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The Bioeconomy Consultants

The Potential for Forest-Based Industrial Biotechnology in Scotland

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A report for Scottish Enterprise, Chemicals Scotland and Forestry Commission Scotland

Authors

David Turley Lead Consultant - Bio-based Feedstocks

Adrian Higson, Lead Consultant - Bio-based Products

Michael Goldsworthy, Consultant

Efthalia Arvaniti, Consultant

Disclaimer

Version

This version is a slightly modified update of the original to take account of findings and outcomes from a later report commissioned by Scottish Enterprise from E4tech on the Opportunities for Biorefining in Scotland, which included assessment of a wider range of available wood resources in Scotland. It also updates the original roadmap.

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NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and bio-based products.

NNFCC, Biocentre,
York Science Park,
Innovation Way,
Heslington, York,
YO10 5DG.

Phone: +44 (0)1904 435182
Fax: +44 (0)1904 435345
E: enquiries@nnfcc.co.uk
Web: www.nnfcc.co.uk

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Executive summary

The emerging bioeconomy both in the EU and globally is offering new opportunities for development of high-tech industries and jobs in the chemicals sector. Increasingly, lignocellulosic plant biomass is being developed as a cheaper and more environmentally sustainable and acceptable source of feedstocks for bio-based fuels, chemicals and materials.

The forestry and chemicals sectors are both important contributors to Scotland's economy, but both are subject to increasing global pressure from competitors. Scottish Enterprise in partnership with Chemicals Scotland and Forestry Commission Scotland is keen to understand what opportunities might be available to exploit the Scottish Forest resource as a feedstock for the biobased chemicals sector.

This analysis sought to understand the net domestic forest wood resource that could be made available to support bio-based product industries in Scotland, the nature of the existing infrastructure and academic base, the potential opportunities that this resource is capable of supporting at world scales of production capacity and the steps required to realise these opportunities.

The net sustainably-harvested non-timber forest resource that currently remains after other uses are accounted for was calculated as 785,000 odt/yr. Rapid delevopment of the biopower sector, based on deployment of currently planned plants, could potentially reduce this to around 74,000 odt/yr (at the higest levels of bioenergy deployment using domestic feedstocks) until post 2020, when timber harvest volumes increase.

Scotland currently has very limited industrial chemical interest in bio-based chemicals, the few existing tend to work with relatively simple plant extracts. Only one pulp and paper mill in Scotland now uses virgin wood and this uses mechanical rather than chemical pulping, the latter being easier to exploit for biobased chemical production. In contrast, in the academic sector, academic/industry and associated knowledge clusters, there is a wide range of underpinning knowledge in biomass transformation and biotechnology relevant to the development of biobased chemicals but there appears to have been little focus on use of forestry as a feedstock resource to date.

The suitability of Scottish forest resources and capacity issues affecting use in 'forest', 'thermochemical' and 'sugar' biorefinery platform process routes was examined. A range of possible chemical transformation routes and outputs is possible. Focus was placed on chemical products identified by previous studies as being particularly suited to exploitation in the UK, namely;

- 3-hydroxypropionic acid (3-HP)
- Butanol

- Glucaric acid
- Lactic acid
- Levulinic acid
- Methyl methacrylate (MMA)
- Polyethylene
- Polyhydroxyalkanoates,
- Sorbitol
- Succinic acid
- Syngas
- Xylitol

The market potential for each of these was examined and opportunities were ranked based on a semi-quantitative scored assessment of market opportunity and Scottish infrastructure and resource to support development.

The influence of feedstock demand had a strong impact on rankings, favouring high value chemicals with relatively small (on a global scale) market demand, where a newcomer could command significant market share. Priorities for exploitation of each chemical are outlined in the report. However, rather than focussing on specific chemicals, greater benefit can be gained by focussing on the issues that favour Scottish interests.

Most biobased chemical development, including that in the forest sector, has typically built on existing starch, sugar or wood processing industries, lowering the hurdles to development. Unfortunately, Scotland lacks such plants. In addition, the cost of sugar derived from Scottish forest feedstocks will have to compete with that from sugar and starch crops, and other lignocellulosic resources, or risk companies siting processing plants elsewhere.

While the traditional wood processing sector has been operating for decades and serves a number of established and mature chemical markets, the opportunities offered by biotechnology and thermochemical developments are relatively recent and in many cases have still to prove commercial viability, particularly when using wood and forest residue feedstocks. Bio-based transformation of syngas and sugar to chemicals also needs to be refined to deliver high efficiency or cost reductions to open market opportunities. Identifying the most promising chemical targets remains difficult in a myriad of potential opportunities.

Given the developing status of the technology, Scotland needs to closely monitor existing demonstration projects in this sector and the products targeted. Scotland should seek partnerships with the relevant industries and technology partners in countries with similar extensive temperate forest resources and similar aims and objectives. This could be with a view to joint initiatives to develop plants in Scotland or to exploit and develop IP developed in Scotland, potentially on a global scale. A roadmap of priority actions is provided.

1 Introduction

The emerging bioeconomy both in the EU and globally is offering opportunities for the development of new bio-based industries, particularly where biomass feedstocks are readily available.

Biomass offers a source of sugars and lignin that can be exploited to produce both commodity and specialty chemical products through a wide range of chemical and biotechnological approaches. Similarly, biomass can be used as a low-carbon feedstock for thermal dissociation and chemical and catalytic reformation into an extensive palate of chemical feedstocks.

The Forest & Timber Technologies sector employs 40,000 people in Scotland and generates £1.7bn annually. While timber offers a high value outlet, there is significant potential to utilise timber by-products arising from the sector as a valuable feedstock resource for the chemical and biotechnology sectors. Chemical Sciences are also an important contributor to the Scottish economy. There are around 200 chemical sciences companies in Scotland employing some 14,000 people directly and 70,000 indirectly, generating over £9 billion each year. With exports worth almost £3 billion, this is one of Scotland's most important economic sectors.

According projections by industry[1], the Industrial Biotech (IB) market in Europe could develop from 28 billion € in 2013 to 41 billion € in 2020, and up to 52 billion € in 2030. While this represents a wide range of sectors of application, it clearly represents a growing market opportunity for any associated enabling skills and resources.

Working to exploit the potential emerging opportunities in the bio-based technology sector requires industries across a range of sectors to pool relevant expertise and knowledge to enable development of new supply chains and address the inevitable barriers and issues thrown up during scale up and commercial development phases.

This study looks to identify opportunities for exploitation of Scotland's forest resource by bio-based non-timber industries and to prioritise these for further examination and to develop steps towards possible exploitation. Such opportunities will not emerge without significant effort and investment finance based on a clear understanding of the opportunities available. Development of biobased products requires the integration of a number of different industries and skills (see figure 1) with actions to support this.

[1] BIO-TIC Market Roadmaps. http://www.industrialbiotech-europe.eu/bio-roadmaps/market/

Table 1. Example skill areas and areas of industrial expertise required to develop biobased chemicals and materials and the cross sector integrating actions required

Land level> Biomass production	Process integration/optimization/ intensification - Carbon/energy/water efficiency and scale up	Life-cycle Analysis (LCA) - Technoeconomic/Environmental evaluation	Knowledge Tranfer - Entrepreneurship - Supply chain integration - Business model development - Access to funding
Plant genetics			
Plant science and crop management			
Forestry and silviculture			
Land management			
Environmental impact			
From land to plant			
Supply chain management			
Transport			
Storage			
Trade			
Wood processing to platform chemicals**			
Biomass characterization, analytical chemistry			
Mechanical pretreatment and material separation			
Thermochemical pretreatment			
Chemical engineering -Upstream			
Chemical engineering - Downstream			
(Bio)Process engineering			
Reactor and process design			
Wood chemistry			
Catalysis and Biocatalysis*			
Gasification and pyrolysis			
Polymer chemistry			
Material chemistry			
Manufacture engineering			
AD and other waste treatment			
Platform chemicals to intermediate products*****			
Fermentation			
(Bio)process engineering			
Reactor and process design			
Synthetic chemistry			
Biocatalysis*			
Chemical engineering -Upstream			
Chemical engineering - Downstream			
Polymer chemistry			
Material chemistry			
Manufacture engineering			
AD and other waste treatment			

{Catalyst= Inorganic, organic; Biocatalyst = enzymes, whole cells}

**Biocatalyst development> Cell biology, synthetic biology, systems biology, fermentation technologies*

***Platform chemicals = Sugars, lignin, extractives, oils, pyrolysis oil, Syngas, Biogas, Biochar, Tars, Biogas*

**** Intermediate products = Bulk chemicals, Fine chemicals, materials, fuels, etc.*

1.1 Approaches

The analysis was undertaken as four linked themes

1. a landscape analysis to determine
    a. net availability of the Scottish domestic wood resource by type
    b. current interests in the Scottish chemicals and biotechnology sectors, in the use of, and potential for use of, bio-based feedstocks
    c. research sector interests currently focussed on this sector or on related supporting areas and technologies
2. a horizon scan to identify the possible future bio-based opportunities available including;
    a. key transformational processes and potential opportunities and likelihood of domestic forest resources being able to meet these
3. review of challenges in delivering the above opportunities
4. SWOT analysis of the most promising opportunities

The key findings are used to derive a set of actions and a roadmap to drive innovation and exploitation.

As the analysis work required for 1 and 2 is relatively long and data heavy, the underpinning analysis is contained in an Annex Report, from which the shorter sections in the body of this report draw.

1.1.1 Identification of key chemicals of interest

The range of chemical materials that can be derived from biomass is vast. A number of studies have attempted to identify the most promising bio-based chemical targets for development[2], including some that have targeted the most promising opportunities for the UK[3]. In these cases the myriad of opportunities available has been rationalised based on an understanding of

- The degree of development of the underlying transfomational processes (biorefinery pathway)
- Economics (reflecting the value of the resulting product and net costs of production)
- Industrial viability (direct market substitution or existing commercial production)
- Size of market opportunity

[2] Bozell, J.J. and Petersen G. (2010) Technology development for the production of biobased products from biorefinery carbohydrates – the US Department of Energy's "Top 10" revisited. Green Chemistry v 12, p539-554. Pub RSC, UK.
[3] NEXANT Chemical Systems internal report for NNFCC

- Ability of the compound to serve as a platform chemical for useful derivatives (flexibility)

NNFCC examined the results of such analyses and along with its own knowledge base in this sector, rationalised the number of chemicals examined to identify the opportunities either most likely to fit with existing Scottish chemical interests or alternatively used them as a proxy to identify;

- what types of biorefinery platforms would fit with, and could be supported by the available Scottish Forest feedstock resource, and
- the type of markets that offer the most promising route for expoloitation in Scotland.

Drawing on this previous work and NNFCC's knowledge base the following were selected for further examination as some of the most promising bio-based chemical opportunities for the UK with relevance to forestry-derived feedstocks:

- **3-hydroxypropionic acid (3-HP),** an important 3-carbon chain building block molecule
- **Butanol,** emerging as an important developing bio-based building block
- **Glucaric acid,** an example of a high-value industrial biotechnology target chemical, listed by the US DoE as one of the top 12 bio-based building block chemicals.
- **Lactic acid,** primarily used in poly lactic acid (PLA) polymer production.
- **Levulinic acid,** a prime intermediary for a number of large volume markets and was listed as one of the top 10 bio-based building block chemicals in DoE list updates.
- **Methyl methacrylate (MMA),** a precursor for acrylic and Perspex
- **Polyethylene,** linear low density (LLDPE) and high density polyethylene (HDPE) produced from bioethanol-derived ethylene
- **Polyhydroxyalkanoates,** a wide-ranging group of natural polymers
- **Sorbitol,** a promising chemical intermediate, particularly for isosorbide for use in polyethylene terephthalate applications (plastic bottles)
- **Succinic acid,** an important platform 4-carbon chain building block
- **Syngas,** biomass derived syngas is emerging as a major area of interest for both direct conversion to fuels or as a carbon feedstock for fermentation to fuels and chemicals
- **Xylitol,** primarily used as a low calorie sweetener, currently extracted from wood pulping operations.

In addition the potential for further development of traditional wood processing chemical products and by-products (lignin derivatives) were examined.

The above examples were used to identify the key issues affecting development and to examine the areas offering the most promising opportunities for wider exploitaition of the Scottish forest resource.

2 Forest wood resource in Scotland

Forest coverage in Scotland stands at over 1.3 million hectares, equivalent to around 18% of the total land area of Scotland. There have been significant efforts over recent years to improve diversification in Scottish forestry, with many varieties of pine, larches and other conifers being more widely planted, but currently Sitka spruce continues to dominate the forest resource.

Coniferous species account for 79% of the standing forest area, but this dominance is much stronger on the Forestry Commission estate (97%). Around 35% of all forestry in Scotland is owned by the Forestry Commission, which is most actively managed.

Despite the difference in forest area (479,000 ha owned by Forestry Commission compared with 904,000 ha in private hands), each produces a similar output of roundwood. Future increases in output are expected to come primarily from the private sector.

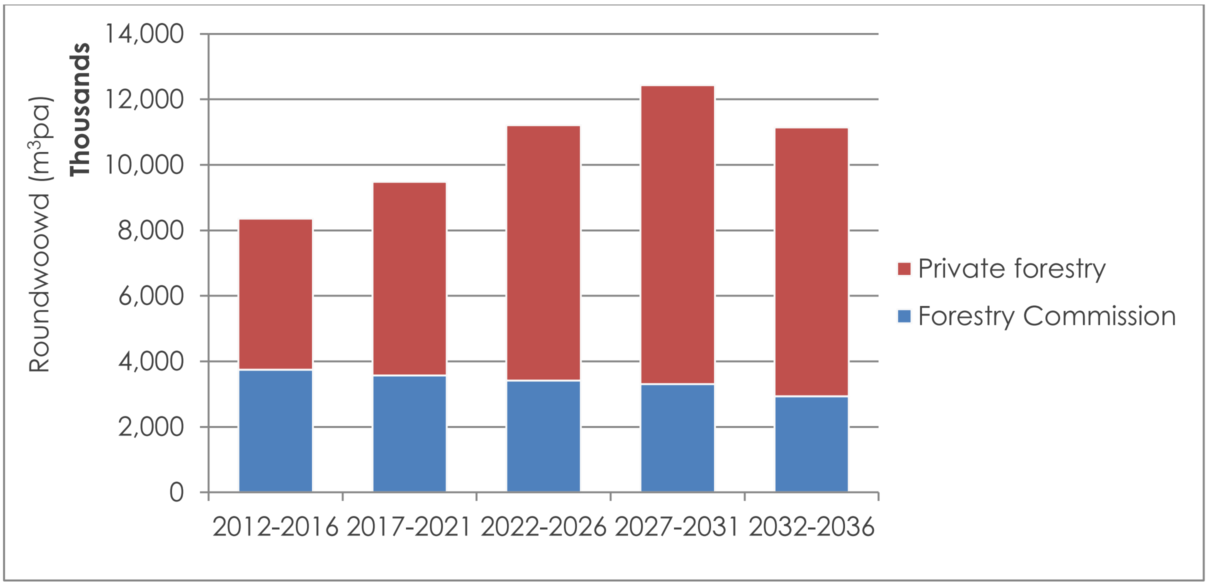


Figure 1. Forecast availability of roundwood timber from Scottish Forestry between 2012 and 2036[4]

Timber is the primary market driver for roundwood production. However, other market outlets; pulp and paper, wood panel and now bioenergy markets, support growth of the forestry industry by providing a demand for lower value wood fibre

[4] [Forestry Commission. 2012. UK 25-Year Forecast of Softwood Availability.]

materials. The development of Scotland's Industrial biotechnology sector could result in additional competition for these low value wood fibre resources.

