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## Mapping the Development of UK Biorefinery Complexes (NFC 07/008)



A Report Prepared For the National Non Food Crops Centre  
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# 1. Executive Summary

The development of new biofuels markets in the UK represents an important strategic element of government policy in transitioning to a future low carbon economy. Current fiscal incentives are now successfully facilitating a nascent UK biofuels sector. However, the challenge of developing a truly sustainable biofuels economy that can deliver environmentally beneficial transport fuels to customers at low cost whilst providing an attractive financial return to manufacturers and investors remains daunting. To achieve a step-change in the economics of biofuel production requires a radically different manufacturing capability such as that provided by the biorefinery concept. Based upon current manufacturing platforms in the oil and petrochemical sectors, future biorefineries will process large volumes of biomass feedstock to produce biofuels and a diverse suite of valuable co-products. Large scale process integration will maximise both energy and materials conversion efficiencies and economies of scale will be exploited to deliver capital efficiencies and cost effective co-production of value added chemicals. In contrast to oil refineries, the biorefinery will exploit state-of-the-art bioprocessing technologies in addition to the more conventional thermochemical processing routes.

This project set out to provide a platform for a coordinated activity on UK Biorefinery development and utilise roadmapping tools to map out the various critical pathways to achieve the successful implementation of these large manufacturing complexes. A comprehensive literature review was completed and revealed that considerable R&D activity is being focused on the development of enabling technology for deployment of biorefinery complexes. The US is leading the way in this respect and has large, well coordinated multidisciplinary and cross-sectorial R&D programmes underway to deliver national targets for biofuels production. Outside of the US the approach to technology development is somewhat fragmented and the UK does not appear to have a broad based strategic activity in the area. Advances in bioscience are driving down the estimated costs for second generation biofuels production using lignocellulosic biomass and technology deployment is reported to be on the brink of commercialisation. However, a number of challenging barriers remain and early adopters of second generation biofuels technology are likely to be economically disadvantaged against conventional biofuels utilising crop based feedstocks. Advanced biorefinery deployment remains a long term goal with general consensus suggesting commercial implementation beyond the 2020 timeline

Two different biorefineries were envisaged for the UK: One relatively small “whole crop” biorefinery complex producing bioethanol, lactic acid and high value extractives from wheat and wheat straw and one larger “two-platform” biorefinery complex producing

synthetic diesel and bioethanol from mixed biomass feedstocks. Limitations inherent in current UK biomass supply chains will likely to constrain the scale of even modestly sized biorefineries and impact on the ability of such complexes to maximise economic performance through economies of scale. In addition, emphasis will be placed on biorefineries that are flexible with regard to biomass feedstock type and can readily access global biomass feedstocks traded in commodity markets. The longer term availability of large volumes of energy crops and the development of biomass densification technology to produce readily transportable bio-oils will provide a platform for more effective feedstock supply infrastructure.

Technology mapping studies have emphasised the multidisciplinary and cross sectorial nature of the R&D programmes required to successfully deliver UK biorefineries within the 2020 -2025 timescales. Essential requirements for the development of enabling technologies have been identified and aligned behind existing UK science base skills. Specific technology barriers have been identified and categorised. From this exercise four key priority research areas were identified for particular focus; biomass supply chains, biomass pre-treatment, synthesis gas clean-up and pilot plant demonstration activities.

The UK science base has world class capabilities in a number of core development areas for biorefineries and in some fields such as improved energy crops, novel thermophile development and biomass pyrolysis, UK researchers have high profile roles. However, it is clear that a much broader engagement of the UK science base is required to develop a concerted and coordinated research activity that embraces a wide spectrum of different scientific disciplines. The roadmap developed from this project should be used as a platform for greater engagement of the UK stakeholders in biorefinery development. It is proposed that the first part of this process should be a targeted workshop coordinated by the NNFCC to establish general consensus on the key development timelines for critical enabling technologies for biorefinery development. The roadmap should be considered a dynamic document to be reviewed and updated on a constant basis as the technology advances and governmental policies and legislation develops.

## 2. Report Context

Plant biomass represents a rich and varied resource for the production of power, heat, transport fuels, chemicals and other bio-based materials. The widespread uptake of consumer products derived from sustainable plant sources offers the potential of stimulating new economic development, assisting in the preservation of the earth's finite resources and helping deliver international and national environmental policies for greenhouse gas reductions. Government policies are now successfully catalysing the emergence of both renewable energy and biofuels sectors in the UK. However, the realisation of a true low-carbon economy will require the development of an infrastructure and manufacturing capability that can provide large volumes of plant-based products to a high specification and at competitive cost. In future, these plant – derived products will be produced by large, integrated manufacturing complexes known biorefineries. Based upon current manufacturing platforms in the oil and petrochemical sectors, biorefineries will process large volumes of biomass feedstock to produce biofuels and a diverse suite of valuable co-products. Large scale process integration will maximise both energy and materials conversion efficiencies and economies of scale will be exploited to deliver capital efficiencies and cost effective co-production of value added chemicals.

The commercial implementation of biorefineries is a long term goal and requires the parallel development of advanced process technology, a sustainable biomass feedstock resource and supply infrastructure, new and viable markets for biorefinery co-products and a supportive regulatory and policy framework. Such complexity dictates that concerted and coordinated planning is undertaken now if biorefineries are going to be a commercial reality within the next fifteen year timeframe. A number of countries are now actively developing and coordinating multifaceted action plans to deliver their environmental and economic long term goals through biorefinery deployment. Huge R&D resources are being directed towards this biorefinery development and coherent and well coordinated programmes have been implemented to foster a multidisciplinary approach to the development of essential enabling technologies. Although there is some coordinated activity in the UK within individual technology areas and sectors, there is little evidence of an overarching strategy that engages all UK stakeholders in biorefinery development.

This report has been commissioned by the National Non-Food Crops Centre to map out the potential pathways to successful biorefinery deployment in the UK. This roadmapping exercise will assist the National Non-Food Crops Centre by providing:

- A comprehensive update on the latest state of the art in biomass processing for fuels and chemicals production.

- A review of the critical pathways and high priority research needs required to encourage biorefinery development.
- A review of the current core expertise that exists in the UK across a range of disciplines relevant to biorefinery development.
- A platform for the National Non-Foods Crops Centre NFCC to engage with all UK stakeholders in the biofuels and chemicals sectors to facilitate development of robust strategies for biorefinery development utilising UK biomass feedstocks.

This report is intended as a working document to help provide guidance, catalyse discussion and gain consensus on an appropriate action plan for coordinated and collaborative multidisciplinary R&D programmes targeted at key areas of biorefinery development. It is envisaged that this technology roadmap will become progressively more detailed through successive iterations. As a priority, this report should form the basis of a workshop to engage targeted UK stakeholders in discussion. The aim of this first workshop would be to provide a critique and validation of the preliminary roadmap, gain consensus on key actions and to cascade the agreed formalised roadmap to a wider audience.

The mapping report begins in chapter 3 with an overview of the current state of the art in biorefinery development; in particular the existing opportunities, challenges and remaining constraints are detailed. This chapter is a distillation of a larger literature review on biorefinery development that was completed as the first part of this roadmapping project. Chapter 4 depicts two distinctive biorefinery complexes that could be potentially deployed in the UK for the production of bioethanol and bio-derived synthetic diesel utilising UK biomass feedstocks and each producing a suite of value added co-products. Chapter 5 breaks down the development of biorefineries into a number of strategic areas and identifies the important barriers and opportunities for the successful development of the biorefinery configurations discussed in Chapter 4. Chapter 6 contains the biorefinery roadmaps and identifies four key priority areas for biorefinery research and development. Chapter 7 provides a discussion of some of the key issues arising from this study including the potential for disruptive technologies to radically impact upon the deployment of UK biorefineries. Finally the conclusions and recommendations are detailed in Chapter 8.

### 3. Introduction to Biorefinery Development

The fossil fuels; oil, coal and natural gas are the primary energy sources that have powered modern industrial civilisation. In 2005 the global consumption of these resources was the equivalent of over 9 billion tonnes of crude oil [1]. The demand for these resources is set to increase even further given the dramatic economic expansion occurring in countries such as China and India. However, this trend is not sustainable. It is now almost universally accepted that continued use of fossil resources at current rates will result in irrevocable damage to the environment and the effects of global warming caused by increased levels of greenhouse gases in the atmosphere are now evident. Fossil fuels, by their very nature are finite and in the case of oil, the point is rapidly approaching at which this resource is being consumed faster than it can be recovered from the ground. Security of supply is now a primary concern for countries that are primarily reliant on imported crude oil to meet their domestic energy requirements. North Sea reserves are depleting rapidly and by 2020, the UK could be dependent on imports for three-quarters of its total primary energy needs.

To address these critical issues of climate change and energy security requires the implementation of concerted and coordinated regulations and policies to reduce demand for fossil hydrocarbon resources and stimulate low-carbon energy resource diversification. The European commission has recently released proposals for a common energy policy which calls for the adoption of binding targets on 20% green house gas reductions by 2020 [2]. The DTI “Energy White Paper”, released in 2003, set out the UK’s government policy on renewable energy and confirmed the 2010 target for 10% of all electricity generation to come from renewable sources [3]. A major element in the delivery of the low carbon economy is the innovative development of sustainable routes to efficiently utilise the world’s abundant biomass resources for energy, fuels, chemicals and materials production. In 2005, the European Commission released the Biomass Action Plan which builds upon existing directives in the Electricity, Heat and Transport sectors and aims to increase biomass utilisation from its current value of 4% of total EU energy requirements [4]. In the UK, the government commissioned a Biomass Task Force to identify and provide solutions to the obstacles that prevent further contribution of biomass resources to the attainment of targets on renewable energy [5]. In response to this output from this study, a joint DTI/DEFRA biomass action plan was published last year [6].

The transport sector is the largest single energy consumer in the UK [7] and in 2005 contributed some 22% of the total greenhouse gas emissions (556 million tonnes of carbon equivalents) [8]. Biomass is currently the only renewable energy source that has

the potential to significantly reduce the greenhouse gas emissions from the transport sector in the short term without causing major disruption to the existing fuel supply infrastructure. The technology to produce biofuels, such as bioethanol and biodiesel, is well established and utilises readily available commodity raw materials such as wheat, corn, sugar beet and oilseed rape. Emerging biofuel markets are now demonstrating tremendous growth rates and global production is estimated to exceed 35 billion litres per year. This trend is set to continue; the US president called for national biofuel production targets to be expanded to 35 billion gallons by 2017 so that a 20% reduction in gasoline consumption could be achieved over the next ten years [9]. In an extension of the biofuels targets set in 2003, the European Commission has recently proposed that 10% of all EU transport fuels be produced from biofuels by 2020 [10]. In addition to the existing tax derogation on biofuels, the UK government introduced a renewable transport fuels obligation which mandated that by 2010, 5% (energy basis) of all fuels sold at the pump should be of a renewable origin [11]. These policies have successfully catalysed the development of an indigenous UK biofuels industry. In 2005, biofuels contributed some 0.24% of the total UK road fuel sales and the greater majority of the 118 million litres sold was imported into the UK. In contrast, the 2006 biodiesel production capacity alone in the UK was estimated to be 500 million litres and bioethanol production is planned to commence in 2007 at a number of new facilities. The UK now has at least 15 bioethanol and biodiesel production facilities either in operation, being constructed or at the planning stage. The potential biofuels capacity of these plants exceeds 2 million tonnes.

The two predominant commercial biofuels are bioethanol and biodiesel. Bioethanol is a biofuel substitute for petrol and can be used as a 5% blend in conventional vehicles as certified by the EU specification EN228. Bioethanol is produced via the fermentation of carbohydrate sugars derived from commodity agricultural products such as sugar cane, corn, wheat and sugar beet. Bioethanol production for transport fuel use is well established in countries such as Brazil, which implemented ambitious bioethanol programmes in the 1970's to reduce reliance on imported petroleum feedstocks. The United States, now the world's biggest producer of bioethanol, has for many years subsidised the bioethanol industry to help develop large production capability and reduce dependence on petroleum imports. In the US, bioethanol production is based on corn starch whilst the rapidly expanding bioethanol industry in Europe is predominantly based on cereals and sugar beet feedstocks.

Biodiesel, a substitute for mineral oil diesel, is generally utilized as a 5% (B5) blend in Europe and is covered by the EU specification EN14214. Higher blends of biodiesel can be utilised but this requires some vehicle modification. Biodiesel is a mixture of fatty acid methyl esters and is produced by the transesterification of vegetable oils with

methanol. The major Biodiesel feedstocks are the commodity oil crops; oilseed rape, soy, sunflower and palm.

Conventional biofuels have made, and will continue to make, a significant contribution to reducing greenhouse gas emissions in the transport fuel sector. However, these conventional biofuels contain a number of intrinsic limitations which may ultimately reduce their role to that of a transitory solution for reducing transport fuel greenhouse gas emissions until more advanced biofuel technologies options can be developed and implemented. These issues are summarised below:

- Production technology for both bioethanol and biodiesel is mature and limited scope exists to provide a step-change improvement in the economics of these processes.
- Conventional biofuels utilise arable crops such as oilseed rape, cereals and sugar beet. Such food crops are relatively expensive and can display price volatility as supply and demand tightens. Crops in tropical climates such as sugar cane and palm oil present alternative lower cost feedstocks but there are serious issues concerning the environmental impact of a large scale expansion in the planting of such crops.
- The capacity to meet the rapidly growing market demands for bioethanol and biodiesel will be ultimately limited by the availability of arable land and competition for feedstocks from the food and feed industries.
- Arable crops, such as cereals and oilseed rape, require significant inputs of materials such as fertilisers, pesticides and herbicides. Life cycle analysis has demonstrated that the use of these inputs negatively impacts upon the overall greenhouse gas savings achievable with conventional biofuels.
- Bioethanol and biodiesel do not represent the optimum transport fuels. The differences in chemical composition, physical properties and energy content of these materials when compared to their fossil fuel counterparts present a number of issues that either limit the amount of biofuel that can be blended with conventional fuels or adds complexity and cost to the supply chain infrastructure.

Ideally the optimum biofuel would utilise a low cost, high yielding renewable non-food biomass feedstock that delivered the highest amount of greenhouse gas reductions per litre, had a minimal environmental footprint and similar chemical and physical properties to existing petroleum fuels to ensure seamless substitution into the existing fuel supply infrastructure.

There are a number of potential biofuel systems that address the majority of the issues described above. However, the technology required to deliver these so-called “second generation” biofuels is complex, costly and not yet demonstrated at a commercial scale. Huge amounts of research funding is being directed towards this area and commercialisation of both second generation bioethanol and biodiesel fuels is likely to occur in the short to medium term although early adopters are likely to be economically disadvantaged against conventional biofuels. These advanced biofuel systems utilise adventitious low-cost lignocellulosic biomass feedstocks. Lignocellulosic ethanol is produced via the fermentation of sugars derived from the cellulose and hemi-cellulose polysaccharides present in biomass such as wood, agricultural residues and municipal waste. Synthetic diesel can be derived from biomass utilising both gasification and Fischer-Tropsch technology, both processes well known in the refining and petrochemical industries. The resultant synthetic diesel, known as BTL Diesel (“Biomass to Liquids”), is chemically similar to state-of-the-art low sulfur synthetics diesels produced from natural gas or coal. Numerous life cycle analysis studies have shown that second generation biofuels can deliver increased greenhouse gas savings when compared to traditional biofuels.

The majority of the technology development for lignocellulosic ethanol is taking place in the US, with Europe taking the lead in the development of high temperature gasification and BTL technology development. UK activity in both of these important areas in the UK is relatively small and localised in only a few academic centres.

The production of biofuels at a scale sufficient to meet increasing substitution targets set by national and international governments and at a production cost to be both competitive with conventional fuels and provide a sufficient return on the capital invested will require a step-change in current manufacturing capability. Such a step-change could be realised by the deployment of the “biorefinery” concept. The biorefinery concept, is modelled on current Oil and Petrochemical refineries and describes a large complex comprised of highly integrated individual processing units that utilise a flexible range of biomass feedstock’s to produce power, biofuels, renewable chemicals, feed and biomaterials. As with a modern day oil refinery, energy savings are maximised through process integration synergies and economies of scale are exploited for the cost effective co-production of value added chemical intermediates.

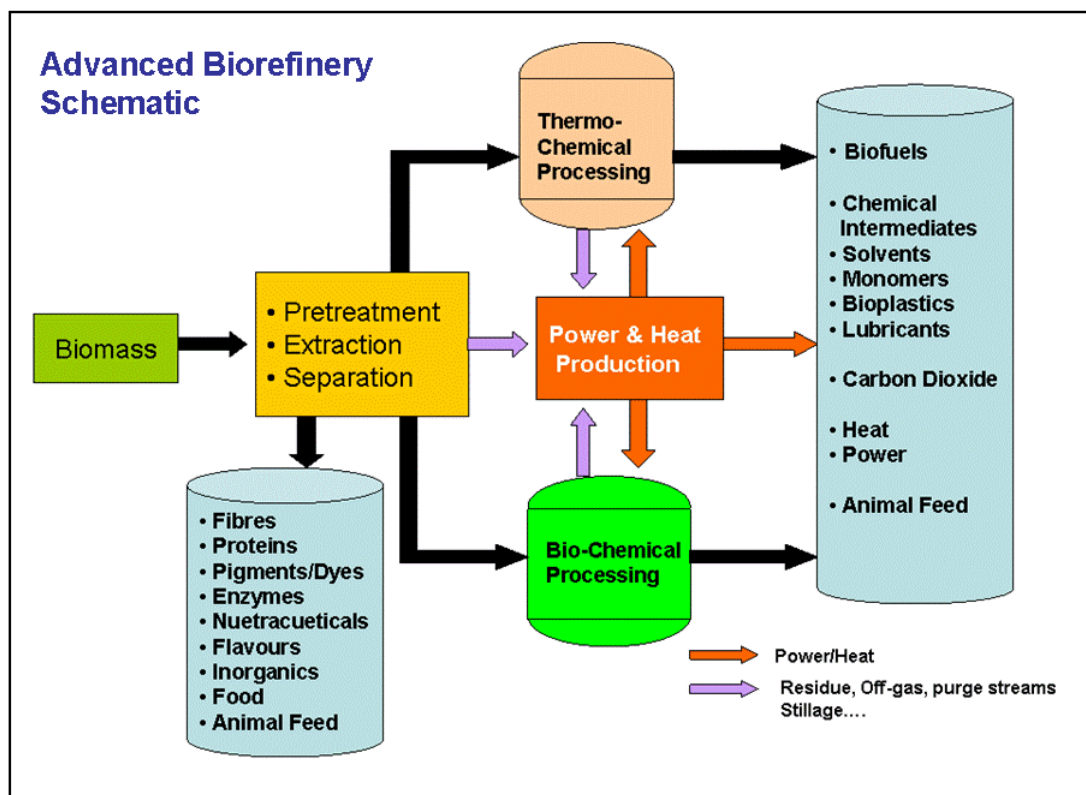
The biorefinery will utilise a range of low cost biomass feedstocks which will undergo fractionation into lignin, hemicellulose, cellulose and starch components for processing into a suite of valuable products. The carbohydrate components will be converted utilising a combination of state-of-the-art biological and chemical process technologies. As practised in oil refineries, the efficient management of complex flows of materials and

energy in the biorefinery complex will be paramount to utilise every element of the raw material feedstock and maximise integration benefits for improved energy savings and reduced processing costs.

*The biorefinery concept describes a large highly-integrated complex incorporating individual processes that synergistically convert biomass feedstocks into power, biofuels and value-added chemicals.*

A generic biorefinery schematic is shown in Figure 1. There are a number of interesting analogies that can be drawn between the biorefinery and the oil refinery:

- As with crude oil, biomass is a complex mixture of components that requires separation on introduction to the refinery. Crude oil is simply fractionated using distillation whilst biomass requires more complex physical and chemical fractionation methods.



**Figure 1 Schematic of a Generic Biorefinery Complex**

- The oil refinery uses a wide array of high temperature catalytic processes. The biorefinery will utilise both high temperature catalytic processes and state-of-the-art biochemical processes to provide greater flexibility in the choice of product portfolio. In the majority of cases the oil refinery uses highly efficient mature catalytic technology with the potential for only small incremental improvements over time. The biorefinery will apply novel and innovative biocatalytic routes with scope for radical improvements over time.
- Over the years oil refinery processes and product slates have changed to meet market demand. Biorefineries should be designed with the same principle. State-of-the-art biochemical process may allow more flexible processing and the potential for multi-product synthesis from common process units.
- Crude oil is extracted from the ground and its composition is fixed within certain boundaries that change from location to location. Biomass feedstock is grown and ultimately could be tailored for both optimum processing and end market application through the utilisation of both plant breeding and genetic engineering.
- Oil refineries have huge processing capacities to achieve maximum economy of scale. A typical oil refinery processes around 200,000 barrels of crude oil per day, some 10 million tonnes per year. Biomass feedstock logistics are likely to limit biorefinery processing capacity but volume should be maximised to gain economy of scale benefits.
- In an oil refinery every element of the crude oil barrel is utilised to manufacture products or power processes. In a biorefinery, every component of the biomass feedstock will be similarly utilised.
- Oil Refineries and Petrochemical complexes produce chemical building block such as olefins and aromatics which are derivatised to form intermediates for the polymers, solvents and detergents markets. Biorefineries will utilise advanced bioprocessing technologies to produce highly functionalised unique platform chemicals for derivatisation to valuable chemical intermediates.

