of drivers and trends. These represent broader areas of movement within the scenario focus which will impact on future market development:

- **Traditional feedstock prices**: Cost differentials between oil and naphtha prices and bio-based feedstock prices directly influence the competitiveness of shifting to bio-chemical production routes. The margins producers can get from petrochemical products versus bio-chemical ones will determine the attractiveness of the market
- **Technology: availability of low-cost solutions**: Currently, for most products, producing chemicals through bio-chemical routes is considerably more expensive compared to traditional production routes. For other products, the technology does not even exist yet (or has not been commercialised). Technology needs to provide low cost solutions and the possibility for scaling up production
- **Land availability, bio-feedstock availability**: Especially in debates around biofuels, land use has been a controversial issue. Converting land for producing energy crops (or any bio-based feedstocks) competes with other land uses - notably food production, where rising food and deed demand (driven by population growth and increasing prosperity) is a critical driver and significant limitation on the uptake of biofuels and IB chemicals

- **Societal acceptance of industrial biotechnology and boundaries for use of genetic modification**: Historically, the chemicals industry has received significant societal scrutiny on its environmental impacts with numerous NGOs lobbying against it. Although this has slightly subsided, genetically modified organisms (GMOs) have attracted negative attention from the media, public and NGOs, especially regarding their use in food products. Public acceptability and perceptions of costs and benefits of industrial biotechnology (and using GMOs) vs. traditional chemical production will influence the demand for products
- **Consumer demand** (including societal desire for "green" products): Consumer demand is primarily affected by product attributes and features. In addition some consumers are increasingly conscious about the impacts of their consumption and choosing products that have low-impacts on society is seen as a way to contribute to a low-carbon economy
- **Regulations and taxes**: Private sector investments are largely dependent on how governments regulate their industries and even more so, how they see these regulations will likely develop in the future. Regulations provide opportunities (e.g. the Renewable Transport Fuels Obligation encouraging investments in renewable fuels in the UK) as well as challenges to companies' operations (e.g. carbon prices to fossil-fuel intensive businesses) thereby influencing investments in IB chemicals
- **Financial incentives**: These can encourage investments in sectors, such as IB, where IB production methods and costs are currently less competitive to traditional production methods. Following the *fuels first then chemicals* path, incentives for investment in biofuels production are likely to encourage investments in IB (for chemicals derived from biofuels). Because of the need to develop low-cost technology solutions, subsidies for research and development in these technologies could potentially further encourage IB investments
- **Trade protectionism**: Global liberalisation opens up borders and enhances trade flows, while domestic demand for protectionisms restricts these. Trade protectionism influences the IB market through for example impacts on biofuels. Biofuel production is located where feedstock costs are lowest, which is why for example Brazil leads in a global production in sugar cane, the USA in maize, the EU in wheat and Indonesia in palm oil. If trade flows to or from these countries are restricted, this will have significant implications on supply and demand balances. This impacts not only biofuel derived chemicals, but other traded components of chemicals or the final products

The identification of forces is important in scenario development as they ensure all political, economic, social, environmental and technical issues are considered when identifying future IB opportunities and challenges.

Identifying market drivers and trends
Under each force, we identified a number of underlying drivers and trends. These are clearly distinguishable, singular movements in the wider environment with a high, direct and/or indirect impact on the UK:

- Drivers are developments that have high impacts on IB market, with high uncertainty about the outcomes
- Trends are developments with medium to high impact, but rather high certainty of direction

The key drivers and trends identified are summarised in the table below and discussed later in this section.

Table 3: Overview of drivers and trends considered in the study

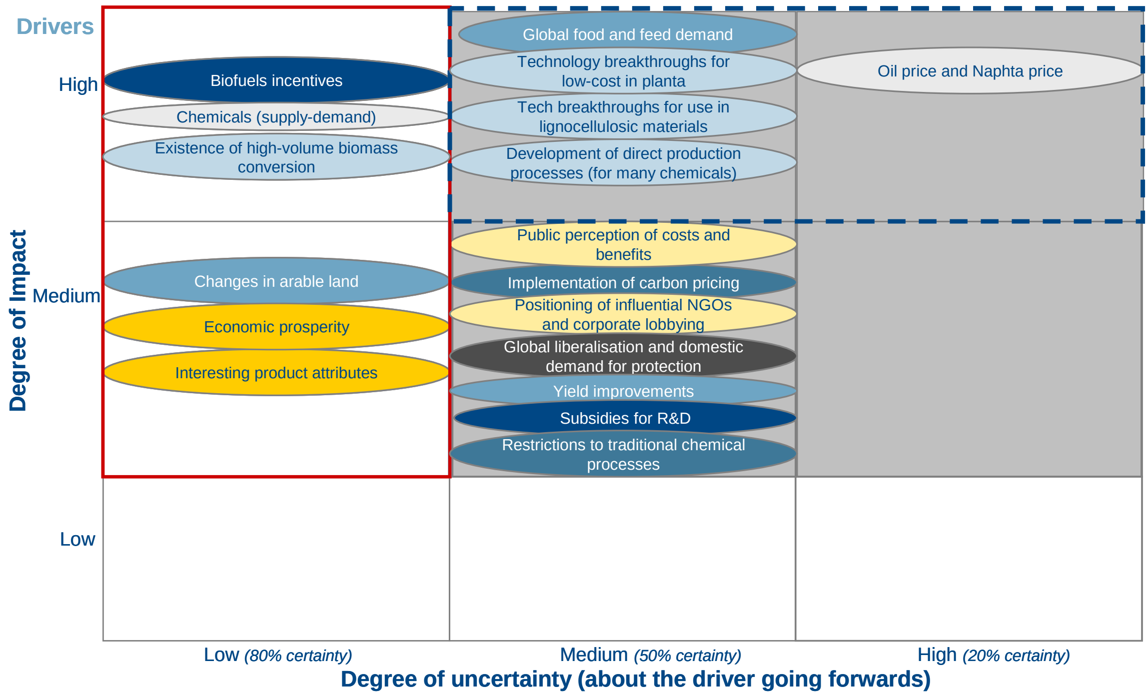
Force		Drivers and Trends
1	Traditional feedstock prices	1.1 Oil price (based on global demand–supply balance) and Naphtha price (supply related to oil demand) 1.2 Chemicals (supply-demand)
2	Societal acceptance of IB and boundaries for use of GM	2.1 Positioning of influential NGOs and corporate lobbying 2.2 Public perception of costs and benefits
3	Consumer demand (incl. societal desire for low-impact products)	3.1 Economic prosperity (GDP growth) 3.2 Product attributes (including societal desire for low-impact products)
4	Technology: availability of low-cost solutions	4.1 Existence of high-volume biomass conversion 4.2 Technology breakthroughs for low-cost *in planta* chemical production 4.3 Technology breakthroughs for use in lignocellulosic materials 4.4 Development of direct production processes
5	Land availability, bio-feedstock availability	5.1 Global food and feed demand (commodity prices) 5.2 Changes in arable land (e.g. deforestation, desertification etc.) 5.3 Yield improvements (bio-feedstocks and food crops)
6	Regulations (esp. GMOs) and taxes	6.1 Restrictions to traditional chemical processes (including emerging environmental regulations) 6.2 Implementation of carbon pricing
7	Financial incentives (e.g. that stimulate biofuels)	7.1 Biofuels incentives 7.2 Subsidies for R&D
8	Trade protectionism	8.1 Global liberalisation and domestic demand for protection

The classification of drivers and trends was conducted through interviews with IB-IGT members, drawing on the experience of ADL's Chemicals practice and results from previous unpublished IB-IGT scenario development exercises (including a workshop on future strategic drivers of IB which assessed each driver according to impact, urgency and direction of travel). The assessment conducted by Bioscience for Business KTN provided overview of technology drivers for the IB IGT.[10]

This classification is presented in Figure 3. The colours used correspond with Table 3 above. The order the drivers are placed in each square of the matrix does not reflect relationships between the drivers i.e. the drivers in the top left hand square are all high impact, low uncertainty.

The key drivers for developing scenarios are those that are identified as high importance but of high uncertainty, as they are potential causes of major change (included within the dotted square in Figure 3). This has enabled us to define a set of distinct, high-level, critical drivers to underpin the scenarios. The trends, defined as high importance and a high level of certainty were used in several cases as parameters for the model but were not varied according to each scenario.

Figure 3: Classification of drivers and trends



[10] http://www.berr.gov.uk/files/file51234.pdf

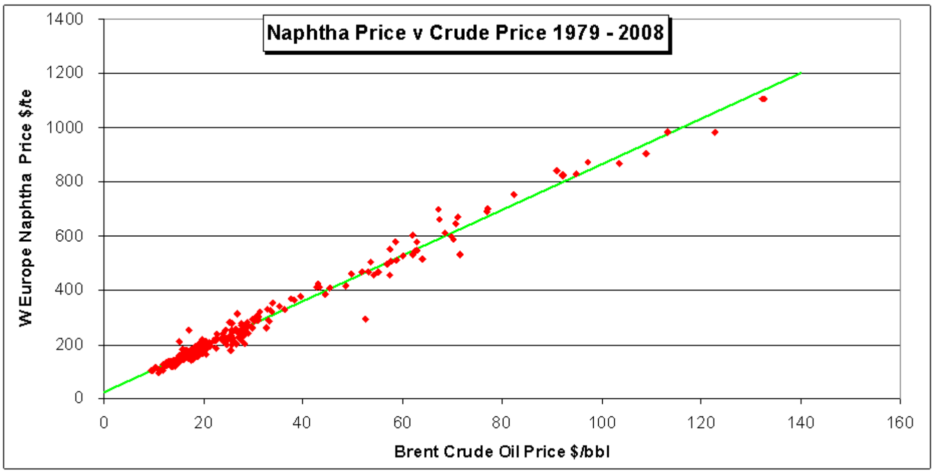
Detailed description of key drivers (high impact, medium-high uncertainty)

The drivers included within the dashed line in Figure 3 were used to form the basis of the scenarios. For each of these drivers a range of potential end-points were identified. These end-points represent a range of values that can be used to describe each value and are used to define the scenarios (as described in Table 4) and as inputs into the model. The endpoints were derived through ADL expertise, interviews with IB-IGT members and considerable literature search.

Oil and Naphtha price

As mentioned earlier, the prices for naphtha are a significant component of the costs for producing chemicals, particularly high volume, low value chemicals. Naphtha is closely related to crude oil prices (see Figure 4) such that oil prices are used in the scenarios due to availability of data and familiarly of this variable.

Figure 4: Naphtha price vs. Crude oil prices 1979-2008



Source: Lywood Consulting Ltd.