A detailed assessment of forest by-product wood arisings and competing market demands is provided in the Annex Report. The following sections draw on this analysis.

Assuming timber quality wood (>14cm diameter) would achieve the highest premiums, the wood resource for non-timber opportunities was deemed most likely to be derived from small roundwood, harvest residues and sawmill residues. As coniferous species dominate the managed forest resource, the analysis of resource arisings is focussed on softwood.

To assess net availability of non-timber wood fibre resources, calculations were made of arisings over time of small roundwood, forest residues, sawmill residues, arboricultural arisings and stump and root biomass along with the anticipated demand of competing industries (wood panel, pulp & paper and bioenergy).

As the wood fibre resources considered are either residues or co-products, their production is reliant on activities in the timber industry. Consequently, supply estimates are highly dependent on future forest harvesting forecasts as provided by the UK Forestry Commission.

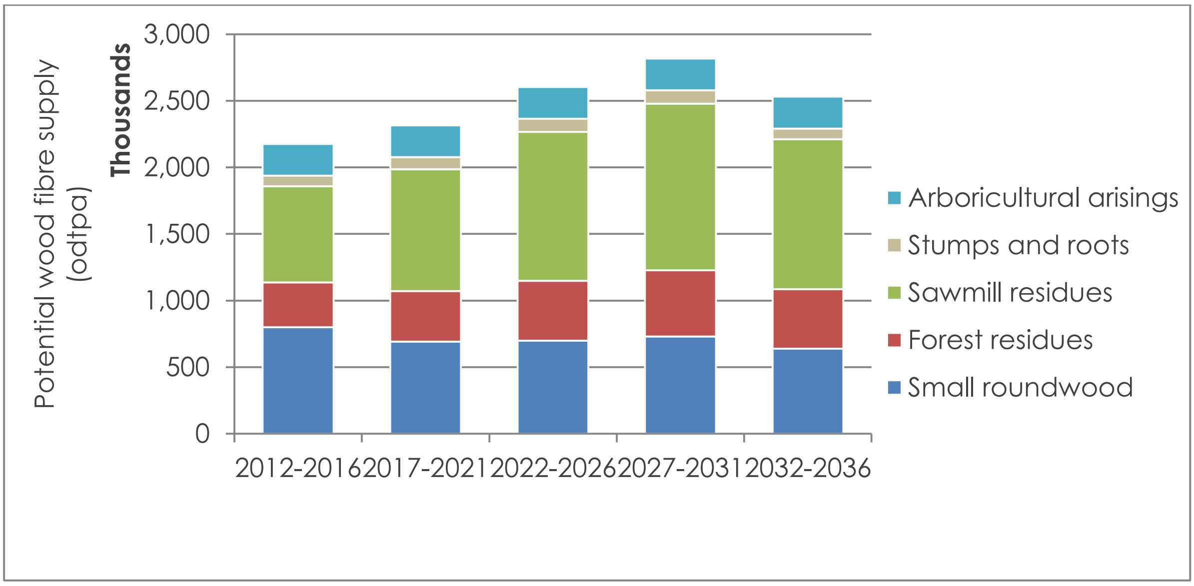


Figure 2. Estimated current and future supply of non-timber wood fibre resources from Scottish softwood

Future roundwood production is predicted to decline slightly then stabilise in response to previous adoption of improved harvest management practices (for timber output).

Forest residues represent a currently underexploited resource, although this will require significant effort and investment to collect. The analysis assumes only 80% of the available resource can be collected due to terain or other constraints, the analysis also assumes around 40-50% of the harvest residues are retained in situ to conserve soil nutrients and provide other environmental benefits. Forest harvest residues are relatively bulky. Economic transport distances are typically of the order of 50 miles, which could affect access. Mechanical baling or chipping at the roadside can help reduce such problems. The potential availability of forest residues is expected to increase over time, in line with incresed harvest of roundwood.

The forest harvest residue assessment excludes needles that typically account for up to 30% of forest harvest residue biomass. These could provide a resource for extractive industries (e.g. for the fragrance sector). Up to 120,000-170,000 fresh tonnes/annum are potentially available, though logistics of collection are likely to be difficult.

Sawmill residue outputs are based on Forestry Commission historical estimates of sawmill wood consumption, and the assumption that sawmill throughput will mirror the growth in timber harvesting (*this would represent a 1m tonne increase on current throughput*). A slump in demand or increased competition from imports could significantly affect output estimates.

Extraction of stump wood and roots is not common in the UK, in part due to environmental and soil protection concerns as well as cost. A resource of around 78,000 oven-dried tonnes per annnum is estimated to be potentially available, rising to 100,000 odt/yr.

Recent estimates for the Forestry Commission estimate that just over 700,000 green tonnes (gt) of arisings are generated by the activities of local authorities, landscapers, tree surgeons and forestry services in Scotland each year. Around one third is green waste, with the remainder split between brash (310,000 gt) and roundwood (166,000 gt). Together, this represents a potential woody biomass resource of 238,000 odt/yr. Given the wide variety of bodies involved in generating these arisings, forecasting future volumes is very difficult, and future arisings are assumed to remain at current levels.

2.1 Combined non-timber wood fibre resource

Combining the above resources, the current annual supply of non-timber wood fibre is around 2.2 million odt, with potential to increase to more than 2.8 million tonnes.

In part this is based on assumptions of harvesting intentions within the private sector, which accounts for most of the increase in harvested wood volume. This assumes that private owners adopt effective management practices. Without a strong demand for timber in the UK, harvest residue resources are unlikely to increase from current levels.

2.2 Net availability of non-timber wood fibre resource

The wood panel industry has grown in the UK, but diversified to use recovered and recycled wood as well as virgin wood residues. Three wood panel producers are based in Scotland, using around 0.75 million odt/yr of virgin wood fibre. Demand for board products remains high and there is fierce competition with imports. The production and demand situation is not expected to change in the near future.

The UK paper and pulp industry has historically used small roundwood and sawmill residues. However, the numbers of integrated pulp and paper mills utilising virgin wood fibre has declined substantially, only two now remain in the UK, including UPM Caledonian in Scotland, and Iggesund at Workington, Cumbria (both of which use mechanical rather than chemical pulping methods). The UK paper industry predominantly uses recovered waste paper or imported pulp. The UPM site typically uses 280,000 gt/yr (140,000 odt) of domestic wood fibre. With no plans for expansion or closure, demand is anticipated to remain unchanged.

Demand for wood fibre by the bioenergy sector has grown rapidly in recent years. The current biopower capacity requires around 650,000 odt of virgin fibre, alongside waste and recycled wood input. Expansion of the sector, based on developer intentions, is expected to increase the demand to 1.4 million tonnes (after excluding plants likely to rely on imported wood pellets). Biomass feedstock demand for heat is anticipated to be much smaller, at up to 100,000 odt. This represents an assessment of the maximum amount of biomass that may be used in the energy sector as not all planned plants may progress to full commissioning, particularly if the Scottish Government insists on only supporting CHP developments. So biomass demand may be less than indicated here. In addition, the bio-based chemicals sector may be able to outbid energy markets for wood where long term contracts do not protect supplies.

Financial support for biomass power generation under the Renewables Obligation is time limited. Demand on the biomass resource is expected to decline from 2027 onwards, when some of the earliest commissioned plants will come to the end of their support period, which could gradually release up to 0.5 million tonnes of current biomass demand.

2.3 Total demand and net availability

Across all sectors the current annual demand for non-timber wood fibre is estimated at around 1.4 million odt. The growing potential demand from bioenergy will increase the total annual non-timber wood demand to up to 2.2 million odt or more by 2017 before falling back between 2032 and 2036. However there is a degree of uncertainty associated with such estimates, which represents an estimate at the higher end of the scale.

After accounting for other uses, the remaining potential net availability of non-timber wood fibre is around 785,000 odt/yr currently, assuming all the identified resources can be harvested and collected. In the worst case scenario, rapid expansion in the bioenergy sector could constrain availability to around 74,000 odt/yr until post 2020 (i.e. in the medium term) and may cause problems if harvest residues are not effectively mobilised. Increasing net availability is predicated on increased timber processing, leading to a return to at least current estimates of net availability (i.e. up to 790,000 tonnes) post 2032.

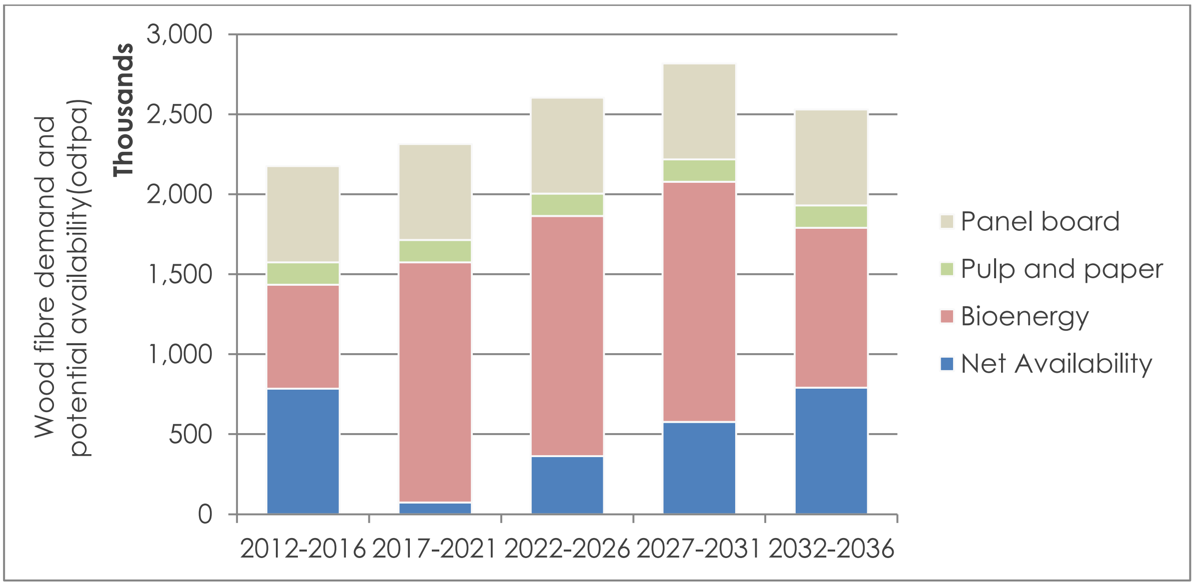


Figure 3. Estimated use of non-timber wood fibre resources by existing industries and anticipated net availability for other uses (assuming all planned biomass plants >5MW are commissioned)

This assessment assumes that all enterprises will be able to source wood exclusively. The actual resource available to new uses such as biotechology applications may depend on the ability to outbid other existing uses.

E4tech in a parallel study[5] examined the net availability of a wide range of woody biomass resources for biorefinery applications in Scotland. After the estimated demand from the panel board, pulp and paper and bioenergy was subtracted from the total supply of wood waste, energy crops, forest residues and co-products (taking account of an updated 50 year harvest forecast by the Forestry Commission) net availability was estimated at around 615,000 odt per year (lower than that estimated by NNFCC, indicating uncertainties in some of the underlying data), potentially decreasing to 364,000 odt in 2030 depending on the degree of take up in

[5] Biorefining in Scotland Research Project (Nov 2014), E4tech Ltd. Report for Scottish Enterprise

the heat sector. The differences in future resource predictions reflect uncertainty in uptake in other sectors, particularly in the bioenergy sector, though this would be constrained if higher value outputs were developed, as the ability to pay by renewable heat applications is capped by support payments.

3 The Scottish chemicals and biotechnology sector

The ability to extract, process and refine materials from the Scottish forest resource, and the ability to further exploit these materials to retain added value in the Scottish economy is dependent on the presence of a strong and adaptable chemicals and chemical engineering capability.

An analysis of the Scottish chemicals sector is provided in the Annex Report (Annex II) which draws heavily on previous work by Chemical Sciences Scotland. In summary the findings of the analysis indicate:

- Bulk organic chemicals production is fiercely competitive and represents a declining market in the UK, but it is an area to which Scotland is linked through its association with interests in North Sea oil refining
- Scotland has a diversified range of speciality product companies, producing added value materials, with clusters in the manufacturing of surface coatings, mastics and rubber, inks, pharmaceuticals, personal care and cleaning agents
- Scotland hosts a number of major chemical companies, but with no head office, there is limited ability for autonomous decision making, this is bolstered by a wide range of SME's
- The speciality chemical companies tend to be foreign-owned and/or represent niche or specialist manufacturing sites with little scope for diversification, but working at the high value end of the market
- The pharmaceutical and fine chemicals sector represents a number of SME's and spin outs, but it faces similar issues to the speciality chemicals sector
- The sector as a whole shows little interaction and is fragmented in its activities and representation

Despite such issues, Scotland possesses a number of chemical industry clusters such as that typified by Grangemouth. Scotland has existing commercial interests in the biofuel sector, but most companies currently working with bio-based feedstocks tend to be working with relatively simple plant extracts in the personal care or pharmaceutical sectors. Only one company was identified as working with chemicals extracted from the forestry sector.

The pulp and paper sector has gradually declined and moved away from virgin wood pulp. There are no chemical pulping mills in Scotland that would otherwise provide additional opportunities to exploit added value products from wood fibre.

There appears to have been relatively little interaction to date between the Scottish forest and chemicals sector, and little experience in using biomass derived chemicals. This would need significant effort to address and build new working relationships.

3.1 The existing industrial biotechnology sector

Work by Life Science Scotland, identified 43 Scottish-based companies with interests in the industrial biotechnology sector, review of this identified small clusters of company interests in the healthcare and pharmaceutical sectors. However many of these represent 'facilitating' or equipment companies.