If biorefinery complexes are to aspire to oil refinery economics and conversion efficiencies then they should be designed on complimentary principles. These can be summarised as follows:

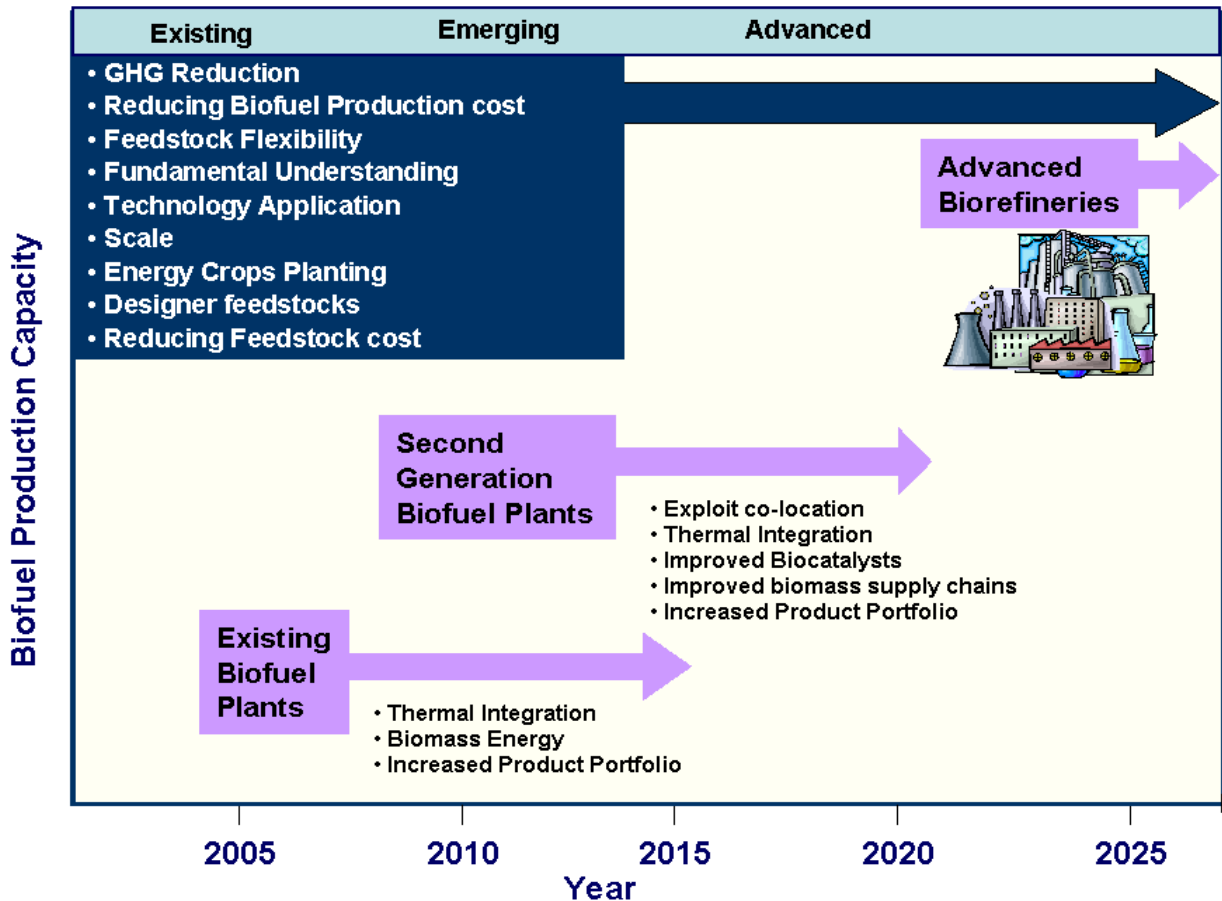
- A large throughput capacity to maximise economy of scale benefits.

- A world-scale biofuel production capacity to provide a sustainable economic platform over the lifetime of the investment and also to provide sufficient volume of biomass raw material streams for cost effective production of value added co-products.
- A wide suite of valuable products ranging from bulk to speciality chemicals.
- Synergies will be maximised through integrated processing and holistic operation on one large site. The various biomass feed streams should be joined by pipe.
- Self sufficiency in heat and power, deriving all its needs from the biomass input. Additional value can be generated through export of renewable electricity to the grid.

The commercial deployment of advanced biorefineries is a long term goal requiring the parallel development of advanced process technology, a sustainable biomass feedstock resource and supply infrastructure, new and viable markets for biorefinery co-products and a supportive regulatory and policy framework. Such complexity dictates that concerted and coordinated planning should be undertaken now if biorefineries are going to be a commercial reality within the next fifteen year timeframe. A number of countries are now actively developing and coordinating multifaceted action plans to deliver their environmental and economic long term goals through biorefinery deployment.

Due to the challenging barriers described above coupled with the huge capital investment required for such a large stand-alone complex, the development of biorefineries will likely occur through incremental advances in the existing biofuel infrastructure. Figure 2 demonstrates the anticipated timelines for advanced biorefinery development. In principle, current bioethanol and biodiesel production facilities can be considered as rudimentary biorefineries in that they produce a range of other valuable co-products in addition to the primary biofuel product. This is particularly true for wet mill ethanol facilities in the United States. A further move towards biorefinery principles can be seen in bioethanol plants currently being designed that incorporate the combustion of fermentation residue streams to produce heat and power.

Conventional bioethanol facilities are now broadening their co-products portfolios to generate additional value. Examples of this include the extraction of high value chemicals from primary feedstocks, such as proteins from rapeseed meal. Another example of this approach is the technology currently being developed to extract corn oil from DDGS produced in bioethanol dry mills and convert it into biodiesel. The remaining DDGS residue can then be used to generate heat and power for the plant [12].



**Figure 2. Timelines for Biorefinery Development**

The next stage in biorefinery development will be the commercial deployment of second generation bioethanol and BTL diesel facilities. The production of second generation biofuels will form the backbone of larger biorefinery complexes. Early adopters of second generation biofuel technology may well exploit co-location with existing infrastructure such as conventional biofuel plants, pulp mills and power stations. As in the case with conventional biofuels facilities, second generation biofuels facilities will drive production costs down by intensifying thermal integration between processes and expanding their product portfolios to add value to their operations.

The overall drivers, potential barriers and long term vision for biorefinery operation in the UK are tabulated overleaf. These aspects are discussed in the context of the following categories; environmental, economic, technological, societal and policy

	<b>Drivers</b>	<b>Possible Barriers</b>	<b>Vision</b>
<b>Environmental</b>	<ul style="list-style-type: none"> <li>Reduce transport sector emissions</li> <li>Improved biofuels with greater CO<sub>2</sub> reduction capacity</li> <li>Reduced fossil fuel dependence</li> <li>Renewable energy</li> <li>Manufacture of renewable chemicals and biodegradable plastics</li> <li>Effective use of waste materials</li> <li>Divert materials away from landfill</li> </ul>	<ul style="list-style-type: none"> <li>Perceived uncertainty over CO<sub>2</sub> role in global warming</li> <li>Perceived biofuel credibility due to unsustainable production elsewhere</li> <li>No buy-in from NGO's</li> <li>Impacts on biodiversity of large scale energy crop planting.</li> <li>Impacts of large scale biomass transportation</li> </ul>	<ul style="list-style-type: none"> <li>Most energy efficient producer base for biofuels and bio-based chemicals and materials</li> <li>Mass market production of biodegradable materials</li> <li>Holistic and sustainable utilisation of natural resources</li> </ul>
<b>Economic</b>	<ul style="list-style-type: none"> <li>Competitive UK biofuel industry</li> <li>Increased trade and reduced biofuel imports</li> <li>New &amp; sustained jobs in manufacturing &amp; agricultural sectors</li> <li>UK Chemical Industry competitiveness</li> <li>Increasing crude oil price trend</li> </ul>	<ul style="list-style-type: none"> <li>Huge capital investment</li> <li>Unattractive to capital venture market</li> <li>Poor returns for early adopters.</li> <li>Biofuels not cost competitive</li> <li>Cheap biofuel imports</li> </ul>	<ul style="list-style-type: none"> <li>Successful and sustainable UK biofuels industry</li> <li>Lowest cost producer base for biofuels and bio-based chemicals and materials</li> </ul>
<b>Technology</b>	<ul style="list-style-type: none"> <li>Opportunities for innovation</li> <li>Advances in Biotechnology</li> <li>Exploit UK capability in key areas</li> </ul>	<ul style="list-style-type: none"> <li>Lack of fundamental knowledge and expertise</li> <li>No access to critical technology</li> <li>UK scientific community not engaged</li> <li>Lack of coordinated planning</li> <li>Disruptive Technology</li> </ul>	<ul style="list-style-type: none"> <li>World leading, highly effective technology for production of biofuels and bio-based chemicals and materials.</li> <li>Exploiting advances made by engaged UK science base</li> </ul>
<b>Societal</b>	<ul style="list-style-type: none"> <li>Rural regeneration</li> <li>Feedstock balance to non-food crops</li> <li>Consumer demand for green &amp; ethical products</li> </ul>	<ul style="list-style-type: none"> <li>Non engagement with public</li> <li>Public refusal to accept use of genetically engineered biocatalysts and crops</li> <li>Planning permission for large complexes</li> </ul>	<ul style="list-style-type: none"> <li>Provision of low cost biofuels and green products into marketplace</li> <li>Smoother transition to low carbon economy</li> </ul>
<b>Policy</b>	<ul style="list-style-type: none"> <li>Comply with International policy</li> <li>RTFO</li> <li>Meet longer term renewables targets</li> <li>Energy security of supply</li> </ul>	<ul style="list-style-type: none"> <li>Incentives not linked to biofuel performance (GHG reduction)</li> <li>No policy on bio-based chemicals &amp; materials</li> <li>Longevity of existing policies not commensurate with capital investment decision making</li> </ul>	<ul style="list-style-type: none"> <li>Effective, integrated and consistent policies to deliver and sustain beneficial UK production of bio-based fuels, chemicals &amp; materials.</li> </ul>

## 4. Future Scenarios for UK Biorefineries

### 4.1 Introduction

The purpose of this section is to detail two possible biorefinery configurations that could be deployed in the UK within the 2020-2025 timeframe. These biorefinery complexes will then form the basis of the technology roadmapping exercise detailed in the next two chapters. The biorefinery configurations were chosen after a thorough review of the state of the art in global biorefinery development and the decision making process was facilitated by following a set of guidelines:

- The configurations chosen should meet the majority of the criteria outlined on page 12 and 13 for advanced biorefineries.
- One biorefinery complex was designed for bioethanol production the other for biomass derived synthetic diesel production.
- Two distinct biorefinery concepts were chosen particularly with a view to contrasting advanced fermentation process technology with that of high temperature biomass to liquids process technology and additionally two different scales of operation.
- The biorefineries chosen should incorporate process technology that is actively being developed at the current time, such that commercial implementation by the 2020 – 2025 timescale is realistic. Particular emphasis should be placed on products and processes that are receiving significant amounts of R&D funding and are being developed by industry led consortia.
- The biorefineries will utilise UK biomass resources and the scale should be commensurate with the potential biomass volumes available in 2020-2025.
- The major co-products associated with biofuel production should have existing, or potentially, large and sustainable end markets. Platform chemicals should have a wide range of downstream derivatisation options and be competitively differentiated from similar chemical intermediates derived from petroleum sources.

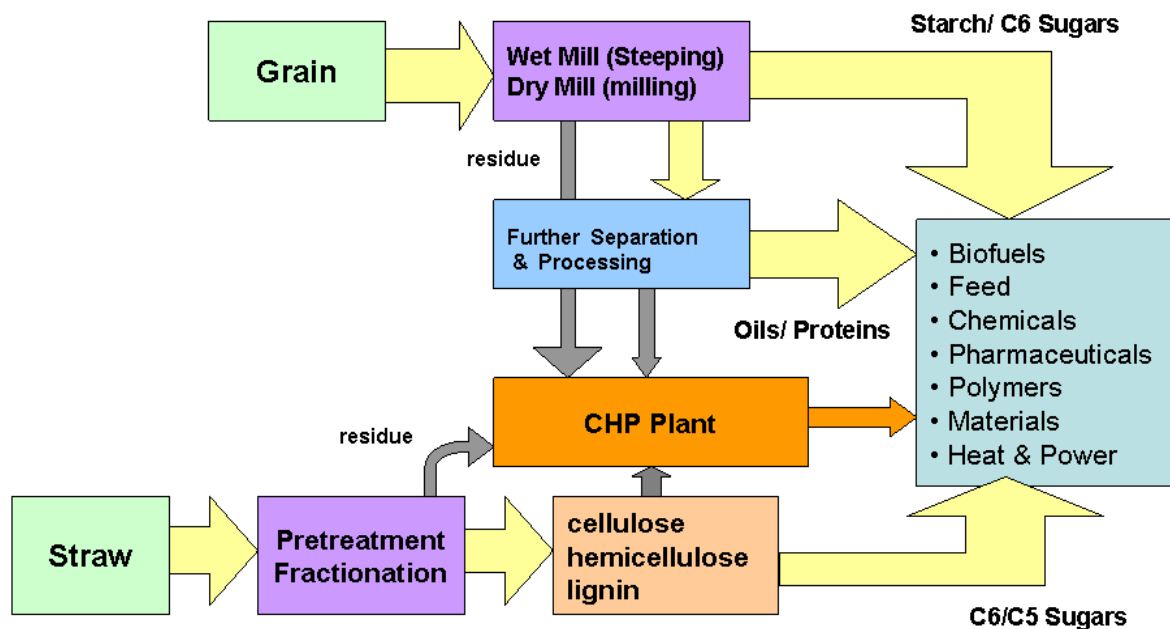
Based upon these guidelines two biorefinery configurations were chosen; the first utilising the whole crop biorefinery approach to produce bioethanol and lactic acid from wheat feedstock, the second utilising the two platform biorefinery concept to produce bioethanol and synthetic diesel from mixed biomass feedstocks. In both cases alternative options for value added chemicals are discussed. It should be noted that this qualitative decision making process is solely intended to facilitate the roadmapping

process and identify key barriers to biorefinery deployment in the UK. This process is not intended as a substitute for a more rigorous techno-economic evaluation necessary to define with certainty the likely product portfolio of future UK biorefineries. However, the issues identified and discussed in this roadmapping process will be generic to all biorefinery developments. It is envisaged that this report will be a precursor to more detailed techno-economic evaluation and modelling of possible biorefinery configurations. Specific biorefinery modelling tools to determine the economic capability of different configurations are now being developed and discussed in Chapter 5.

## 4.2 Cereal Based Whole-Crop Biorefinery Complex

The first UK biorefinery design is based upon the “whole crop” biorefinery concept and utilises cereal feedstock, both the grain and the straw, to produce bioethanol, lactic acid and a range of other co-products. The whole crop biorefinery incorporates fractionation of the grain kernel into distinct component for tailored processing into valuable products.

### 4.2.1 Whole Crop Biorefinery Concept



**Figure 3 Schematic of a Whole Crop Biorefinery Complex**

The whole crop biorefinery concept utilises cereal feedstocks such as wheat and corn but in contrast to existing bioethanol facilities, the entire crop is utilised including the cereal straw and corn stover to produce biofuels and other chemicals. This concept could also be expanded to include oilseed rape (oilseeds, meal and straw). The whole crop biorefinery beneficially integrates both novel lignocellulosic conversion technology and more conventional starch fermentation processing. The utilisation of the entire crop generates feedstock cost savings and increasing the productivity of arable land for biofuels (yield biofuel/hectare). A simplified schematic of a cereals whole crop biorefinery concept is shown in Figure 3.

The individual process steps in the biorefinery can be summarised as follows:

- The grain is fractionated either by dry milling with some physical separation of the grain components into raw material streams or by wet milling and separation of the grain into distinct component streams after steeping.
- The grain starch is hydrolysed to provide a glucose sugar stream for bioprocessing to produce bioethanol or other chemicals such as lactic acid, 3-hydroxypropionic acid and succinic acid.
- Further extraction and separations can be performed on the other grain components to provide valuable proteins, oil and non-starch polysaccharides for upgrading into high value polymers, nutraceuticals, pharmaceuticals and specialities.
- The residue from the various conversion and extraction processes can then be used as a biomass fuel to produce heat and power for the complex and export electricity to the grid to add further value to biorefinery processing operations. Energy conversion can be performed in a boiler/ steam turbogenerator or more preferably a combined cycle gas turbine to improved conversion efficiency.
- The agricultural residue from the crop (cereal straw, corn stover...) is shredded and milled down to a smaller particle size and fed to the biomass pretreatment section for part fractionation of the material into lignin, cellulose and hemicellulose components and activation of cellulose to increase its reactivity towards hydrolysis.
- The cellulose and hemicellulose polysaccharides are hydrolysed to fermentable glucose and pentose sugars (mostly xylose and arabinose). Depending on the nature of the previous pretreatment section, the hemicellulose polysaccharides may already be solubilised and hydrolysed to oligomers and monomeric sugars.
- Conversion of the both the glucose and pentose sugars to bioethanol and chemical intermediates such as organic acids (lactic acid, 3-hydroxypropionic acid, succinic acid, xylitol, furfurals or levulinic acid) using both fermentation and conventional chemistry. The glucose and pentose sugar streams can be processed individually to broaden product portfolio or together to maximise yield of one particular product.

- The residual lignin from the processing of the cereal straw or corn stover is then combined with the stillage residue from the grain processing section and utilised as fuel to provide heat and power for the plant and electricity export to the grid. Although not sufficiently developed at the current time, process technology could also be available in future biorefineries for the conversion of a portion of the lignin to valuable chemical intermediate such as phenols.

The whole crop biorefinery concept was first explored in the early 1990's by the BIORAF consortium; an EU funded activity which looked at both wheat and oilseed rape processing [14]. Current bioethanol production facilities in Brazil can be considered as transitional whole-crop biorefineries in that the bagasse, the residue from sugar cane processing, is combusted in the facility to provide heat / power and electricity export to the grid.

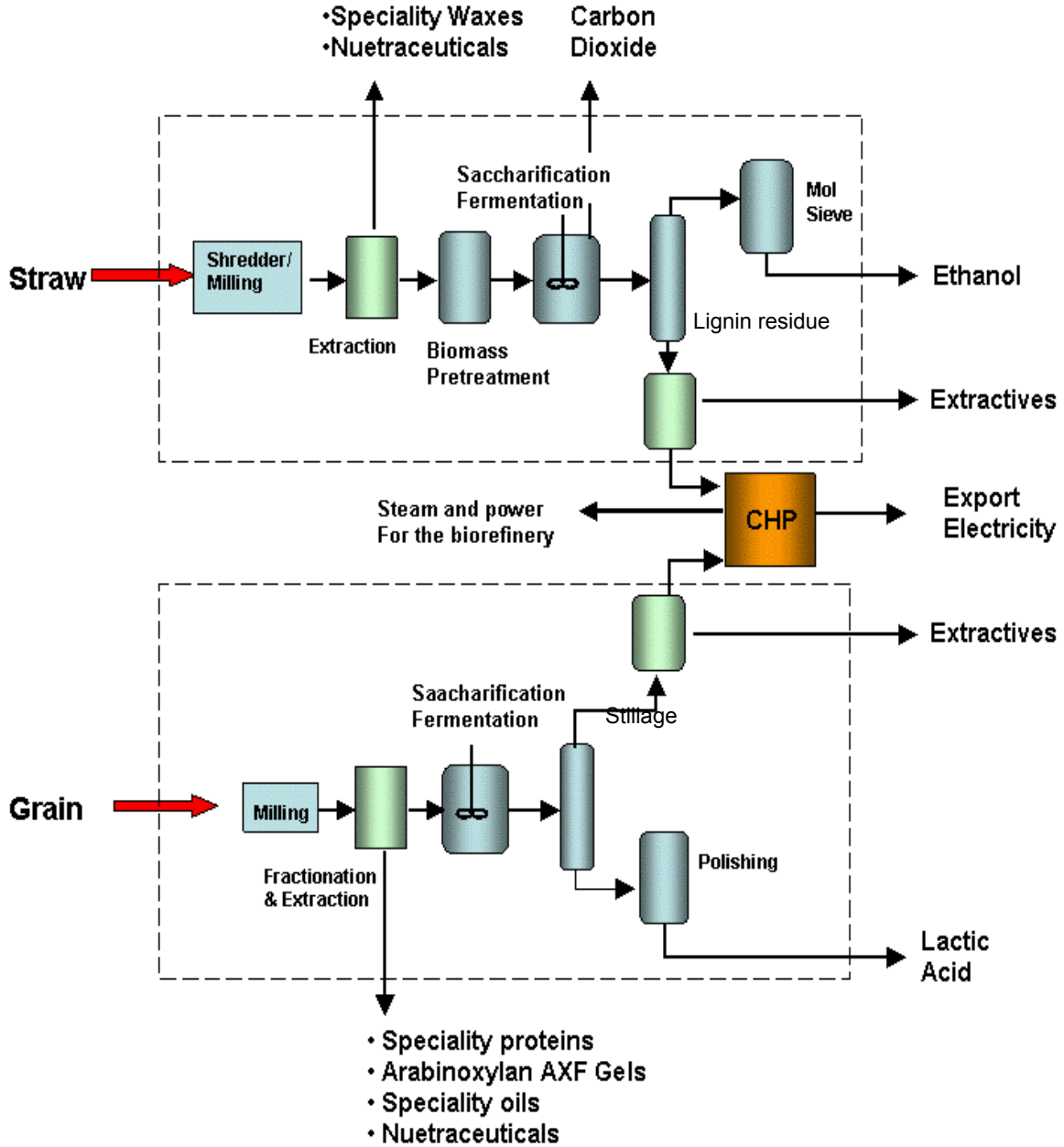
The deployment of advanced whole crop biorefineries in the 2020 – 2025 timeframe is dependent on the successful development of a wide range of improved process technologies ranging from engineering solutions for materials fractionation (grain and straw), innovative fermentation systems, new reactor designs, product separations and membrane systems. In addition, new and sustainable markets will need to be identified and developed for both the bulk and high value chemicals produced by the whole crop biorefinery. These issues are discussed further in Chapter 5.

#### **4.2.2 UK Wheat based Whole Crop Biorefinery**

This biorefinery utilises wheat grain and wheat straw to produce both bioethanol and lactic acid as the two major products. Lactic acid was chosen as the chemical intermediate not just because of the potential of the novel biodegradable polymer; polylactic acid [15] but also because of its versatility as a starting material for a wide range of other valuable chemical intermediates such as acrylic acid [16, 17]. The biorefinery also produces a slate of other smaller volume, high value materials such as speciality waxes, fatty acids, proteins and other valuable non-starch polysaccharides. The biorefinery is self sufficient in heat and power, utilising the lignin and the stillage residues to provide biomass fuel for conversion in a CHP plant. The biorefinery complex deploys a wide range of new and innovative process technologies that are currently under development today.