There are a number of underlying factors underpinning the oil price chosen in the four scenarios:

- $50/bbl – There is a noticeable reduction in oil demand which could be fuelled by an increased drive towards significantly more efficient road transport and a switch towards non-petrol based transportation, with the combustion engine being displaced by electric and low-carbon alternatives. There is also significant stability in the major supply regions, resulting in a lower likelihood of any supply shocks and lower overall oil prices

- $100/bbl - Global demand for oil continues to be driven primarily from transport demand, but growth in this sector is modest, impacted by the current economic slowdown for the next few years. On the supply side, again there is pretty much a status quo, with continued unrest in the Middle East adding to supply concerns as easily accessible reserves are consumed and slightly more difficult to access oil becomes the marginal source of supply
- $150/bbl - This represents a significant tightening of the global supply and demand balance for oil, with increased and sustained demand from the transport sector, particularly in the developing economies. New supplies are also considerably harder to secure, with new sources coming from increasingly difficult to access or unconventional reserves

Technology breakthroughs for low-cost *in planta* production

In order to be able to exploit *in planta* opportunities, significant GM breakthroughs to produce chemicals at low(er) cost are required. In practical terms, this requires being able to achieve extraction rates of approximately 10% of the weight of crops for use in suitable chemicals. Given current state of technology, extraction and purification can be achieved readily in appropriately designed biorefineries. However, existing genetic modification technology will need to evolve beyond traits conferring herbicide tolerance and pest resistance, and towards those making plants more suitable for chemical extraction (e.g. increased yield of secondary metabolites; ease of processing; starch quality, etc.).

Technology breakthroughs for lignocellulosic and algal materials

In order to scale-up biofuels production and therefore the production of bio-fuel derived chemicals to the levels required for high-volume chemicals, technology breakthroughs for producing biofuels from lignocellulosic and algal biomass need to be achieved. Technology for producing bioethanol from lignocellulosic materials would need to enable production at prices at a level equivalent to approximately 60 USD/bbl to make them competitive[11], assuming all necessary technology breakthroughs will occur. It is assumed that, if a viable and sizable biofuel industry forms, chemicals derived from biofuel waste and by-products will follow independently (similar to the formation of the petrochemical industry in the early 1900s).

[11] Royal Society (2008) "Sustainable Biofuels: prospects and challenges" RS policy document 01/08, pg. 49, www.royalsociety.org, estimates that the price of oil in 2006 varied between 50-80 USD/bbl and projections for ethanol from lignocellulosics in 2030 range between 40-105 USD/bbl. However, taking into account the lower energy content of ethanol (61%), ethanol produced from lignocellulosic materials would have to achieve prices as low as 60 USD/bbl for them to become more attractive compared with gasoline

Direct production processes such as fermentation and biocatalysis, mainly applied in the manufacturing of high value and low volume chemicals, have been developing successfully in the past few decades. Building on this existing knowledge base to extend the technology know-how to other high value, low volume chemicals is therefore much more likely to succeed compared with technology breakthroughs in lignocellulosic or algal materials. In this report it has been assumed that the market share of white biotechnology in direct production processes will approximately double by 2025. Extending the direct production processes into more high volume chemicals will be more challenging due to the low-cost nature of these materials, i.e. where competition from proven and highly optimized petrochemical process alternatives is more severe.

Feedstock availability for IB is dependent on the demand for food and feed – there is direct competition with crops for food and feed and these will always win if supply cannot meet demand for both. In our model, we include this driver through using feedstock prices as inputs and looking at land use required in each scenario and comparing this with availability. Feedstock prices are especially relevant for *in planta* and biofuel-derived chemicals. A shift to technologies that use waste and by-products as feedstocks, or feedstocks that can be grown on non-agricultural land would significantly decrease competition with food.

Trends (medium/high impact, low uncertainty)
In Figure 3 above, trends are highlighted with the red box on the left side of the figure. These are mainly used to provide context for the scenarios. They are likely to have either a medium or high impact on the IB market and how they are going to develop in the future is fairly certain.

Government incentives
Government incentives, such as renewables obligations are short-term mechanisms to encourage investments in uptake of new technologies and manufacturing new products. Alternative new mechanisms may be put in place in the mean time. The impact of these mechanisms could potentially be quite significant, especially for the biofuel-derived chemicals.

Chemicals (supply and demand)
Prices of high volume chemicals are largely dependent on their key raw material inputs, i.e. naphtha and crude oil. The price of traditional chemicals is an important driver for the success of biochemicals; a low chemicals price will require IB-derived chemicals to be much more cost-competitive to gain market share. This is less an issue for low volume chemicals, where a much smaller portion of the cost is determined by raw material inputs.

Existence of high-volume biomass conversion

A necessary pre-condition for the emergence of a large-scale bio-chemical industry is the existence of high volume biomass conversion, most likely one that produces biofuels. Following the principle of *"fuels first, then chemicals",* chemical companies will subsequently identify fractions of waste products from fuel production that can be further valorised by adding on unit operations[12] and transforming them into "biochemicals" (as opposed to petrochemicals). These unit operations must be of a so-called "world-scale" nature, i.e. sufficiently large to achieve economies of scale that are also attained elsewhere in the petrochemical industry. Hence the biorefineries involved must operate in the same order of magnitude to be competitive with traditional refineries. It is useful to realize in this respect that the current petrochemical industry converts only ~ 5% of annual global oil production – the rest being used as fuel.

The cost-competitiveness of today's petrochemical industry rests to a large extent on its ability to "piggy-back" on the large-scale, low-cost infrastructure that has been developed to produce fuels cost-effectively (while providing tax or excise income to most governments).

Changes in arable land

Future changes in arable land will impact availability of biomass feedstocks. Between 1995 and 2005, arable land area increased by 24 million hectares globally and in 2006, 21% of all arable land was used for oil crops[13]. In the UK, arable land currently represents around 24% of total land area.[14] Changes to arable land area over the last 25 have been relatively insignificant. It is therefore unlikely that large areas of additional arable land will be available in the future. Yield improvements and demand for food and feed are likely to have a much bigger impact on the development of industrial biotechnology.

Economic prosperity

Economic prosperity will have some impact on the demand for IB products. High economic growth is likely to increase energy demands and the case for IB could be strengthened. Based on long-term OECD projections[15], global GDP growth rates range from 1.45%-2.79% in OECD countries, and from 2.79%-5.14% in non-OECD countries. For the UK IB industry, recovering from the current recession will have implications in the short term affecting investments, but looking at 2025, impacts are likely to be less significant given relatively low GDP growth rates.

[12] Unit operation: Combination of closely related process steps to achieve a particular chemical transformation or purification

[13] Kampman et al. (2008) "Agricultural land availability and demand in 2020", CE Delft, pgs. 7-9

[14] Defra Statistics, March 2009

[15] OECD (2008) "Environmental Outlook to 2030", OECD, Paris

Product attributes

A few previous studies commissioned by BERR on behalf of the IB-IGT have focussed on consumers' interests in IB-based products[16]. They reveal that customers' knowledge in general of what industrial biotechnology is was weak and few had a particular desire for IB-based products. However, the study conducted by McDonald (2008) revealed that 16% of respondents desired sustainable, organic or "natural" products, particularly in the pharmaceuticals, food and personal care segments.

A survey conducted by Opinion Leader (2008) also showed respondents having an interest in increased efficiency and low-impact products, however, they were reluctant to make changes to lifestyles or pay more for low-impact products.

In examining public perceptions, the BREW report[17] quotes a number of studies that conclude that particular features such as bio-based packaging materials could encourage customers to pay extra for some purchases. It is therefore fairly certain that demand for products with superior performance and lower impacts are likely to grow especially if prices for IB products do not exceed traditional ones.

Additional Drivers (medium impact, medium uncertainty)

Public perception of costs and benefits

As mentioned in relation to the trend on interesting product attributes, the public is not fully aware of what industrial biotechnology is. The benefits of IB are perhaps also more difficult to understand, as the usefulness and application of IB products and technologies is not as obvious as for other technological innovations (e.g. mobile phones). A simple Google search will directly suggest links with cloning and genetic modification, which have been widely rejected by the public and NGOs. If environmental benefits of IB (and also Genetically Modified Organisms) can be proven and are generally accepted, societal acceptance of IB is unlikely to be a burden. This will depend on whether technology breakthroughs that are sustainable are achieved. The BREW report's examination of public perceptions shows that environmental impacts are considered an important factor in gaining acceptability of large-scale use of biomass for producing bulk chemicals. The main barrier for acceptance seems to be "the fear of the unknown" according to the study conducted by Opinion Leader[18].

[16] Opinion Leader (2008) "Public Perceptions of Industrial Biotechnology"; McDonald, J (2008) "Industrial Biotechnology in the Chemicals and Chemistry-using Industries in the UK: Follow-up Survey to assess Barriers to Implementation and Opportunities for Growth"

[17] Patel, M. et al. (2006) "Industrial Biotechnology in the Chemicals and Chemistry-using Industries in the UK: Follow-up Survey to assess Barriers to Implementation and Opportunities for Growth" pg. 264

[18] Opinion Leader (2008) "Public Perceptions of Industrial Biotechnology", IB-IGT

Nevertheless, when considering where GM technology can be improved to address public (and scientific) concerns, emphasis should be placed on technology to avoid unwanted diffusion of genetic material in the environment, and long-term stability of the modified crops.

Carbon pricing
There is a reasonable amount of uncertainty around the development and level of future pricing in carbon markets and developments of the Kyoto Protocol after 2012. The primary effect will be on discouraging fossil-fuel intensive industries and attracting attention to energy efficiency. For IB, this is likely to impact investments in biofuels and technology development around processes to enhance resource use and process efficiencies, or move to using wastes or by-products as feedstocks. However, carbon prices alone will not create a market for IB and this driver is therefore medium impact.

Global liberalisation and domestic demand for protection
Currently, liberal global markets provide producers with the possibility to optimise their feedstock use by choosing those feedstocks that are cheapest. Whether these are domestically supplied or imported from other countries is determined by price. If competition with food increases, countries would become more protective of their land use and feedstock supply and might limit the amount of feedstocks available for export. For industrial biotechnology, this could have impacts on the types of feedstocks available and certainly their prices. Because developments in domestic protectionism are difficult to predict, uncertainty is relatively high.

Yield improvements
Yield improvements are an important contributor to feedstock prices. They also have potential to decrease strains on land use and competition with food as each hectare becomes more productive. However, if crop prices increase simultaneously, strains on land are likely to increase, as people are encouraged to cultivate more land in pursuit of higher returns. UNEP (2007)[19] recorded average yield improvements between 1987 and 2007 to range between 17-40% with large regional differences. It is likely that yield improvements will occur in the future, but the scale of their impacts is uncertain.

Subsidising R&D
Subsidising R&D activities can influence IB through technology breakthroughs. However, the amounts needed for different levels of impacts are difficult to estimate making the driver medium impact and uncertainty. This driver differs from the "government incentives" in that it focuses on the R&D process rather than directly supporting sales of specific IB products.

[19] UNEP (2007) "Global Environmental Outlook, GEO-4", pg. 86, available online at: http://www.unep.org/geo/geo4/report/GEO-4_Report_Full_en.pdf, accessed April 16, 2009

Restrictions to traditional chemicals processes
Restrictions to traditional chemicals processes could cause companies to shift to bio-chemical production routes faster than "normal" market forces. They could also encourage technology investments. However, it is currently rather uncertain whether these kinds of restrictions will apply in 2025. If research and development efforts are not sufficient to enable companies to shift to IB profitably, restrictions could potentially damage the country applying such restrictions, by encouraging industry to move production to other countries.