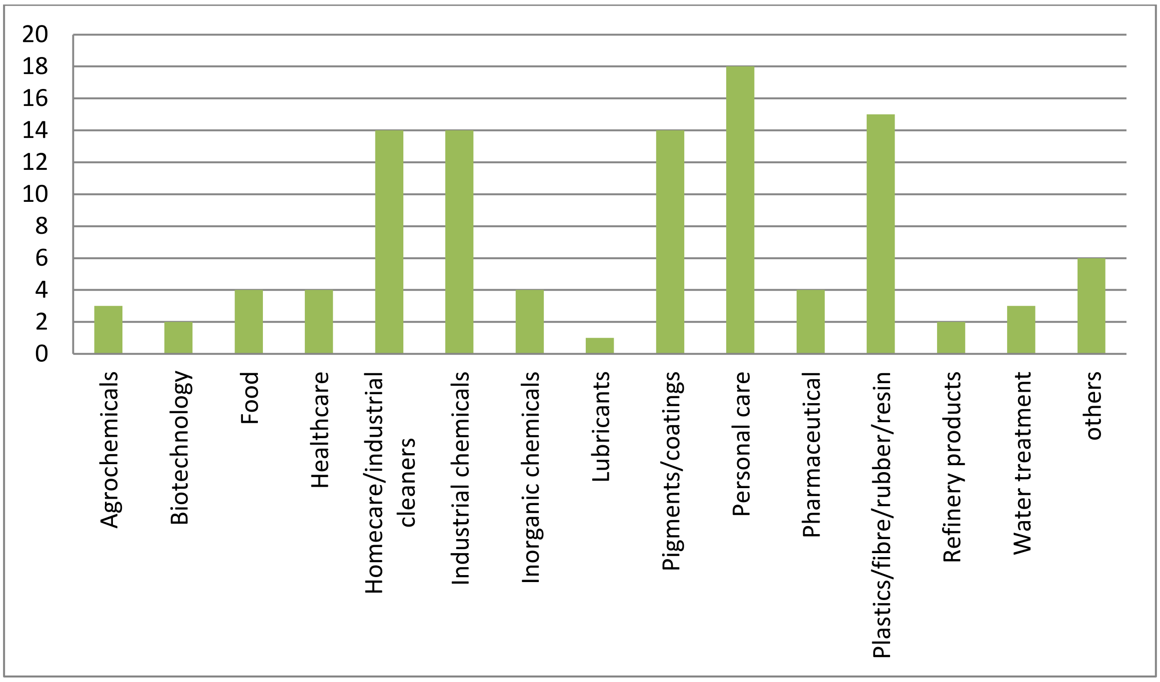


Figure 4. Clustering of company interests amongst those identified by Life Sciences Scotland as having an interest in industrial biotechnology

Again, with the exception of one company involved in the wood supply chain, none of the identified companies currently has specific interests in the forest sector, but several demonstrate expertise in fermentation technologies and equipment manufacture that would be of relevance to the development of a forest based biotechnology sector.

This indicates that any large scale bio-based chemical development would be starting from a very low level of existing industry knowledge and expertise which could hamper development. However there are important clusters of experience in industrial fermentation that could be drawn upon to assist any such development.

While much of the technology and IP development in industrial biotechnology relies on academics and small spin out companies, the input of major chemical companies is required to lead and drive innovative developments, given the risks and investment in scale-up and testing required. Much large-scale bio-based chemical and material development to date has been borne on the back of food (starch and sugar) processing operations or chemical companies looking to provide biodegradable polymers in product portfolios to address issues in the packaging sector. In the forest sector, biobased chemical developments by forest and paper companies in Europe such as UPM have developed from their integrated chemical pulp and paper mill interests.

SME's in the sector have a role to play in developing potential niche products from the forest sector, developing technologies and approaches that can be taken on and scaled-up by others once concepts are proven. In other cases there may be small scale applications that can be exploited at a scale that suits the Scottish chemical and industrial biotechnology sectors allowing gradual development and expansion.

4 The Scottish research sector

4.1 Academic research centres

Scotland has a high quality and diverse University and Research Centre base with a strong base in the chemical, chemical engineering and life science sectors. There is also an extensive range of underpinning knowledge in areas relevant to the development of biobased chemicals and materials from Scottish forestry.

However, only one institute focuses exclusively on the forestry sector (Forest Products Research Institute), with objectives that parallel those looking to exploit the forest wood fibre resource. Other research establishments work in areas of significant relvance to the transformation and utilisation of forest biomass including those in Table 2.

There are a number of additional research facilities (See Annex Report – Annex III) that have expertise in forestry management, synthetic and cell biology, catalysis, biofuels, chemical processing and process management that would also be relevant to the objective of adding value to Scottish Forestry but where this does not yet feature as a prominent objective.

Table 2. Research institutes with significant research interests of relevance to non-timber utilisation of wood fibre from forestry

University of Dundee, College of Life Sciences	Involved in development of biofuels and bioenergy generation
The Biofuel Research Centre, Edinburgh Napier University	Development of biofuels from renewable, sustainable sources
Forest Products Research Institute, Edinburgh Napier University	Transformation of forest resources into high value products
Chemical Engineering, Strathclyde University	Design of advanced chemical reactors
Institute of Chemical Sciences, School of Engineering and Physical Sciences, Heriot-Watt University	Chemical synthesis and cell biology
Institute for Innovation, Design & Sustainability (IDEAS), Robert Gordon University	Industry-relevant novel technologies for renewable energy and materials, and novel reactor design
Institute of Agronomy, Orkney College UHI	Development of plants and plant-based products
School of Engineering, Systems, Power and Energy, University of Glasgow	Energy engineering research, gasification, cell engineering, synthetic cells and systems to provide new biological functions
SynthSys (formerly CSBE), The University of Edinburgh, Heriot-Watt University and BioSS	Systems and Synthetic Biology. Combining theory and informatics with molecular biology to understand and re-design biochemical systems

4.2 Other research clusters and partnerships

Partnering and other initiatives have led to the development of academic and acedemic/industry partnerships to address specific issues or development needs. A number of these have relevance in exploiting biological resources including those listed in Table 3.

There are a number of additional initiatives (See Annex Report, Annex III) that would also have some relevance to the objective of adding value to Scottish Forestry but this does not yet feature as a prominent objective.

The analysis of existing academic research interests and other research partnerships highlights that while there is a significant broad interest in chemicals and biotechnology, where biomass is concerned, interests tend to be focussed on energetic applications. Very few research institutes and research centres appear to have focussed on forestry as a resource. However, there are a wide range of research interests in the biotechnology sector and others with interests in thermochemical transformations that could be well positioned to exploit and focus on the forest resource given sufficient incentive or drivers to devote attention to this.

Table 3. Research partnerships and initiatives with interests or expertise of relevance to non-timber utilisation of wood fibre from forestry

Scottish Network for Combustion & Gasification Engineering (CombGEN), School of Engineering of University of Glasgow	Development of computational tools to optimise the processes of combustion and gasification of various sources of fuel energy, including biomass
Environmental Research Institute (ERI)	Chemical screening of native species, Metabolomics - Analysis of products for key chemical and biochemical characteristics. Biofuels - chemical, biological and physical specification of feedstocks, products and wastes.
EaStCHEM	enzymology, biologically targeted synthesis. heterogeneous catalysis and molecular synthesis
WestCHEM	Catalysis & Synthesis, Chemical Biology, Synthetic Biology, Complex Chemical Systems, Nanoscience & Materials Chemistry
Manufacturing and Materials , Edinburgh Research Partnership in Engineering, (ERPE)	Synthetic biology and industrial biotechnology, nanomaterials, and polymers/polymer composites. Optimising chemical manufacturing
Scottish Biofuel Programme	Biobutanol, bioethanol, wastes to energy applications
IBioIC – industrial biotechnology centre for commercialisation of high-value manufacturing in the life science and chemistry-using sectors	Sustainable feedstocks (including unconventional gases), enzymes and biocatalysis/ biotransformation, cell factory construction and process physiology, downstream processing, integrated bioprocessing.
Edinburgh Genome Foundry, University of Edinburgh	Synthetic biology – design, construction and validation of novel gene constructs to provide new biologically-based devices and systems, and redesigning existing biological systems for useful purposes.

5 Wood composition

Wood is primarily comprised of cellulose, hemicelluloses and lignin along with a small amount of 'extractives'

Table 4. Typical composition of stemwood

	Cellulose	Hemicellulose	Lignin
Softwood	40-45%	25-30%	25-35%
Temperate hardwood	40-50%	25-30%	20-25%

While there is generally little difference in the major cellulose and hemicellulose components between hardwoods and softwoods, there is a difference in hemicellulose composition.

Cellulose is a linear glucose (C6) polymer while hemi-celulose is a general term covering polysaccharides with a mix of C6 and C5 & C6 sugar constituents. The constituent sugars in softwoods are typically present in the order; mannose (C6), xylose (C5), glucose (C6), galactose (C6) and arabinose (C5).

Hardwoods tend to contain higher levels of xylans (polysaccharides containing xylose) than softwoods. The xylan in hardwoods is also less branched and less acidic in nature. The xylan content of softwoods such as Spruce species and Scotts Pine is typically around 7% but this can rise to 20% or more in hardwoods like birch and can reach 35% in some birch species. Hence these species are preferred comercially where xylose is the target.

The different hemicellulose polysaccharide configurations in different species can result in different hydrolysis (breakdown) rates resulting in different sugar yields for the same extraction processes and process conditions.

Lignin is a complex polymer containing aromatic alcohols and is very heterogeneous in nature. The overall lignin content of softwood is generally lower than that of hardwood. The constituent lignin alcohols (lignols); p-coumaryl, coniferyl, and sinapyl are incorporated into lignin in the form of phenylpropanoids; (p-hydroxyphenyl, guaiacyl, and syringyl respectively). Again there are differences in the ratio of aromatic alcohols that predominate in soft and hardwood lignin. Guaiacyl tends to dominate softwood lignin while a mixture of guaiacyl and syringyl forms dominate hardwood lignin. Due to the complexity of lignin, its main commercial uses tend to be in relatively unmodified forms, or it's simply burnt for energy.

Extractives are a very wide range of diverse chemical substances concentrated in the bark, needles and in the sapwood. Typically they account for 2-3% of wood compostion. These constituents are phenolics, fats, waxes, terpenes and terpenoids and aliphatic alcohols in a wide variety of forms. The main commercial interests are resins (a source of natural turpentine) and tannins. Most of the opportunites link to processors looking to add value to wood-pulping operations.

Wood provides an abundant source of carbon for conversion into many different chemicals and materials. This can be exploited most simply by using thermochemical technologies to convert wood to syngas (mainly CO and H_2), or alternatively by breaking wood down into its constituent parts and individual sugar monomers as part of a 'biorefinery' approach. These processes are detailed below.

6 Biorefinery definitions

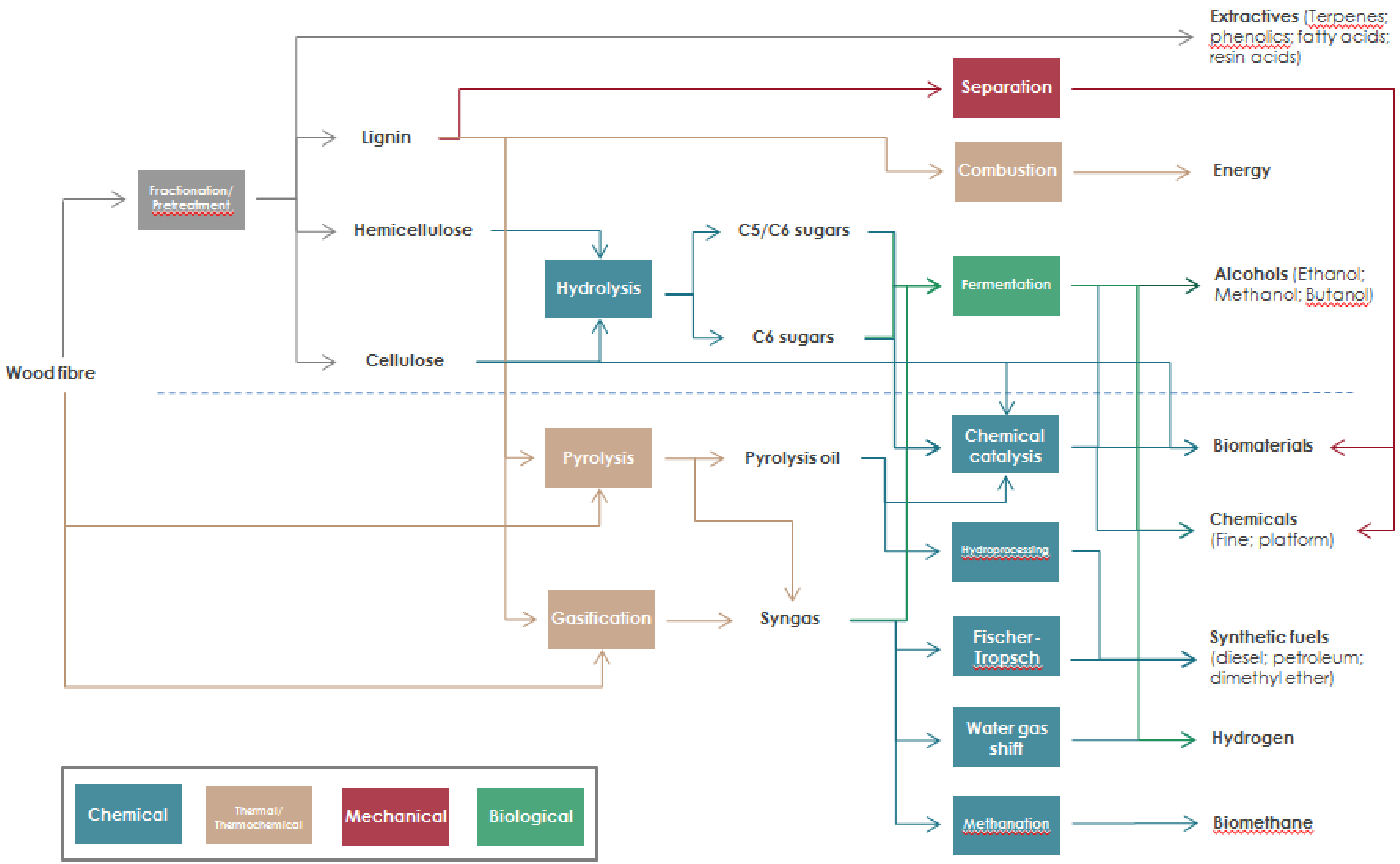
Production of bio-based chemicals through an integrated biorefinery processes is usually more cost-efficient and offers additional market opportunities. This mirrors the approaches adopted in the fossil-fuel sector; refining and fractionating fossil feestocks into a wide-ranging palate of materials for different market sectors.