The biorefinery processes some 2000 tonnes per day of wheat straw and 820 tonnes per day of wheat grain to produce approximately 500 tonnes per day of bioethanol and 400 tonnes per day of lactic acid product. The size of the facility was fixed at a relatively small scale to portray a biorefinery complex with relatively localised feedstock supply chains. A schematic of the biorefinery complex is shown in Figure 4 and the individual processing steps are detailed on page 21.

Figure 4 Schematic of a UK Wheat Based Whole Crop Biorefinery



### **Straw to Bioethanol Section**

- Wheat straw is shredded and milled to a small particle size to enable it to be slurried into a pumpable mixture and to increase its surface area for downstream processing. Sieving and washing steps are performed to remove unwanted materials. Improved milling technologies will be deployed to reduce energy requirements of particle size reduction.
- The comminuted straw stream is subjected to a supercritical carbon dioxide extraction process to remove valuable waxes. The waxes can be fractionated further to provide high value materials for the cosmetics industry and nutraceuticals such as phytosterols used as cholesterol reducing agents in foods [18, 19, 20]. The straw contains approximately 1 wt% of waxes giving a potential product stream of around 20 tonnes per day assuming total extraction. Large scale extraction will require the development of new markets for the wax extract
- The straw is then fractionated in a biomass pretreatment process to solubilise the majority of the hemicellulose component into sugars and increase the reactivity of the cellulose component. The pretreatment technology chosen is the dilute acid process developed by NREL [21, 22]. The resultant solid and liquid phases are separated and solid phase is washed to remove degradation products such as furfurals. The liquid phase is neutralised by overliming. The solid and liquid phases are recombined to form slurry. Pretreatment process technology will have advanced such that both sugar losses and waste production are minimal.
- The resultant slurry from the pretreatment section is fed into a SSCF (simultaneous saccharification and co-fermentation) reactor which combines cellulase enzyme catalysed hydrolysis of the cellulose stream to produce glucose with co-fermentation of the glucose and hemicellulose sugars (glucose, xylose, arabinose...) to produce bioethanol. The cellulose hydrolysis is performed by highly active cellulase enzymes and the co-fermentation of the glucose and xylose sugars are performed by genetically designed thermophilic microorganisms. The SSCF process not only reduces capital costs by combining two separate processes but also reduces any product inhibition in the first cellulose hydrolysis step by continually removing the glucose product via its conversion to bioethanol.
- The product broth from the SSCF reactor is fed to the rectifier section to separate the bioethanol, in the form of a bioethanol/water azeotrope, from the lignin residue and cell materials (distillation bottoms). The bioethanol/water mixture is then sent to a molecular sieve for dewatering to produce the final dried bioethanol product. An alternative to molecular sieve drying is the use of membrane pervaporation technology; such systems could provide significant energy savings over molecular sieve dewatering.

- Current yields for bioethanol from straw are reported to be of the order of 0.2 tonne bioethanol per tonne of straw. However if all sugars are efficiently utilised then the theoretical yield is 0.34 tonnes bioethanol/straw tonne [23]. On this basis the yield of the biorefinery complex is set at 0.25 tonne bioethanol/tonne of straw to allow for incremental improvements in lignocellulosic conversion achieved in earlier stand-alone lignocellulosic bioethanol facilities. The product flow rate is therefore 500 tonnes /day of bioethanol.
- The distillation bottoms containing the lignin residue is then fed to a CHP unit to generate steam and power for the plant. The lignin residue stream will be of the order of 360 tonnes per day (18wt% of the original straw content). The CHP unit will utilise biomass gasification combined cycle technology to provide highest energy conversion efficiency. This volume of biomass fuel will be sufficient not only to provide heat and power for the bioethanol section of the biorefinery complex but also to generate additional value by supplying renewable electricity to the grid. A similarly sized corn stover bioethanol plant was reported to produce an additional 5.14 KWhrs per gallon of bioethanol produced for export to the grid (1700 KWhrs/tonne bioethanol) using a conventional boiler/steam turbogenerator [24].
- Before the CHP unit provision is made for a lignin extraction facility to provide raw material for conversion to higher value chemicals and materials rather than send the entire lignin residue stream to the CHP unit for heat and power generation. This could be operated flexibly depending on the electricity price. Lignin can be converted into a range of valuable chemicals including phenols. However it is unlikely that such conversion technology would be commercially demonstrated by the 2020 timescale.

### **Grain to Lactic Acid Section**

- After screening and washing the cereal grains are fed to the milling section. In contrast to conventional dry milling operations, fractionation technology has been developed such that the wheat grains can be readily separated into individual components such as the bran, germ and protein fractions prior to the fermentation of the starch component. The grain contains around 10-13wt% protein and 22-25wt% bran. Wheat protein has a potentially higher value if it is extracted before the fermentation step. A wide range of valuable materials can be made from wheat proteins including food emulsifiers, foaming agents and animal feed additives. Non food applications of gluten proteins include adhesives, films and coatings [25]. An EU coordinated research programme has demonstrated the potential of gluten protein as a starting material for strong transparent biodegradable films for packaging applications [26]. High value chemicals such as specific proteins and arabinoxylan polymers (AXF) can be extracted from the wheat bran. AXF polymers are thermostable gels and can potentially be used as slow release agents and as high

value food additives [27]. Other high value products extracted from wheat bran include dietary fibre and ferulic acid which can be converted into high value flavour additives such as vanillin [28]. All extractions will be performed using highly efficient supercritical carbon dioxide extraction techniques and large scale use of organic solvents will be avoided. In addition to protein and bran the wheat kernels also contain appreciable amounts of valuable germ oil that can be extracted. The oil contains highly unsaturated fatty acids and can be used in the cosmetics industry, tocopherols (vitamin E) are also present in relatively large amounts in the germ oil

- After fraction the wheat starch is then sent to a SSF (simultaneous sacchification and fermentation reactor) to be converted into lactic acid. This process combines the hydrolysis of the starch to individual glucose monomers and the subsequent conversion of glucose to lactic acid using a genetically designed microorganism such as *Lactobacillus* bacteria or *Rhizopus* fungi. The latter has the ability to work under low pH conditions and therefore does not need the addition of calcium hydroxide to maintain neutral pH.
- After fermentation, the non-fermentables, cell materials and other solid materials are separated from the product broth and the resultant stillage dried and then sent to the CHP unit for heat and power generation. A further extraction process may be included to remove any valuable components of the stillage stream such as proteins that were not removed in the front end fractionation step.
- The difficult separation of lactic acid will be performed using a state-of-the-art recovery unit. A number of potential engineering solutions are currently under development to replace the inefficient solvent extraction technique, these include, ion-exchange resins, reactive separation (esterification) and electro dialysis techniques. Potential exists for a continuous fermentation and product recovery system using membrane bioreactors coupled with electro dialysis.
- The production rate of lactic acid is estimated to be 400 tonnes per day, this is based upon a 90% yield from the starch feedstock (starch ~ 60wt% of the original grain but some starch loses built due to front end fractionation processes and incomplete fermentation)

#### **4.2.3 Alternative Co-Products for the Wheat based Whole Crop Biorefinery**

An interesting alternative to lactic acid as the major co-product in the biorefinery would be 3-hydroxypropionic acid (3-HP). As with lactic acid, 3-HP is a potential platform intermediate for a range of interesting three carbon chemicals including 1,3 propanediol, acrylic acid, malonic acid and acrylamide. Cargill is directing considerable research effort towards the development of an efficient 3-HP production route and is working with Codexis to develop improved genetically engineered organisms for the fermentation of carbohydrate feedstocks [29]. It is anticipated that the potential yield of 3-HP would be

similar to that of lactic acid in the whole crop biorefinery provided that current process development is successful.

#### **4.2.4 Wheat based Whole Crop Biorefinery Location**

The use of straw as a feedstock dictates that the biorefinery should be situated in areas of high cereal density such as the South East, Lincolnshire and Humberside. The 38MW Ely Power station burns 220 thousand tonnes of straw per year and has a catchment area of 60 miles radius. A simple calculation reveals that a whole crop biorefinery with a 660 thousand tonne straw throughput capacity per year (330 days operation) would require a catchment area of just over 100 miles radius. Straw delivery by road would require 100 heavy truck deliveries per day each carrying 20 tonnes of straw bales. On this basis it is clear that the biorefinery would need to be situated near to ship or rail transport infrastructure. It is also necessary to consider the biorefinery products when deciding location and on this basis it is desirable to be near to fuel blending facilities and chemicals infrastructure. Therefore likely plant sites are close to the oil refineries in North Lincolnshire and Essex. It is apparent that even for a relatively small bioethanol production capacity (165 thousand tonnes per year) feedstock logistical issues are important when supply is reliant on a single lignocellulosic feedstock. However future developments such as improved harvesting methods for cereal straws and increasing the intrinsic straw yield of the cereal could resolve this issue to a certain extent.

#### **4.2.5 Products Summary**

<b>Feedstock</b>	<b>Products</b>
<b>Wheat Straw (2000T/day)</b>	<b>Bioethanol (500T/day)</b>
<b>Wheat Grain (820T/day)</b>	<b>Lactic Acid (400T/day)</b>
	<b>Alternate Co-product: 3-hydroxypropionic acid (400T/day)</b>
	<b>Natural waxes</b>
	<b>Proteins for biodegradable materials</b>
	<b>Protein animal feeds</b>
	<b>AXF polymers</b>
	<b>Germ oil (Fatty Acids)</b>
	<b>Tocopherols (Vitamin E)</b>

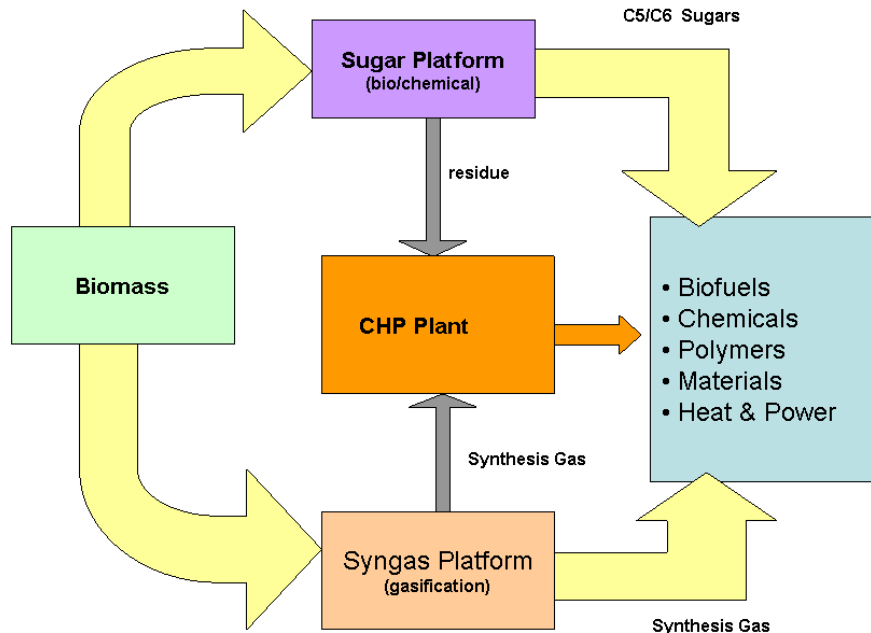
### 4.3 Combined Biochemical and Thermochemical Biorefinery Complex

The second UK biorefinery design combines both thermochemical and biochemical conversion technologies for optimum feedstock flexibility and is designed at a significantly larger scale. The gasification process can convert all the components of the biomass to synthesis gas, a building block for many major chemical products. The biorefinery can exploit many years of synthesis gas process technology development performed in the petroleum and chemicals industries.

#### 4.3.1 Two-Platform Biorefinery Concept

This biorefinery concept integrates two biomass conversion platforms; the sugar platform and the thermochemical platform. The sugar platform concerns the production of fermentable sugars from lignocellulosic materials [30] whilst the thermochemical platform concerns the high temperature gasification of biomass to synthesis gas and its subsequent conversion to fuels, chemicals and power [31]. The combination of these two platforms in one integrated biorefinery complex provides tremendous flexibility with regard to the biomass feedstock and the suite of products possible.

A schematic of the two platform biorefinery complex is shown in figure 5 [13].



**Figure 5 Schematic of a Two Platform Biorefinery Concept**

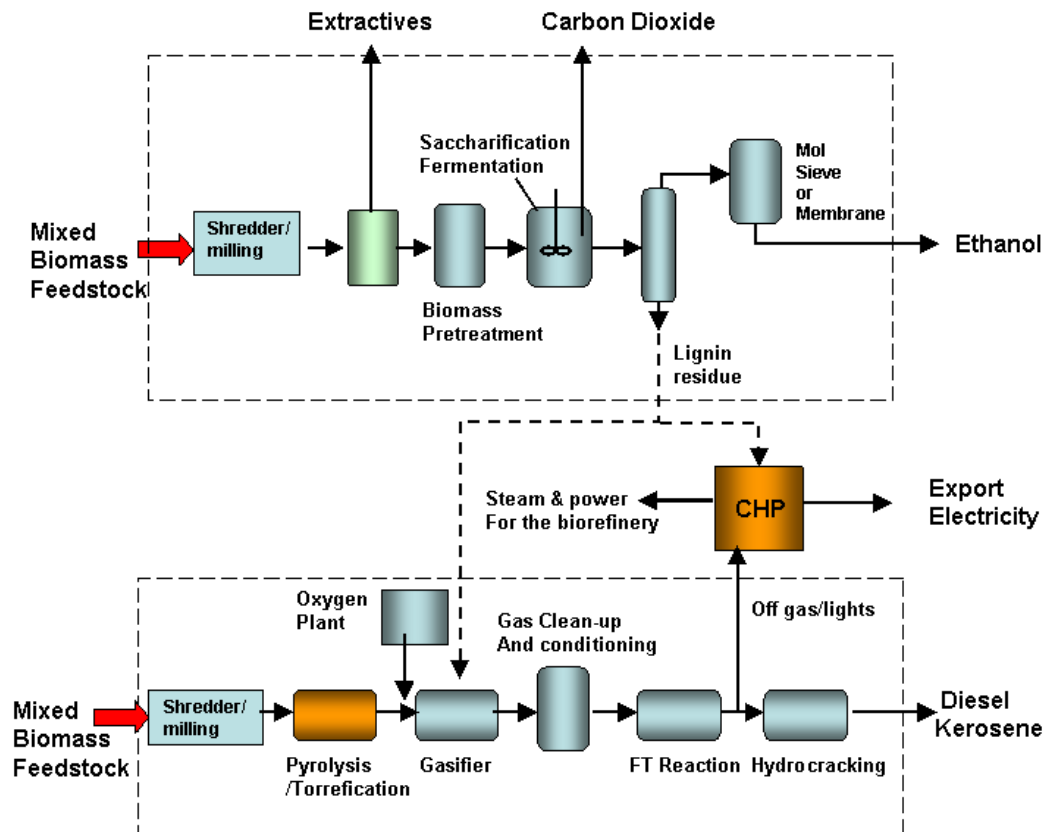
The individual process steps can be described as follows:

- Lignocellulosic biomass such as woody materials, biodegradable municipal solid waste fractions, agricultural residues and energy crops are shredded/chipped to an appropriate particle size and fed to the both the fermentation process and the gasification process.
- Prior to gasification, the biomass feedstock for the gasification process may be adventitiously converted into a denser form by flash pyrolysis to produce a bio-oil or by torrefaction to produce a brittle easily crushed solid ("bio-coal"). This step is necessary to facilitate the operation of the high pressure gasification biomass feed system. The densification of biomass feedstocks can be performed at the biorefinery or at a decentralised unit closer to the biomass production/harvesting site. Biomass densification at the production/harvesting site will also greatly reduce the inherent problems in transporting low density materials and extend the biorefinery feedstock catchment area.
- The biomass feedstock is converted at high temperature and pressure in an oxygen blown gasifier to produce synthesis gas, a mixture of carbon monoxide and hydrogen which is then treated to remove particulates, tars and other harmful impurities. The synthesis gas is then passed through a water gas shift reactor to increase its synthesis gas ratio ( $H_2/CO$ ) from 1.0 to 2.0 so that it is stoichiometrically correct for downstream conversion in the Fischer–Tropsch process.
- The synthesis gas is then converted into a hydrocarbon wax and light gases in the Fischer-Tropsch process. The hydrocarbon waxes are converted to diesel, kerosene and naphtha boiling range materials in a hydrocracker unit. The light gases produced in the Fischer-Tropsch reactor and the hydrocracker can either be recycled back to the gasifier or fed to a CHP unit for heat and power production for consumption in the biorefinery.
- The Sugar Platform route is similar to that described in the previous whole crop biorefinery route for bioethanol production from straw. Again the lignin residue from the fermentation is sent to the CHP unit to generate heat and power for the biorefinery and additional electricity for export to the grid. Alternatively the lignin residue could be fed to the biomass gasifier for additional synthesis gas production to maximise synthetic diesel yield.
- This biorefinery complex can be designed to produce a range of other valuable chemicals for instance methanol or a mixed alcohols stream can be produced from

the synthesis gas feedstock and the lignocellulosic fermentation route can be used to produce platform chemicals such as 3-hydroxypropionic acid or succinic acid rather than bioethanol.

#### 4.3.2 UK Based Two-Platform Biorefinery Concept

This biorefinery will utilise a range of biomass feedstocks to produce both bioethanol and synthetic diesel. Unlike the previous biorefinery complex the scale chosen is relatively large to maximise economy of scale benefits and explore the potential of developing large biomass supply chains. The biorefinery complex will utilise 7000 tonnes per day of agricultural residues, energy crops, wood materials and biodegradable municipal waste fractions to produce approximately 500 tonnes per day of bioethanol and 1,100 tonnes per day of synthetic diesel (approximately 8000 barrels per day). In this case the bioethanol may also be considered as a platform chemical for conversion into valuable intermediates such as ethylene or acetic acid. Although production is geared to both bioethanol and synthetic diesel the manufacture of alternative products such as mixed alcohols will be discussed. A schematic of the biorefinery complex is shown in figure 6 and the individual steps are discussed in more detail below.



**Figure 6 Schematic of a UK Two Platform Biorefinery Complex**

## **Biomass Gasification Section**

- 5000 tonnes per day of mixed biomass feed are chipped/milled to produce a small particle size material and either fed to a flash pyrolysis reactor to produce a biomass bio-oil or a torrefaction unit to produce a denser solid that can be ground down to a fine particle size. As discussed it will be advantageous to perform this operation in numerous smaller units closer to the various biomass feedstock production sites. Circulating fluid bed or entrained flow gasifiers can be used for biomass gasification and both systems have well documented advantages and disadvantages for this application. However at the scale employed here ( $\sim 1000\text{MW}_{\text{th}}$ ) the gasifier will likely be an entrained flow type reactor. The entrained flow gasifier operates at  $\sim 1300\text{C}$ . The oxygen for the partial combustion is provided by an on-site air separation unit.
- The resultant synthesis gas product contains a number of contaminants such as particulates, tars, volatile metals,  $\text{NH}_3$ ,  $\text{HCN}$ ,  $\text{H}_2\text{S}$ ,  $\text{COS}$  and  $\text{HCl}$ . The lower temperature fluidised bed gasifier also produces significantly more methane and tars when compared to the entrained flow gasifier. The biggest technical challenge facing the biomass gasification to liquids process is the efficient removal of all of these contaminants prior to the Fischer-Tropsch reactor downstream. Off the shelf technologies previously developed for coal gasification are available for these various purification steps including both wet gas cleaning (scrubbing) and dry gas cleaning (adsorbents) methods. However, efficient removal of tar compounds from the synthesis gas stream is still being developed; the likeliest option being catalytic cracking with nickel based reforming catalysts. Fischer-Tropsch catalysts are very sensitive to poisons and there are very strict requirements for the synthesis gas purity and composition
- The synthesis gas now needs to be conditioned by increasing the synthesis gas ( $\text{H}_2/\text{CO}$ ) ratio from 1.0 to a value closer to that necessary for the Fischer Tropsch reaction  $\text{H}_2/\text{CO} \sim 2$ . The synthesis gas ratio is readily adjusted using the Water Gas Shift reaction which reacts carbon monoxide with water to produce carbon dioxide and hydrogen ( $\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2$ ). The water gas shift process operates at around  $300\text{C}$  and 15-25bar and is a common process unit in petrochemical refining. In addition to increasing the  $\text{H}_2/\text{CO}$  ratio the WGS reaction also increases the carbon dioxide content of the gas. Carbon dioxide is an inert diluent in the Fischer-Tropsch process and will build up in the recycle loop. To avoid this, the carbon dioxide content is reduced by utilising commercially available solvent extraction processes such as Rectisol and Sulfinol.

- The synthesis gas is converted in the Fischer–Tropsch process to a waxy product containing a wide range of linear alkanes and alpha-olefins. The Fischer-Tropsch reaction is highly exothermic and a number of reactor designs have been developed to accommodate this feature including fixed bed, fluid bed and slurry phase reactors. The reaction is performed at a pressure of 20-40 barg and a temperature of 200-250C. The catalyst for the process can either be cobalt or iron based; an advantage of iron catalysts is that they have intrinsic water gas shift activity and so may not require the water gas shift unit when processing synthesis gas streams with low H<sub>2</sub>/CO ratios. Cobalt catalysts produce more wax than iron catalysts. The Fischer-Tropsch process also produces around 10% of light hydrocarbon gases (C1 – C4). The synthesis gas conversion is not complete in the reactor (60 – 80% conversion) and the unreacted synthesis gas containing the light gases can be recycled back to the gasifier. In addition a portion of the off gas can be fed to a CHP unit (combined cycle) to produce heat and power for the plant and electricity for export to the grid.
- Finally the waxy product from a Fischer-Tropsch process can be broken down into a range of valuable hydrocarbon products such as diesel, kerosene and naphtha. This process is performed by hydrocracking, a standard refinery operation.

### **Biomass Fermentation Section**

- The section is very similar to the straw to bioethanol section described in the previous “whole-crop” biorefinery complex. 2000 tonnes per day of mixed biomass feedstock is fed to this section for the production of 500 tonnes per day of bioethanol. In this particular case the stillage residue can be either fed to the CHP unit to generate heat and power or fed to the entrained flow biomass gasifier to produce more synthesis gas and increase the yield of synthetic diesel. The lignin residue stream is of larger volume than that of the straw fed process due to the use of woody biomass feedstock in addition to agricultural residues. It is assumed that the biomass pretreatment technology is sufficiently developed as to be able to process a wide variety of lignocelulosic materials.