4.2 Description of scenarios

The process for developing the scenarios was based on the consideration of four criteria:

- **Possibility -** The events within each scenario should have the potential to become reality
- **Coherence -** The events within each scenario should logically fit together
- **Uniqueness -** Each scenario should be different from the others
- **Usefulness -** Each scenario must have value for testing strategic options

Taken together, the selected scenarios should cover a number of possibilities that could occur in the future. The scenarios are based on combinations of end-points for each of the key drivers (see Table 4). This is a slightly different approach to earlier work by IB-IGT as the scenarios developed here are defined by inputs rather than outputs and allowed quantification of different scenarios.

We started by conducting a high-level assessment of the degree of correlation between each of the key end-points. The end-points were placed within a matrix and based on ADL analysis each pair of end-points was classified according to their degree of correlation: strongly positively related, weakly positively related, unrelated, weakly negatively related and strongly negatively related. This process ensures that the scenarios are logically consistent and represent the wide range of market conditions that could exist in 2025.

In line with earlier work conducted by IB-IGT, the scenarios developed were strongly informed by the drivers related to the uptake of IB and technology development. Four scenarios were developed, primarily based on either high/low differentials between feedstock prices and high/low levels of technology breakthrough (Table 4). These were supported by information on other trends (for example information within Table 5). These two tables therefore summarise the key underlying assumptions used in the model. By definition none of the scenarios is more or less likely to occur than the other.

Table 4: Details on endpoints used to develop scenarios

Driver	Stuck	Knock On Wood	Green Bloom	Electrified
Oil price	100 USD/bbl (medium)	150 USD/bbl (high)	150 USD/bbl (high)	50 USD/bbl (low)
Technology breakthroughs for low-cost *in planta*	No breakthroughs	Breakthroughs occur, with *in planta* produced high value and low volume chemicals to reach 4% of global IB sales by 2025, 2% for low value and high volume		
Technology breakthroughs for lignocellulosic ethanol and algal feedstock production	No breakthroughs	Breakthroughs occur sufficient to bring the costs of biofuel production from lignocellulosic or algal material down below cheapest crop-based alternative		Breakthroughs occur, but low oil prices prevent these from bringing comparative costs low enough
Development of direct production processes	Proportion of sales produced via IB: 7.7% for high value and low volume; 3% for low value and high volume (assuming IB chemical is 15% cheaper to produce than traditional chemical)	Proportion of sales produced via IB: 12.5% for high value and low volume 5% for low value and high volume (assuming IB chemical is 15% cheaper to produce than traditional chemical)		
Global food and feed demand	High biofeedstock prices (£/tonne) Sugar cane (Brazil):13 Maize (US):65 Wheat (UK):115 Rapeseed (UK):215 Soybean:500180 Palm oil:300 Wheat straw: 53 Switchgrass:55		Low biofeedstock prices (£/tonne) Sugar cane (Brazil):8 Maize (US):50 Wheat (UK):70 Rapeseed (UK):120 Soybean:110 Palm oil:170 Wheat straw:25 Switchgrass:30	
Public perception of costs and benefits (incl. GM acceptability)	Reduction in the incentives to undertake R&D, particularly for *in planta* chemicals		Incentives in place to pursue R&D work on IB alternatives, especially *in planta*	

Sources: FAOSTAT: PriceSTAT, Lywood Consulting Limited, Klein et al. (1996) "Biofuel feedstock assessment for selected countries" Oak Ridge National Laboratory available at www.osti.gov/bridge, Arthur D. Little analysis

We have included other drivers in the model through various inputs that link to the drivers.

Table 5: Main inputs and assumptions used in the model

Feedstock	Yield (tonnes/hectare)	Conversion efficiency (litres biofuel/tonne feedstock)
Sugar cane	70	65
Maize	4.50	320
Wheat	7.50	325
Rapeseed	3.54	395
Soybean	2.00	180
Palm oil	19.3	220
Wheat straw	12 (proxy for wider range of lingocellulosic materials)	205
Switchgrass	10	340
Algae	100	400

Chemicals category/ representative chemical	Annual market growth rates (%)	Chemicals price (£/tonne)	Carbon intensity (tCO_2e/tonne)
Low volume: A1	3%	20,000	2.5
High volume: A2/PLA	1.5%	1,750	4
Low volume: B1/Specialty plastics	3%	9000	5
High volume: B2a/Butanol	1.5%	700	1.9
High volume: B2b/1,3-propandiol	1.5%	700	2.5
Low volume: C1/PHA	3%	15,000	5
High volume: C2/MMA	3%	1,800	6

Biofuel data	UK demand		UK production	Biofuel by-product conversion
	2007 transport fuel demand	2025	2025 biofuel demand (limited to 10% of future transport fuel demand, on an energy basis)	Biomass converted into chemicals: 2.5% for lignocellulosic materials 1% for other bioethanol feedstocks 4% for algae and rapeseed
Bioethanol	20 million tonnes	25 million tonnes	4.4 million tonnes	0.2-0.4% for high-value and 1.4-2.1% for low-value chemicals from bioethanol
Biodiesel	19 million tonnes	25 million tonnes	3.1 million tonnes	All 4% converted into high-volume chemicals from biodiesel

Sources: FAOSTAT: PriceSTAT and ProdSTAT, Lywood Consulting Limited, Nexant ChemSystems (2008) "Biochemical opportunities in the United Kingdom" NNFCC, Klein et al. (1996) "Biofuel feedstock assessment for selected countries" Oak Ridge National Laboratory available at www.osti.gov/bridge, Johnston et al. (2008) "Resetting global expectations from agricultural biofuels" Environmental Research Letters, available at stacks.iop.org/ERL/4/014004 (pg. 2 and 4), NNFCC Non-food crops database, Chemistry Innovation Knowledge Transfer Network (2007) "NE Region Biorefinery Opportunities" (pgs. 75,105,107), http://www.iogen.ca/cellulosic_ethanol/what_is_ethanol/cellulose_ethanol.pdf, Arthur D. Little analysis

In addition to the inputs and drivers mentioned above, carbon prices, government mandates and financial incentives are tested to identify levels at which they have an impact on the outcomes for each scenario.

Using the combinations of end-points detailed in Table 4 and together with the criteria listed above, we developed each scenario as a narrative. This is developed by considering each driver in turn and identifying connections and mutual implications. This is supplemented by the addition of plausible events describing the potential trajectory of the scenario. The narrative description of each scenario is described in Table 6 below:

Table 6: Descriptions of scenarios

Name	Description
Stuck	**In "Stuck" the focus for growth is in fine and specialty chemicals due to the absence of significant biofuel technology breakthroughs as the world cycles between high and low prices for oil and food crops. This is a world where drivers dominant today persist** White biotechnology expands in fine and specialty chemicals based on the fermentation platform, and exploitation of biocatalysis technology; the large oil price cycles prevent large-scale investments in high volume fermentation methods by the private sector alone Without a technology breakthrough in either lignocellulosic ethanol or biodiesel production, the biofuel industry remains dependent on arable crops that compete heavily with other food crops, and require (oil-based) fertilizers; the price of crops and oil are coupled and "cycle" up and down Biofuels are seen to compete with other land uses, notably food production; *in planta* production suffers from the same problem and only grows in niche, fine chemical areas Nevertheless, in periods of high food prices, the acceptance in Europe for GM foods is slowly increasing, as the world needs more and cheaper food
Knock On Wood	**In "Knock On Wood", there is an initial boom in lignocellulosic ethanol technology in addition to the growth in fine and specialty chemicals. The long term growth levels off due to competition with food** 2010: Emergence of lignocellulosic ethanol technology with early commercialization in the USA followed by South America and Europe 2020: All new ethanol plants are based on lignocellulosic materials; 5% of Europe's and the US's fuel demand is met by lignocellulosic ethanol. Oil prices remain high given complex supply-demand situation. The public, alerted by higher food prices (mainly driven by the high oil price which causes fertilizer costs to rise), becomes increasingly concerned about the impact of biofuel production 2025: Most low-cost by-product/waste feedstocks have been exploited. Large agro-exporting countries limit the area that is planted with energy crops; Energy crops continue to be grown, but cannot further expand As the industry cannot scale up, the secondary bio-chemical industry remains focused on smaller scale biocatalysis and fermentation opportunities

Name	Description
Green Bloom	**The ability to exploit feedstocks that do *not* compete with arable crops results in the development of a thriving bio-chemical industry akin to the petrochemical boom of the early 1900s** 2011: Algae biodiesel technology breakthrough with first demonstration plant following within two years. At the same time, but independently, lignocellulosic ethanol technology emerges and is commercialized 2017: Nearly 3% of OECD diesel demand is now met by land-based algae biorefineries; The technology is readied for off-shore production The price of petrol and biofuels structurally "decouples"; Following the *"fuel first, chemicals next"* pattern, attractively priced biodiesel by-products offer opportunities for biorefineries to valorize by-products The new bio-chemical industry is focused on feedstocks that avoid competition with food crops where there are high costs due to oil-based fertilizers and political sensitivities 2025: Large scale off-shore production of biodiesel and biochemicals is taking shape. The UK is benefitting most strongly; it contributes vital technological and offshore know-how to the large floating biorefineries that are being built all over the world, particularly in tropical seas • Exploitation of lignocellulosic ethanol technologies levels off as low-cost feedstocks (including waste products and by-products) are extensively utilized • Similarly *in planta* technologies also make inroads, though these never occupy more than 5% of total land use Fermentation-based chemicals are increasingly important for specialty and fine chemicals
Electrified	**Despite IB technology breakthroughs, a sustained drop in demand for crude oil makes white biotechnology only competitive for low volume/high value chemicals** Up to 2015: Concerns of extreme oil price volatility, security of supply and climate change results in co-ordinated policies to promote a "new energy future" 2020: Breakthroughs in powering the electric car has led three of the world's largest car companies, GM, Toyota and BMW, to ramp up production of affordable and powerful electric cars. The required electricity is provided by a combination of fossil fuel and renewable power generation with emissions reductions enabled by carbon capture and storage technologies Combined with sustained government efforts to address climate change and energy security, the world experiences the first real drop in demand for oil by 2025. While this process is slow, it results in a sustained low oil price in a long-term Existing infrastructure of oil production and refining shifts to product mostly diesel (the fuel of choice for trucking) and naphtha – overcapacity drivers prices down for the longer term After 2025, naphtha (and diesel) is cheap, and with oil reserves now able to satisfy over 100 years of future demand, petrochemicals are highly competitive • Investment in industrial biotechnology focuses on high cost niche products. This is supported by the increasing use of biocatalytic processes and genetic modification of plants • Interesting breakthroughs in lignocellulosic ethanol production fail to create a large bio-chemical industry, due to cost

5. Modelling results

5.1 Overview of the model

The model is based on the economic attractiveness of IB chemicals vis-à-vis traditional petroleum-based chemicals. This allows the model to show how IB production might develop under a range of assumptions around major inputs (i.e. oil-based feedstock prices against bio-feedstock prices). It is also possible to identify where assistance may be needed to stimulate production or demand for IB products, and indicative levels of support required to do this.