There are a number of different potental pathways though which forest biomass could be directed to deliver value-added chemical and material products, see Figure 5.

The available options can be grouped into defined biorefinery pathways to aid discussion and analysis. In this case we use the relevant biorefinery classifications defined by IEA Task 42 namely;

- The '**forest-based biorefinery**' – exploiting forest biomass for simultaneous production of pulp (paper) and chemicals, reflecting traditional wood processing practices.
- The '**thermochemical biorefinery**', and in this case the '**syngas platform**', where biomass is subject to high pressure and extreme heat in a gasifier, where it is combusted in a low oxygen environment to produce syngas which is then cleaned and modified using biological or catalytic processes to produce fuels, alcohols or a range of base chemicals (ethylene, propylene, butadiene).
- The '**sugar platform**' – fractionation of biomass by physical, chemical and biological means into its main structural components and conversion of these into individual sugar monomers to serve as fermentation or chemical feedstocks, with residual lignin used as an intermediary for chemical feedstocks.

Figure 5. Possible pathways to exploit added value products from wood



7 Future opportunities for the forest-based biorefinery

The two most commonly used wood fibre fractionation technologies are the Kraft and sulfite chemical pulping processes, both widely utilised by the pulp and paper industry. While mechanical pulping is also widely used, the resultant product stream is not as refined.

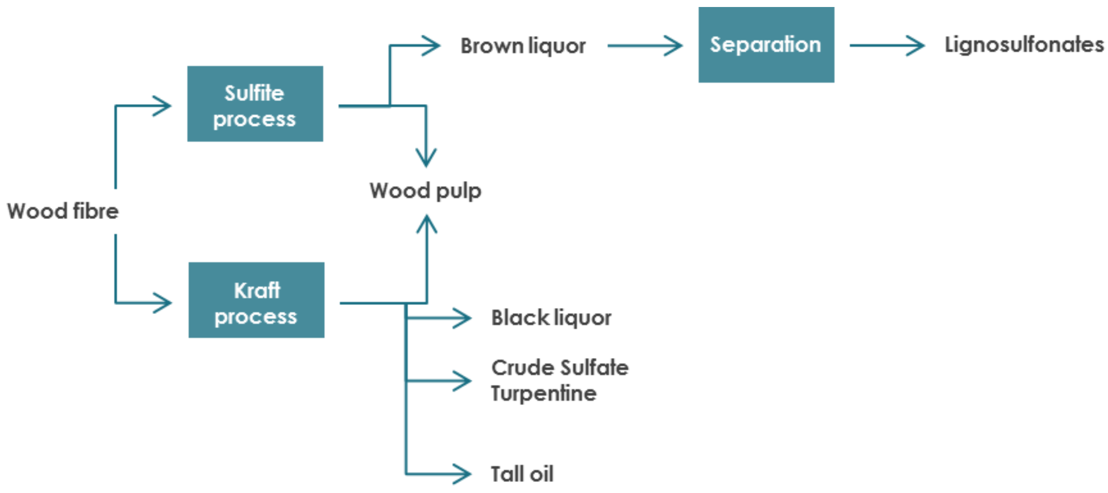


Figure 6. Product streams from Kraft and Sulphite pulping processes

7.1 Sulphite process

The sulfite process involves the chemical degradation of lignocellulose using bisulphite under acidic conditions. The technology is especially suited to producing 'dissolving pulp', with a very high cellulose content (>90%) which can be used for the manufacture of cellulose acetate and cellulose ethers, both of which have a variety of commercial applications. Other applications include cellophane and viscose fibres (e.g. textile fibres Modal and Lyocell). The wood pulp can also be hydrolysed to produce fermentable sugars

Brown liquor, containing residual organic compounds and chemicals, is produced as a by-product. The liquor contains lignosulfonates which have commercial applications as a dispersant or binder in construction, mining and agricultural industries or it can be used as a feedstock to produce vanillin. The liquor is most commonly combusted in a recovery boiler to generate energy.

7.2 Kraft process

The Kraft process is by far the most commonly used method of wood fibre fractionation. The process is also better suited to treatment of resinous softwood species as extractives can be effectively removed from the cellulose and lignin product streams. However, the process is not as well suited to producing dissolving pulp.

The Kraft process involves the steam treatment of wood fibre, followed by cooking with sodium sulfide in alkaline conditions at high pressure. In addition to the wood pulp, the process also produces by-products of crude sulphate turpentine (CST) and tall oil, both of which contain extractives. CST predominantly contains terpenoids while tall oil contains rosin, fatty acids, sterols and lignin soaps.

Black liquor, similar to brown liquor in the sulfite process, is also produced by the process. This contains much of the lignin and is typically utilised to generate energy in the processing plant.

7.3 Market opportunity for the existing wood processing industry

The sulfite process, with higher purity cellulose ouput, is more suited to integration with downstream industrial biotechnology interest than the Kraft process. A wide range of products can be manufactured from sulphite pulping products.

Viscose wood pulp demand, estimated at 4.3 million tonnes, is responsible for around 75% of the global dissolving pulp market. The market is growing at a steady rate of around 11%, although supply continues to outstrip demand.

Speciality wood pulp grades account for the remaining dissolving pulp market, with demand remaining relatively stable. Global demand for cellulose acetate is estimated at around 700,000 tonnes per year, with an annual market growth of around 1% . Acetate tow, used in cigarette filters, is the main application. The current market for cellulose ethers - used in emulsifier and adhesive applications - is around 350,000 tonnes with annual growth of around 2-3%.

Demand for lignosulfonates is currently estimated at around 1-1.5 million tonnes per year, with the majority serving medium value applications such as concrete admixtures, animal feed binders and ceramics . The market for lignosulfonates is expected to grow by around 2-3% in the near future.

These pulp and niche chemical markets are currently stable and well-served, with many markets oversupplied. Additional demand resulting from any unexpected market growth could therefore be expected to be met through existing assets at least in the short-term. Annual supply of lignosulfonates could be increased to up to four million tonnes by fully utilising the capacity of existing facilities. In the absence of more profitable markets, lignin streams are comonly used in energy recovery systems to provide heat and power.

The pulp and paper industry in Scotland currently relies on imported and recycled pulp. Only one integrated pulp and paper mill remains, operated by UPM. This plant uses locally-sourced wood fibre and mechanical pulping rather then chemical pulping. It would be a significant expense to consider retro-fitting the facility to serve chemical markets via sufite pulping, which is much more energy intensive.

7.4 Emerging opportunities for cellulose – Nanocellulose

There is growing interest in the emergence of specialised cellulose applications. Nanocellulose is a material composed of nanoscopic cellulose fibrils. The material exhibits properties similar to many gels, demonstrating high viscosity when static and low viscosity when agitated. Nanocellulose also has mechanical properties similar to Kevlar and glass fibre, and interesting gas barrier properties. A wide range of potential applications are available including:

- non-caloric stabilisers or gellants in food ingredients
- reinforcing agents in paper materials, plastics or cement
- emulsifiers or dispersants in personal care products, paints and coatings

High-performance composites, packaging, electronics and medical devices are likely to provide the key markets for nanocellulose in the future, although the material could penetrate a wide variety of other niche markets. The cost of production will be the main factor in determining initial market applications.

Market growth of nanocellulose is very uncertain, with product development still in its early phases. Global production estimates vary hugely, with those for 2014 ranging from 5-240 tpa and those for 2017 ranging from 20-780 tpa[6]. There a numerous multi-billion dollar markets potentially available to nanocellulose. However, there remain many challenges, not least the cost of production, before an established market is developed. A pure source of cellulose will also be required and this could favour sulphite processes.

Building an industrial sector in Scotland focused on nanocellulose development is a high risk strategy that would require coordinated development with industry and research institutes for the purposes of product development and scale-up demonstration.

7.5 Developing technologies

A number of companies are now examining opportunities to develop forest-based biorefineries that are moving away from the traditional wood product markets.

Lignol Innovations is a Canadian company which has developed a biorefining technology for production of fuel-grade ethanol and biochemicals from wood. It employs an ethanol-based organosolv step to separate lignin, hemicellulose components and extractives from the cellulosic fraction of woody biomass. The cellulosic fraction can be used to generate high yields of glucose which can then be readily converted to ethanol or other sugar platform chemicals. The liquor from

[6] ArboraNano. 2012. The economic impact of nanocellulose.

the organosolv step is processed to recover lignin, furfural, xylose, acetic acid, and a lipophylic extractives fraction. Lignol anticipates that plants requiring as little as 100 metric tonnes per day (around 35,000 tpa) of dry woody biomass could be economic with multiple product outputs. The demonstration plant was supported by a $30 million investment, but it appears it's proving difficult to secure investment to develop a commercial scale plant in the US or Canada.

Borregaard has invested £14 million in a demonstration plant for its BALI process, a modified sulphite pulping process, designed to produce sugar solutions (via an enzymic hydrolysis step) and lignosulfonates as by-products. This has been shown to work with softwood feedstocks which can otherwise prove difficult to process. Borregarrd is now looking for investment to help scale up to full commercial scale, with interest in linking the process to bio-butanol production.

These developments still have to prove themselves commercially at scale, and the investment risks are high. It is difficult to estimate development timescale or scalability of projects to meet Scotland's needs at this time, so a watching brief is required. Scotland has research interests in this sector through the Forest Products Research Institute, based at Edinburgh Napier University.

7.6 Summary conclusions

The technologies employed in Scotland's remaining integrated pulp and paper mill are not suited to support the development of a bio-based chemicals sector.

Traditional markets for Kraft and Sulphite pulp products are already well served and show only limited growth potential.

Assuming UPM were interested, significant investment would be required to re-position the existing UPM facility towards new and novel chemical production and the technical and commercial viability of this approach has yet to be proven at scale. However, the potential for conversion to chemical pulping, or establishment of a new plant should be examined by working with the existing interests in the sector and examining opportunities for inward investment and co-operation.

7.7 SWOT analysis – expanding traditional wood processing industries

Strengths	**Weaknesses**
Existing wood pulping experience in Scotland and existing plant. Existing pulping plant utilises local wood fuels to service its traditional markets – which also helps to develop wood supply markets. Diverting current industry outputs to deliver into to high value chemical applications would not impact on current wood demand unless plant capacity was expanded (i.e. not limited by anticipated wood resource). Research interests in this sector through the Forest Products Research Institute, based at Edinburgh Napier University	Only mechanical pulping technology present in Scotland with limited capacity to expand to new markets. Speciality cellulose and fibre markets are relatively stable and growing only slowly. Speciality cellulose derivatives markets are tied to developments with key clients, makes new entry difficult. Likely to be difficult to raise finance to compete in traditional market sectors.
Opportunities	**Threats**
Potential for expanding exisiting wood pulping plant to chemical pulping, or to develop new plant with suitable support and investment if UPM or other interests are keen to explore this avenue. Nanocellulose offers potential new and expanding market opportunity that could be linked to food, chemicals and electronics sectors in Scotland. Scale of opportunity is difficult to estimate. Existing Scottish chemical interest in the surface coatings and cleaning chemicals sector could have an interest in wood-derived extractives – fragrances, terpene solvents and resins, produced as by-products of pulp production. Industrial development is currently focussing on wood to fuel and chemical technologies based on demonstration projects, if these projects can be scaled commercially this could offer an incentive for new investment in the sector.	Existing wood chemical derivative markets are well served by existing global players (and oversupplied in some cases – e.g. lignosulfonates). Most recent investments are currently occurring in other areas of Europe (Finland and France). Only 1 (large) supplier of wood lignin derived vanillin which has saturated the available limited market. Lignosulphonate can be used as fuel in processing plant – which sets a nominal energy value on the by-product.

8 Thermochemical biorefinery – syngas platform

Gasification is a thermal conversion technology. The feedstock is heated to high temperatures (around 700°C to 1500 °C) in a restricted oxygen environment, or in the presence of steam to deliver a completely gaseous product stream (synthesis gas or syngas) which is primarily a mix of hydrogen and carbon monoxide. The syngas can be cleaned and burned to produce electricity or further processed to manufacture chemicals, liquid fuels, substitute natural gas (SNG), or hydrogen. Different processing conditions lead to different gas mixtures and contaminant levels. Use of higher temperatures in gasification technologies usually results in improved yields of hydrogen and carbon monoxide in the syngas, enhancing the suitability of the gas for use in downstream chemical processing technologies. The technology is widely used in the fossil fuel sector (on coal, gas and petroleum), but has more recently been used with biomass feedstocks.

Softwood fibre undergoes gasification far more rapidly than hardwood, resulting in greater production of soot-forming particles in the syngas due to incomplete combustion[7]. This issue is further exacerbated by the high level of extractives in softwoods. These particles can remain in the combustion chamber or heat exchanger as soot, tar or creosote, causing lasting damage to the gasification unit. Therefore, hardwood is typically better suited to gasification than softwood.

The crude syngas produced from most gasification processes requires significant 'conditioning' to meet the specification for catalytic synthesis of fuels or chemicals or for use in fermentation processes. Gas clean-up comprises cracking, reforming or removal of tars and hydrocarbon gases, dust and particle filtering, scrubbing or catalytic absorption of contaminants such as sulphur, nitrogen, fluoride compounds and carbon dioxide, and adjustment of H_2 to CO ratio via a Water-Gas Shift reaction. The difficulties and additional costs encountered in gas clean up and achieving the right H_2 to CO ratio are evident in the lack of commercial scale examples and many demonstration projects have struggled. No biomass gasification to chemicals plants are planned for the UK currently.

8.1 Thermochemical plants

Biomass gasification plants are much smaller (up to 160 MW_{th} currently) than the typical coal or petroleum coke gasification plants used in the power, chemical, fertilizer and refining industries which can range from a few to several thousand MW_{th} in terms of syngas output. This is due to the amount of material that has to be collected. Most existing plants, including the largest biomass and waste wood fired plants focus on heat and power production, as there is less need to invest in gas clean up. A few plants are targeting biofuel (Fischer-Tropsch diesel), methanol, or methane (SNG) production, but these are at a demonstration scale currently. World-scale plants would be of the order of 100kt/yr of advanced fuel output.

Capex estimates for a 160 MW biomass to methanol (120-130 kt/yr) gasification plant are of the order of £100-150m based on a Choren Industries study for NEPIC[8] using pre-existing facilities in Teesside. Without this, costs would be higher still.