#### **4.3.3 Alternative Products for the Two Platform Biorefinery Complex**

Instead of producing Fischer-Tropsch liquids the synthesis gas can be converted into a variety of different chemical products including methanol, dimethyl ether, ethanol or mixed alcohols. Of these, only methanol production is an established commercial technology. Ethanol production from synthesis gas is still at early stage of development and is being pursued using conventional high temperature catalytic routes and novel fermentation processes. Of most interest, is the production of a mixed alcohols stream

containing methanol, ethanol, n-propanol, n-butanols and small amounts of higher alcohols. In this case, the reaction is performed at 250 - 300C and pressures of 50 - 100barg. The catalysts used can either be a modified copper methanol catalyst or a sulfided molybdenum catalyst [44]. Considerable product flexibility within the mixed alcohols is achievable by changing the catalyst or the reaction conditions. In this way product selectivity can be switched from predominantly methanol more towards higher alcohols. A product yield of about 1,500 tonnes per day of mixed alcohols is achievable from 5000 tonnes per day of biomass feedstock. The methanol can be converted in a Methanol to Olefins, Gasoline and Diesel Process (MOGD) to produce biofuels and olefin building blocks whilst the larger alcohols can be used in a variety of solvent and polymer applications. Although this process has been around for many years, the conversion of synthesis gas to mixed alcohols remains to be commercially demonstrated. This can be related to the inherent poor selectivity and stability of existing catalyst technology.

#### **4.3.4 Location for a UK Two Platform Biorefinery Complex**

Although the scale of the biorefinery complex appears large, it is not optimal in terms of achieving the maximum benefit from economies of scale. Reports have suggested that BTL plants need to be of the order of 2000-4000MW<sub>th</sub> in size to achieve this [32]. Even so, the development of biomass supply chains that can deliver 7000 tonnes per day (approximately 2.3 million tonnes per year) of feedstock to the biorefinery will provide a significant challenge. In contrast to the previous biorefinery complex, this facility benefits from feedstock flexibility and can access a wide range of abundant and relatively low cost biomass resources. The primary biomass feedstocks for the two-platform biorefinery facility are likely to be industrial wood wastes, forestry products, municipal wastes and energy crops. As such the optimum location for this biorefinery is likely to be closer to a large conurbation with abundant industrial and municipal solid wastes rather than arable croplands. Energy crops such as miscanthus and short rotation coppice could represent a potential biomass resource of 8-10 million tonnes by 2020 -2025 and if biomass densification technologies are commercially implemented by this period could be readily transported over longer distances to the biorefinery. The biomass feedstock requirements of this plant are likely to represent 7-10% of the total UK biomass production potential and competition for this resource from other markets sectors such as renewable power generation suggest that the biorefinery should also be sited close to a port to exploit imported biomass feedstocks traded on the commodity markets. As with the smaller whole crop biorefinery complex siting next to existing fuel blending and chemical infrastructure would be adventitious.

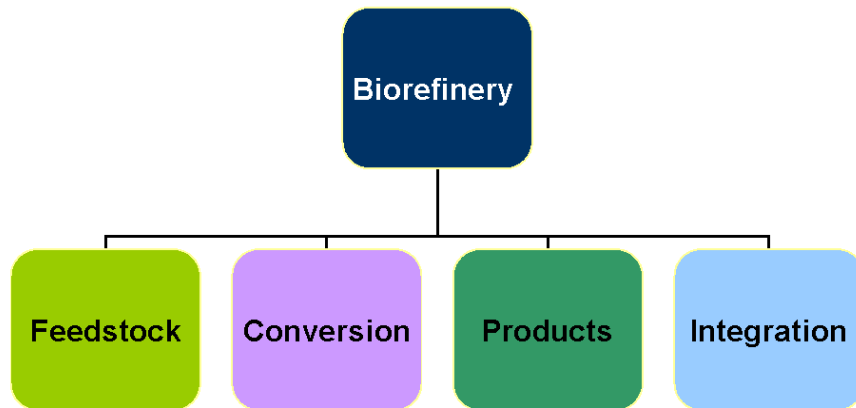
#### 4.3.5 Products Summary

Feedstock	Products
Mixed Biomass (7000T/day)	Bioethanol (500T/day)
Energy Crops	Fischer-Tropsch Liquids (1,100T/day)
Woody materials	Or alternatively
MSW	Mixed Alcohols (1,500 T/day)
Agricultural Residue	

## 5. Components for Biorefinery Delivery

To facilitate the delivery of large and complex multidisciplinary research programmes it is beneficial to split biorefinery development into a small number of more manageable components, or platforms. This approach was adopted by the US Department of Energy to facilitate management and delivery of their comprehensive biomass R&D programmes. This approach is also adopted here and the four platforms chosen are Feedstock, Conversion, Products and Integration (See figure 7). Each area will be analysed in detail to identify key barriers and opportunities for technical development. In addition, relevant UK activity to each specific area is identified.

**Figure 7: Platforms for Biorefinery Delivery**

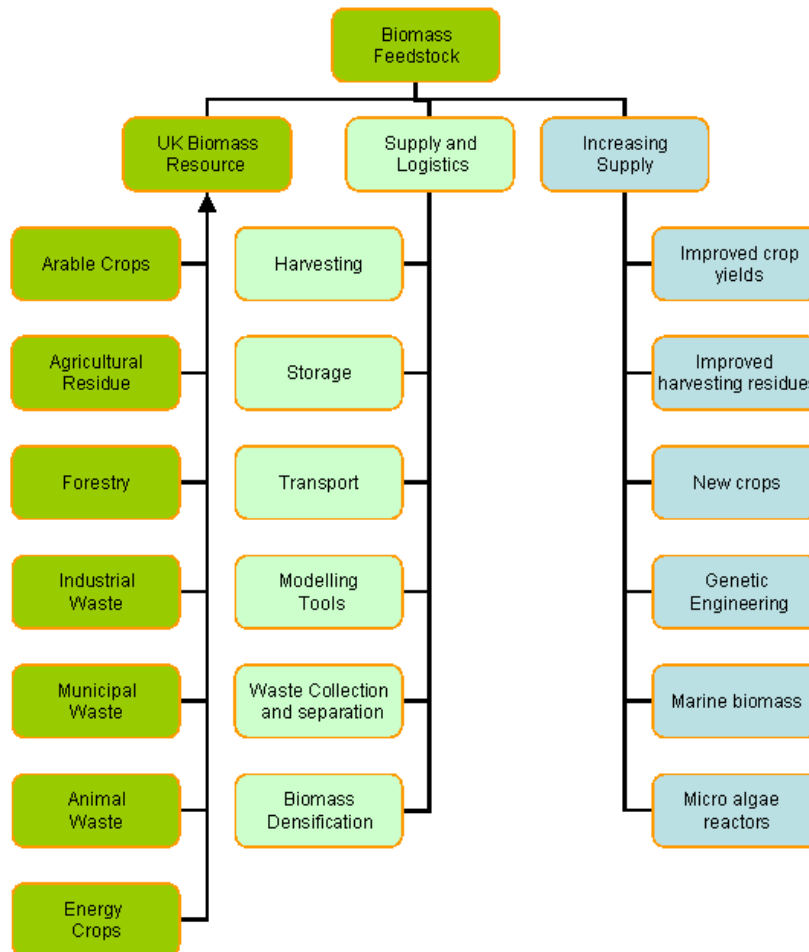


### 5.1 Biomass Feedstocks

Plant derived biomass represents a huge resource of mostly untapped sustainable carbon; global reserves of sustainable biomass are reported to be in the region of 200 billion tonnes of which only around 6 billion tonnes are currently utilised. Recent studies have shown that the US could potentially produce 1.3 billion tonnes of biomass per year by 2030 without impacting on its ability to produce sufficient food and feed [33]. A similar study reported that the EU could sustainably produce some 185 million tonnes of biomass by 2010 [34]. It is recognised that the UK has sufficient arable land to meet the RTFO requirement for 5% biofuel substitution by 2010 through domestic oilseed rape biodiesel and cereal based bioethanol production. However, to go significantly beyond this substitution level will require the development of new non-food biomass supply chains. With widespread planting of energy crops and accessibility to wood and MSW streams the biomass resource available in the UK could potentially be in the region of 25 to 30 million tonnes by 2020. However, to realise this volume of biomass requires improvements in areas such as energy crop agronomy and waste separation

technologies. Existing biomass supply chains are not designed for the large volumes of feedstock required by a biorefinery complex. Although some progress is now being made particularly with a view to supplying the growing renewables energy sector, considerably more focus will need to be dedicated to this area if large scale biorefineries are going to become a commercial reality. In the longer term the use of genetic engineering techniques to design plant with increased biomass yields and structural/compositional traits useful for industrial processing will become important. Other longer term prospects for increasing biomass supply include the development of the marine biomass resource and use exploitation of micro algae. Developing efficient supply chains for the delivery of biomass feedstocks at competitive cost and consistent quality will be a key factor in the deployment of large biorefineries in the UK. The components of an effective biomass supply chain development are detailed in Figure 8 and individual elements are described in more detail in Tables 1,2 and 3.

**Figure 8: Components of Biomass Feedstock Supply**



**Table 1; Biomass Supply and Logistics**

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Biomass Harvesting</b>	Improved harvesting and baling methods for straw.  Whole crop harvesting	Increased yield per hectare. Reduced transport costs	Current infrastructure geared towards large low density bales. Compacting, wafering or briquetting options are currently too expensive.  Issues with increased straw removal from land not defined (soil erosion, soil nutrients...)	<ul style="list-style-type: none"> <li>• Anglian Straw</li> <li>• Northern Straw</li> <li>• Lawrence David Ltd</li> <li>• Cranfield University</li> <li>• Loughborough Univ.</li> <li>• Harper Adams College</li> </ul>
	Improved harvesting and baling methods for energy crops.	Increased yield per hectare. Reduced transport costs	Most SRC harvesting and chipping equipment developed in Scandinavian countries. CRL (UK) has harvesting technology	<ul style="list-style-type: none"> <li>• Bical Ltd</li> <li>• Coppice Resources Ltd</li> <li>• Bio-Renewables Ltd</li> <li>• Renewable Fuels Ltd</li> </ul>
	Improved sensors for quality control & assurance (e.g. moisture content)	Improved feedstock consistency Reduced wastage of feedstock. Real-time analysis	Limitations in current technology.	
<b>Biomass Storage</b>	Improved systems with increased storage lifetime.  Large storage systems	Current storage facilities not suitable. More cost effective storage systems with minimal biomass loss. Size commensurate with biorefinery scale	To-date little development of unconventional large scale storage systems.	<ul style="list-style-type: none"> <li>• Bioenergy Technology Ltd</li> <li>• First Renewables Ltd</li> <li>• Forestry Contracting association</li> <li>• Kielder Forest Products Ltd</li> </ul>
<b>Biomass Transport</b>	Biomass compaction and chipping	Improved materials handling and reduced transport costs. Larger catchment areas for biorefinery	Most technology for wood chipping developed in Scandinavia. Cost	<ul style="list-style-type: none"> <li>• Ecoenergy Ltd</li> <li>• Forestry Contracting Association</li> <li>• Coppice Resources Ltd</li> <li>• Bio-Renewables Ltd</li> <li>• Sheffield University</li> </ul>
<b>Modelling Tools</b>	New tools for analysing and optimising of complex biomass supply systems	More efficient biomass supply chains. Assist in strategic planning & coordination of R&D activities.	Models in early stage of development. Oak Ridge National Laboratory (US) and Wageningen University (NL) have well developed systems.	<ul style="list-style-type: none"> <li>• ADAS</li> <li>• Cranfield University</li> <li>• Imperial College</li> <li>• TSEC-BIOSYS activity</li> </ul>

**Table 2: Increasing Biomass Supply**

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Improved Crop Yields</b>	Higher yielding cereals	Increased yield of bioethanol per hectare.	None: New higher yielding varieties entering marketplace. Crop management and agronomy continue to increase yield	Wide: HGCA, Agricultural Colleges, Trade Associations and Grain suppliers.
	High Starch Cereals	Increased yield of desirable component In crops Higher yield of bioethanol per hectare.	Few. Higher starch varieties for biofuels entering marketplace in 2-3 years. Plant breeding and agronomic methods to increase starch yield of current cereals.	Wide: HGCA, Manchester University Agricultural Colleges and Grain suppliers.
	Higher yielding Energy Crop	Increased yields of biofuels per hectare. Increased biofuel GHG reductions	High yields of Miscanthus and SRC Willow difficult to achieve in the UK. Observed biomass yields need to be significantly increased.	<ul style="list-style-type: none"> <li>• ADAS</li> <li>• Rothamstead</li> <li>• Cranfield</li> <li>• IGER</li> <li>• Bical Ltd</li> </ul>
<b>New Crops</b>	New improved Energy crops.	Increased yields of biofuels per hectare. Increased biofuel GHG reductions	Reed canary grass and Switchgrass show potential but further research needed on establishment and management, large scale crop trials required DEFRA programmes – significant funding activity underway.	<ul style="list-style-type: none"> <li>• Rothamstead</li> <li>• ADAS</li> <li>• IGER</li> </ul>

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Biotechnology</b>	Exploit advances in biotechnology such as genomics, marker assisted breeding and genetic engineering to deliver improved biomass feedstocks	<p>Crops with higher yields, higher tolerance and reduces agronomic inputs.</p> <p>Crops with tailored compositions to have increased levels of desirable component (ie increased starch )</p> <p>Incorporate attractive plant traits for downstream biorefinery processing (less lignin, reduced recalcitrance...)</p> <p>Plant factories: crops with high value constituents co-production high value chemicals</p>	<p>More detailed fundamental understanding required along with analytical capability</p> <p>Public resistance to genetically modified crops</p> <p>Potential negative impacts on environment and biodiversity need clarification.</p> <p>Long term planning required</p>	UK recognised as being world class in plant science and plant genetics –many centres of expertise
<b>Marine Biomass</b>	Exploit untapped seaweed biomass reserves around UK coastline	New potentially highly productive biomass resource that doesn't compete for limited land.	Harvested only on small scale for food. Limited information on potential as a biomass resource for energy or fuels but some activity in Japan, Norway and US.	Scottish Association for Marine Science
<b>Micro algae</b>	Untapped biomass resource for both vegetable oils and biomass.	New source of high yielding resource for biomass and vegetable oils (biodiesel) . Micro algae demonstrate extremely high photosynthetic efficiency and growth rates.	No commercial demonstration. Small number of companies developing micro algae technology in US, SA, NL and Israel. Fast growth requires photobioreactor development.	<ul style="list-style-type: none"> <li>• Next Generation</li> <li>• University of the West of England</li> </ul>

## 5.2 Conversions

As discussed in Chapter 3, the effective utilisation of the available and abundant lignocellulosic biomass resource for biofuel production will significantly increase the UK's domestic production capability above that provided by conventional arable crop feedstocks. In addition such "second generation" biofuels offer the potential of reduced greenhouse gas emissions and greater compatibility with existing transport fuel infrastructure. The chemistry required to deliver these new biofuels is difficult and considerable research funds are continuing to be directed towards the development of improved process technology. However, literature reports suggest that the deployment of both second generation bioethanol and synthetic diesel process technology is likely over the next 2 -5 years. This section is concerned with the development of the two major technology platforms for second generation biofuel production; the biochemical and the thermochemical routes.

The commercial implementation of both bioethanol and synthetic diesel production processes utilising lignocellulosic feedstocks will provide a major milestone in the transition to advanced biorefinery complexes.

### 5.2.1 **Biochemical Route: Lignocellulosic Systems for Bioethanol**

This technology platform is concerned with the efficient fractionation of lignocellulosic materials into their component parts, conversion of the cellulose and hemi-cellulose polysaccharide components into free sugars and then fermentation of these sugars into bioethanol. Considerable research activity has been directed towards the development of lignocellulosic routes to bioethanol over the last twenty five years [35, 36, 37]. Over this period, a number of large scale pilot projects have demonstrated the technical feasibility of producing bioethanol from lignocellulosic material. However, it is only now with the application of state-of-the-art bioprocessing techniques and the right economic climate for capital investment that commercialisation seems likely. One of the reasons for this long lead time is the presence of a number of challenging technical hurdles directly related to the composition and nature of the lignocellulosic feedstock. The whole conversion process can be broken down into a number of key individual steps:

- Feedstock Pretreatment
- Liquefaction and Saccharification of the polysaccharides
- Fermentation of the resultant sugars to bioethanol.

In principle these steps are the same as those present in the conventional dry-mill process that converts grain starch to bioethanol. However, each of these steps presents a different technical challenge when lignocellulosic feedstocks are considered:

**Feedstock Pretreatment:** Due to the recalcitrant nature of the lignocellulosic feedstock, forcing conditions are required to sufficiently pretreat the feedstock and disrupt the lignin-hemicellulose-cellulose plant cell wall structure so that the polysaccharides can be accessed for conversion. This is achieved by partly fractionating the lignocellulose into its component parts and reducing the crystallinity of the cellulose component such that it can be more easily hydrolysed into glucose sugars. There are a number of different pretreatment processes all of which are at different stages of development [38, 39, 40]. These pretreatment processes are combinations of physical, chemical, biochemical or thermal treatments. An optimal pretreatment process should meet the following performance criteria:

- Maximise the yield of both glucose and pentose sugars in downstream processing operations
- Facilitate the recovery of lignin for valorisation
- Minimise the degradation of sugars into chemicals that inhibit downstream enzymatic processing such as furfural and hydroxymethyl furfurals.
- Be flexible with regard to the nature of lignocellulosic feedstock
- Does not require expensive biomass size reduction (milling) before pretreatment
- Utilise low cost chemicals and minimise waste production
- Has low energy requirements and low capital intensity

Each individual pretreatment technology has its own strengths and weaknesses regarding the performance criteria above and there is no consensus on the best option. Importantly, it appears that there is no universal biomass pretreatment system and each process technology has beneficial attributes for certain feedstocks. The pretreatments closest to commercialisation are the dilute sulphuric acid, the concentrated sulphuric acid and the steam explosion processes. All of these processes represent a significant capital cost element towards the overall bioethanol production cost from lignocellulosic feedstocks. The capital cost of a dilute acid pretreatment process for a 56 million US gallon bioethanol plant is of the order of \$25 million. The dilute sulphuric acid pretreatment process was reported to present, albeit marginally, the most cost effective system [40]. Hence the dilute sulphuric acid system, as developed by NREL, was chosen for the biorefinery configuration detailed in Chapter 4 but with the expectation of significant improvement in processing costs and reduced waste production.

The greater majority of technology development in this area is occurring in the United States funded by the USDA and DOE with some activity in Canada and isolated pockets in Europe in Italy and Sweden.

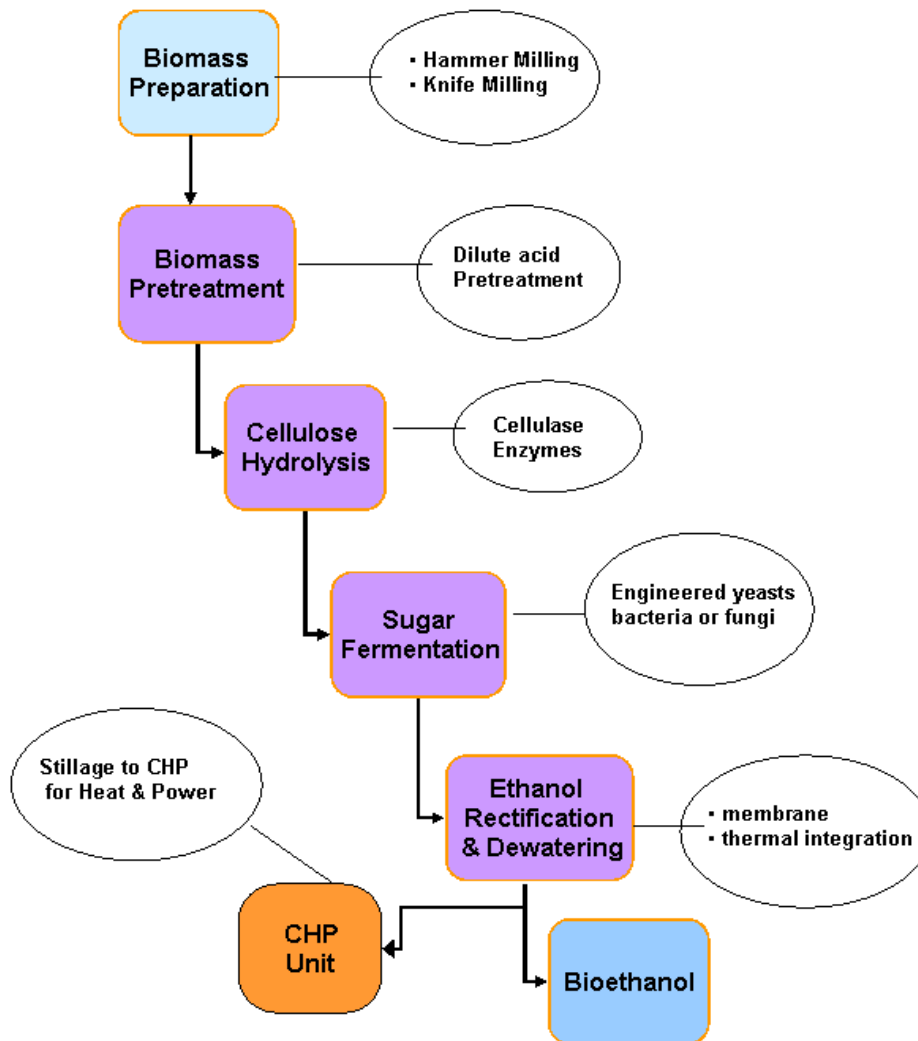
**Cellulose Hydrolysis:** In conventional bioethanol synthesis using starch crops, the glucose sugars for fermentation are readily obtained from the hydrolysis of starch using low cost and active amylase enzymes. Unlike starch, cellulose is not hydrolysed by conventional amylase enzymes and requires the application of sophisticated cellulase enzymes to perform the saccharification. Even though tremendous progress has been observed in this area recently and cellulase enzyme costs have been reduced by thirty fold, some challenging barriers still need to be overcome to develop a commercially viable cellulase enzyme system. One of the difficulties in developing new cellulases is the fact that they comprise a cocktail of different enzymes. These enzymes have specific roles within the cellulose saccharification process including the creation of free cellulose chains ends, cutting these chains to free cellobiose units (glucose dimers) and finally hydrolysis of cellobiose to produce glucose. New cellulase enzyme packages are likely to be needed for different biomass feedstocks and pretreatments. A number of companies are now exploiting state-of-the-art bioprocessing techniques to develop proprietary microorganisms for cellulase hydrolysis. Both bacteria and fungi can produce enzymes for cellulose hydrolysis but the majority of research has concentrated on aerobic fungal systems. Iogen who are close to the commercialisation of straw based bioethanol process have a proprietary cellulase system based upon a genetically modified fungus [41]. Thermophilic cellulase enzymes that can operate at higher temperatures than conventional systems are generating considerable interest. Such systems offer potential benefits in increased reaction rates, higher yield and higher thermal integration potential with the rest of the bioethanol plant.