Key data inputs are captured via drivers, as well as other underlying base data, with scenarios being defined by different driver end-points (as described in Section 4.1 - Detailed description of key drivers). The model also has options for using policy levers, for example through direct support of IB (e.g. a subsidy) or indirect support (e.g. mandated levels of IB). The combination of these two sets of inputs allows the user to explore the implications of changes in underlying drivers as well as possible support initiatives.

The focus is on modelling output for each of the six categories defined in Figure 1 (see Section 2.3) in a manner that captures the relevant high-level drivers in sufficient detail so as not to make the model overly complex and relatively easy to understand.

The starting point in the model is the current market for UK IB chemicals, and its place within the global chemicals industry. The overall global and UK chemical market is divided between fine/specialty and platform chemicals, and the current proportion of IB within each is estimated (see Section 4.1 for more details). The proportion of IB is then further broken down by the six production categories (dedicated single-compound production, biofuel-derived and *in planta*), to provide a starting value for the different IB categories.

One of the principal drivers of IB development is the rate at which technologies become available to allow IB alternatives to substitute traditional chemicals. This is captured by the *breakthrough rate* defined as:

> *the rate at which technological innovations allow biotechnology alternatives to produce the same chemical (either in whole or during part of the manufacturing processes) sufficiently cheaper to make it competitive with the traditional chemical, thereby displacing a percentage of a chemical groups' production with IB*

Taking the modelling forward, there are two principal factors that will change the value of the global chemicals industry, the volume of chemicals produced and the price of chemicals sold. Both of these will influence the growth of the market overall, and hence the value of the IB sector; if the IB sector retains a constant percentage share of the overall market; increases in either (or both) total chemical sales volumes and in the price of chemicals will increase the value of the IB market.

The other factor that will change the value of the IB market is the changing share of chemical production. Where cheaper or better alternatives can be produced via the IB route than can be produced through traditional production methods, then the share of IB of the overall market will increase, increasing the value to IB manufacturers.

The extent to which changes in market sizes are modelled for each of the six categories is discussed below:

Dedicated production chemicals

A1 chemicals (low volume, high value)

For high value chemicals produced by dedicated production the over-riding factor determining the uptake of IB is the continued development of technological breakthroughs – there are significant rewards for developing cheaper or more cost effective means of production, given the high value of chemicals being sold. To capture this, the model tracks technological breakthrough rate through time, with the breakthrough rate in 2025 being approximately double that of the current penetration rate (moving from 6.2% share of overall chemical sales in 2007 to 12.5% between now and 2025).

A2 chemicals (high volume, low value)

For the high volume low value dedicated production chemicals a similar logic is applied as to the A1 Category with one important exception. The future penetration of IB in the platform chemicals group is still a function of technological breakthrough, but the pace of research is linked to the relative attractiveness of IB alternatives compared to traditional chemicals, i.e. a high comparative differential between oil and bio-feedstock prices will encourage increased technology development via commercial imperatives for cost saving.

To capture this, we model the production cost of a representative IB chemical, including the costs of purchasing and converting feedstocks, processing costs (fixed and variable operating costs) and capital costs. We then compare these with the relative costs of a traditional alternative. The price of the traditional alternative is proxied by adjusting a reference chemical price by changes in oil price, where the change is proportional to that chemical's production costs that can be attributed to the oil price.

When the cost of producing the IB chemical alternative is sufficiently lower (at least 15% lower) than the price of the traditional chemical then there is sufficient incentive to undertake the R&D necessary to allow its manufacture. Once this has happened, the percentage of platform chemicals that are produced by IB is a function of the breakthrough rate that in most scenarios is assumed to increase the percentage of dedicated production IB from a current level of 2.4% in 2007 to 5% by 2025.

Biofuel-derived chemicals

For the biofuel-derived chemicals categories the overarching driver is the biofuel production itself. Bio-based chemicals can be developed from some of the by-products such as high value protein-based plastics or glycerol-derived 1,3-propandiol, and production facilities will be built to valorise these by-products where it is cost-effective and economically viable to do so.

To capture this, the starting point is modelling the production of biofuels. This is, in essence, the same calculation as for the A2 category, where the cost of producing either bioethanol or biodiesel is calculated, i.e., the cost of sourcing feedstocks and converting them into biofuels at different conversion rates, other fixed and variable production costs, and capital costs to build the biorefinery. This biofuel production cost is then compared with the cost of the petroleum-based equivalent, which is again adjusted as a function of the oil price. The biofuel-derived chemicals will be produced when it is more cost-effective to do so. The volume that is produced is assumed to be a function of future transport fuel demand, set at ~10% in 2025. This represents an upper limit. If there are, for example, limitations on the availability of feedstocks or biorefinery capacity then this will cap the total volume of biofuel-derived chemicals produced in the UK.

Production within the UK can come from a number of sources (including different lignocellulosic materials, where necessary technological advances have been made, and the use of algae as a feedstock for biodiesel in some scenarios), though we have used wheat as the primary source of bioethanol and rapeseed as the primary source for biodiesel.

Other potential global sources of biofuels were also modelled, including Brazilian ethanol produced from sugarcane, US ethanol from corn, US biodiesel from soybean and Asian biodiesel from palm oil. This allows the model to investigate the impact of cheaper sources of biofuels being produced internationally and then imported into the UK.

Once the level of UK biofuel production has been established, then the attractiveness of utilising by-products can be evaluated and, if it makes economic sense then some of the by-products will be diverted into IB chemical production. For bioethanol we assume that 2.5% of total lignocellulosic biomass for biofuels can be converted into chemicals, while for first generation bioethanol feedstocks (such as wheat), this percentage is slightly lower at 1%[20]. For biodiesel, we assume that 4% of biomass (namely algae and rapeseed) can be converted into chemicals.

Out of these figures we have divided the proportion of biomass to be used for bioethanol as 15% being converted to high value, low volume chemicals and 85% being converted to low value, high volume chemicals. All 4% is converted to high volume, low value chemicals in the biodiesel route.

Again, the attractiveness is based on the relative cost of producing the chemical from the by-product feedstock (including fixed and variable costs and capital costs), compared to the oil-adjusted price of the traditional chemical. Where it is economically attractive to do so, the IB chemical will be produced. Finally, the percentage of the chemical group that this IB production represents is calculated from the assumed volume of sales in the group and the IB production.

In planta chemicals

For *in planta* chemical production, the modelling approach is similar to that for the A2 category, where the cost of producing a green biotechnology alternative is compared to the value of the traditional chemical, again proxied through changes in the oil price. Where there is a sufficient cost saving R&D breakthroughs will see a proportion of the overall market produced via this route.

To achieve this we estimate the costs of producing chemicals via the biochemical route based on the cost of growing and transporting crops to an extraction facility, the costs of extracting the chemical (assuming a 10% yield of material from the plant matter, capturing extraction efficiencies and material density within the plant material), and fixed and variable operating costs, in addition to the cost of building an extraction facility.

[20] The conversion rate for lignocellulosic feedstocks is derived from the percentage of C5 sugars resulting from potential processes and the potentially lower proportion of by-products used as animal feed. The conversion rate for wheat, corn, sugar cane are kept low as this is an established market where much of the by-product is currently used for animal feed (Dried Distillers Grains with Solubles - DDGS)

When the cost of producing the biochemical alternative is sufficiently lower (at least 15%) than the price of the traditional chemical then there is sufficient incentive to undertake the R&D necessary to allow its manufacture. Once this has happened then the percentage of platform chemicals that are produced using IB is a function of the breakthrough rate, that for C1 (high value, low volume products) is assumed to reach 4% by 2025 and for C2 (low value, high volume products) it is assumed to reach 2% by 2025.

5.2 Modelling functionality

The model has been designed to assess land-use and CO_2 savings calculations and allows restrictions to be placed on feedstock availability, conversion capacity and other variables. Finally we are able to test the response of the IB market in response to levers such as subsidies, carbon prices and mandatory requirements.

Land use and CO_2 savings calculations

To estimate the land use requirements associated with the different IB production levels, the model works back from total IB production levels using the relevant conversion efficiencies (mass of bio-based feedstock to mass of IB chemical) and crop yields (tonnes bio-feedstock per hectare) to obtain the required hectares for each chemical. The exception to this is the biofuel-derived where the same logic applies, but the starting point for the calculation is the quantity of biofuel produced, not the quantity of biofuel-derived IB chemical.

Calculations on the CO_2 savings for each of the chemical groups is the product of the volume of chemical produced and the differences between the carbon intensity of the traditional product and the carbon intensity of the IB equivalent. However, for the biofuel-derived chemicals this does *not* include the carbon savings from the biofuel itself, only CO_2 savings from the biofuel-derived chemical as this was beyond the scope of the model.

Other IB limitations

While the above discussion has focused on the breakthrough rates as being a limitation to IB production, there are other limiting factors that can, and should be taken into account. These mainly include the availability of bio-based feedstocks and the availability of conversion capacity.

The availability of feedstocks is primarily affected by the availability of land to grow them, and this is a function of both the total available land and the level of competition with food or biofuels (biomass for direct heat and/or electricity generation).

The availability of conversion capacity could be a function of the ability to build sufficient biorefineries within reasonable distance of feedstocks or simply the ability to physically construct the volume of biorefineries within a certain timescale.

In either case, the model has the ability to limit IB production on the basis of feedstock availability or conversion capacity.

As mentioned previously, in addition to modelling the development of the IB sector under a range of scenarios, the model needed to be able to test how the results would change under a range of possible government interventions. For this purpose, a number of policy levers were included as a function in the model:

- ***Subsidies*** **–** Direct measures could encourage IB development. Where there is a shortfall between the cost effectiveness of an IB alternative compared to the traditional product, the presence of a subsidy (in the form of a £/tonne payment to the producer from the government, via a number of potential mechanisms) could be enough to close the gap and encourage IB production. To assess the impact of possible direct support, functionality was built into each of the chemical groups to allow such a measure to be passed to the chemical producer
- ***Minimum percentages of IB*** **–** Like direct measures such as subsidies could promote the development of IB, indirect measures such as the introduction of requirements for minimum percentages of chemicals to be sourced from IB can also act as stimulants. In the model, the A and C category chemicals can have minimum percentage requirements set against them, forcing the model to produce more than would have been ‘economically’ attractive
- ***Carbon pricing*** **–** Another indirect support mechanism could be the implementation of carbon pricing, where the manufacture of chemicals is affected by their carbon intensity and the cost of carbon they face in the market. In the model this is represented by an additional cost (to both the traditional chemicals and the IB alternatives) of producing chemicals that is a function of their carbon content. For traditional chemicals, the introduction of a carbon price will manifest itself through an increase in the price of the chemical (based on the assumption that the cost of carbon will be passed on to consumers in a fully competitive market). For the IB alternatives, carbon still has an impact and this is reflected through an increased cost of producing the chemical given its carbon intensity (although this is lower than that of traditional chemicals). The relative movements of these two carbon impacts improve the economic attractiveness of IB versus traditional chemicals as carbon price increases

By using these additional features we are able to explore the impact of potential government interventions to help support the development of IB under different scenarios.

5.3 Overview of results

To quantify the market for IB in 2025, we have run the model for the four different scenarios for global and UK market values, UK production volume and CO_2 savings. These results are summarised in Table 7 with values representing the totals for each scenario.