Large biomass gasification plants have been established in Finland, due to the large forest resource available and associated industries. Tall oil from papermaking is the primary feedstock. UPM with technology partner Haldor Topsøe has built the Lappeenranta biorefinery (tall oil to FT Diesel plant) at a cost of 150 Million€, designed to produce 100,000 tpa of diesel fuel. It is expected to start production

[7] Ecolink Solutions. ABCAT heating test with softwood and native hardwood.
[8] http://www.nebr.co.uk/_cmslibrary/files/gasification_of_biomass.pdf

during 2014. UPM also has a wood–fed gasification plant at demonstration stage. UPM has recently received €170 million for a wood-fed 100 kt BTL project (biodiesel and naptha) to be built in Strasbourg, alongside its existing pulp and paper facilities. A similar scale plant is in development for Ajos BTI in Finland.

Other pilot biomass to liquid fuel (BTL) demonstration plants in development include, BioTFueL in France (€113 million) (Uhde technology), Bioliq plant at Karlsrhue and the CEA Bure Saudron Pilot plant, France. In contrast NSE Biofuels Oy (Finland) and Choren's (Friberg, Germany) projects have closed after failing to secure further finance for development, demonstrating the difficult financial situation in which such innovative technologies are developing where investment risks are relatively high.

Scotland has some expertise in this sector with industrial syngas to liquid reactor technology supply companies (Gas2) linked to Robert Gordon University and the Wilton Centre (Cleveland) and gasification interests at the School of Engineering, University of Glasgow. These are brought together under the CombGEN network which works to address combustion and gasification engineering challenges through partnership activities.

8.2 Thermochemical and biological fermentation plants

In recent developments, Ineos Bio have developed a bacterial fermentation technology to convert syngas to ethanol. Currently this is running at pilot plant scale (24kt/yr) in the US (with a $130 million investment). The primary feedstock is the bio-based component of wastes (yard waste), but wood waste and forest harvest residues (oak, pine, pallet wood waste) have also apparently been successfully converted to ethanol with this patented technology, though more evidence on this is required.

The biofuels market has been the key driver of this development and policy uncertainty in the European and UK situation has meant such investments have not been placed in the UK, despite early intentions to site plants in Teesside by Ineos.

Scale-up and economic performance again needs to be verified and a world scale plant would be of the order of 100ktpa.

While Scotland has existing interests in syngas and gasification, as well as in fermentation systems it is not clear that there has been any concerted efforts to link these different interest groups to pursue this developing sector.

8.3 Feedstock demand for thermochemical pathways

The feedstock demand of world scale plants serving the fuel sector is significant (reflecting low margin, high volume products) and would be limited by domestic wood supplies in the short to medium term. The scalability of syngas plants requires further examination to determine whether smaller plants requiring less feedstock could be directed towards provision of chemicals via IB approaches.

Table 5. Wood feedstock demand for typical world-scale thermochemical plants

Biomass fractionation process	World scale plant output (kt/yr)	Feedstock demand odkt/yr	Comment on feedstock demand
Thermochemical to FT fuel	100	460,000	Could only be supported domestically post 2027
Thermochem and fermentation to ethanol	100	304,000 – 405,000	Could only be supported domestically post 2022

8.4 SWOT analysis – syngas platform

Strengths	**Weaknesses**
Existing research and some industry expertise in fossil gasification and syngas sectors that could be quickly re-focussed Existing academic and industry partnerships in place Technology is much more feedstock tollerant than biochemical pathways	Very high wood feedstock demand of world scale plants exceeds Scottish net availability in short to medium term (but not yet clear if this could be downscaled for chemicals production). No previous experience of working at this scale of wood supply. Resinous softwoods typical of Scotish forest sector may require more specialist care to reduce fouling and ash problems. Focus on high value chemicals requires expensive syngas clean up adding to CAPEX cost
Opportunities	**Threats**
Moving from biofuels to biochemicals as technology advances significantly improves the potential returns and reduces risks associated with policy changes potentially affecting biofuel markets Ready market opportunity in biofuels sector that could be switched to chemicals in part or whole as relevant technology comes onstream Potential to link to ethylene production (from bio ethanol pathway) to support bioPE production	Technology is still at a demonstration stage and securing investment will be difficult without further incentives Would tie Scotland into this single technology route due to feedstock constraints Biofuel market sector is policy dependant which is a risk for investment

9 Sugar Platform

9.1 Technology status for wood sugars

Sugars are an important feedstock in the chemicals sector, both as raw feedstock for chemical transformation and in providing the energy and feedstock carbon for fermentation processes. The latter opens up an extensive range of possible chemical and biological transformational pathways to generate a myriad of useful compounds and materials from wood-derived sugars. The drive to develop more sustainable and cheaper sources of sugars for biofuel production has focussed interest on accessing sugars from biomass.

Biomass is recalcitrant and currently needs physical and chemical treatments to separate its component materials. The kraft, sulfite pulping and organosolve methods have already been described.

A number of other pre-treatments have developed for use in biofuel pilot plants including;

- Dilute Acid Hydrolysis – biomass is steeped in hot sulphuric acid to free the cellulose and hemicellulose. The resulting cellulose is broken down using cellulase enzymes and the hemicellulose is hydrolysed by the acid into to its constituent sugars.
- Steam explosion – where biomass is subject to steam under pressure and the pressure is rapidly released to burst open the biomass structure.
- Ammonia fibre expansion (AFEX) - liquid ammonia is added to biomass under moderate temperature (70-120C) and pressure (7-25 Bar) then the pressure is rapidly released. This process frees the cellulose, hydrolyses hemicellulose, removes and depolymerises lignin.

Degradation products from such pre-treatments (furfural and lignin degradation products) can inhibit subsequent hydrolysis and fermentation processes. Most pre-treatment processes are less effective when used on high-lignin feedstocks, such as forest biomass. Organosolv and sulfite pre-treatment are the only two processes that can achieve over 90% cellulose conversion for forest biomass, especially when using softwood species. The sulfite process is the most energy efficient and robust process, with very low production of fermentation inhibitors.

Currently there are many pilot and demonstration facilities operating on a small scale. The IEA Identifies 43 biochemical fuel demonstration or operational cellulosic plants[9]. However, there is no commercial plant currently utilising wood biomass, though a few small demonstration projects are utilising woody biomass and several are 'planned'.

The cost of cellulosic ethanol is currently not on a par with that of sugar and starch-derived ethanol, but this reflects the different levels of technical development and refinement to date. Beta renewables has recently opened the world's first commercial-scale cellulosic ethanol facility in Crescentino, Italy. This is a $350 million

[9] Status of advanced biofuels demonstration facilities in 2012. A report to IEA Bioenergy Task 39. http://demoplants.bioenergy2020.eu/files/Demoplants_Report_Final.pdf

joint venture project, producing 60ktpa of ethanol, primarily from agricultural wastes. It is anticipated that a next generation commercial plant of c150kt ethanol would require around £200m of investment.

Chemical and biological treatment of wood for production of chemicals is therefore at a similar early stage of development to thermochemical options, but in this case wood-feedstocks appear to present additional problems to those of other biomass feedstocks. It may be that wood feedstocks are more suited to specific processes such as the organosolve process, but this needs further evaluation and practical assessment in current pilot plants to identify the most suitable treatment processes.

9.2 Potential chemical opportunities

The development of bioethanol markets, to provide low carbon fuels, has created a 81 billion litre global market and focussed interest on the opportunities available to develop other higher value uses for biomass resources in the chemicals sector. Excluding biofuels, current global bio-based chemical and polymer production is estimated at around 50 million tonnes[10], which includes traditional timber products. In contrast, global petrochemical production of chemicals and polymers is estimated at around 330 million tonnes. This shows that there is significant headroom for growth through where biobased materials offer an advantage.

The range of potential chemicals of interest includes those already used by the chemicals industry and therefore with demonstrable market demand, as well as new structures formed or derived from bio-based chemical building blocks. However, the market for biobased building blocks is still relatively infant, with only a few fully commercial examples to date. In contrast to the biofuels sector, there are no specific policy mandates to encourage uptake. Biobased chemicals therefore have to compete in the chemicals market primarily on their own merits.

Replacing existing fossil-derived materials on a like-for-like basis means that bio-based products can access markets very rapidly and at scale by integrating with existing infrastructure. Equally, the bio-based alternative must be available at competitive cost.

A good example is the development of polyethylene (PE) derived from bio-ethanol. In this case increasing fossil feedstock price and low sugar price means that bio-PE has been commercialised at large scale and the 'green credentials' offered by bio-PE are seen to be worth a premium by end users, that can be worth 30% or more depending on the value proposition of the end market use.

10 Raschka A. and Carus, M. (2012) Industrial material use of biomass. Basic data for Germany, Europe and the World. http://www.nova-institut.de/bio/ 28 pages.

Industrial biotechnology can offer the potential to reduce chemical processing steps or reduce wastes that would be otherwise costly to deal with, that overall result in reductions in production costs. For example xylitol production from xylose requires high temperature and pressures, whereas microbial derivation from fermentation of lignocellulose or hemicellulose could significantly reduce processing energy requirements and therefore costs of production.

Some bio-based materials may offer new functionality or characters at an affordable cost. For example the fermentation product lactic acid is used to produce the bio-degradable polymer poly lactic acid (PLA) which is now widely used in packaging applications, replacing fossil-derived polymers.

9.3 Current bio-based chemical markets and industry interest

The key uses, market size and current leading company interest in the key biobased chemical building blocks identified as having some relevance to the Scottish Forest sector are detailed below.

Table 6. Uses, markets and key players for key bio-based chemicals

Chemical and its biological derivation	Uses	Market	Key players
3 Hydroxypropionic acid (3-HP) Fermentation from glucose. Embryonic developing technology.	Important C3 chemical building block. Derivatives include; 1,3-propanediol, acrylic acid and esters, malonic acid, acrylamide and hydroxyamides, acrylonitrile, and ethyl ethoxy propionate (EEP).	Derivative market – of 3.6mt globally, 0.8 mt in W. Europe. UK is a major consumer.	Akzo Nobel is a major butyl acrylate consumer for paints. No UK acrylic production capacity.
n-Butanol Microbial fermentation (Clostridium sp) from sugars (ABE process producing ethanol and acetone as by-products). Mature technology but process yields need improving.	A key building block chemical in the coatings, adhesives and inks market and an intermediate in the global polymers market. Butyl acrylates are widely used as monomers in the production of latex paints, lacquers, enamels. critical intermediate in the production of melamine resins, plasticizers and amines.	3.4 mt global market for conventional butanol. Further 122mt potential in biofuel sector. 0.7mt market in W Europe.	No petrochemical butanol plant in the UK. Interest include Celtic renewables (Scotland), Green Biologics (England). Cathay Industrial Biotech, Solvert, Butalco, Cobalt/Rhodia. Several large producers competing for market share. Akzo also has interest as major butyl acrylate consumer for paints.

Ethanol (cellulosic) Thermal and chemical pre-treatment (to separate major structural components of biomass) followed by enzymatic hydrolysis and fermentation of resulting sugars with enzymes and yeast	Direct transport fuel substitute (as bioethanol) Key bio-based feedstock for bio-polyethylene production	Global bio-fuel market of around 75 mt.	Many commercial operators in play in US and growing in Europe. Well established market with existing supply chains
Glucaric acid Chemical oxidation of glucose with nitric acid (conventional). Microbial fermentation from glucose in development. Early development technology.	Used in polyamides, health supplement (calcium D-glucarate) detergents (replacement for phosphates). Lactone derivatives have solvent applications.	Expensive material currently with limited availability.	Rivertop Renewables have a pilot plant in the US.
Lactic Acid Microbial fermentation from glucose Mature technology – commericalised.	Primarily use in polylactic acid (PLA) polymer (packging materials and fibres), also in personal care and solvent applications. competes with a number of materials with similar properties.	650Kt global market growing at 10%pa. EU demand 25kt/y. PLA growing at 22% pa. Lactic acid solvent market is estimated at 3.6 to 4.5 million tons per year.	Interests include; Purac (Netherlands) (lactic acid lead), Cargill/NatureWorks (US) (Global PLA leader), Galactic/Futerro, Henan, Jindan, BBCA. Teijin Fibres (Japan), Hi Sun (China), Pyramid Bioplastics (Germany) Cellulac (UK & Ireland) Vertec have interest in bioSolvents. Developments focusing on Asia currently.
Levulinic acid Acid catalized dehydration of C6 sugars. Mature technology and high yielding.	Derivatives include; pyrrolidones, lactones and levulinic esters. Candidate for applications in solvents, polyurethanes and thermoplastic. A prime platform chemical for a number of large volume markets.	Only 1 commercial plant (Casserta, Italy) producing 3kt/yr.	Maine BioProducts, Avantium, Segetis, Circa Group, but potential competition from China in a very small market niche.

Methyl methacylate (MMA) Several pathways including: fermentation of glucose to methacrylic acid, itaconic acid or isobutyric acid and onward conversion to MMA, or fermentation direct to MMA. Alternatively via ALPHA technology using bioethylene, biomethanol and CO in 2-stage chemical process. Bio-based methacrylic acid represents developing technology at R&D stage.	used as monomers in a variety of polymers with a broad spectrum of applications - acrylic sheet (perspex), surface coatings, moulding compounds, emulsion polymers). Largest application is transparent sheets of extruded PMMA (Plexi-glass). Around 22% of MMA goes into coatings/paints and 20% into moulding resins (as MBS).	UK is a major MMA market. Global MMA demand is estimated at 2.5 million tons, growing at over 5%pa, and 10% pa in Asia. European consumption is around 825kt, UK around 150kt.	Lucite (UK), is a leading producers (230kta) (Teesside). Has PMMA production site in Lancashire. (Alpha process working at 120kt/y). Also one of the UK's leading acrylic coatings resins suppliers. Five producers dominate West European production: Lucite (UK), Rohm (Germany), Arkema (France & Italy), Repsol (Spain), and BASF (Germany). Lucite/Mitsibushi Rayon and Evonik/Arkema showing interest in bioderived MMA.
Polyethylene (LLDPE) Utilises bio-ethylene derived from bioethanol. Commercialised.	Film packaging materials. Key opportunity currently is for substitution at premium price.	18.4 million tonne global market growing at 7%pa into which bio-LLDPE can substitute. UK uses 900,000 tonnes.	320kt/yr Ineos plant capacity in UK (Grangemouth) (Sole UK producer). Dow, Braskem and Solvey all have sugar to polyethylene projects (Solvay 55 kt/yr PE, Braskem 180kt/yr PE).
Polyethylene (HDPE) Utilises bio-ethylene derived from bioethanol. Commercialised.	Blow, film and injection moulding. Expected to replace polypropylene in injection moulding applications. Key opportunity currently is for substitution at premium price.	29.6 mt global conventional HDPE market showing 2.1% long-term growth. anticipated. 790kt UK market. UK imports 500kt/yr.	Grangemouth (Ineos) capacity now closed. Capacity additions in Western Europe are expected to be moderate. Dow, Braskem and Solvey all have sugar to polyethylene projects (Solvay 55 kt/yr PE, Braskem 180kt/yr PE).