**Fermentation of Pentose Sugars:** Pentose sugars make up a considerable percentage of the sugars present in lignocellulosic biomass. Unlike glucose, however, these sugars can not be fermented using conventional yeasts but require the development of highly specific microorganisms. More than twenty years research has been directed towards this goal and recent advances in metabolic engineering have led to a spate of proprietary microorganisms based on fungi and bacteria for xylose fermentation. Although the majority of this work has been performed in the US, the UK does have core expertise in the area: Agrol Ltd has developed proprietary genetically engineered thermophilic bacteria *Bacillus Stearothermophilus* for the fermentation of pentose and glucose sugars and is collaborating with US Company Colusa Biomass Energy Corporation in the commercialisation of a new lignocellulosic bioethanol plant [42].

The generic process scheme for bioethanol production from lignocellulosic materials is shown in Figure 9. In this scheme hemicellulose is partly hydrolysed by the pretreatment step and then fully hydrolysed in the cellulose hydrolysis step. There is no separation of the glucose and pentose sugar streams and the two are co-fermented to produce bioethanol. Due to the large number of individual processes in the overall conversion of lignocellulosic biomass into bioethanol considerable scope exists for process integration

and capital cost reduction. One such scheme is the Simultaneous Saccharification and Co-fermentation process (SSCF) currently under development which combines both the cellulase hydrolysis and the co-fermentation of the glucose and pentose sugars. Not only does the SSCF process reduce the number of reaction

**Figure 9 Schematic of a Lignocellulosic Bioethanol Plant**



vessels but it also minimises the problem of product inhibition affecting the hydrolysis reaction because product glucose sugars are removed by the fermenting microbes. Because the temperature required for hydrolysis is higher than that required for fermentation, thermophilic microorganisms are being developed that will ferment glucose and pentose sugars under these conditions. The UK has a strong science base in

thermophiles and companies such as TMO Biotech have licensed thermophile technology to commercial ethanol producers. Although there are a large number of engineered microorganisms for the co-fermentation of glucose and the pentose sugars, issues such as product inhibition, sensitivity to inhibitors and the production of unwanted by-products remain concerns until these systems are demonstrated at a commercial scale. The individual process elements are now discussed in more detail in Table 3.

**Table 3; Fermentation Routes to Lignocellulosic Ethanol**

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Biomass Pretreatment</b>	Cost effective fractionation of biomass into lignin and sugars for discrete processing	<p>Reduced capital and operational costs.</p> <p>Increased sugar yields downstream</p> <p>Cheaper sugars for fermentation</p> <p>Reduced energy use and waste production</p>	<p>Array of technologies being developed. No clear winner to date. Techniques are crude and seemingly specific to biomass type</p> <p>High capital costs. Pretreatment adds \$0.3/gallon to cost of ethanol</p> <p>Dilute acid process generates considerable amount of gypsum waste product and also produces degradation products which impact on fermentation downstream.</p> <p>Empirical development to-date. Need greater fundamental understanding of cell wall structure - activity relationships with digesting chemicals/enzymes</p> <p>Access to technology</p> <p>Long term genetically modified biomass with less resilient structure may provide solution but issues remain over public acceptability. Considerable fundamental R&amp;D required to develop understanding and analytical tools. US is setting up Genomics Research Centre (\$250M) to study such aspects.</p>	<p>Most large scale practical expertise concentrated in US with some isolated activity in EU. No lab scale/pilot plant activity apparent in the UK</p> <p>Wide UK expertise in bioscience fundamentals for long term biological solution eg CNAP-York Forestry Commission SCRI</p>
	Exploit advances in biotechnology to provide biomass with less recalcitrance for easier processing			

**Table 3: Fermentation Routes to Lignocellulosic Ethanol (continued)**

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Cellulose Hydrolysis</b>	<p>Improved cellulase enzymes for cost effective cellulose saccharification</p> <p>New thermophilic cellulase enzymes</p> <p>Combined Saccharification And Fermentation Process</p>	<p>Reduced processing costs. Remove some of burden from front end biomass pretreatment.</p> <p>Improved thermal integration. Faster reaction rates</p> <p>Reduces product inhibition</p>	<ul style="list-style-type: none"> <li>• Inefficient cellulose activation in biomass pretreatment section.</li> <li>• Low hydrolysis rates</li> <li>• Product and substrate inhibition</li> <li>• Poisoned by degradation products</li> <li>• Cellulase cost still too high at \$0.1 to \$0.2/gallon ethanol. Need to be closer to \$0.03/gallon.</li> </ul> <p>Potential issues with acceptance of genetically modified microorganisms in UK</p> <p>Considerable commercial activity in this cellulase hydrolysis with JV's between ethanol companies and biotech companies. Mostly in US</p>	UK strong base in thermophile research
<b>Pentose Sugar Fermentation</b>	<p>Improved fermentation microorganisms for effective xylose sugar conversion.</p> <p>Identify techniques to remove inhibitory degradation products from hydrosylate stream</p> <p>Thermophilic enzymes for Combined Saccharification And Fermentation Process</p>	<p>Maximise ethanol yield from lignocellulose. feedstock</p> <p>Reduced capital cost and improved ethanol yield</p>	<p>Wide range of proprietary modified fungi and bacteria systems developed. However none demonstrated at a commercial scale.</p> <p>First lignocellulosic ethanol plants may not ferment xylose.</p> <p>Requires reaction under high solids loading.</p> <p>Potential issues with acceptance of genetically modified microorganisms in UK</p>	<ul style="list-style-type: none"> <li>• TMO-biotec</li> <li>• Agrol Ltd</li> <li>• Imperial College</li> </ul> <p>UK strong base in thermophile research</p>
<b>Ethanol Dewatering</b>	<p>Alternative separations technology to mol sieve drying</p>	<p>Reduced energy separations. Continuous operation</p>	<p>Small scale membrane technology demonstrated. Improved zeolite based membrane technology in development</p>	Bath University

### 5.2.2 Thermochemical Conversions: Biomass to Liquids

This section is concerned with high temperature processes for the conversion of biomass to transport fuels, particularly synthetic diesel utilising the so-called Biomass to Liquids process. Some focus will also be placed on pyrolysis and torrefaction high temperature biomass densification techniques. Such biomass densification processes are likely to play a critical role in facilitating the development of long distance supply chains that can deliver large volumes of biomass to the biorefinery gate at a competitive cost without unduly compromising the greenhouse gas savings associated with the product biofuels. In contrast to fermentation technology, process technology for thermochemical conversions are, for the most part, well established and in some cases practised commercially for many years in the petrochemicals sector using petroleum and gas feedstocks. BTL process development is being led by Europe, and the first commercial scale process is reportedly due for deployment in 2011 in Germany [43].

There are three main primary thermal processes for converting biomass; combustion, gasification and pyrolysis (see figure 10). All of these processes differ in the amount of oxygen present during thermal conversion. The primary products from these processes can be utilised to generate heat and/or power in downstream energy conversion processes or, in the case of gasification and pyrolysis, utilised as a feedstock for transport fuels and chemicals. There are a number of important differences between biomass fuels and conventional fossil fuels. These distinctions are important when considering thermochemical conversion of biomass for energy, fuels and chemicals:

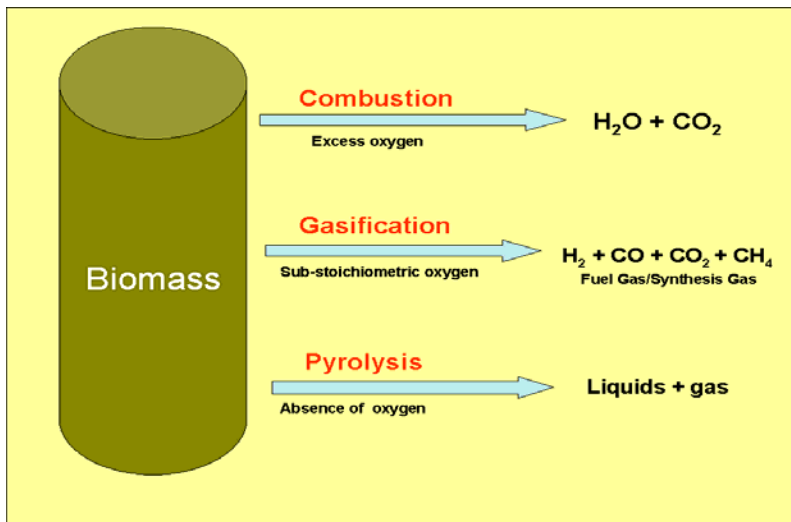
- The calorific value of biomass (LHV = 15-18MJ/kg) is much lower than that of fossil fuels such as coal (LHV ~ 30MJ/kg) and natural gas (LHV ~ 53 MJ/kg).
- Biomass invariably contains retained moisture and also relatively high amounts of minerals such as potassium and sodium and in addition can contain high amounts of halides that can lead to acid gases. Drying of biomass prior to gasification is a energy intensive process.
- Biomass has a low volumetric energy density, is difficult to transport and requires significant energy to mill/chip to smaller particle sizes.

All of these factors can combine to add complexity to process engineering when converting biomass in high temperature processes.

Of the primary processes shown in figure 10, combustion is the most established technology for deriving energy from biomass. Considerable biomass is used in this

manner for small scale domestic heating, larger scale combined heat and power applications (2–10MWe) and stand alone power plants (20 – 100's MWe).

Electricity is produced from biomass combustion by generating steam at high pressure and directing this through steam turbines or steam engines. The 36MW straw-fired power station at Ely is an example of this. Generating electricity in this fashion is inefficient and considerable energy is lost as waste heat. Modern coal-fired combustion plants typically have an energy efficiency of 40%, biomass-fired plants considerably less. If the hot exhaust gases from the steam turbine are used to generate hot water for heating or steam for industrial use then energy efficiencies can be increased to around 80%. This is known as Combined Heat and Power (CHP) and examples of large biomass CHP plants in the UK include Sembcorp's £60 million 30MWe Wilton10 plant and Eon's £90 million 44MWe power plant at Lockerbie both utilising wood fuel and due on stream later this year. Combustion technology is well developed for biomass combustion and includes fluid bed burners for larger plants. CHP units are commonplace in Northern Europe due to many years of successful facilitation by governmental policies. The situation is different in the UK with output-based government support only applicable to electricity generation rather than combined heat and power [5].

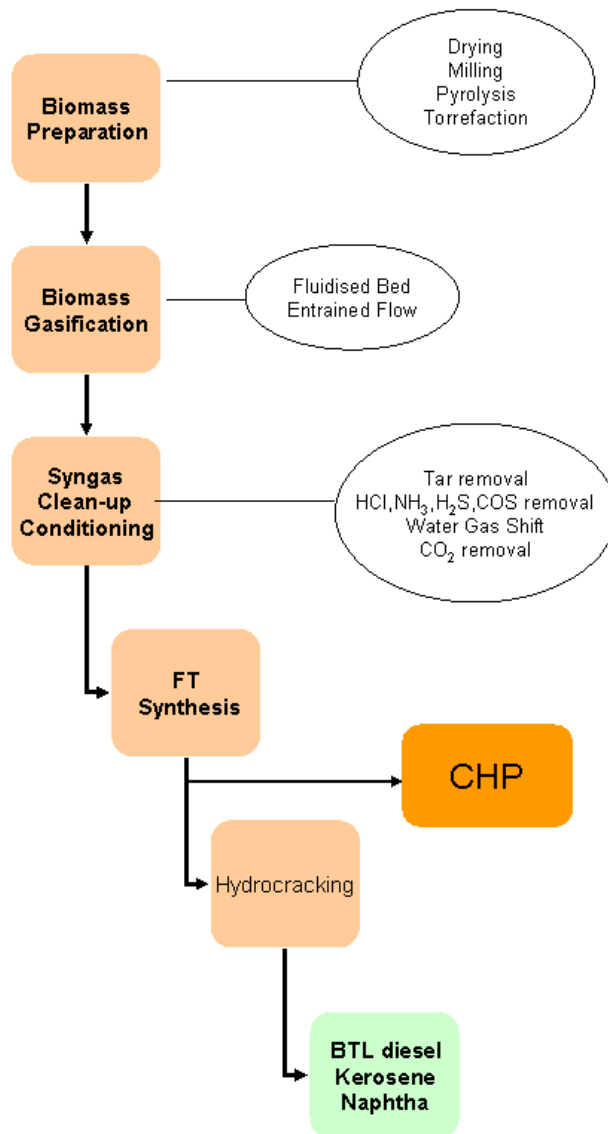


**Figure 10 Primary Thermal Conversion Processes for Biomass**

Due to limitations associated with the steam cycle, greater efficiencies in electricity generation can be achieved using gas turbines or gas engines. In this case the biomass feed is gasified with air to producer gas which is then fully combusted downstream and the hot pressurised combustion gases used to drive a gas turbine. The producer gas is a mixture of carbon monoxide, carbon dioxide, hydrogen and methane. Gasification technology is more complex and capital intensive than combustion processes for heat

and power production and therefore more suited to large scale applications. Biomass gasification processes are at a relatively early stage of development and are particularly complex due to the extra requirement for gas clean-up. Biomass integrated gasification combined cycle units (BIGCC) will form an integral part of biorefinery complexes utilising waste residue and lignin streams to generate heat and power for the individual processes. A simple schematic of the main processes integrated within a BTL process are shown in Figure 11 and discussed in detail below.

**Figure 11 Schematic of a BTL Process**



**Pyrolysis/Torrefaction:** The thermal decomposition of biomass in the absence of oxygen can be tailored towards the production of solids, liquids or gases depending on the temperature utilised and the residence time of the biomass in the reactor. Most pyrolysis research has focused on the effective production of liquids (Bio-oil) from biomass by utilising moderate product temperatures (~500C) and short contact times (~1 second). Such fast pyrolysis techniques generate bio-oil, gas and solid char as products with the liquid yields approaching 75%. The gas and solid char can be used as energy sources to provide heat and power for the pyrolysis process. Effective heat transfer to the biomass is critical during fast pyrolysis and a number of different reactor designs are being developed to achieve maximum liquid yield including fluidised beds and rotating cone designs. The bio-oil produced contains an acidic mixture of oxygenated hydrocarbons and appreciable amounts of water. A number of technical challenges remain to be addressed in this area including developing effective means to separate char from the product during processing and increasing the stability of the product bio-oil which has a tendency to undergo phase separation on storage.

Pyrolysis offers great potential for the realisation of an easily transportable biomass derived liquid fuel and chemical feedstock. Additionally the use of bio-oil would reduce many of the issues associated with materials handling in gasification reactor feed systems. The pyrolysis of biomass feedstocks can be performed at the biorefinery or in decentralised units closer to the biomass production/harvesting site. Biomass densification at the production/harvesting site will greatly reduce the inherent problems in transporting low density materials and extend the biorefinery feedstock catchment area.

An alternative to pyrolysis, is torrefaction which converts biomass to a brittle easily transportable solid. Torrefaction is performed at lower temperatures than fast pyrolysis and the product is likened to a “bio-coal”. Torrefied biomass could potentially be utilised in existing coal based gasification processes for synthesis gas generation such as entrained flow reactors.

**Biomass Gasification for Synthesis Gas:** Biomass gasification with oxygen, rather than air, produces synthesis gas, a relatively pure mixture of carbon monoxide and hydrogen. Synthesis gas is an important chemical feedstock and is currently produced on a vast scale from coal, oil-residues and natural gas. The major outlet for synthesis gas is in the hydrogen market, where the separated hydrogen is used predominantly in

the ammonia industry and also in refining operations. Synthesis gas is also used as a feedstock for both methanol and synthetic diesel.

Gasification is a very flexible process with regard to feedstock and, in principle, many different carbon sources can be utilised to produce synthesis gas. Unlike fermentation processes, gasification can be used to produce high value products from lignin residues. Historically, gasification technologies have been developed to utilise coal feedstocks but more recent attention has focused on the gasification of natural gas, particularly as a platform for utilising the vast reserves of stranded gas in remote locations. The conversion of stranded gas into synthesis gas which can then be converted into either synthetic diesel or methanol produces a transportable liquid product which can be shipped to market locations. These “gas to liquid” (GTL) processes are operated on a vast scale and are now being implemented in regions such as Qatar, Trinidad and Alaska.

To-date there has been little demonstration of biomass gasification systems that can operate at the large scale necessary for economic production of synthesis gas feedstock for fuels and chemicals production (gasifiers from 500MW to above 1000MW scale). Although an area of much debate, the likeliest options for gasification reactor technology are large, high pressure, oxygen blown fluidised bed and entrained flow reactors. Successful development of biomass gasification technology for BTL processes will need to overcome a number of challenging barriers including; cost effective drying of the biomass feedstock, inefficient biomass handling and feeding systems, ash sintering, slagging and purification of the synthesis gas product. Of these issues, gas clean-up (tar removal) is widely recognised to be the major technical hurdle. Both fluidised bed and entrained flow systems have advantages and disadvantages when addressing these aspects of biomass gasification:

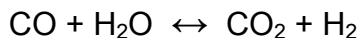
- Fluidised bed gasifiers are operated below a temperature of 1000C to guard against problems with ash slagging and sintering in the reactor. Under these conditions, significant amounts of methane are present in the product synthesis gas stream along with medium amounts of tar. To maximise, the carbon efficiency of the gasification process the unreacted methane must be converted to synthesis gas in a downstream catalytic reforming step. To date high pressure fluidised bed biomass gasification systems have not been demonstrated at a realistic commercial scale for BTL and fluidised bed systems are likely to be limited to 300-400MWth in size.
- Entrained flow gasifiers are already demonstrated at a large commercial scale for coal gasification. These reactors operate at temperature around 1300C and ash slagging is accommodated in the reactor design. At these high temperatures, methane and tar concentrations in the reactor outlet are greatly reduced relative to

the fluidised bed system. However, entrained flow reactors require very fine particles of biomass feedstock and expensive construction materials due to high temperature. Unlike coal, biomass is very difficult to pulverise and grind down to the required particle size.

**Synthesis Gas Clean-up and Conditioning:** The biggest challenge in the development and commercialisation of BTL processes is the integration of the biomass gasifier with the downstream Fischer-Tropsch process. Depending on the gasification technology chosen the product synthesis gas contains a range of impurities such as heavy hydrocarbons (tars), particulates, volatile metals,  $\text{NH}_3$ , HCN,  $\text{H}_2\text{S}$ , COS and HCl. Fischer-Tropsch catalysts are very sensitive to poisons and there are very strict requirements for the synthesis gas purity and composition. Such requirements place great emphasis on a highly effective synthesis gas clean up. Due to the wide range of impurities present a multi-step approach is taken to synthesis gas cleaning. As the majority of these impurities are present in synthesis gas streams produced from coal and oil-residues, commercially available technologies exist for their removal. Both hot gas and cooled gas cleaning options are available. Particulates can be removed by cyclones, electrostatic filters and wet scrubbers. Acid gases can be removed by wet scrubbing or solid adsorbents. Zinc oxide filters or commercial solvent based systems can be used for hydrogen sulphide removal.

As yet there is no effective commercially demonstrated technology that exists for the removal of tars from the synthesis gas streams. Such tars create huge problems by condensing out in downstream heat exchangers, filters and other areas. Tars can be removed by wet scrubbing, thermal decomposition and catalytic reforming. Of these catalytic cracking appears to be the most promising solution and research has concentrated on two catalytic systems; non-metallic calcined dolomites (natural calcium/magnesium oxides) and nickel based catalysts. Dolomite catalysts have been evaluated in fluidised bed reactors but can suffer from severe catalyst attrition and low activity. Nickel based catalysts are well known for other steam reforming processes and have proven to be highly active for both tar destruction and methane reforming. However, nickel based catalysts are significantly more expensive than dolomite systems and are susceptible to catalyst poisoning by sulphur compounds and deactivation under reaction conditions.

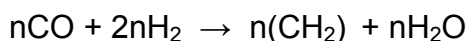
The synthesis gas produced from the gasification of biomass has a  $\text{H}_2/\text{CO}$  ratio close to 1.0; this is too low for Fischer-Tropsch synthesis and needs to be increased to a value closer to 2. The synthesis gas  $\text{H}_2/\text{CO}$  ratio is readily adjusted using the Water Gas Shift Reaction which reacts carbon monoxide with water to produce carbon dioxide and hydrogen.



The water gas shift (WGS) process operates at around 300C and 15-25bar and is a common process unit in petrochemical refining. In addition to increasing the H<sub>2</sub>/CO ratio the WGS reaction also increases the carbon dioxide content of the gas. Carbon dioxide is an inert diluent in the Fischer-Tropsch process and will build up in the recycle loop. To avoid this, the carbon dioxide content can be reduced in the synthesis gas by commercially available solvent extraction processes such as Rectisol, Selexol and Sulfinol. These extraction processes will also remove other contaminants in the synthesis gas such as hydrogen sulphide.

Gasification and synthesis gas clean-up may account for up to 75% of the capital investment of a BTL plant. The majority of the purification stream will be composed of commercially available technology. Some scope exists for capital and operational cost reduction of this purification through innovative technology including the application of novel ceramic membrane systems for both oxygen production and combined water gas shift reaction and hydrogen separation.