Table 7: Summary of results for scenarios

Summary of results	Stuck (oil price at 100 USD/bbl)	Knock On Wood (oil price at 150 USD/bbl)	Green Bloom (oil price at 150 USD/bbl)	Electrified (oil price at 50 USD/bbl)
Global IB market value (billion £)[1]	150	346	360	220
UK IB market value (billion £)[2]	4.4	11.4	11.8	6.2
UK IB production (million tonnes)	0.8	1.9	2.2	0.5
CO_2 savings[3] **(million tonnes CO_2 p.a.)**	2.0	4.7	5.2	1.4

Source: Arthur D. Little; Note 1: This does not include the global market for biofuels which could be over £150bn. Note 2: This does not include the wider biofuel market which could range from less than £1bn to over £7bn for the UK. Note 3: If calculated based on the production volumes for the UK the model is using in this study, CO_2 savings from bioethanol production would be between 1.3 and 10 million tonnes of CO_2 and savings from biodiesel production would be between 3.0 and 9.7 million tonnes

The highest market value is achieved in the Green Bloom scenario with a UK market of £11.8 billion and 2.2 million tonnes of chemicals produced. This would require around 2.5 million hectares of land, although as with the other scenarios this doesn't account for imports or the utilisation of by-products or co-products, waste or improvements in yield and conversion rates,(compare with total agricultural land available in the UK: 18 million hectares in 2007[21],[22]) and could save 5.2 million tonnes CO_2 equivalent.

[21] Defra Statistics, March 2008

[22] For low volume dedicated production (A1), it is assumed that any growth is expected to come from incremental technology development including process improvements in efficiencies. Therefore no additional land is needed to provide additional feedstocks. The volume (and therefore market value) for biofuel derivatives (B1) is dependent on the volume of biofuels (and therefore feedstock availability and land for biofuels). Land use for both B1 and B2a is grouped together (for modelling purposes) and reflected in the results under land use for B1

Beyond 2025, it is expected that this market will continue to grow at a similar rate; further growth would be associated with chemical production requiring minimal use of land (e.g. chemicals from algae).

The Knock On Wood scenario with a UK market value of almost £11.4 billion requires around 200,000 hectares less land and will deliver 0.5 million tonnes less CO_2 savings due to production volumes decreasing by approximately 15% compared with the Green Bloom scenario.

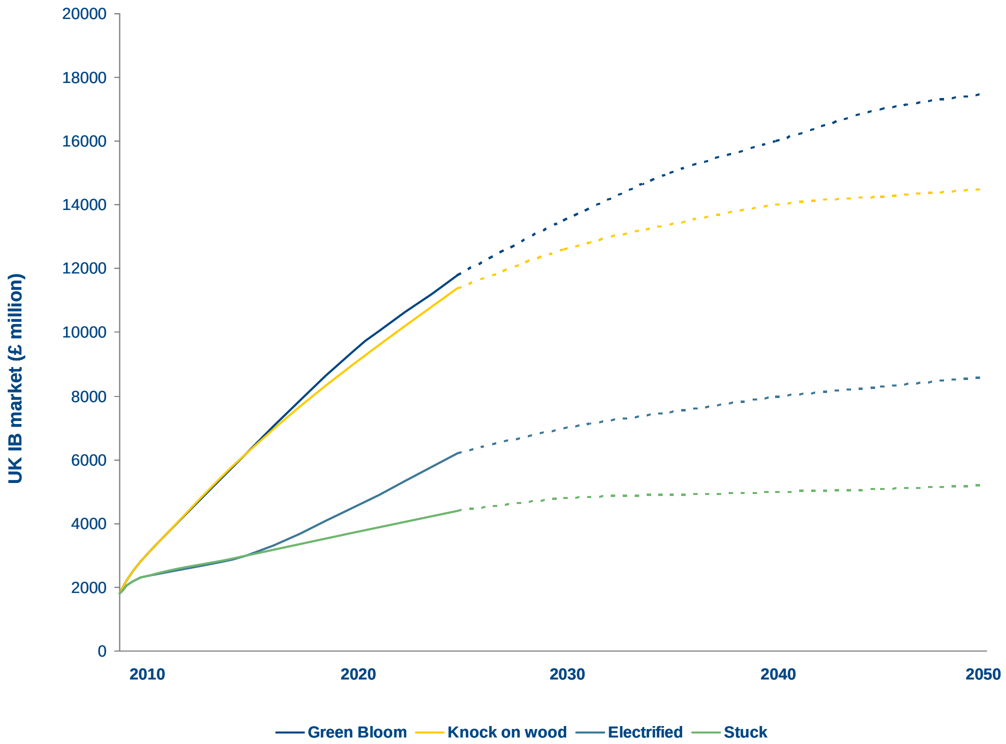
These differences are due to the absence of breakthroughs in algal technologies and limitations to land use for lignocellulosic feedstocks linked to competition with food and feed. After 2025, it is expected that the market will level off as low-cost feedstock sources in the UK would have been exhausted; however international markets could continue to grow.

In comparison, under the Electrified scenario the volume of chemicals produced is the lowest of all the scenarios primarily due to low oil prices; land use is significantly reduced under the Electrified scenario delivering around 1.4 million tonnes of CO_2 savings. While the rate of market growth could be higher between 2015 and 2020, it will level off after 2025 due to low delta with traditional feedstock prices.

The Stuck scenario has the lowest market value at £4.4 billion. A lack of technology breakthroughs forces the biofuels industry to remain dependent on arable crops competing heavily with food and feed requiring around 2.7 million hectares of land. Volatile oil prices further prevent long-term investments restraining the growth of IB. It is anticipated that the slow growth rate would continue beyond 2025 reflecting ongoing breakthroughs in low volume/high value products.

The summary results displayed above in Table 7 are presented below in a graph. This graph also shows the trajectories for each of the scenarios going forward until 2050.

Figure 5: UK IB market values for scenarios until 2050



Source: Arthur D. Little analysis. Note: Baseline for the UK IB market value for 2009 is based on estimates for the market in 2007 (see Table 2). Intermediate market values (in £ billion) are summarised in the table below)

The potential intermediate market values for IB in the UK are presented in the table below. This is drawn from current market values (see Table 2), the modelling of potential market sizes in 2025, and possible pathways discussed in the text above. It should be noted that numbers in italic have not been modelled.

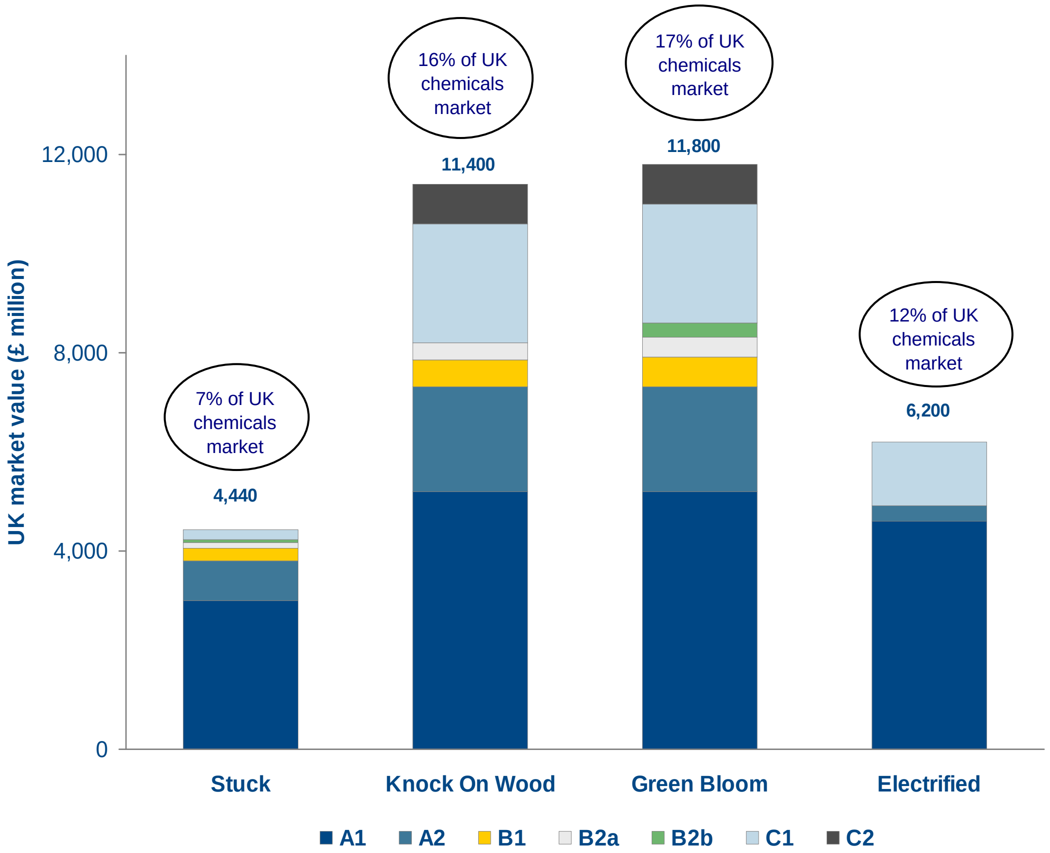
Table 8: Possible intermediate and longer term market values

Time	Green Bloom	Knock On Wood	Electrified	Stuck
2015	*6*	*6*	*3*	*3*
2020	*9.4*	*9*	*4.5*	*3.7*
2025	11.8	11.4	6.2	4.4
2030	*13.5*	*12.6*	*7*	*4.8*
2040	*16*	*14*	*8*	*5*
2050	*17.5*	*14.5*	*8.6*	*5.2*

All figures UK IB market values in £ billion

Figure 6 compares UK market values for 2025 between the scenarios showing also a further breakdown by chemical categories. An overall conclusion is that market opportunities for biofuel-derived chemicals are limited in all scenarios as producing biofuels in the UK remains comparatively expensive. However, there are niche markets for all biofuel-derived chemicals in three of the four scenarios. Where technology breakthroughs occur in using lignocellulosic materials, bioethanol-derived chemicals (B1 and B2a) are more attractive compared with biodiesel-derived products (B2b). Biodiesel-derived chemicals become more competitive when algal feedstocks can be exploited (as in the Green Bloom scenario).

Figure 6: UK market values for 2025 split by scenario and chemicals categories



Source: Arthur D. Little analysis

High value chemicals produced *in planta* (C1) and chemicals produced through dedicated production (A1 and A2) represent the largest market values in all scenarios. As the technology and processes for dedicated production are more advanced, continuous incremental technology development is important in developing these markets; the production of these chemicals is less affected by changes in feedstock prices.

Lower value and high volume products produced through dedicated production (A2) are slightly more dependent on both feedstock prices and technology breakthroughs, but the market will be attractive as long as there is a clear cost differential between traditional and bio-based feedstock prices. High value chemicals produced *in planta* are relatively competitive when feedstock availability is not limited.

Low value and high volume products produced *in planta* (C2) are attractive only when significant technology breakthroughs are achieved and in scenarios with high oil prices. Relatively high production costs restrain the required scale-up for high volume production and due to the high volumes of feedstocks needed, competition with food and feed is likely where feedstock availability is limited.