Polyhydroxyalkanoates (PHAs) Microbial fermentation directly from sugars. Mature technology but needs improved efficiency.	wide-ranging group of natural polymers. Can combine to produce copolymers of different properties, e.g. thermoplastics or elastomers. Applications range from blow-moulded products to elastomeric materials used for hot melt adhesives or pressure sensitive adhesives. Other potential uses are non-woven fabrics, films and fibres, and latex coatings. currently widely applied in the medical and pharmaceutical industries due to their biodegradability.	Market for polymers having similar properties to PHAs is around 13.6 million tons. But PHAs seen as relatively expensive currently. Global PHA capacity is around 100-130kt/y.	Most commercial development currently occurring in US. Interests include; Metex (US), Meridian plastics, Tianjin Green Bioscience Co. (China), Mitsubishi Gas Chemical (Japan), PHB Industrial (Brazil). ADM-Metabolix plant (50kt/y) has recently closed.
Sorbitol Chemical reduction (hydrogenation) of glucose. Commercialised mature technology. Fermentation routes in development from sucrose, fructose and glucose to produce sorbitol.	Most uses currently in the food industry as a low calorie sweetener. Derivatives include isosorbide an important monomer used as a co-polymer with PET in plastic bottle production.	500Kt/yr global market. UK market of ca 80kt/y. Identified as potential for growth to over 2 million tonnes by 2018.	Interests include Roquette, ADM (together hold 70% market share). Established and growing market likely to get more competitive as Asia builds more plants.
Succinic acid Fermentation from glucose Commercialised but requires further scaling up	Key derivatives include 1,4, butanediol γ-butyrolactone (GBL) and Tetrahydrofuran (THF). Main use likely to be in Polybutylene succinate (PBS) a biodegradable polymer with 1,4-butanediol (BDO). Main use of GBL (60%) is in production of N-methyl-2-Pyrrolidone (NMP) – used in specialist solvent applications. Most THF (87%) is used in Polytetramethylene Ether Glycol (PTMEG) production for spandex fibre and polyurethane elastomers.	Small amount of succinic production in Wilton, UK. Biosuccinic acid production capacity is currently around 30-50,000t/y. succinic acid derivative market could rise to 245kt/yr. Global GBL market is around 100 kt. European 30 kt/y with growth of 4.4%pa. Global THF consumption is around 342 000 tons, growing at 10-12%pa.	Bio-succinic acid technology owned by several firms, including BioAmber (French), Reverdia (DSM & Roquette)(Netherlands and France) and Myriant, as well as Purac, (Netherlands). GBL - BASF (only commercial producer in Western Europe) with interests expressed by Du Pont, Lonza, Akzo nobel, Lyondell. PTMEG production developing in Asia. Key leading players; BASF, Dairen Chemical Corporation and Invista. Invista consumes PTMEG for Lycra production at Maydown in Northern Ireland (UK's largest consumer).

Xylitol Catalytic hydrogenation of xylose (C5 sugar) from hemicellulose, or extraction from black liquour (direct fermentation route in development). Commercialised and high yielding.	Xylitol is used as a diabetic sweetener.	Global market of 90,000 tpa. Growing demand, 3-fold development projected.	DuPont acquired Danisco, and is the worlds largest producer from hardwood (black liquor from pulping) and waste corn cobs. Other interests; Xylitol Canada. Most Xylitol is produced in China from corn husks (low/zero cost feedstocks).

9.4 World scale plants, feedstock demands and value added

Table 7 provides a summary analysis of typical world scale production plants for the chemicals in question and associated feedstock demands based on product yields from wood feedstocks. Feedstock demand is expressed as a function of the available Scottish net forest biomass resource to identify where feedstock demands could be met domestically from 2017 out to post 2030, and conversely where demand is unlikely to be met.

The value of downstream products was used to generate an indication of the gross value that could be added per tonne of feedstock used, to enable comparison of alternative processing routes and target chemicals. It is difficult to gain reliable information on costs of processing (capital and operating expenditure) particularly as some processes are only embryonic. So, the data provided gives a broad indication of relative added value. Returns would depend on production costs. The data ranges for gross added value also demonstrate that end market application has a very significant impact on product value. Higher value applications tend to require higher chemical purity and typically represent a small or niche part of the available market space.

Table 7. Typical world scale plant size, feedstock demand and value added per tonne of feedstock for sugar-derived chemicals

	World scale plant	Feedstock demand (odt/yr)	feedstock demand as a function of available domestic net forest resource (see note A)				Value added per t wood feedstock, expressed as a multiple of feedstock cost (assumed £50/t @ 30-40% MC) (note b)
			2017-2021	2022-2026	2027-2031	2032-2036	
3 Hydroxypropionic acid (3-HP) **(for acrylic acid prodn)**	50– 100kt	114- 228kt	🔴🔴 🔴🔴🔴	🟢🟢 🟢	🟢🟢🟢 🟢🟢	🟢🟢🟢 🟢🟢	**£11x** (based on acrylic acid price)
n-Butanol	30- 120kt	177- 710kt	🔴🔴🔴 🔴🔴🔴	🟢🟢 🔴🔴	🟢🟢 🔴🔴	🟢🟢🟢 🟢	**£2.2x-£3.4x**
Ethanol	60- 100kt	266- 443kt	🔴🔴🔴 🔴🔴🔴	🔴 🔴	🟢 🟢🟢	🟢 🟢🟢	**£1x-2.25x**
Glucaric acid	27kt	61kt	🟢	🟢🟢🟢	🟢🟢🟢	🟢🟢🟢	**£7.5x-£17x**
Lactic Acid	100kt	228kt	🔴🔴🔴	🟢	🟢🟢	🟢🟢	**£7.5x-£17x** (high end = pharma grade)
Levulinic acid	3kt	9kt	🟢🟢🟢	🟢🟢🟢	🟢🟢🟢	🟢🟢🟢	**£17x-£25x**
Methyl methacrylate (MMA)	120kt	453kt	🔴🔴🔴	🔴	🟢	🟢	**£5x**
Polyethylene (PE)	200– 320kt (Ineos)	1.5mt- 2.4mt	🔴🔴🔴 🔴🔴🔴	🔴🔴🔴 🔴🔴🔴	🔴🔴🔴 🔴🔴🔴	🔴🔴 🔴🔴🔴	**£3.4x**
Polyhydroxyalkanoates	50kt	291kt	🔴🔴🔴	🟢	🟢	🟢🟢	**£7.5x-£25x**
Sorbitol	40- 60kt	82- 124kt	🔴 🔴🔴	🟢🟢🟢 🟢🟢	🟢🟢🟢 🟢🟢🟢	🟢🟢🟢 🟢🟢🟢	**£5x-£11x** (high end = pharma grade)
Succinic acid	65kt	162kt	🔴🔴🔴	🟢🟢	🟢🟢	🟢🟢🟢	**£7.5-£11x**
Xylitol (from sitka)	15- 60kt	0.3- 1.25mt	🔴🔴🔴 🔴🔴🔴	🟢 🔴🔴🔴	🟢 🔴🔴🔴	🟢🟢 🔴🔴	**£2.2x** (**£7.5x** for high C5 Birch sp.)

Note A - key 🔴, 🔴🔴, 🔴🔴🔴 = more than 100%, 150% and 200% of available net resource; 🟢, 🟢🟢, 🟢🟢🟢, 50-100%, ,25-50% and <25% of the available resource

Note B –The product of typical chemical value and ancicipated yield per tonne of feedstock

9.5 Feedstock demand

Until post 2020, except for a few niche market chemicals (levulinic acid and glucaric acid where levels of exploitation are expected to be low) the feedstock demands of typical world-scale production plants for sugar-derived chemicals are unlikely to be able to be met by the estimated availability of Scottish forest and wood processing residues.

Post 2020, the resource available increases, due to predicted increases in timber harvesting rates and an anticipated downturn in demand from the power sector. However, in the worst case scenario where all biomass power plants progress, plants serving global bulk chemical markets with polyethylene or a large-scale butanol plant (i.e. 120kt/yr) are unlikely to be able to be fully resourced from Scottish forest residues. Smaller developments could be accommodated.

Sugar derived chemicals that have high value and high product yields are the most likely to be supported from domestic forest resources in the mid-term, e.g. 3-HP, lactic acid, sorbitol and succinic acid as well as the niche chemicals above. Polyhydroxyalkanoates suffer from relatively low production rates currently and therefore have relatively high feedstock demand.

MMA is a relatively complicated molecule to synthesise, which gives it added financial value, but it suffers from low sugar to product conversion rates leading to high feedstock demand in order to serve large plants in the polymer sector.

Large scale xylitol production is also a heavy user of forest resource reflecting the low concentration of C5 sugars in Sitka spruce. In contrast using birch species with higher C5 sugar concentrations improves product yields and potential financial returns. Currently, xylose is extracted from existing waste streams - processed corn cobs and by-products of wood pulping rather than being targeted as a particular product. This reflects the benefit of adopting a multi-output biorefinery rather than a single chemical approach, in which xylose could be produced alongside other C6-suger derived chemicals providing multiple revenue streams.

9.6 Added value

The ability to exploit added value from wood depends on the market value placed on the end products, and the price of competitor technologies.

The value added to wood feedstocks by bulk chemicals outlets like those of PE and butanol is relatively low as these reflect mature, well-supplied markets with established technologies, supply chains and established competitors to keep prices low. Any premium is dependent on end user perceptions of its added value as a bio-derived chemical. In the case of PE, currently this can be worth a further 25% or more depending on end use.

The relatively low returns provided by xylitol reflects the current use of low value waste feedstocks in its production, and a relatively well-supplied market, which makes it difficult for other sources to complete.

More complicated molecules that are more expensive to produce and have specific applications can command higher values – e.g. MMA and 3-HP. Materials entering the food chain can also command high prices, e.g. Sorbitol.

New, novel and niche speciality chemicals can attract high prices and offer significant added value, but the prices on offer tend to reflect specific fields of use and lack of well-developed markets (e.g. lack of competition).

Conversely, high prices for some bio-based materials make them less attractive to competitor alternatives. For example levulinic acid prices are nearly twice those of existing fossil derived alternatives in its target markets, restricting wider deployment. The same problem affects polymers derived from polyhydroxyalkanoates.

Glucaric acid's value reflects its current limited availability in the marketplace.

The value of lactic acid reflects its niche as a commercialised bio-degradable polymer widely used in the food packaging sector, with some additional very high value pharma-related applications. However in other sectors of use, costs of production are falling and ethyl-lactate solvent applications are becoming cost competitive with petrochemical alternatives.

10 Barriers and challenges

In addition to the competition with incumbent materials, sugar derived from Scottish forests will also have to compete with that from current sugar and starch-crops to make any inroads. Developers of new plants are tempted to site new plants in the areas of cheapest feedstock supply. However, the presence of strong operational and technological knowhow, good co-operation in application development and the presence of leading brands that will drive uptake are strong reasons to maintain a domestic presence.

10.1 Cost of sugar

One of the key factors affecting competitiveness of forest-derived biotechnology industries is the costs of sugar supply. Glucose is already traded globally from sugar cane, and domestically sugar beet and starch crops (primarily cereals) are used to reduce import dependency on sugar feedstocks.

Given the current nascent state of development it is difficult to obtain reliable, independent information on the cost of cellulosic-derived sugars. However analysis of modelled cellulosic sugar chains by Lux suggests fermentable cellulosic sugar prices are currently 23-28% higher than those of cane sugar[11] a staple of the fermentation industry. This is an area where significant improvement is required to ensure domestic wood feedstocks can compete.

10.2 Cost of competitor wood feedstocks

Similar to the issue with sugar costs, if domestic wood and wood-by-products cannot be delivered competitively against imported wood resources then industries will potentially locate and invest in countries with the cheapest sources of feedstock. The only counter to this is where existing infrastructure and/or processing facilities reduce operating costs. Given that many of the stakeholder interests have a global reach this is a real risk to investment.

10.3 Development timeframes

Assuming the background technology is already well-proven, there is a considerable time period before 1st commercial production can commence. Processes will need to be optimised and efficiency improved, plants will have to be configured and tested and any ensuing problems reviewed and addressed. Typically this can take up to 6 years assuming no significant problems are encountered and the business case is compelling to investors.

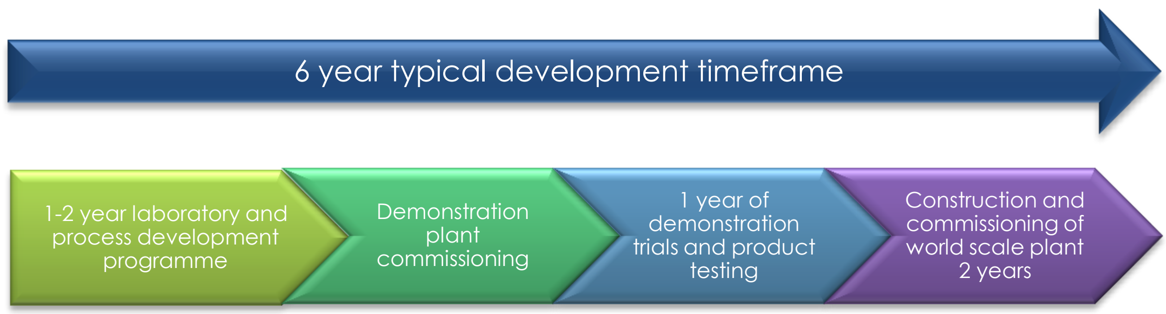


Figure 7. Typical development timescale for biobased chemicals

10.4 Issues affecting development of industrial biotechnology solutions in Europe

A comprehensive review of issues affecting the development of industrial biotechnology (IB) is beyond the scope of this project, but the EU BIO-TIC project, in consultation with partner and stakeholder interests, examined the barriers and

[11] http://www.luxresearchinc.com/news-and-events/press-releases/read/favorable-feedstock-costs-can-drop-cellulosic-sugar-prices-low

hurdles to wider development of IB in Europe[12]. The key issues are summarised below.