**Fischer Tropsch Process:** The Fischer Tropsch process converts synthesis gas into a mixture of linear hydrocarbons with varying chain length. The basic reaction can be represented as follows:



The products are a wide range of linear alkanes and alpha-olefins. The distribution of the hydrocarbons is determined by the reaction conditions, catalyst type and the H<sub>2</sub>/CO ratio of the synthesis gas. The reaction is performed at an operating pressure of 20 – 40bar and a temperature range of 200 -250C and produces waxy products which can then be hydrocracked to synthetic diesel. The catalysts employed for the reaction can either be cobalt or iron based. Significant cost savings could be generated by improvements to the activity and selectivity of the Fischer Tropsch catalysts however catalyst development for Fischer Tropsch technology is mature and radical improvements in performance seems unlikely in the short/medium term.

The Fischer-Tropsch reaction is highly exothermic and a number of reactor designs have been developed to accommodate this feature including fixed bed, fluid bed and slurry phase reactors. The unreacted synthesis gas and light hydrocarbons can be recycled back to the biomass gasifier and also part of the stream combusted to generate heat and power for the BTL process. Another option is to run the Fischer Tropsch process in “once-through” mode, avoid gas recycles and the direct the entire unconverted synthesis

gas to a BIGCC plant for combined fuels and power production. A large number of different process configurations can be envisaged for a future BTL process.

The waxy product from a Fischer-Tropsch process is broken down into a range of valuable hydrocarbon products such as diesel, kerosene and naphtha. This process is performed using hydrocracking, a standard refinery operation.

The Fischer Tropsch process has been practised by SASOL in South Africa since the 1950's using coal as the synthesis gas feedstock. Recent activity has seen the development and construction of large natural gas based plants in China. These plants are vast in scale, with the proposed Shell plant in Qatar having a production capacity of 140 thousand barrels a day of Fischer-Tropsch products (7 million tonnes per year).

### **Other Potential Biofuels Derived from Synthesis Gas**

In addition to synthetic diesel, bio-derived synthesis gas can also be converted into a wide range of other potential transportation fuels including methanol, dimethyl ether, ethanol and mixed alcohols. Hydrogen can also be separated from synthesis gas to provide fuel for PEM (proton exchange membrane) fuel cell vehicles. The hydrogen content in synthesis gas can be maximised through the water gas shift reaction and then extracted using separation techniques such as pressure swing absorption. Advances in ceramic membrane technology would also significantly improve production economics for hydrogen. Life cycle analysis studies have shown that biomass derived hydrogen used in fuel cell cars delivers the highest greenhouse gas savings for a renewable transport fuel. However, a number of challenging technical and logistical issues remain to be resolved before hydrogen powered fuel cell vehicles become a commercial reality.

As described above, synthesis gas can be catalytically converted into a range of oxygenated chemicals which can either be blended directly with transport fuels or converted into more conventional hydrocarbon transport fuels. In addition, these bio-derived chemicals represent potential platform chemicals which can be converted into valuable chemical intermediates; ethylene for instance can be produced by the dehydration of ethanol or via methanol (MTO reaction). Such chemicals could be co-produced with synthetic diesel in a thermochemical biorefinery complex.

**Biomethanol:** Methanol is a major commodity chemical currently produced from natural gas. The global market for methanol is well over 35 million tonnes, the majority of which is used to manufacture formaldehyde for use in the construction sector. Methanol production technology is mature and exploits economy of scale in huge plants (Mega-methanol plants) with production capacities measured in millions of tonnes. Methanol is produced from synthesis gas utilising copper/zinc based catalysts at temperatures of 220C- 300C and pressures of 50 -100 bar.

The production of biomethanol via biomass derived synthesis gas has been considered for some time particularly as a means to upgrade low value black liquor streams in pulp and paper mills. In many ways bio-methanol synthesis is more straightforward than BTL, it is a more selective reaction and there are fewer requirements for downstream separation and upgrading. The energy efficiency of biomethanol synthesis is greater than that of the BTL liquids process. However, this energy efficiency benefit will be reduced if the bio-methanol is subsequently converted into hydrocarbon fuels via a MTG or MOGD processes.

Although methanol itself is no longer considered as a suitable replacement for petrol it can be derivitised to produce a wide range of transport fuels. Methanol is used in the manufacture of both the petrol additive methyl tertiary butyl ether (MTBE) and biodiesel. The catalysts used for methanol synthesis are susceptible to poisoning by impurities such as sulphur compounds so it is essential that the synthesis gas derived from biomass is of high purity. As with the BTL process considerable economic and energy efficiency benefits can be realised by integration of methanol synthesis with heat and power production. Methanol can also be converted into hydrocarbons more resembling conventional petroleum derived hydrocarbon transport fuels using selective solid acid catalysts. Mobil Oil developed and commercialised the Methanol to Gasoline (MTG) process in the early 1980's although this was abandoned soon after due to the rising cost of natural gas which made the process uneconomic. The MTG process relied on a highly selective solid-acid zeolite catalyst. By changing the catalyst and process conditions, the MTG process can be modified to produce either light olefins or a mixture of gasoline and diesel (MOGD process). Although not commercially practised both of these processes have been demonstrated at commercially relevant scale and are considered to be "off the shelf" process technology. If the synthesis gas used to produce the methanol is derived from the gasification of biomass then these methanol processes represent alternative synthetic routes to biofuels. However, the MTG process produces a gasoline range product with a very high aromatics content which does not conform to current petrol specifications. It is for this reason that most interest, particularly in Germany, has focused on the methanol to gasoline and diesel process (MOGD) utilising bio-derived methanol feedstock.

Methanol can be readily dehydrated to form dimethyl ether (DME). DME is similar in properties to LPG and has a high cetane number; consequently it has been promoted as an alternative transport fuel. In addition to the methanol dehydration route, DME can be produced directly from synthesis gas. The Swedish government is funding research at Volvo for the development of bio-derived DME powered truck engines.

**Mixed alcohols and ethanol:** The production of mixed alcohols from synthesis gas is well known and many processes have been developed to large demonstration scale over the last thirty years. Such processes are similar to methanol synthesis but differ in catalyst type and process conditions. The product from mixed alcohol synthesis contains methanol, ethanol, propanol, butanols and smaller amounts of heavier alcohols. The original driver for mixed alcohol production was to find an alternative oxygenated transport fuel for blending with gasoline. However, none of these processes were commercialised due to the deficiencies in catalyst performance and fluctuating crude oil price. A number of research groups have attempted to selectively produce ethanol from synthesis gas with varying degrees of success. As with mixed alcohols production, these synthesis gas to ethanol routes suffer from poor economics due to inherent low catalyst selectivity. Interest in both mixed alcohol and ethanol production from synthesis gas has been rekindled recently due to the increased profile of biofuels. In contrast to high temperature catalytic routes, the conversion of synthesis gas to ethanol can also be accomplished by fermentation with anaerobic bacteria. This system was identified in the early 1980's and is now being developed for the conversion of synthesis gas derived from municipal waste.

**Table 4; Thermochemical Routes for Conversion of Biomass to Synthetic Diesel and other Potential Biofuels**

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Biomass Drying</b>	Cost effective drying of biomass prior to processing. Moisture contents of biomass reduced from 50wt% down to 10-15wt%	Optimise performance in downstream gasification  Energy costs reduced through effective thermal integration with downstream operations.	Requires pilot plant study and modelling tools	
<b>Biomass Pyrolysis</b>	Cost effective production of bio-oil through optimisation of fast pyrolysis techniques.	Easily transportable liquid biomass feedstock to facilitate development of long distance supply chains.	<ul style="list-style-type: none"> <li>• Fundamentals of bio-oil formation and chemistry not well understood</li> <li>• A number of different reactor designs being pursued.</li> <li>• Char separation difficult</li> <li>• Bio-oil phase separation problematic</li> <li>• Bio-oil properties vary with biomass feedstock</li> </ul>	Aston University  Supergen Consortium  Wellman Process Engineering

<b>Biomass Pyrolysis</b>		Biomass feedstock with greatly reduced materials handling issues that can be integrated with existing feed systems on conventional gasifiers	Pyrolysis techniques nearing commercialisation for waste to energy systems. Fast pyrolysis pilot plant developments at a number of European centres inc UK	
<b>Biomass Torrefaction</b>	Cost effective production of higher density biomass solids.	Easily transportable solid biomass feedstock to facilitate development of long distance supply chains.  Biomass feedstock with greatly reduced materials handling issues that can be integrated with existing feed systems on conventional gasifiers	Early stage of development. Not as advanced as pyrolysis techniques.  Research activity centred at ECN in the Netherlands	Aston University
<b>Synthesis Gas Production</b>	Biomass derived route to major fuels and chemical platform	Exploit existing thermochemical conversion technology to produce synthetic diesel and platform chemicals from biomass.  Universal conversion process for many types of biomass. Ability to convert low value lignin component of biomass to valuable fuels and chemicals.  Integration of fuels, chemicals and power production (BIGCC)	<ul style="list-style-type: none"> <li>• High pressure biomass gasification reactors not commercially demonstrated at large scale. Different gasification technologies being developed – no consensus on optimum technology</li> <li>• Bio-derived synthesis gas not cost competitive with natural gas derived synthesis gas</li> <li>• Major capital element of BTL process. Limitations in biomass supply chains may preclude ability to achieve requisite economies of scale for economic operation.</li> <li>• Catalytic tar removal technology not commercially available</li> <li>• Large pilot plant demonstrations in European Centres, none in UK</li> </ul>	<p>Considerable expertise and activity in gasification for heat and power production but little for pure synthesis gas production for synthetic fuels.</p> <p>Aston University</p> <p>Sheffield University</p> <p>Supergen Consortia</p> <p>MEL active in development of improved zirconia tar cracking catalysts</p>

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Fischer Tropsch Process</b>	Synthetic diesel fuels compatible with existing engines and derived from biomass	<p>2<sup>nd</sup> generation biofuel with improved GHG reductions over conventional biodiesel</p> <p>Integration of fuels and power production with cogeneration (once through) concepts</p>	<p>Little in the way of technical barriers – process technology established.</p> <p>Catalyst selectivity to diesel range products could be improved but will require radical step-out in performance (unlikely in short to medium term)</p> <p>Huge capital costs. Difficult to achieve economy of scale due to feedstock supply limitations</p>	<p>All major oil, engineering and catalyst companies developing FT systems (gas and coal).</p> <p>FT catalyst fundamentals: Oxford University</p> <p>No specific activity apparent on bioderived synthesis gas as feedstock</p>
<b>Other Biofuels from Synthesis Gas</b>	Alternative biofuels with improved performance and higher GHG reductions	<p>Exploit large gasification complex to produce range of value added co-products in addition to synthetic diesel.</p> <p>Cost effective competition to conventional sugar fermentation routes to bioethanol and platform chemicals.</p>	<p>Heterogeneous catalyst technology not optimal for selective production of mixed alcohols or ethanol from synthesis gas.</p> <p>Difficult to compete against huge megamethanol plants utilising natural gas.</p> <p>Fermentation technology holds promise for ethanol production from synthesis gas but still at development stage</p>	<p>Catalyst development activity for mixed alcohols and improved methanol systems – not specifically for bioderived synthesis gas:</p> <p>Imperial College Cardiff University Glasgow University</p>

### 5.3 Products

This section is concerned with the suite of products produced in the biorefinery. Transport fuels have already been discussed in detail previously so emphasis in this section is placed on the other product streams. The Chemicals Industry is now focusing increasing attention towards the use of renewable materials as feedstocks. Raw materials derived from biomass offer the potential of competitively priced feedstocks, less intensive processing and highly functionalised starting materials for conversion to innovative and differentiated chemical products and intermediates. This change is being driven by environmental and economic factors coupled with the rapid advances in biotechnology.

The application of biotechnology for chemicals production is well established in the pharmaceutical, fine and speciality sectors and has demonstrated a number of compelling advantages over conventional chemicals production. In contrast, the use of biotechnology for bulk chemicals manufacture has had relatively little commercial impact. However, recent progress in the fundamental understanding and application of new biotechnology areas coupled with the desire for more environmentally benign and differentiated polymers has facilitated the commercialisation of a number of new innovative processes that use agricultural raw materials. The complex nature of developing new biocatalysed routes for plant based chemical production dictates a large degree of multidisciplinary. To accomplish this, chemical companies are forming partnerships with agricultural, food and specialised bioscience sector companies to access vital core skills.

Specific plant components such as carbohydrates, vegetable oils, plant fibre and complex organic molecules known as primary and secondary metabolites can be extracted. Plants can synthesise highly complex bioactive molecules often beyond the power of synthetic chemists and a range of extractives are currently supplied into a wide range of markets from crude herbal remedies through to very high value pharmaceutical intermediates. Cleaner process technologies based upon supercritical carbon dioxide extraction are now being developed to replace existing solvent routes for product extraction from biomass.

An integral part of extracting high value components from biomass feedstocks, cereals in particular, is the efficient fractionation of the grain components prior to chemical processing downstream. Sophisticated milling technology is now being developed so that cereals can be readily separated into individual components such as the bran, germ and protein fractions prior to the fermentation of the starch component. The grain contains around 10-13wt% protein and 22-25wt% bran. Wheat protein has a potentially

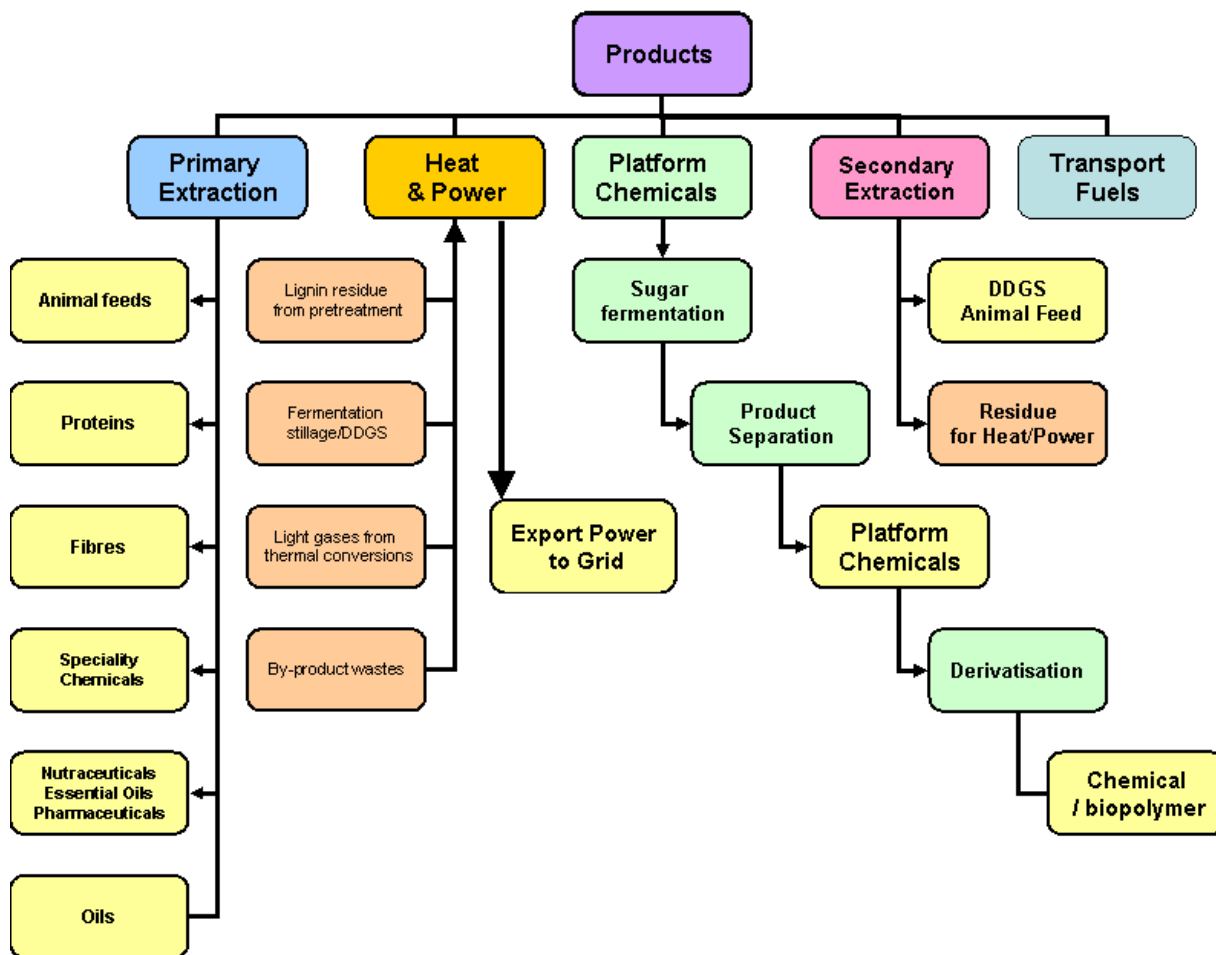
higher value if it is extracted before the fermentation step. A wide range of valuable materials can be made from wheat proteins including food emulsifiers, foaming agents and animal feed additives. Non food applications of gluten proteins include adhesives, films and coatings. High value chemicals such as specific proteins and arabinoxylan polymers (AXF) can be extracted from the wheat bran. AXF polymers are thermostable gels and can potentially be used as slow release agents and as high value food additives. Dietary fibre and ferulic acid can be extracted from bran; ferulic acid can be converted into high value flavour additives such as vanillin. Germ oil can also be extracted from cereal grains; this contains highly unsaturated fatty acids and can be used in the cosmetics industry, tocopherols (vitamin E) are also present in relatively large amounts in the germ oil.

Valuable chemicals can also be extracted from non-starch biomass; speciality waxes and phytosterols used as cholesterol reducing agents in foods can be extracted from straw.

It is only recently that large production facilities have been constructed to convert agricultural crops into bulk commodity chemicals such as polymers. The introduction of large biorefinery complexes will provide large volume streams of biomass raw materials at comparatively low cost for conversion to renewable chemical intermediates. Indeed, the economic feasibility of biorefinery complexes will depend heavily on the successful extraction of high-value specialty components from agricultural feedstocks and the conversion of carbohydrate streams to value added chemicals. The range of possible products produced in biorefinery complexes includes transport fuels, chemicals, materials, animal feed and power are shown in Figure 12.

Chemicals derived from biomass materials are now entering the marketplace; derived from corn starch, both polylactic acid and 1,3-propanediol processes have been commercialised. These new processes have been facilitated by advances in fermentation technology, genomics, molecular genetics, metabolic engineering and biocatalysis. Such products face stiff competition from petrochemical alternatives that exploit existing infrastructure, economies of scale and highly efficient mature conversion technologies. The introduction of new renewable chemical intermediates into the marketplace is challenging due to difficulties in establishing new markets and achieving competitive production costs with new and immature process technology. Current manufacture of bulk chemicals is based predominantly on crude oil and natural gas feedstocks. The Petrochemicals Industry has developed in tandem with Oil Refining and has flourished by successfully exploiting cheap and abundant mineral oil resources. The Petrochemical Industry accounts for around 8% of the total volume of liquid and gaseous hydrocarbon consumed. Petrochemical complexes are often integrated with oil refineries and have evolved into large, flexible and highly efficient manufacturing operations that

maximise the synergistic opportunities of co-location to exploit the various energy and raw materials streams for cost effective chemicals production.



**Figure 12 Schematic Showing Possible Product flows in a Biorefinery**

Petrochemical complexes produce primary chemical intermediates such as ethylene, propylene, butylenes and aromatics, which are further converted into intermediates for the plastics, textiles, solvents and detergent markets. By analogy, there are a number of highly functionalised bio-derived chemicals that can be converted into a variety of potentially useful chemical intermediates. These chemicals are known collectively as “platform chemicals”, this area has been comprehensively reviewed by groups in both the US and Europe [16, 17]. The 12 major platform chemicals identified in the US study [16] are shown in table 5

**Table 5: 12 Major Platform Chemicals**

Building Block	Platform Chemical
C3	Glycerine
	1,3-hydroxypropionic acid
C4	Succinic acid
	3-hydroxybutyrolactone
	Aspartic acid
C5	Glutamic Acid
	Levulinic Acid
	Itaconic Acid
	Xylitol/Arabinitol
C6	2-furan dicarboxylic acid
	Glucaric Acid
	Sorbitol

Of particular interest in this list of platform chemicals is glycerine. Glycerine is a major co-product of biodiesel production however the huge growth in this sector, particularly in the EU, has resulted in a glut of crude glycerine entering the marketplace. As a result the crude glycerine price has collapsed and is now worth little more than waste value. The crude glycerine can be refined into a high purity material, but this involves a complex and capital intensive distillation step and therefore is only available to the big biodiesel manufacturers. Refining of glycerine is only likely to be a short term solution because markets for refined material are expected to be saturated in the not too distant future as extra biodiesel capacity comes on stream, particularly in the US. The depressed price of glycerine has prompted a huge interest in the application of innovative bioprocessing technologies for its derivatisation to higher value chemicals. Glycerine is an excellent platform chemical with over 1500 derivatives and a number of companies are developing commercial processes based on glycerine feedstock: Both ADM and Cargill are developing separate routes to produce propylene glycols and Solvay has just brought on stream a new 10 thousand tonne capacity plant for producing epichlorohydrin, a feedstock for epoxy resin.

The platform chemical chosen for the first biorefinery of this roadmapping project was the C3 building block lactic acid. Lactic acid can be converted into a number of potentially highly valuable chemical intermediates with large markets including acrylic acid, propylene glycol and ethyl lactate (see Table 6). In many cases, these platform chemicals are difficult to manufacture using conventional petrochemical routes and often require complex and costly high temperature catalytic processes. Lactic acid was also chosen because it is already being produced commercially for the production of the

biodegradable polymer; polylactic acid. 1,3 –hydroxypropionic acid represents a viable alternative C3 platform chemical to lactic acid.