Land availability can become a limiting factor in three of the scenarios. Current UK agricultural land area is around 18 million hectares and the land requirements for the Knock On Wood, Green Bloom and Stuck scenarios represent 13-15% of this area. It is notable, however, that crops such as switchgrass can also be grown on non-agricultural land. Therefore, significant breakthroughs in lignocellulosic and algal feedstocks (and especially off-shore cultivation of the latter) would decrease these land use requirements and help avoid competition with food.

Currently, the chemical industry in the UK accounts for just over 4% of emissions out of a total level of UK emissions of 636 million tonnes in 2007. Even when embedded carbon is considered (as in this study), the overall proportion of national CO_2 savings is not high. Even in the most optimistic case, CO_2 savings would amount to 5.2 million tonnes, representing only 0.8% of current UK emissions.[23]

As the modelling was done based on the categories of chemicals, the results for each chemical category for each of the scenarios are summarised in the sections below.

Stuck

Without significant breakthroughs in lignocellulosic ethanol or algal biodiesel production, biofuel-derived chemicals are only marginally attractive. This is mainly due to volatile oil prices that restrain long-term investments in the private sector, and the fierce competition energy crops face with other land uses, notably food production. Bioethanol-derived chemicals (B1 and B2a) have a slightly larger market share compared with biodiesel derivatives partly due to higher yields of the crops used.

[23] However, if savings from biofuels production were also accounted for, savings could be significantly higher. If calculated based on the production volumes the model is using in this study, CO_2 savings from bioethanol production would be between 1.3 and 10.0 million tonnes of CO_2 and savings from biodiesel production would be between 3.0 and 9.7 million tonnes. These estimations are based on figures from Royal Society (2008) "Sustainable biofuels: prospects and challenges" RS policy document 01/08, pgs. 44 and 50, available online at www.royalsociety.org.

Fine and specialty chemicals produced *in planta* (C1) have a small market representing around 5% of the UK IB market. In periods where food prices are high, acceptance in Europe of genetically modified crops slowly increases as the world needs more and cheaper food. However, this is not enough to make high volume products produced *in planta* (C2) attractive as scale-up is pricey and not attractive compared to petrochemical equivalents in an environment where naphtha is periodically cheap.

The market value for chemicals produced through dedicated production (A1 and A2) in this scenario is the smallest compared with other scenarios. This is mainly due to volatile oil prices that prevent long-term investments to be made in the private sector alone.

Unless the UK relies on imports of feedstocks (as is the case at present), land is likely to become a limiting factor for market growth as projected production levels would represent 15% of the UK's current agricultural land and closer to 45% if compared with total UK arable land area. Without technology breakthroughs in lignocellulosic or algal feedstocks, possibilities for reducing land use through improvements in technologies are not significant.

A summary of the results for the Stuck scenario is presented in Table 9 below.

Table 9: Results for Stuck scenario

Production method	Dedicated production		Biofuel-derived			*In planta*		Total
Value and volume	**High value (A1)**	**Low value (A2)**	**High value (B1)**	**Low value (B2a)**	**Low value (B2b)**	**High value (C1)**	**Low value (C2)**	
Global IB market (£ million)	105,100	23,200	8,400	4,300	2,400	7,000	-	150,400
UK IB market (£ million)	3,000	800	244	125	70	200	-	4,440
UK IB volume ('000 tonnes)	152	383	26	150	84	14	-	809
CO_2 savings ('000 tCO_2 p.a.)	247	1,250	86	243	137	45	-	2,000

Source: Arthur D. Little analysis

Knock On Wood

A1 and A2 category chemicals become increasingly competitive with higher oil prices in the Knock on Wood scenario compared with Stuck. For high value chemicals produced through dedicated production, the market share of IB grows from 7.7% in the Stuck scenario to 12.5% and from 3% to 5% for low value chemicals.

High oil prices, while encouraging investment in biochemicals, eventually also drive up fertilizer costs which results in higher food prices causing the public to become increasingly suspicious of biofuels towards 2025. Low-cost by-products and waste feedstocks also begin to run out shortly after causing a slow down in the production of biofuel-derived chemicals. The production of these chemicals is there for more attractive in Knock On Wood compared with Stuck, but less attractive than in Green Bloom.

Production volumes for *in planta* chemicals increase significantly with high value and low value chemicals together amounting to 21% of total UK IB market value. This is driven by high oil prices that allow for sufficient cost differentials to make even high volume *in planta* production attractive.

Even though the volume of chemicals produced in the UK through IB more than doubles and the value of the market increases by almost £7 billion in Knock On Wood compared with Stuck, land requirements decrease by almost 15% and CO_2 savings double. This is due to a significant decrease in biodiesel-derived chemicals production as the world is focused on lignocellulosic ethanol breakthroughs for providing biofuels.

Land required in the Knock On Wood scenario would in theory represent over 10% of current UK agricultural land indicating that despite being able to exploit lignocellulosic feedstocks, land use could limit market growth.

Smaller scale opportunities for dedicated production and *in planta* remain the focus for the biochemical industry in the Knock On Wood scenario. Results are summarised in the table below.

Table 10: Results for Knock On Wood scenario

Production method	Dedicated production		Biofuel-derived			*In planta*		Total
Value and volume	High value (A1)	Low value (A2)	High value (B1)	Low value (B2a)	Low value (B2b)	High value (C1)	Low value (C2)	
Global IB market (£m)	180,700	49,000	19,200	11,800	200	65,700	19,600	346,200
UK IB market (£m)	5,200	2,100	554	342	7	2,400	800	11,400
UK IB volume ('000 t)	260	809	56	319	6	130	309	1,890
CO_2 savings ('000 tCO_2 p.a.)	424	2,300	183	519	10	423	500	4,690

Source: Arthur D. Little analysis

Green Bloom

Compared with the Knock On Wood scenario, results for chemicals produced through dedicated production and *in planta* are identical. The only differences between these two scenarios are that in Green Bloom algal feedstocks become available for use and there are no limitations to the availability of lignocellulosic materials; this slightly increases the figures. These differences are relevant only to biofuel-derived chemicals with the most significant changes reflected in the results for biodiesel-derived chemicals. It is notable that this is the only scenario where high volume biodiesel-derived chemicals (B2b) become more attractive than high volume bioethanol-derived chemicals (B2a) due to breakthroughs in using algal feedstocks.

This scenario is the most optimistic of the four explored in this study and therefore also results in the highest UK IB market value at £11.8 billion. While the production of all chemicals through IB is attractive, high value chemicals remain to provide more lucrative opportunities than the low value chemicals. This continues to reflect the difficulties in remaining cost competitive while needing to scale-up, despite technology breakthroughs.

With the biochemical industry focused on feedstocks that avoid competition with food and feed, *in planta* production is also very attractive – in fact the market value for chemicals produced *in planta* in the Green Bloom scenario is almost equal to that of chemicals produced through dedicated production.

To achieve the production volumes and market values for Green Bloom, 14% of UK agricultural land could be needed to meet the biomass demand for biochemicals. It should be noted that also non-agricultural land could be used for the cultivation of some feedstocks (e.g. switchgrass), which would significantly decrease pressures on land. However, the risk for land use becoming a limiting factor in this scenario still remains.

Due to increased efficiencies across all the production methods, CO_2 savings are the highest in this scenario at 5.2 million tonnes CO_2 saved.

Results for Green Bloom are summarised in Table 11.

Table 11: Results for Green Bloom scenario

Production method	Dedicated production		Biofuel-derived			*In planta*		Total
Value and volume	High value (A1)	Low value (A2)	High value (B1)	Low value (B2a)	Low value (B2b)	High value (C1)	Low value (C2)	
Global IB market (£m)	180,700	49,000	21,700	13,400	9,900	65,700	19,600	360,000
UK IB market (£m)	5,200	2,100	626	387	286	2,400	800	11,800
UK IB volume ('000 t)	260	809	64	361	267	130	309	2,201
CO_2 savings ('000 tCO_2 p.a.)	424	2,300	207	587	433	423	500	5,205

Source: Arthur D. Little analysis

Electrified

Due to sustained low oil prices, petrochemicals become increasingly competitive making the use of industrial biotechnology to produce high volume chemicals unattractive, except for the A2 category chemicals. This is because the drop in oil demand which drives down oil prices is not estimated to occur until around 2020. This will result in some investments in white biotechnology for A2 chemicals while bio-based feedstock prices are still competitive i.e. oil prices remain higher. Comparing the figures in Table 12 with the results of the Green Bloom scenario shows that the results for categories A1 and C1 are lower, primarily due to the extreme volatility in oil prices until 2015 and later the drop in oil prices.

The Electrified scenario is the only scenario in which biofuel-derived chemicals are not attractive. Volatile oil prices are not able to attract enough long-term investment into biofuels in order to develop a market and after the emergence of electric cars, biofuel demand drops off significantly preventing the chemicals industry from being able to valorise on by-products and wastes.

Land use in this scenario is also extremely low compared with the other scenarios; requirement represents only 1% of current agricultural land area. Low volumes of IB production prevent achieving savings higher than 1.4 million tonnes of CO_2 equivalent.

Table 12: Results for Electrified scenario

Production method	Dedicated production		Biofuel-derived			*In planta*		Total
Value and volume	High value (A1)	Low value (A2)	High value (B1)	Low value (B2a)	Low value (B2b)	High value (C1)	Low value (C2)	
Global IB market (£m)	158,800	13,100	-	-	-	48,200	-	220,100
UK IB market (£m)	4,600	300	-	-	-	1,300	-	6,200
UK IB volume ('000 t)	230	216	-	-	-	96	-	541
CO_2 savings ('000 tCO_2 p.a.)	373	701	-	-	-	310	-	1384

Source: Arthur D. Little analysis

6 Risks and opportunities

As illustrated in Chapter 3, industrial biotechnology has the potential to become an important market for the UK. This chapter explores these opportunities and risks in further detail through further testing sensitivities of the key elements in the model and by consideration of key opportunities and risks which have not been captured by the modelling exercise (e.g. exploitation of international markets).

Identifying tipping points enables to look at the situations in which certain chemicals become attractive or unattractive from an economic perspective. We have tested the sensitivities of feedstock costs (traditional and bio-based) and technology breakthrough rates, as these are the main drivers shaping each of the scenarios.

In identifying tipping points, we assume that for each scenario, all other elements are realized as per our estimations and only the mentioned element is changed. For example, in identifying tipping points for oil prices, we assume that all other elements remain unchanged, such as production costs, yields etc. and only the oil price is changed to find the tipping points.

6.1 Key risks for consideration

Risks associated with feedstock prices and availability

Whether chemicals are produced using traditional or biochemical routes, feedstock costs are the most important driver of their market attractiveness and a key risk for the development of the IB markets. For the purposes of this study, the key factor is the relative cost competitiveness of bio-based feedstocks with traditional feedstock prices, namely crude oil and naphtha prices. Because these two are closely correlated (see Figure 4), we have tested the sensitivities for crude oil prices.

By adjusting the oil price, we have identified tipping points at which bio-based chemicals become attractive and unattractive compared with their petrochemical counter parts. These tipping points, presented in Table 13 below, vary by scenarios, where different oil prices have been used.