Key issues affecting development of IB technology innovation in Europe

- Economic viability
  - High cost of sugar feedstocks
  - High energy costs
- Technology
  - Yield and productivity of current microbial production strains and robustness of fermentation – especially tolerance to potentially growth-inhibiting compounds in the feedstock.
- Processing issues
  - Dealing with large amounts of water in fermentation operations and purifying target chemicals (high energy demand)
- Infrastructure
  - Need for more continuous fermentation systems
  - Greater integration of pre-treatment, bioconversion, product recovery and downstream processing
  - Limited demonstration and scale up facilities (a problems for SME's
- Financial
  - Perception of too long a period for return on investment in a competitive investment environment
  - Lack of policy or other incentives to encourage market uptake

The above issues lead to a number of areas where further R&D is required to support the industry in improving process efficiency and reducing costs:

- Process improvements
  - increasing product yield per unit of feedstock
  - targeting of chemicals that are currently difficult or expensive to make from fossil-based feedstocks
  - improved strain engineering
  - developing/selecting microbes that can convert lignocellulosic feedstocks directly to reduce need for refined sugar feedstocks

And further, co-operation and knowledge transfer is required in some areas:

- expertise in scaling up production
- disconnection between the industry and academic research institutions which slows knowledge transfer

The above indicates that there is still much that can be done in biologically mediated processing systems to increase product yields and reduce production costs as well as a number of integration issues to address.

[12] All BIO-TIC roadmaps can be downloaded via the web portal www.industrial-biotechnology.eu

10.5 Integration

Strong co-operation within the value chain is required for any new chemical building block to enter the markets. This calls for development of new partnership networks involving chemical building block producers and developers working with agricultural and forestry interests downstream and consumer brands upstream.

10.6 Emerging risks

10.6.1 Shale gas

There has been a great deal of discussion on the impact of shale gas development on bio-based chemical building blocks. The continuing transition from naphtha to ethane crackers drawing on cheap shale gas to produce primarily ethylene, opens opportunities for alternative sources of C3 and higher carbon-chain chemicals as well as aromatics (ethylene, propylene, benzene and butadiene), which will become scarcer with reduced naphtha cracking (which is mainly based in Europe and Asia). This could increase the financial competitiveness of bio-based derivatives which could fill any emerging gaps.

It is difficult to predict how this market shift will play out, many stakeholders see shale gas impacting largely the U.S. but leaving European chemical markets relatively unchanged. However significant export of shale gas from the US is a possibility, at least in the short-term, which would bolster the impact of exploitation of UK shale gas reserves.

10.7 SWOT analysis – sugar platform

Strengths	**Weaknesses**
Existing academic and industry partnerships in place for both biofuels and industrial biotechnology. Underpinning academic base in cell and synthetic biology offers potential for developing IP in supporting development roles (optimising biosynthesis pathways)	High wood feedstock demand of world scale plants for bulk chemical applications exceeds Scottish net availability in short to medium term. Very few existing relevant chemical industry interests in Scotland. Outside of biofuels, there is no specific driver to stimulate uptake of bio-based chemicals and drive substitution – so each has to build market share based on its own merit.

Opportunities	Threats
Most fermentation product markets are at an early stage of development, offering opportunities for innovation Greatest domestic opportunities are for speciality high value molecules with relatively small market demands Ready market opportunity in biofuels sector that could be switched to chemicals in part or whole as relevant technology comes onstream or is improved commercially Biomass pre-processing and fermentation infrastructure can be repurposed to address new emerging market opportunities	Technology in many industrial biotechnology applications is still at a demonstration stage and securing investment will be difficult Price of cellulosic-derived sugar from wood needs to be competitive with current world sugar sources. Similarly Scottish wood prices need to be competitive with those of potential competitors for production plant sites. The biofuel market sector, which is a target market for bioethanol and biobutanol, is highly policy dependant which is a risk for any investment. Markets for chemically modified sugars –sorbitol and xylitol are already well served by existing industry interests using cheap waste feedstocks Chemical industry interests are already coalescing around the most promising developments, in mainland Europe the US and South America (Brazil)

11 Ranking of the most promising opportunities

To assist in identifying a) the most promising bio-based chemical opportunities and b) offering the best 'fit' with the Scottish forest resource and Scottish capabilities, a scoring exercise was undertaken, as detailed below.

11.1 Market opportunity analysis

The potential market opportunity for each chemical (and relevant process) was assessed based on an aggregate weighted score derived from assessment of several scored parameters. Within each parameter, each opportunity was assessed using the information presented earlier in this report and a relative ranking score awarded. Scores were normalised in some cases around specific values to identify both positive and negative attributes. The parameters considered included;

- **Potential value added to feedstock** a semi-quantitative assessment of the final product value (£/t) and total product yield per tonne of forest feedstock. Scores were banded based on multiples of base feedstock price (ca £50/t) and normalised around a figure of twice the feedstock price. This score accounted for 10% of the overall aggregate score.
- **Wood demand per tonne of output** a semi-quantitative assessment of process efficiency, normalised around an average for all processes considered. Accounted for 20% of aggregate score.
- **Potential for market expansion –** subjective assessment based on market data, normalised around 'little growth potential'. Accounted for 25% of aggregate score.

- **Existing competition in market** – subjective assessment based on market data. Scoring normalised around ‘few existing key players’. A well-developed market with existing players would attract a negative score representing a highly competitive market place. Accounted for 20% of aggregate score.

11.2 Scottish opportunity analysis

The ability of Scottish resources and existing interests to capitalise on the above market opportunities were scored similarly according to the following parameters;

- **Feedstock availability** to service world scale plants (post 2020) (normalised at utilisation of between 50-100% of available net forest wood resource)
- **The presence of relevant Scottish industry interests** – subjectively scored from ‘interests only outside EU’ (highly negative) to ‘presence of Scottish commercial interests in bio-based product’ (highly positive)
- **Interest in product, process or area within the Scottish Research base** subjectively scored from ‘no evidence of active research‘ to ‘industry and academic groups focused on chemical of interest’ on an increasingly positive scale

  In the above cases in deriving the aggregate score, equal weighting was given to scores for each parameter.

Clearly some of the ranking is very subjective in the absence of detailed data, but the approach provides a means of providing a relative comparison of opportunities. The summary output of this analysis is shown graphically below.

11.3 Output from ranking analysis

The results of the ranking exercise are shown below, opportunities in the top right hand corner signify the most promising prospects where there are some positive Scottish attributes to encourage or facilitate development. Conversely opportunities in the top left indicate potentially strong market opportunities, but where there are some relative material weaknesses in the Scottish resource or infrastructure to support development. Figures falling below the ‘Y’ axis denote opportunities with some relative market weakness compared to others.

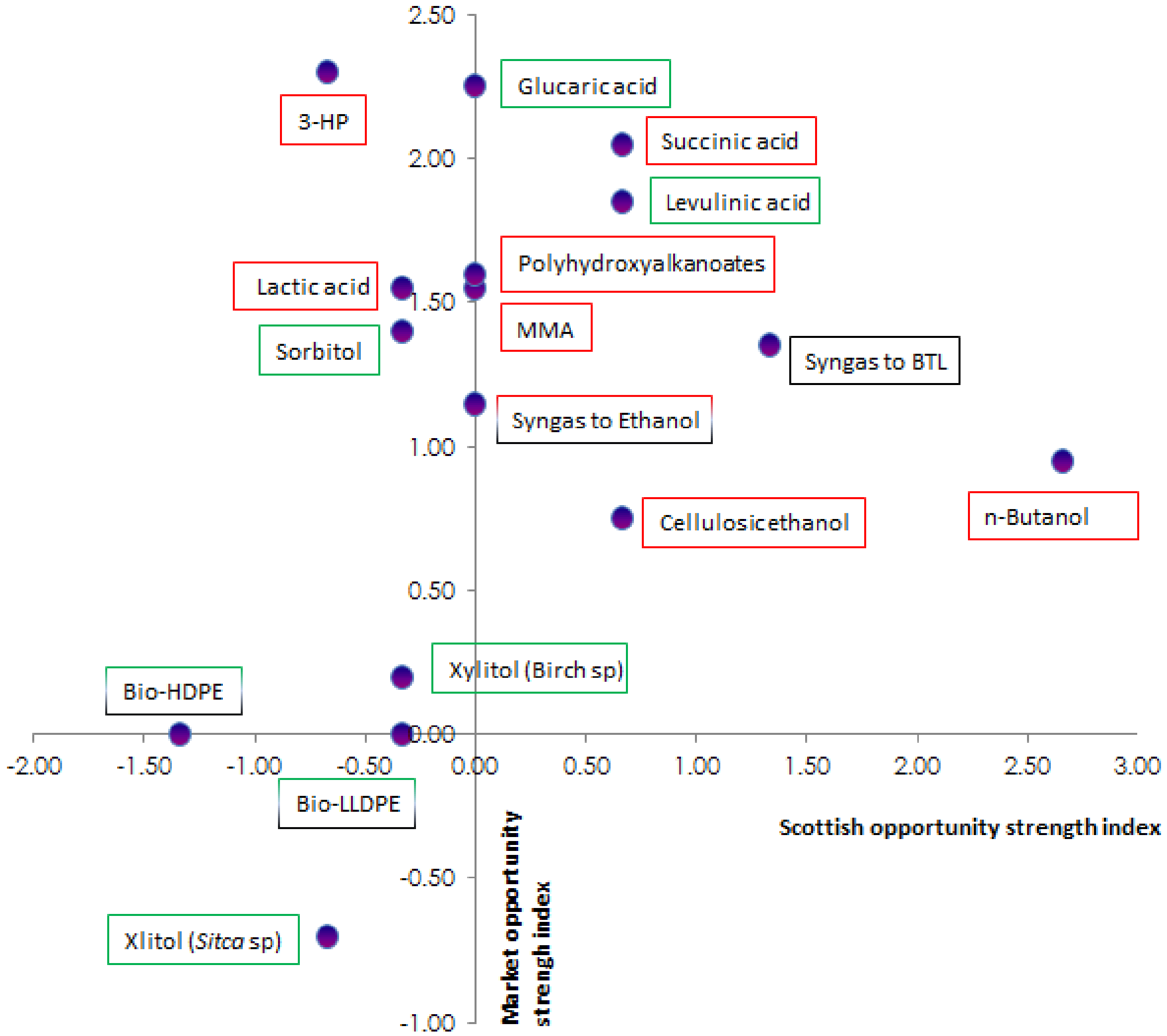


Figure 8. Results of opportunity ranking exercise

> *Key: Red box = Industrial biotechnology processes, green box = green chemistry processes, black box = thermochemical processes. Dual coloured boxes equate to sequences or alternative production pathways*

Currently Scottish industry is not well focussed on bio-based chemicals and interest is predominantly at an academic or early stage development. So, the influence of feedstock demand has a strong impact on the above results, favouring high value chemicals with relatively small (on a global scale) market demand, where a newcomer could command significant market share.

The presence of butanol, ethanol and 'syngas to BTL' in the 'promising opportunities' section reflects the current political support for development of biofuels, which encourages academic interest, and in the case of butanol the addition of a Scottish industrial spin-out with interest in its development.

Succinic acid and levulinic acid score relatively highly, representing high value chemicals with relatively low feedstock demand that could be accommodated domestically, however in both cases, and particularly for levulinic acid, development is at an early commercial stage. Significant work would be required to develop commercial success in these areas.

Establishing new chemical production needs a significant market driver. While the chemical opportunities identified represent the most promising for the UK, including Scotland, that's no guarantee that industry see these as priorities for development. This makes it very difficult to pick winners and build strategies for development around specific chemicals.

Rather than concentrating on the specific chemical opportunities themselves greater benefit can be gained by understand the characteristics of the opportunities that favour Scottish domestic development of bio-based chemicals.

Most development in the biobased chemical sector has arisen from exploitation of existing processes, utilising products for alternative means, or in looking to add value to processes or by-products. The following examples demonstrate this.

Braskem, a petrochemical company, started the first commercial production of bio-based polyethylene in 2010, using ethanol derived from sugarcane. This development benefitted from the company's existing investment and infrastructure associated with large scale ethanol production for transport. Braskem are now also moving towards the commercial launch of bio-based polypropylene.

Cargill, is a global food company and processor that has diversified into industrial products building on its cereal and corn starch interests. Cargill and Dow Chemical jointly formed Natureworks to commercialise lactic acid production from corn starch in the US in 2002, utilising feedstock from a co-located corn processing plant, built to produce corn oil and ethanol in Nebraska.

The world's first large scale bio-based succinic acid plant was built by ARD and DNP Green Technology, which formed BioAmber to commercialise its production, which started in 2010. The plant is situated within the Pomacle-Bazancourt bio-refinery which includes the Cristal Union sugar production plant, the Chamtor wheat-processing plant, the Cristanol ethanol plant. BioAmber sources glucose from the Chamtor wheat wet mill.

The section on forest-biorefineries demonstrates how interests in the pulp and paper sector (e.g. UPM and Borregaard) are focussing on ways of converting pulp process by-products to biofuels, primarily through thermochemical approaches.

These examples show how developments typically build on existing bio-based processing industries, as this lowers the hurdles to development significantly. Unfortunately, Scotland has no large scale ethanol production plant, no large scale starch or crop processing plant (with the exception of some grain milling) and its pulp and paper sector is small and focussed on mechanical pulping technologies that (as has been mentioned earlier) are less well suited to development of downstream chemical production.

In terms of the ranking exercise, many of the most promising opportunities arise from industrial sugar-based fermentation processes, with niche or fine chemicals commanding a price premium over bulk applications, while feedstock requirements are relatively modest. Similarly, opportunities based on chemical derivation from sugar which deliver high-value chemicals score highly – glucaric acid, levulinic acid and sorbitol. However, only the latter has reached successful levels of commercialisation to date while the former are still in development as attempts are made to reduce costs and increase competitiveness, which conversely could decrease their future attractiveness.

A key problem for sugar-based chemical opportunities as outlined earlier is that commercial developments focus on using relatively cheap sources of sugar – sugar cane and starch resources, or alternatively waste biomass resources. This puts those considering use of lignocellulosic sugar resources at a disadvantage until costs can be reduced. For example, work on lactic acid and PHA's has predominantly focused on the US, using corn starch as a feedstock.

Opportunities based on syngas also show some promise, but again this technology is still at a relatively early demonstration stage of development, developments targeting the fuel sector by nature are likely to be very large and involve significant investment. The economics of scaling such technology to applications with smaller outputs requires evaluation.

At the other end of the scale, Xylitol is produced in only small volumes from most coniferous wood species, selecting higher yielding birch species can improve output significantly. However the concentration of xylose sugar feedstock in wood is such that it is rarely competitive to target xylose production on its own, but only as part of a bio-refinery process.

The results of this work highlight that a significant amount of technical development is still required in many areas to deliver viable business propositions. While there is a lot of media coverage about the opportunities available from bio-based chemicals there are still relatively few good commercial examples. The area should be seen as 'in development' and as such this offers opportunities to those that can recognise these and capitalise on them.

Scotland is not the only country looking at these possible opportunities and competition can be expected to be significant where industry has already coalesced around particular specialist interests, and where outlooks are global in terms of looking for the most promising opportunities to site processing plants.