**Table 5: Lactic Acid Platform Chemical and its Derivatives**

Platform Chemical	Potential Derivatives	Applications	Market Size
<b>Lactic Acid</b>	Polylactide	PLA biodegradable polymer	Currently 140KT (capacity) but could be 3.5MT by 2020
	Ethyl lactate	Solvent	Currently ~ 20KT could be >100KT as a green solvent
	Acrylic Acid	Acrylates, coatings, super absorbent polymers, adhesives	Currently ~ 2.5MT
	Propylene Glycol	Antifreeze, polyesters, detergents	Currently ~1.3MT

Although lactic acid production is practised commercially using fermentation technology, a significant reduction in the capital and operational costs can still be achieved by the application of innovative bioscience and novel separations technology. Table 6 details the opportunities and remaining challenges for biorefinery co-product development

**Table 6: Co-products in Biorefinery Complexes**

Element	Opportunity	Drivers	Barriers/Status	UK Activity
<b>Biomass Fractionation into primary components</b>	Cost effective fractionation of cereal grains into valuable proteins, bran chemicals and oils.	Increase yield of valuable plant components prior to downstream processing for biofuels.	New cereal milling engineering techniques being developed	Satake Centre, Manchester University
<b>Extraction of high value chemicals</b>	Cost effective extraction of high value chemicals from biomass	Increase yield of high value components extracted from plants.  Replace use of environmentally harmful solvents system	Supercritical CO2 extraction techniques being developed. Established technology in other sectors. Commercially operated at small scale for chemical extraction from biomass.  Markets for novel extractives not well developed.  Potential for rapid saturation of smaller markets and reduction of product value	<ul style="list-style-type: none"> <li>• Botanix</li> <li>• York University</li> <li>• Leeds University</li> <li>• Nottingham University</li> </ul>

<p><b>Development of new routes to Lactic Acid</b></p>	<p>Low cost routes to valuable chemical intermediate lactic acid.</p>	<p>Lower cost intermediate with improved yields and reduced wastes.</p> <p>Exploit advances in bioscience to develop improved microorganisms for carbohydrate fermentation to lactic acid.</p> <p>Current separations technology sub-optimal and produces significant amount of waste.</p>	<p>Currently produced by fermentation of relatively expensive glucose feedstocks using <i>lactobacillus</i> bacteria which requires expensive nutrients.</p> <p>pH maintenance of reaction required with calcium salts which generates considerable gypsum waste.</p> <p>Lactic acid difficult to purify from dilute solutions.</p> <p>Considerable R&amp;D being directed towards new microorganisms that are more pH tolerant and thermophiles for increased reaction rates.</p> <p>Novel membrane, ion exchange and dialysis separations and combined reactor/separation being evaluated.</p>	<p>UK has world class science in biotechnology, thermophiles and bioreactor design.</p> <p>Little apparent R&amp;D activity in lactic acid production</p>
<p><b>Upgrading of lactic acid to valuable chemical intermediates</b></p>	<p>Cost effective production of a range of valuable and renewable biodegradable polymers and chemical intermediates.</p>	<p>Improved process for PLA polymerisation and new routes to renewable acrylic acid, propylene glycol and ethyl lactate</p>	<p>Relatively high PLA costs affecting market growth – new coupled fermentation/extraction reactor designs being evaluated.</p> <p>Other intermediates at development stage. Argonne National labs have developed membrane reactor for continuous production of ethyl lactate a potentially valuable green solvent.</p> <p>Improved catalysts required for dehydration and hydrogenation of lactic acid.</p>	<p>UK core skills in heterogeneous catalyst development and bioreactor design.</p> <p>Platform chemical upgrading R&amp;D activities at York University, Cardiff University. Imperial College</p>

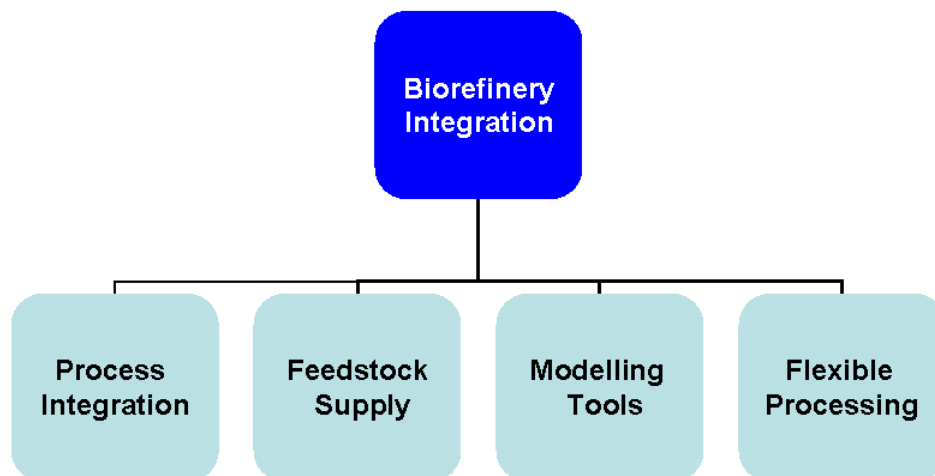
## 5.4 Biorefinery Integration

The previous sections in this chapter have detailed both the opportunities and technical challenges of producing biofuels and value-added chemicals from biomass feedstocks in the near to long term. To achieve the optimum manufacturing platform for these products both in terms of production cost, energy utilisation and product slate flexibility will require considerable focus on the effective integration of the different process elements within the biorefinery complex. In this regard biorefinery complexes aspire to achieve the level of materials and thermal integration achievable in modern day oil refineries. Although best practise can be exploited by considering both oil refineries and petrochemical complexes it is essential to the successful development of biorefineries that R&D is focused in the short term on critical integration issues. These issues include:

- Development of effective modelling tools for design and performance
- Thermal integration
- Utilisation of all carbohydrate streams
- Minimisation of all waste streams

The individual elements of the biorefinery integration platform are summarised below.

**Figure 13 Components of Biorefinery Integration**



Effective integration of a variety of biochemical, chemical and thermal processes within one large complex will require the development of new sophisticated modelling tools. Oil refineries and petrochemical complexes maximise economic performance through efficient allocation and distribution of the myriad of raw material streams to individual processing units. To a certain extent this feedstock distribution and product allocation can be tuned to match external markets. Similarly, the efficient management of these complex flows of materials and energy in the biorefinery complex will be essential to maximise integration benefits for improved energy savings and reduced processing costs. Such mathematical optimisation tools are now being developed to provide information on the optimum configurations for biorefinery complexes both for economic and environmental performance. Such models aim to provide information on:

- Cost benefit analysis of different biorefinery configurations
- Sensitivity analysis to external market perturbations
- Sensitivity analysis to technology development

Such information can be used to set R&D targets for economic biorefinery development. Most activity in this area is currently being pursued in the United States with the development of linear excel based spreadsheet optimisation models and more sophisticated Aspen based models.

Utilisation of all carbohydrate raw material streams in the biorefinery will require effective separations and purification technology to ensure that exacting feedstock specifications are met for each individual process. Extensive pilot plant trials are required to demonstrate that biochemical, chemical and thermal processes can be effectively integrated and each individual process can produce high yields of products from “realistic” feedstocks containing contaminants likely to be found in biorefinery streams. A large number of such biorefinery pilot plant/demonstration projects are currently being funded in the US and Europe.

Oil refinery operation allows a certain degree of freedom such that product slates can be changed to meet fluctuating market demand by modifying hydrocarbon streams between individual process units. Biorefineries should be designed with the same principle. Indeed, advances in biocatalysis and bioreactor design offers the long term potential of increased flexibility in that multi-product synthesis from common process units may be achievable

**Table 6; Delivery Components for Effective Biorefinery Integration**

Element	Opportunity	Drivers	Barriers/Status	UK Expertise
<b>Biorefinery Modelling</b>	Effective tools for the design and performance measurement of potential biorefinery configurations	<p>Ensure correct focus in design of R&amp;D programmes.</p> <p>Identify appropriate portfolio of co-products</p> <p>Provide early stage evaluation of economic benefits.</p>	<p>No technical barriers</p> <p>Widespread activity in the US, NREL developing excel based spreadsheet whilst Dartmouth/Princeton developed Aspen model to evaluate efficiencies of various biorefinery configuration.</p>	Widespread modelling expertise. Small Amount of activity in modelling biorefinery complexes (Manchester University).
<b>Pilot plant Trials</b>	Demonstrate technical feasibility of process integration in biorefinery complex	<p>Demonstrate integration at commercially realistic scale and using real feeds.</p> <p>Provide data for modelling, biorefinery design and economic evaluations.</p> <p>Provide confidence to investment community</p>	<p>Pilot plant equipment expensive.</p> <p>Difficult to obtain government funding in UK for large scale activities.</p> <p>Large number of pilot scale/demonstration scale biorefinery projects funded by DOE in US.</p> <p>Some EU funded demonstration projects on Biorefineries – aside from a few exceptions little UK involvement in these.</p> <p>European centres such as VTT and ECN specialise in large scale demonstration of integrated biorefinery technology</p>	Little UK activity. Some pilot plant activity on individual process elements eg pyrolysis
<b>Flexible Bioprocessing</b>	Multi-product synthesis from individual process units tailored to market requirements	<p>Reduced capital cost</p> <p>Improved economic performance of biorefinery responsive to market demands</p>	Early stage of development.	Wide level of relevant expertise in UK UCL, CoEBio3

## 6.0 Mapping Biorefinery Development

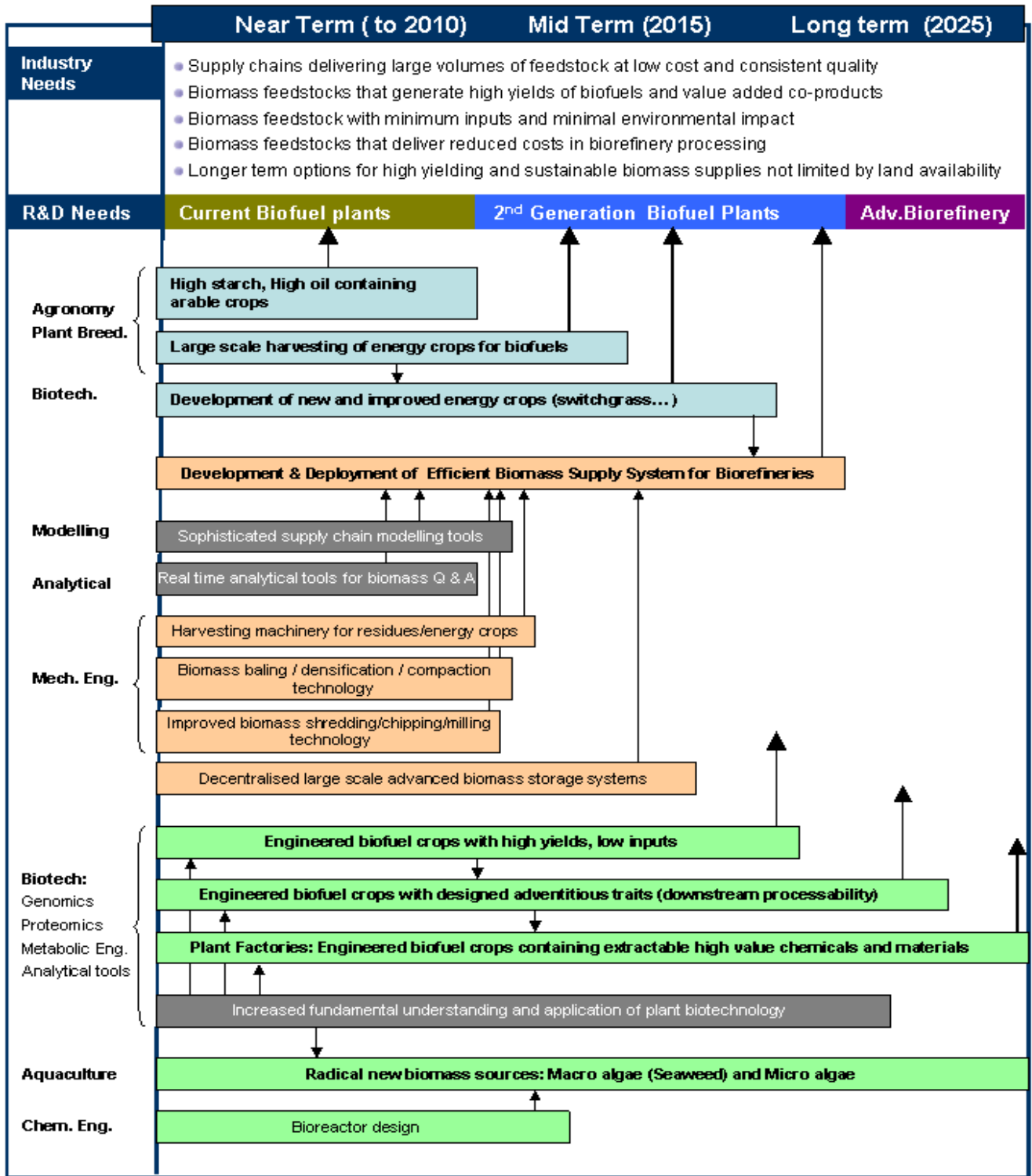
In this section standard roadmapping techniques are employed to develop an understanding of the key development timelines for each biorefinery platform area and in particular identify the interrelationships between the individual technology components within each platform area. Commercial drivers are detailed for each platform and essential science capabilities are aligned behind development activities.

Technology development requirements are predicated on the deployment of large advanced biorefinery complexes in the 2020 -2025 timescale with second generation lignocellulosic ethanol plants and Biomass to Liquid Plants being first deployed in the 2010 -2015 timescale. Although a number of smaller lignocellulosic ethanol plants are due to be constructed over the next few years and the first BTL plant planned for construction in 2011, it is likely that such early second generation technology adopters will require significant financial assistance to compete economically against both fossil derived transport fuels and first generation biofuels such as starch based bioethanol and vegetable oil derived biodiesel. Such financial assistance will include capital grants and fuel duty exemptions. It is within this timeframe that government plans to facilitate the commercial deployment of second generation biofuel technology by directly relating fiscal incentives to the inherent capacity of the biofuel to reduce greenhouse gas emissions whilst minimising other environmental impacts during its production.

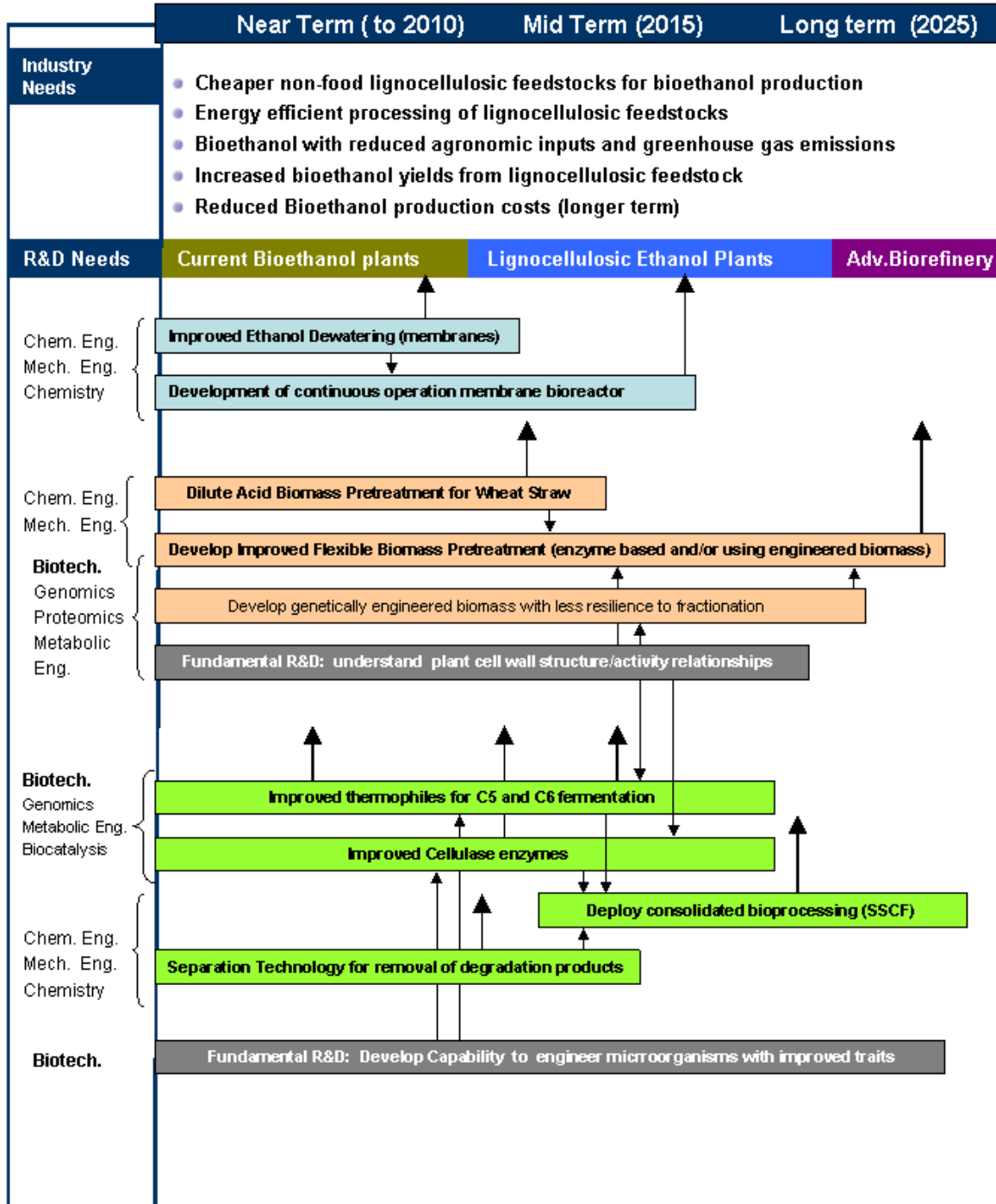
At the end of this section, 4 key priority R&D areas have been identified and discussed in further detail. Such areas are considered to be critical technology barriers to the successful development of biorefinery complexes within the UK and require concerted and coordinated R&D programmes to identify commercially feasible solutions. Such areas also represent opportunities for the creation of wealth through the application of the UK science base in core technology areas.

As discussed at the beginning of this report, the aim of this mapping process is to highlight technology barriers to biorefinery deployment and identify the appropriate multidisciplinary and cross sectorial research programmes to address such issues. At this stage of the mapping process, the timelines associated with some of the individual activities are centred on basic assumptions concerning technology status and development lead times. The next stage of the mapping process should aim to apply greater rigour to this process and achieve broader consensus through the use targeted workshop activities. This roadmap is intended to facilitate such engagement.

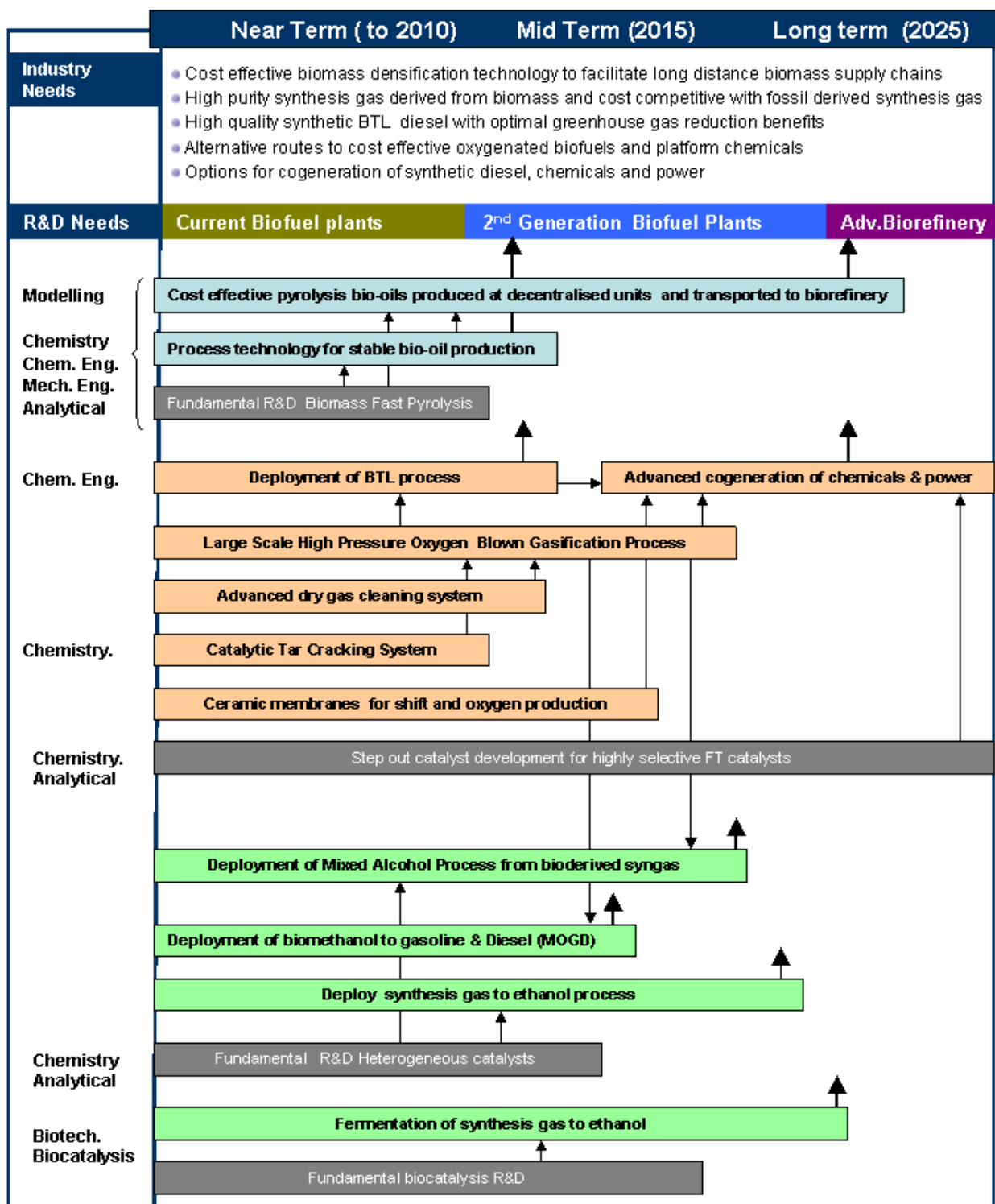
**Roadmap 1: Biomass Feedstock Supply Chains**