Table 13: Tipping points by scenario for oil prices

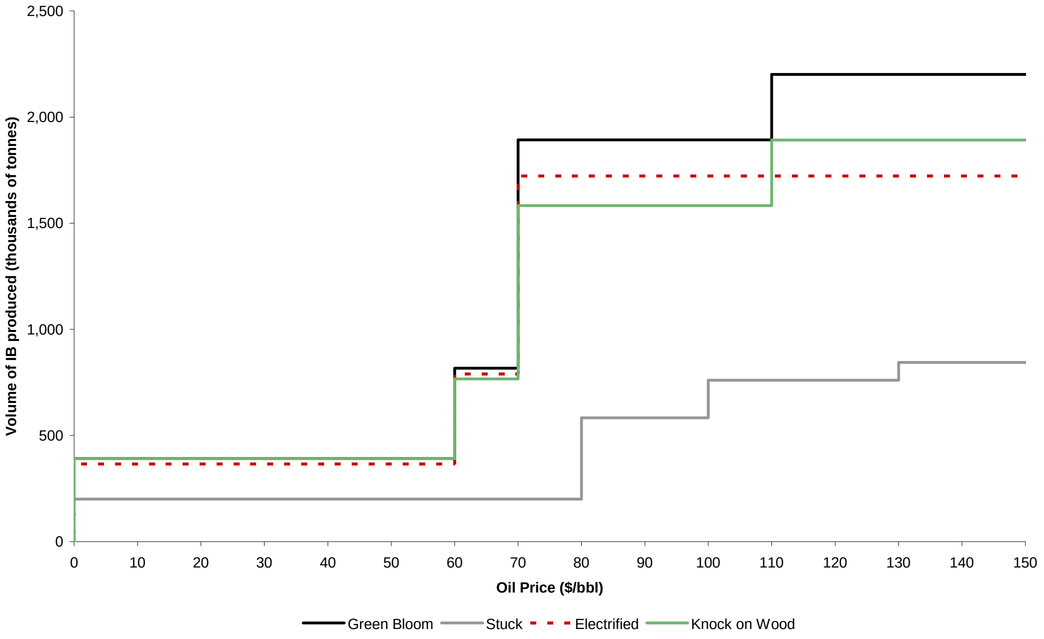
Category/Scenario (USD/bbl)	Green Bloom	Knock On Wood	Electrified	Stuck
High volume dedicated production (A2)	70	70	70*	90
Bioethanol derived (B1&B2a)	60	60	60	80
Biodiesel derived (B2b)	70	70	70	100
High volume *in planta* (C2)	110	110	110	130

* In the Electrified scenario, baseline oil price used is 50 USD/bbl therefore it will not require a "minimum" oil price (tipping point) to make it attractive. The 70 USD/bbl quoted above is the price at which attractiveness increases – the market share of IB production for A2 rises from 2.4% to 5%. Source: Arthur D. Little analysis

The share of feedstock costs compared to the total chemical production costs in the Stuck scenario are much higher in the Stuck scenario, which also results in higher tipping points. These results are also displayed in Figure 7 below. ***With current bio-based feedstocks prices, IB is not competitive with traditional chemical production when the oil price below $60/bbl for most scenarios***.

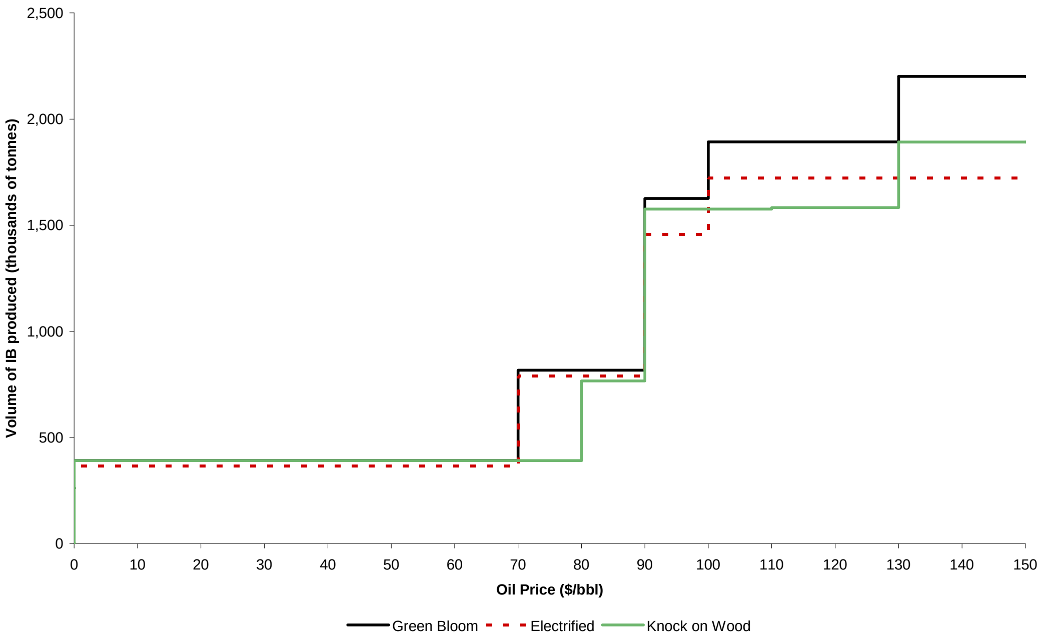
Adjusting the prices for bio-based feedstocks affects the oil price at which up take of IB becomes attractive. Figure 8 illustrates that ***where high bio-feedstock prices are used rather than low feedstock prices, the price of oil required to be competitive increases by 20-30 $/bbl*** (i.e. the curves in Figure 8 are to the right compared to Figure 7). This is due to a shift in the delta between traditional and bio-based feedstocks. Conversely, if low feedstock prices are used in the Stuck scenario (which is based on high feedstock prices) the oil price curve moves to the left (see Figure 9).

Figure 7: Impact of changes in oil price to volume of IB products produced by scenario



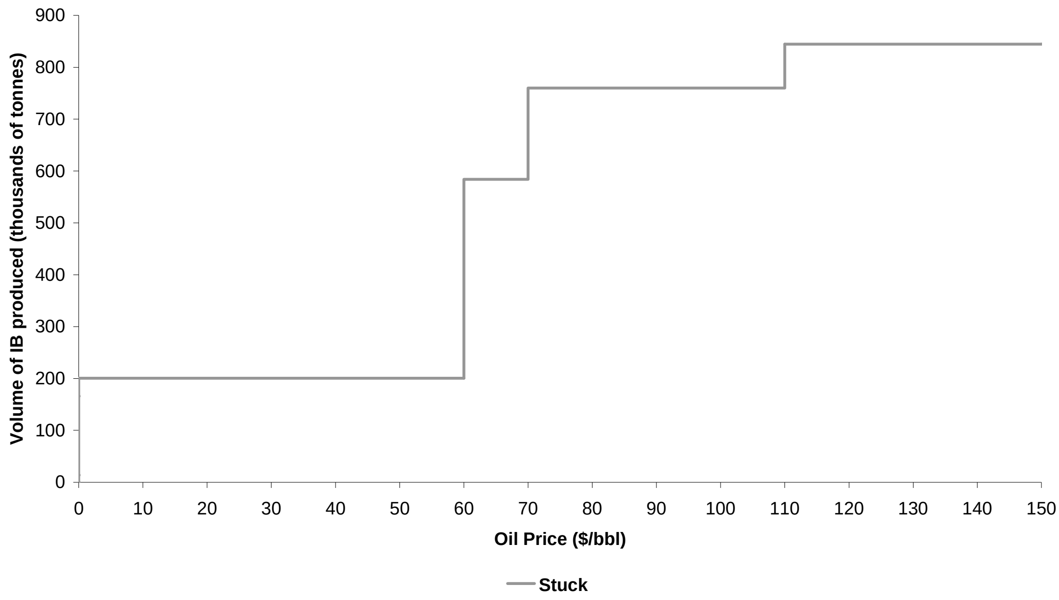
Source: Arthur D. Little analysis

Figure 8: Impact of changes in oil price to volume of IB products with high feedstock prices for Green Bloom, Electrified and Knock on Wood scenarios



Source: Arthur D. Little analysis

Figure 9: Impact of changes in oil price to volume of IB products with low feedstock prices for the Stuck scenario



Source: Arthur D. Little analysis

The risk associated with changes to oil prices is significant and not readily mitigated. By maintaining or increasing efforts to develop low volume chemicals (especially A1 and C1), the UK's chemical sector could potentially avoid excessive exposure to oil price volatility. While reducing bio-feedstock prices can be important in some cases it is unlikely to counteract a scenario where oil prices are low.

Risks associated with volumes of chemicals produced in association with biofuels

An important parameter within the model, associated with the volumes of B1, B2a and B2b chemical categories is the percentage of biomass that could be used for chemicals as a by-product from biofuels production. The sensitivity of this parameter was tested.

Our base case assumes that for first generation bioethanol feedstocks such as wheat or corn, 1% of the biomass for biofuels would be converted into chemical products. For lignocellulosic materials, this proportion would be slightly higher at 2.5%. For biodiesel our base case assumes 4%. The rationale for these parameters is mentioned in Section 5.1.

If these conversion rates were all increased to 5%, the market values and production volumes would be significantly higher for biofuel-derived chemicals: their combined market value in the UK would reach £2.4 billion compared to £1.3billion in the base case. This would represent almost 20% of the total UK IB market value in the Green Bloom scenario compared with 11% in the base case. Production volumes would increase by almost half a million tonnes. The impact of lowering the conversion rate for lignocellulosic biomass from 2.5% to 1.6% (equal to that of first generation feedstocks) has also been tested. This results in decreased market values for bioethanol derivatives from £1 billion to £0.4 billion for the Green Bloom scenario.

For the other scenarios (except where B1 and B2 chemicals are not produced anyway under the Electrified scenario), changing the conversion rate would result in similar relative changes between the biofuel-derived chemicals compared with the A and C categories.

This analysis shows that the rate at which biomass (as a by-product of biofuel production) can be converted into chemicals, can have an impact on the size of the market for biofuel-derived chemicals. However, even with an optimistic conversion rate (such as the 5% demonstrated above), the market for biofuel derivatives is not as attractive as for the chemicals produced through dedicated production or in planta.

Risks associated with land availability

Feedstock availability is directly linked to land availability and we have therefore tested the implications of constraints on land use. ***If land available for IB production is limited to 1.7 million hectares, then biofuel-based production under the Green Bloom, Knock on Wood and Stuck scenarios becomes slightly restricted***:

- Under Green Bloom and Knock on Wood, this will cause bioethanol-derived products to decrease in output and market value by around 24% while biodiesel-derivatives are unchanged due to the ability to exploit off-shore facilities
- The decrease for bioethanol derivatives under the Stuck scenario is slightly less at around 12%. Under the Stuck scenario, there is not enough land for biodiesel derived chemicals without technology breakthroughs and it becomes unattractive

In all scenarios, production of chemicals through dedicated production, and in planta production of high value chemicals is not affected by the 10% constraint to agricultural land. However, high volume *in planta* chemicals will be significantly affected. Constraints on land of 10% cause that C2 chemicals are not produced, as they are at the “bottom priority” because they have the highest tipping points and the model interprets them as the “least value” products.