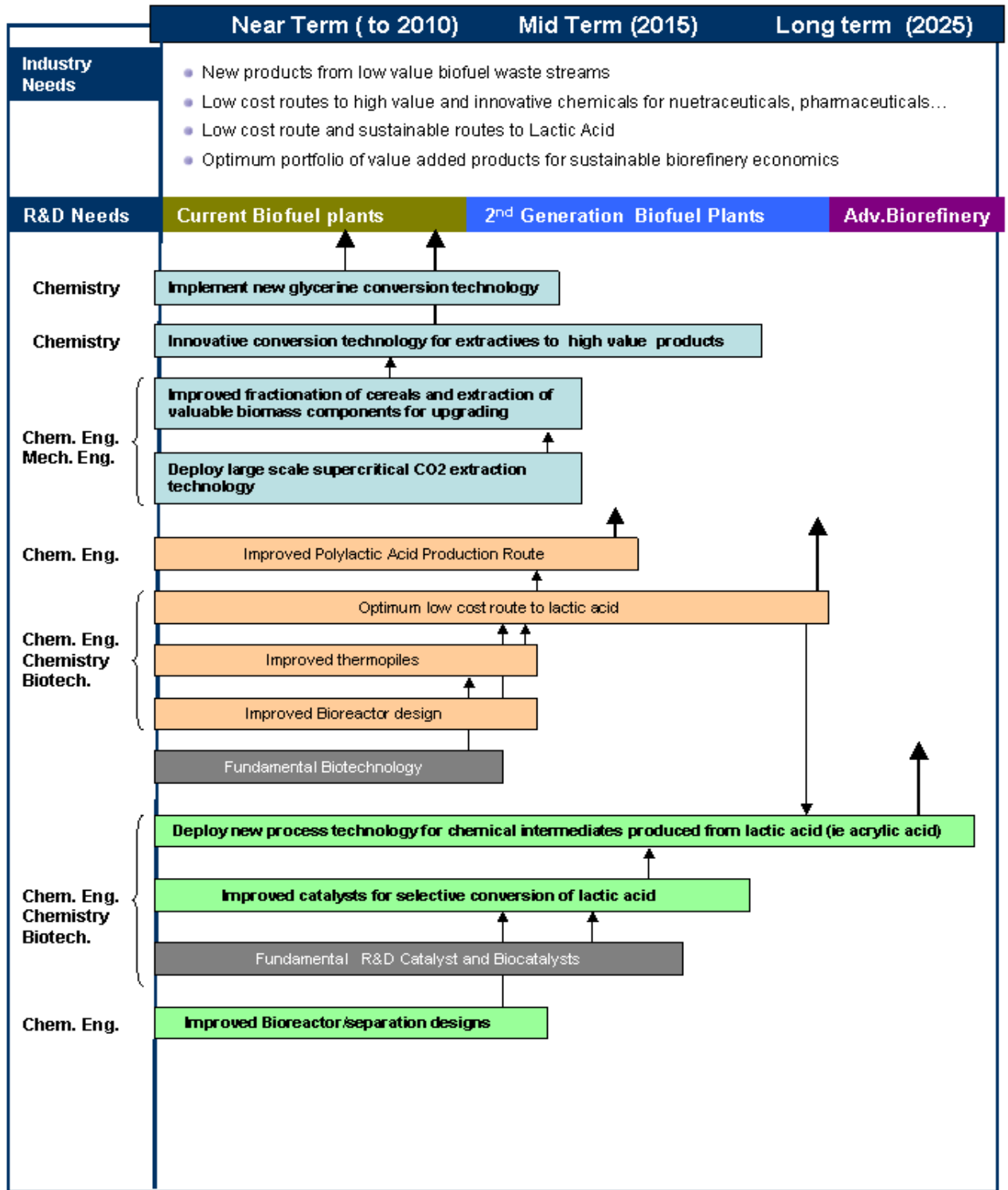
## Roadmap 2: Low Temperature Lignocellulosic Routes to Bioethanol



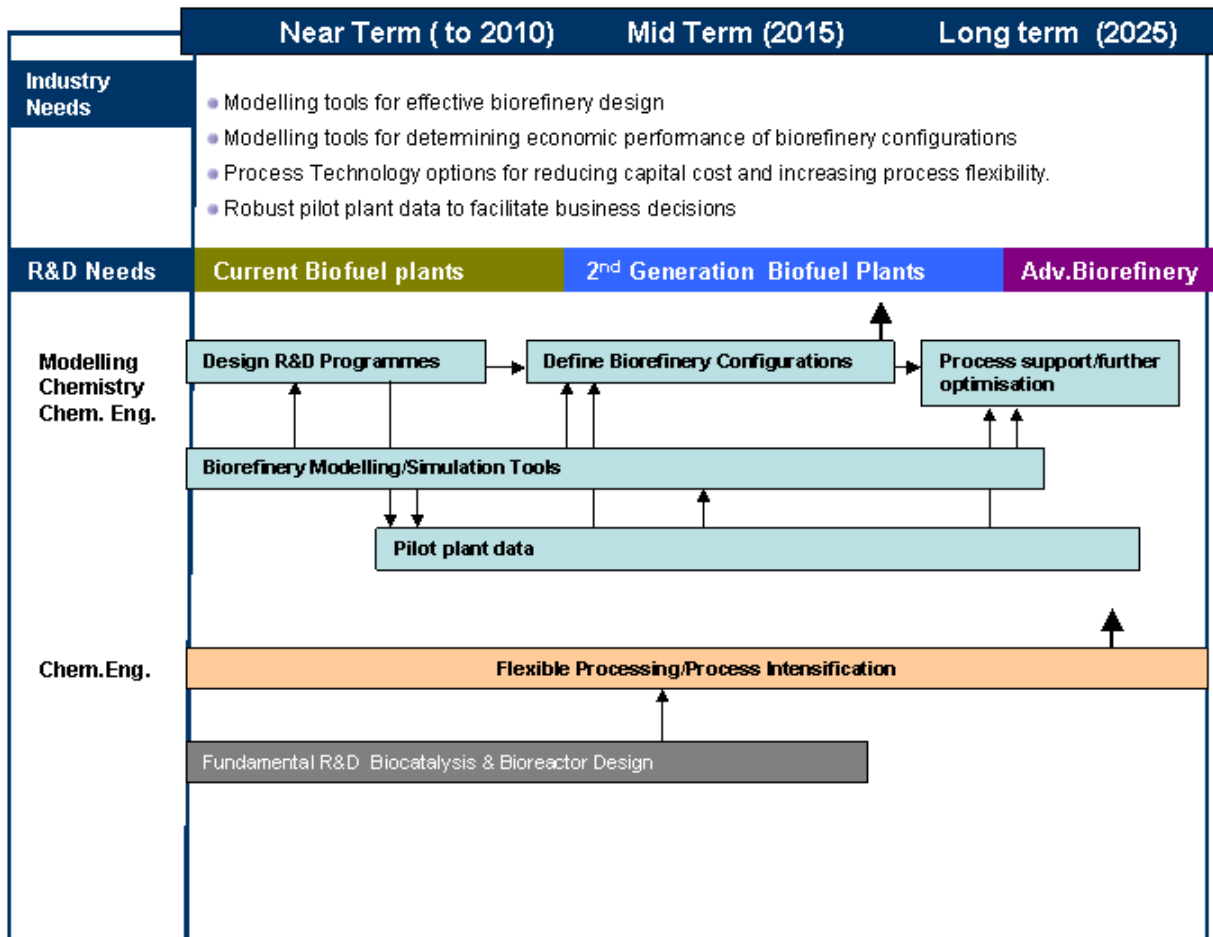
### Roadmap 3: Thermochemical Routes to Biofuels and Chemicals



## Roadmap 4: Co-production of Chemicals



### Roadmap 5: Biorefinery Integration



Four key research priorities have been identified from this mapping process; the development of effective biomass supply chains, the development of improved biomass pre-treatments, the development of improved bio-derived synthesis gas clean-up technologies and demonstration of integrated technologies at commercially relevant pilot plant scale.

These individual priority areas are summarised in the following tables.

### Priority Area 1: Biomass Supply Chains

Description	Criticality	UK Perspective	Action Plan
Development of robust supply chains that can deliver large volumes of sustainable biomass feedstock at low cost and consistent high quality to the biorefinery gate	<p>Successful biorefinery deployment depends on supply of large volumes of low cost biomass with minimal environmental impact.</p> <p>Large volumes of biomass essential to achieve economy of scale for biorefinery operations.</p> <p>Long term success will depend on introduction of decentralised supply and storage systems and development of biomass densification technologies</p>	<p>Biomass supply chains now being set-up for emerging renewable energy sector albeit at much smaller scale than that required for biorefineries.</p> <p>Longer term aspects such as biomass densification (pyrolysis) and energy crop supply look strong</p>	<p>Leverage existing activities</p> <p>Develop supply chain demonstration projects to demonstrate feasibility of supplying thousands of tonnes per day of biomass to a biorefinery.</p> <p>Develop modelling tools to identify optimum UK location for biorefinery and design effective biomass feedstock supply</p>

### Priority Area 2: Biomass Pretreatment

Description	Criticality	UK Perspective	Action Plan
Fractionation technology for the effective separation of lignocellulosic biomass into its constituent sugars for downstream processing	<p>The equivalent of the CDU in the oil refinery. Effective technology essential for production of sugar streams at low cost whilst minimising sugar losses and production of degradation products that inhibit downstream fermentation.</p> <p>Current process options are not optimal being either energy intensive, use acids, produce significant waste or involve large chemical recycles.</p> <p>Current technology adds significant capital cost to lignocellulosic conversion via fermentation</p>	<p>Seemingly little activity in this area.</p> <p>UK has strong science base in longer term solutions to overcome biomass recalcitrance such as genetically engineered plants and improved enzymes for lignocellulose digestion.</p>	<p>Identify areas of best practise for biomass pretreatment in particular generic UK feedstocks (e.g. cereal straw).</p> <p>Develop consortium R&amp;D activity for short term and longer term pretreatment technology</p>

### Priority Area 3: Synthesis Gas Clean-up

Description	Criticality	UK Perspective	Action Plan
<p>Integrated multi-step process for the production of biomass derived synthesis gas of high purity for downstream processing in Fischer-Tropsch and Methanol synthesis processes.</p>	<p>Major remaining technology barrier for Biomass to Liquids processes. Tar removal from gas the main element.</p> <p>Clean-up and conditioning, a significant element of biomass derived synthesis gas cost.</p> <p>All majority of purification technology is off the shelf, costs could be further reduced through application of innovative dry gas cleaning techniques including membrane technologies</p>	<p>Considerable activity in biomass gasification for the production of fuel gas but little evidence of concerted effort in purification of synthesis gas for large scale chemicals production.</p> <p>Strong science base in reactor engineering and membrane separation processes.</p>	<p>Engage scientific community</p> <p>Develop coordinated and focused R&amp;D projects to identify optimum gas clean-up technologies.</p> <p>Demonstrate multi-stage technology at pilot plant scale integrated with synthesis gas conversion process</p>

### Priority Area 4: Pilot Plant Scale Demonstration

Description	Criticality	UK Perspective	Action Plan
<p>Demonstration and validation of integrated biorefinery concepts.</p>	<p>Essential to validate biorefinery concepts under commercially realistic conditions to provide data for full scale design and accurate costing and production economics.</p> <p>Robust pilot plant data provides confidence to investment community on technical and economic feasibility of biorefinery</p>	<p>Currently no large scale pilot plant facilities for demonstration of integrated concepts.</p> <p>US and rest of EU have identified centres of excellence for large scale technology demonstration activities in integrated biofuels production. These academic centres receive considerable government financial assistance.</p>	<p>Develop case for pilot plant activity in key areas of biorefinery integration. Identify appropriate government funding streams and identify optimum location for facility.</p> <p>Promote further UK involvement in EU consortia bidding for biorefinery demonstration projects</p>

## 7. Discussion

The UK market for biofuels is demonstrating rapid growth and considerable new production capacity for both biodiesel and bioethanol is planned over the next few years. In addition significant development activity is now being directed towards the next generation of biofuels. Driven by the need to maximise environmental benefits, these second generation biofuels will utilise innovative conversion technologies to produce synthetic diesel and bioethanol from sustainable and low cost lignocellulosic raw materials. A huge amount of R&D activity, particularly in the US, is being focused through large multidisciplinary programmes to develop effective technology platforms for commercially feasible lignocellulosic biomass conversion. Outside of the US, such R&D activity is fragmented particularly in the UK where engagement across all the necessary scientific disciplines appears limited and little coordinated activity is apparent. The technology required to deliver these “second generation” biofuels is complex, costly and not yet demonstrated at a commercial scale. Although the commercial implementation of both second generation BTL synthetic diesel and lignocellulosic bioethanol plants is reported to be likely over the next four years in countries such as Germany and the US, early adopters of this technology are unlikely to be cost-competitive when compared to conventional biofuel facilities. Significant technical barriers remain for both BTL synthetic diesel and lignocellulosic bioethanol that have yet to be effectively resolved. For BTL synthetic diesel; effective gas clean-up technology is required to provide cost competitive bio-derived synthesis gas that is completely compatible with downstream Fischer-Tropsch processing. In contrast, a large number of challenging technical barriers remain for lignocellulosic bioethanol production, the most critical of which appears to be the need to identify effective pretreatment technology to facilitate the cost effective and waste-free fractionation of the recalcitrant lignocellulose material into its constituent sugars and lignin. The UK has core scientific expertise in the enabling technologies required to address these barriers such as heterogeneous catalysis and membrane separations but there appears to be limited engagement in these activities.

Second generation biofuels technology will comprise the key conversion platforms in large integrated biorefinery complexes. Based upon current manufacturing platforms in the oil and petrochemical sectors, biorefineries will process large volumes of biomass feedstock to produce biofuels and a diverse suite of value added co-products. Such biorefinery complexes are a long term prospect. The general consensus is that large advanced biorefineries processing more than 1000 tonnes per day of biomass will be commercially deployed in the 2020 -2025 timeline. This long lead time for biorefinery implementation in the UK can be related to a number of factors including:

- The existing biomass feedstock infrastructure which is limited in volume and cannot currently supply biomass at a competitive cost

- Limitations in current biomass conversion technology and lack of modelling tools
- Volatile cost of crude oil
- The huge capital investment required for a large biorefinery complex on a greenfield site, likely to be significantly higher than an equivalent oil refinery at the same per barrel of daily capacity basis.
- Uncertainties in the investment community due to concerns over longevity of favourable governmental policies towards biofuels and the risks associated with the commercialisation of new process technology.

The existing UK biomass feedstock infrastructure was not developed to supply large biorefinery complexes requiring many thousands of tonnes per day of raw materials. The difficulty in developing new biomass supply chains that can deliver sufficient feedstock at the right cost to a UK biorefinery gate was highlighted as a major barrier to the commercialisation. This is highlighted in the study of the two biorefinery configurations considered in this mapping exercise. The two different biorefineries were chosen as to be representative of a regionally supplied complex and a large globally supplied complex. However, even the relatively small biorefinery with a modest production capacity of 900 tonnes per day of bioethanol and lactic acid produced from cereal straw would require a very large catchment area if placed in a typical cereal producing region on the east coast of the UK. Larger UK biorefineries will need to be flexible regarding biomass feedstock type and be sited close to ports so that large volumes of internationally commodity traded biomass can be readily accessed. The nature of biomass availability in the UK and current status of biomass supply chains suggest that the scale of biorefineries will be limited and the ability to maximise economy of scale economics will be constrained. In the longer term, this situation will be addressed by the widespread planting and harvesting of high yielding energy crops and the utilisation of biomass densification technologies such as pyrolysis to produce easily transported bio-oil.

The biorefinery concept is not new; it has been practised in the ethanol wet mill process for many years, albeit at a much smaller scale. In fact, existing biofuel facilities are now integrating biorefinery principles into their operations; biodiesel plants are developing new ways to add value to glycerine co-products by conversion to chemical intermediates or by utilisation as a fuel for integrated heat and power production. Similarly, corn bioethanol companies are now evaluating the dried distiller's grain co-products, normally used as animal feeds, for alternative higher value markets. However, biorefinery complexes will be vast in comparison and maximise both energy and materials conversion efficiencies and economies of scale will be exploited to deliver capital efficiencies and cost effective co-production of value added chemicals. Energy

efficiencies in biorefineries will aspire to those currently observed in modern oil refineries (>85%).

Advances in bioprocessing coupled with the desire for more environmentally benign chemical intermediates with added functionalities are driving the commercialisation of novel bio-derived products. Lactic acid was chosen as the major co-product in this mapping exercise due to its potential as an intermediate for acrylic acid and propylene glycols. In addition, lactic acid has already entered the market place as a monomer for the biodegradable polymer, polylactic acid. Considerable scope remains for improvements to process technology in this area and further reductions in lactic acid production cost can be envisaged through the application of improved thermophiles for substrate fermentation and novel bioreactor concepts. In both of these areas the UK science base is strong and evidence suggests that a number of academic groups and organisations are now actively pursuing new routes to platform chemicals.

Due to the long term nature of the technology planning described in this report significant potential exists for the development of disruptive technology that could displace the need for advanced biorefineries. A number of such scenarios can be envisaged and will be discussed further here. There are a number of alternative biofuels at various stages of development including biobutanol, dimethylether and hydrogen. Biobutanol is produced via fermentation of sugars whilst dimethylether and hydrogen are produced from bio-derived synthesis gas. Irrespective of the merits of these alternative biofuels, it is clear that they would benefit from integrated production in large biorefinery complexes and many of the technical barriers discussed in this report would remain common to these alternative biofuels e.g. the need to produce high purity cost competitive bio-derived synthesis gas. Liquid biofuels produced from biomass are often described as transitional systems until hydrogen powered fuel cell vehicles become a commercial reality. Even if current commercial barriers to hydrogen fuel vehicles were resolved in the short term, the hydrogen would be produced from large biomass gasification complexes which would again benefit from the application of biorefinery concepts e.g. process integration and high value co-product portfolio management. An alternative approach would be to have decentralised smaller gasification units at individual filling stations although this resolves some issues surrounding hydrogen storage and transportation it is likely to be severely disadvantaged economically against large centralised complexes. A radical departure would be the large scale splitting of water using renewable energy (wind, solar...) to produce hydrogen but this a very long term prospect. General consensus suggests that the hydrogen economy remains a long term goal. A more likely development that could impact upon some of the roadmapping discussed in this report is the utilisation of existing refinery infrastructure to produce petrol and diesel from biomass feedstocks. The production of diesel via the conversion of vegetable oil in refinery hydrocrackers has already been demonstrated by both Neste

Oil and ConocoPhillips who are now commercialising this technology. Further work in the United States has demonstrated the feasibility of converting vegetable oils and biomass pyrolysis bio-oils for the production of diesel, petrol and olefins in laboratory scale hydrocracker and FCC reactors. The use of pyrolysis bio-oils is of interest because of the flexibility in biomass feedstock source however more technical development is required to effectively remove oxygen from the bio-oil prior to refinery processing. Even if the biofuels were produced completely from existing refinery operations it is likely that future advances in bioprocessing would present a compelling case for integration of innovative low temperature biochemical processes within the refinery infrastructure.

The UK science base has world class capabilities in a number of core development areas for biorefineries including plant science, genomics, genetic engineering, pyrolysis, biocatalysis and chemical catalysis. It is clear that successful biorefinery development will require a concerted and coordinated research activity across a wide spectrum of different disciplines. It is also abundantly clear that aggressive investment is now required in targeted areas of research and development for the successful long term deployment of large advanced biorefinery complexes. In this regard the UK is now well behind the US and a number of other EU countries in developing national coordinated biorefinery programmes. Although there are relevant coordinated activities within individual areas and scientific disciplines it is critical that a more comprehensive and inclusive approach towards biorefinery development coordination is undertaken to ensure rapid development of essential enabling technologies and to promote the formation of functioning supply chains across relevant sectors.

## 8. Conclusions

- A comprehensive literature review of the state of the art of biorefinery development has been completed and a report issued. This review revealed considerable R&D activity focused on the development of enabling technology for deployment of biorefinery complexes. This is particularly the case in the US where large well coordinated multidisciplinary and cross-sectorial R&D programmes are being heavily funded by government to deliver national targets for biofuels. Research activity outside of the US is somewhat fragmented. The UK does not appear to have a broad based strategic activity in this area.
- Considerable progress is being made in the development of enabling technology for biorefinery implementation particularly in those areas that exploit state-of-the-art developments in bioscience. The estimated production costs of second generation biofuels that utilise advantaged lignocellulosic feedstocks are being reduced. However, a number of challenging barriers remain and early adopters of second generation biofuels technology will require significant government financial assistance to be competitive against conventional biofuels. Advanced biorefinery deployment remains a long term goal with general consensus suggesting commercial implementation beyond the 2020 timeline
- For the purpose of this study two different biorefineries have been envisaged for the UK: One relatively small “whole crop” biorefinery complex producing bioethanol, lactic acid and high value extractives from wheat and one larger “two-platform” biorefinery complex producing synthetic diesel and bioethanol from mixed biomass feedstocks. Potential issues regarding biomass feedstock supply for such biorefineries have been debated and optimum locations identified.
- Inadequacies in UK biomass feedstock supply infrastructure are likely to constrain the scale of even modestly sized biorefineries and impact on the ability of such complexes to maximise economies of scale. The longer term availability of large volumes of energy crops and the development of biomass densification technology to produce readily transportable bio-oils will mitigate against this.
- Technology mapping studies have emphasised the multidisciplinary and cross sectorial nature of the R&D programmes required to successfully deliver UK biorefineries within the 2020 -2025 timescales. Four key priority areas were identified; biomass supply chains, biomass pre-treatment, synthesis gas clean-up and pilot plant demonstration activities.

- The UK science base has world class capabilities in a number of core development areas for biorefineries including plant science, genomics, genetic engineering, and biocatalysis and chemical catalysis. It is clear that successful biorefinery development will require a concerted and coordinated research activity across a wide spectrum of different disciplines and that aggressive investment is now required in targeted areas of research and development for the successful long term deployment of large advanced biorefinery complexes in the UK.

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