Analysis from a slightly different angle suggests that producing 5% of the UK's current high volume chemicals through *in planta* would require ~ 3% of current agricultural land to be planted with a (modified) crop[24]. A sizable portion of the UK's high value, niche chemicals could be produced through the *in planta* approach; Already with ~ 3% of the UK's agricultural land, a full quarter of the UK's fine and specialty chemicals production could be produced, something even more attractive when these modified chemical crops could be grown on marginal land[25].

Both Green Bloom and Knock On Wood scenarios draw on the development of lignocellulosic feedstocks; these are likely to be sourced from agricultural land or from land previously used for grazing. This would amount to under 2 million hectares from a total UK land area of 24 million hectares[26]. However, the use of lignocellulosic feedstocks is also limited by the cost of transportation of feedstocks. A plant of 200,000 tonnes (which is likely given experience to date), could result in smaller levels of production for B2 categories of chemicals. In particular, production of chemicals could be focused on ethanol itself rather than biofuel by-products where the market evolves with chemical complexes rather than an integrated biorefinery.

As an additional exploration into land requirements for biofuels (though these are not modelled *as fuels* in this study) we have calculated the proportion of current transport fuel demand for different feedstocks. For example, under a hypothetical scenario, all the arable land in the UK for wheat straw would only satisfy 5% of current UK transport fuel demand. Although this example is theoretical as it is not practical to assume that 100% of arable land would be dedicated to biofuels production, not to mention for production of only one feedstock, the example provides interesting insights on the orders of magnitude for land required.

[24] Assuming a current market value of € 25 billion for commodity chemicals with 5% being produced *in planta* = € 1.1 billion. Assuming 10% can be obtained in biomass on a weight basis requires the production of 5 million tons biomass per annum. In switchgrass that produces 10 tonnes of biomass/hectare, this would require 0.5 million hectares or 2.7% of total UK agricultural land

[25] Assuming a current market value of € 36 billion for fine and specialty chemicals with 25% being produced *in planta* = € 8.4 billion. Assuming 10% can be obtained in biomass on a weight basis requires the production of 6 million tons biomass per annum. In switchgrass that produces 10 tonnes of biomass/hectare, this would require 0.6 million hectares or close to 3.1% of total UK agricultural land

[26] ADAS report to NNFCC (2008) Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities

6.2 Key opportunities for consideration

Implications for the UK chemicals market

In the coming 15 years based upon the scenarios that have been developed, the UK chemicals market is not expected to see dramatic changes, rather a gradual shift of one production platform to the other. Even in the most optimistic scenario, the UK market share of industrial biotechnology is estimated to remain a modest 7% to 17%, much of which can be served by existing companies. More specifically, we would note the following implications for the UK market:

Chemicals and chemical-using sectors

The model only considers the former, i.e. the chemical industry itself. Added value derived from the IB chemicals produced could therefore be even larger. Downstream industries like personal care, cleaning products, packaging, and the like can purchase IB products, add value and market such products to specific end consumer groups.

New applications & products

Biocatalysis and fermentation may be expected to continue their growth path, thus being applied in an increasing variety and amount of chemicals produced. This may concern relatively low volume, high value chemicals like specialty plastics (e.g. PHA) but may also extend to more high volume chemicals such as Danisco/Genencor's isoprene. Alternatively, commercialization, for example, of DuPont/Tate&Lyle's production of 1,3-propandiol from sugars may produce a "platform chemical" from which other chemicals can be derived. Notably, where biofuel production reaches scale, there are opportunities for new platform chemicals that can be easily derived from waste or by-product material. For example, 1,3-propandiol obtained through conversion of biodiesel-derived glycerol.

Limited displacement of existing chemicals

Based on the limited and gradual extension of industrial biotechnology, dramatic displacement of chemicals produced today is not widely expected, though it may happen in isolated cases. Moreover, taking into account that the overall chemical market is expected to grow, in volume terms only very few chemicals could experience a noticeable volume drop.

New competitors may enter the market
Nevertheless, the structure of the chemicals market may change. To the extent that the above developments are not pursued by existing (chemical and pharmaceutical) players, there is an opportunity for new companies to enter the IB market. Each of the three production platforms offers such opportunities. A good example is Danisco/Genencor which is becoming active in the chemicals market based on its ability to develop new production technologies. Also, a company like Monsanto, which has completely shed its chemical affiliation, might re-enter through its ability to modify crops into producing chemicals. Finally, companies active in production of biofuels may see opportunities to valorise waste- and by-products into the chemicals market, either through joint ventures or by themselves.

Economic opportunities for the UK
From the ADL market research and expertise, employment within the chemical industry can be estimated as 250 tonnes per employee per year for fine and speciality chemicals and 2500 tonnes per employee per year in more commodity chemicals. If combined, this results in employment from manufacturing of over 6,000 FTE (Green Bloom) over 2,000 FTE (Stuck scenario), over 3,000 FTE (Electrified) and 6,000 FTE (Knock on Wood). However these figures are indicative estimates only and include a number of positions which would not be “additional”. Furthermore these numbers will need further consideration as they do not include employment created across the value chain (e.g. production of feedstocks) or from technology development.

Opportunities to service a significant global market
The global employment and GVA associated with IB will be much higher than the UK figures. While this model has not looked at this in detail, there are undoubtedly opportunities for the UK to exploit IB knowledge through export of technology and know-how developed in the UK.

Opportunities associated with technology development or breakthrough
For most chemical groups, limitations on the market come from technology development rather than lack of financial incentive. Technology breakthrough rates are a key driver in the model, therefore any changes to these assumptions will have a direct bearing on the results. For example, a halving of all breakthrough rates in any of the scenarios (Green Bloom, Knock on Wood, Stuck and Electrified) will halve the resulting penetration of IB and resultant market size and CO_2 savings.

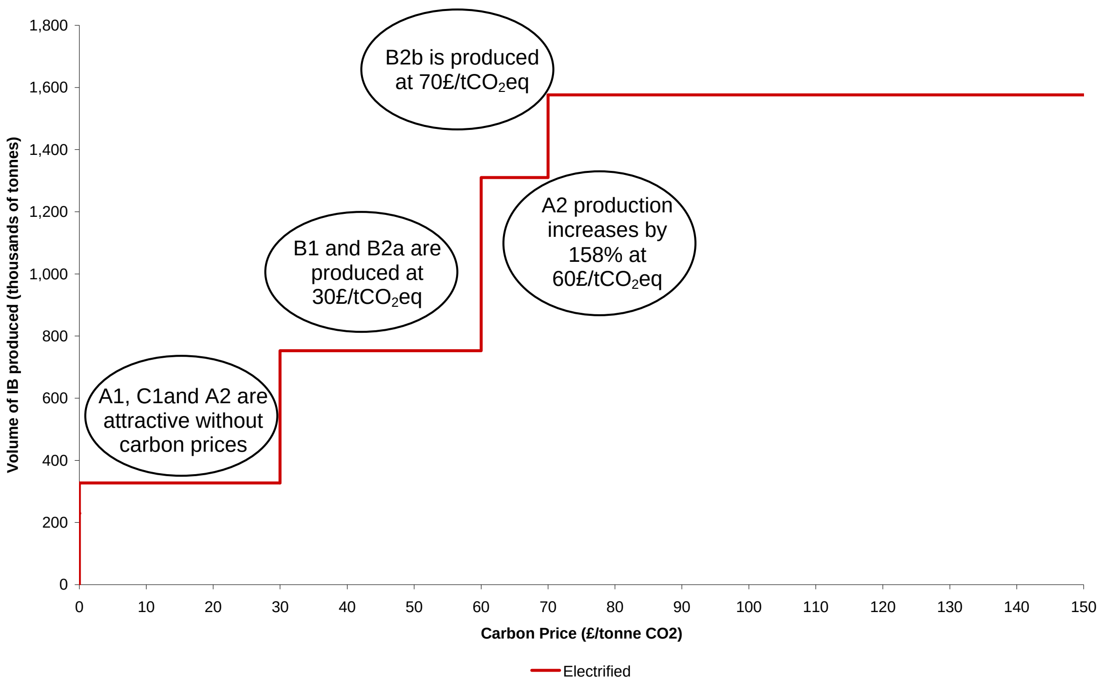
In order for the UK to benefit from lignocellulosic feedstocks, significant breakthroughs need to happen either in terms of conversion efficiencies (e.g. an overall improvement of around 35% over current levels for wheat straw), or a significant decrease in total operating costs. Most likely a combination of the two will be required for a sustainable lignocellulosic biofuels industry to develop. There are similar opportunities for algal feedstocks, although these might be more challenging.

Opportunities associated with exploitation of low carbon emissions of IB

As discussed in the results section, IB can play a role in reducing emissions within the sector. While there are numerous mechanisms used by governments to reduce emissions, the use of a carbon price through markets (e.g. Emissions Trading Scheme) is important. In this case however, carbon prices do not cause chemical production to become unattractive under the Stuck, Green Bloom and Knock On Wood scenarios[27] as oil prices are already high; further carbon prices would only raise the cost of production of traditional chemicals even further.

Where there is a low oil price (i.e. $50/bbl in the Electrified scenario), price of carbon can have an impact on production. This is illustrated in Figure 10.

Figure 10: Impacts of carbon prices on production under the Electrified scenario (low oil price)



Source: Arthur D. Little analysis

[27] Note: Under carbon prices above £300/tonne, chemicals within the C2 category could be produced in the Stuck scenario

The curve above illustrates the different levels at which carbon prices have an impact on production volumes, compared with “base-case” numbers in the Electrified scenario. B1 and B2a become economically attractive to produce compared with petrochemical alternatives when carbon price reaches £30/tonne CO_2 equivalent, if oil prices are as low as USD 50/bbl. Biodiesel derivatives require a higher carbon price of £70/tonne CO_2 eq. The graph also displays the impact of a carbon price on A2: while it is produced even in the base case, production would significantly increase at £60/tonne CO_2 eq.

Assessment of incentives to support IB chemicals production

Beyond support for technology development and monetizing the carbon savings of products, there are additional incentives that, in theory, could stimulate the industrial biotechnology market. Our model has the capability to calculate the impact of incentives on market size for each chemical category. For example:

- In the Electrified scenario, if a support level of £100/tonne of product produced for chemicals in the A2 category and £500/tonne of product for chemicals in the C2 category could ensure that 5% of high volume chemicals could be produced through *in planta and* direct production each
- In the Stuck scenario, incentives of £300/tonne of product produced for chemicals in the C2 category would ensure 5% of high volume chemicals could be produced through *in planta*

For the B categories, the incentives are all linked to encouraging biofuel production – in order to provide sufficient production volumes – rather than needing to encourage the utilising the waste products. As the quantitative model excludes biofuels as such, the interventions related to their economics are outside the scope of this study.

However, it should be noted that most chemicals are limited by technology rather than by the lack of incentives. The government could support technology breakthroughs by encouraging investment into certain technologies, but breakthroughs are extremely difficult to predict and thereby optimise the targets and amounts of support. For the biofuel-derived chemicals, any mandates for producing biofuels would naturally have an impact on derivative chemicals production.