Scotland suffers from some disadvantages in terms of a lack of existing processing facilities and with constraints on its forest resource. However it has an important academic knowledge base in relevant areas that could be brought to bear on any barrier issues.

Outside of transport fuels, there is no clear driver to consider uptake of bio-based chemicals, beyond interests that can take advantage of 'natural' or 'green' credentials. The advantages of such materials need to be more clearly communicated to help build interest, involvement and market pull, and to encourage interest from major chemical manufacturers.

An important requisite to developing a domestic industry in this sector is to gain a better understanding of the country's chemical industry needs and aspirations to help focus efforts.

11.3.1 Impacts on species selection for future planting

With the exception of any specific driving interest in pentose sugars (for Xylitol production) there is no evidence of a need for any shift in the forest species composition to deliver into the bio-based chemicals sector. Conversely, a shift in species caused by other factors (e.g. adaptation to changing climatic conditions for example) is unlikely to affect any markets developed on the back of Scotland's current forest species mix.

Softwood species cause more clean-up problems for syngas production, but it is not yet clear whether this will cause significant problems going forward, requiring tighter control on species used for feedstock. This is an important consideration when reviewing the developing technologies for producing chemicals from syngas. Similarly heterogeneity in the sugar constituents of hemi cellulose can affect sugar yields from pre-treatment processes, requiring further examination with the most promising technologies.

11.4 Priority targets

Based on the foregoing assessment, the following priority ranking of chemical opportunities is proposed to assist priority setting.

1st priority

Chemical market opportunities where Scotland has some existing industry and research interests and product development capability, where there is room for market development and forest feedstocks could support development in the medium to long-term. For example;

- **n-Butanol** - ideally targeting chemicals rather than fuels sector, but would be compatible with existing fossil fuel infrastructure to help build capacity in interim.

2nd priority

Chemical market opportunities where there is room for market development and forest feedstocks could support development in the medium term, but further technical development is required. For example;

- **3-HP** - an important chemical building block with applications in surface coating sector where there are Scottish chemical industry interests.
- **Glucaric Acid** – an emerging chemical building block at early demonstration stage.
- **Levulinic Acid** - an emerging important chemical building block at pilot scale development currently, but with several commercial interests.
- **PHA's** - wide range of potential uses and several commercial interests.
- **Succinic acid** – Important platform molecule, and small amount of existing UK production (Wilton), several commercial interests in development.

3rd priority

Chemical market opportunities where there is room for market development, but development is limited by current state of the process technology and/or feedstocks limitations in the medium term. For example;

- **MMA** – at large scale (120kt plant) accessing sufficient feedstock could be a limitation on development. UK industry interest in development.

4th priority

Chemical market opportunities where there is room for market development, but infrastructure or feedstock demand is likely to limit development. For example;

- **Bioethanol** – feedstock demand of world-scale plants would limit development and global commodity trading will keep bioethanol prices low.
- **Polyethylene** – limited by factors affecting bioethanol availability.
- **Syngas** – large scale developments for fuel or chemicals are likely to be limited by domestic feedstock availability in Scotland – but could be overcome by importing feedstock.

5th priority

Chemical market opportunities where there is already significant market competition that would make market entry difficult or where feedstock demands could not be met to support commercial-scale plants. For example;

- **Sorbitol** – already large scale commercial production and relatively modest growth anticipated.
- **Lactic acid** – large-scale commercial production in the US with established players and market presence and moves to develop plants in Asia. Further development will be supported by current high levels of investment in US advanced cellulosic processes to provide cheap sugar sources in future.
- **Xylitol** – Established commercial market that would only be viable to exploit as part of a wider wood-based biorefinery initiative.

12 Roadmap

12.1 Technical challenges

12.1.1 Forest resource mapping

Scotland has a limited forest resource, in addition this is unevenly distributed and access restrictions may further reduce availability in some locations. Scotland needs a key understanding of the geography of the available resource and the cost implications of collecting and hauling this resource to identify where processing sites are likely to be sited to ensure Scottish forest resources can be competitive.

12.1.2 Technology readiness

While the traditional wood processing sector has been operating for decades and serves a number of established and mature chemical markets, the opportunities offered by both industrial biotechnology and thermochemical developments are relatively recent and in many cases have yet to prove their commercial viability. The main initial barriers are the commercial status of the underpinning technologies required to deliver syngas or sugar solutions;

- Most thermochemical developments are focused on heat and power production as the easiest route to deployment. Those focused on chemicals and liquid fuels are still at an early demonstration stage. Much still needs to be done from a technical and cost reduction perspective to clean up syngas from forest residues.
- Fermentation of syngas to ethanol is the first demonstrable development of this technology, but commercial success with scale-up and compatibility with significant use of forest feedstocks needs to be proven.
- Lignocellulosic processes developed for bioethanol production are also at a pre or early commercial stage of development and there is little detailed evidence yet of successful use of forest residues at scale.
- The forest industry itself is adapting more traditional wood processing methods – organosolve and sulphite pulping technologies, for wood sugar production, but again these are at an early stage of development, either pre-commercial or seeking to develop commercial testing.

Obtaining wood sugar solutions is only the first part of the necessary technology development, appropriate bio-based transformations need to be developed or improved to deliver higher efficiency or cost reductions to help open market opportunities. However, identifying the most promising is difficult in a myriad of potential opportunities. Market drivers are required to help drive both industry and commercial interest in the opportunities available.

The development of wood processing technologies needs to be monitored in key projects including;

- UPM work on wood to syngas (existing demo and planned Strasbourg development)
- Ineos bio syngas to ethanol platform (Vero Beach, US) and compatibility with use of forest wood feedstocks
- Lignol work on organosolve process to generate sugar-derived chemicals
- Borregaard work on BALI process to generate sugar-derived chemicals (Investment for large scale demo being sought)
- Beta Renewables (Crescentino pilot plant) work on lignocellulosic ethanol and compatibility with use of forest wood resources.

Links should be built with all of the above projects and the industry interests involved, and an understanding developed of the chemical markets being targeted. Cross-over with domestic chemical interests can then be examined.

12.2 Infrastructure challenges

The industrial biotechnology sector is very embryonic in nature. A UK review of the sector in 2012[13] identified 83 companies, of which 3 cover the commodity chemicals and 3 cover fine and speciality chemicals, the latter account for the greater share of turnover. All are SME's.

Scotland, like the rest of the UK, has limited commercial experience or facilities on which to draw help to drive forward a new and novel bio-based chemicals industry. Scotland also lacks large biofuel processing facilities or wood processing facilities suited to conversion to chemical production. Scotland also faces significant pressure on its wood resource from a range of competing uses in the short term until post 2020. Work is required to increase wood output from the forest Sector including collection of harvest residues.

The existing chemicals sector is an important revenue earner for Scotland but there is little evidence that it currently has any interest (evidenced as investment) in developing bio-based alternatives or new materials of interest. It is important to

[13] Strength and Opportunity 2012 – The landscape of the medical technology, medical biotechnology, industrial biotechnology and pharmaceutical sectors in the UK. HM Government publication.

identify where any opportunities lie within the existing chemical industry or where new initiatives are required, for example to support relevant spin-outs, or to help direct industry towards opportunities.

In contrast, Scotland's academic sector is already involved in many relevant areas of research and has started to develop important underpinning clusters of research interests and industry and academic initiatives that should help focus attention on the remaining barriers and challenges. Interests in understanding the metabolic pathways of fermentation microorganisms and the mechanisms of controlling and manipulating these are of global potential and interest and could deliver an important Scottish commercial interest outside any domestic development. A good example is Novozymes, originating in Denmark, that has capitalised on its expertise as an industrial enzyme producer to support the global development of 1st generation and now lignocellulosic ethanol developments.

12.3 Driving development

Scotland has a lot to do to develop a forest-based chemicals sector and faces greater challenges than some if its competitors to capitalise on its academic expertise in this area. Developing partnerships with relevant interests in Northern Europe and North America which have significant temperate forest resources and similar ambitions to add value to their forest resources could assist Scotland in identifying the potential for its forest resource as well as providing routes for exploitation of Scottish technologies and innovation to escape domestic limitations.

Given the constraints, **Scotland needs to look to work in partnership with others**, many of whom have already taken the first steps to develop the forest sector, to find a significant route to market beyond the constraints of its own forest resources. **Developing wider external opportunities would help to justify the investment of £millions in research and development by securing significantly greater returns on investment.**

To drive this, Scotland needs to develop a Task Force to bring together forestry, industry, government, investment and academic interests to help build overseas partnerships and to develop further detailed actions and plans as opportunities develop.

Intervention and support will be required to help develop the sector to ensure that Scotland shares in the likely significant potential financial rewards that the bio-based chemical sector can deliver.

There are existing UK parallels to draw on as a template for the types of actions that are required. Innovation Norway and the UK's Technology Strategy Board (TSB) have signed a Memorandum of Understanding (MoU) with the intention of developing a partnership in areas of industrial biotechnology and biorefining.

NNFCC was commissioned to provide a review of the high level opportunities and synergies for Norway and the UK. This subsequently led a number of company and research exchange visits from both sides, financially supported by respective innovation partners. The time, effort and costs involved in this are significant, but are essential to support the levels of interaction required to build confidence. In addition, TSB and Innovation Norway have agreed to mutually sponsor partnerships that wish to bid into TSB funding programmes. This has led to a number of joint collaborative ventures in the marine algae and forest biorefinery sector.

The key issues are therefore to provide the mechanisms and funding to support exchange of personnel and expertise, and subsequently the funding and means to work together to develop mutually beneficial outcomes.

12.4 Next steps

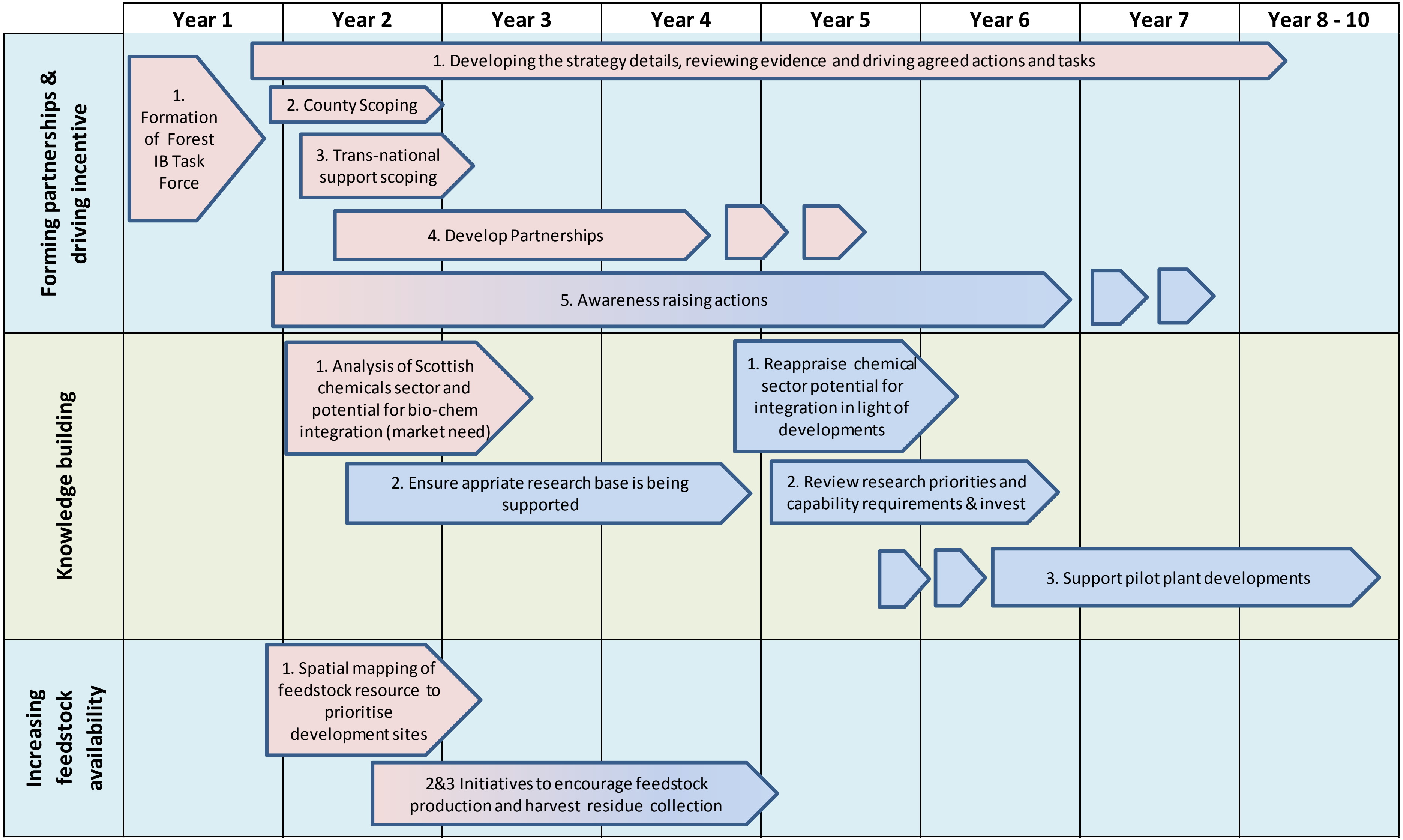
Ref	Action	Lead responsibility
Forming partnerships & driving incentive		
1	Develop the industrial and academic collaborations through establishment of a 'Forest IB Task Force' that will • help develop the dialogue (particularly between the forestry and chemicals sector) and partnerships to take developments forward - Encourage the establishment of partnerships with relevant interests outside Scotland • promote the opportunities available and raise awareness • shape the research agenda • shape the detailed actions required to drive development forward as progress and knowledge moves forward (to own the strategy and drive delivery)	Scottish Enterprise working with Chemicals Scotland and IBioIC
2	Scope and identify countries looking to add value to temperate forest resources and identify forest industry partners and supply chain operators	Scottish Enterprise
3	Review opportunities for encouraging trans-national collaboration and exchange	Scottish Enterprise
4	Develop partnerships and joint initiatives with Northern European and North American partners with similar objectives	Scottish Enterprise
5	Awareness raising actions on the potential for forest-derived chemicals – building case studies to encourage industry involvement	Scottish Enterprise working with Chemicals Scotland and IBioIC
Further knowledge building		
1	Analysis of the Scottish chemicals sector and Grangemouth complex (chemical products and production scales) and linked industries to identify potential synergies and opportunities for integration of bio-based chemicals. Key interest would include: Akzo Nobel, Lucite, Cellulac, Du Pont, Dow, BASF, Ineos, Invista.	Scottish Enterprise to fund
2	Ensure an appropriate academic research base is being supported and focussed on key developmental issues affecting the sector	Scottish Enterprise and IBioIC

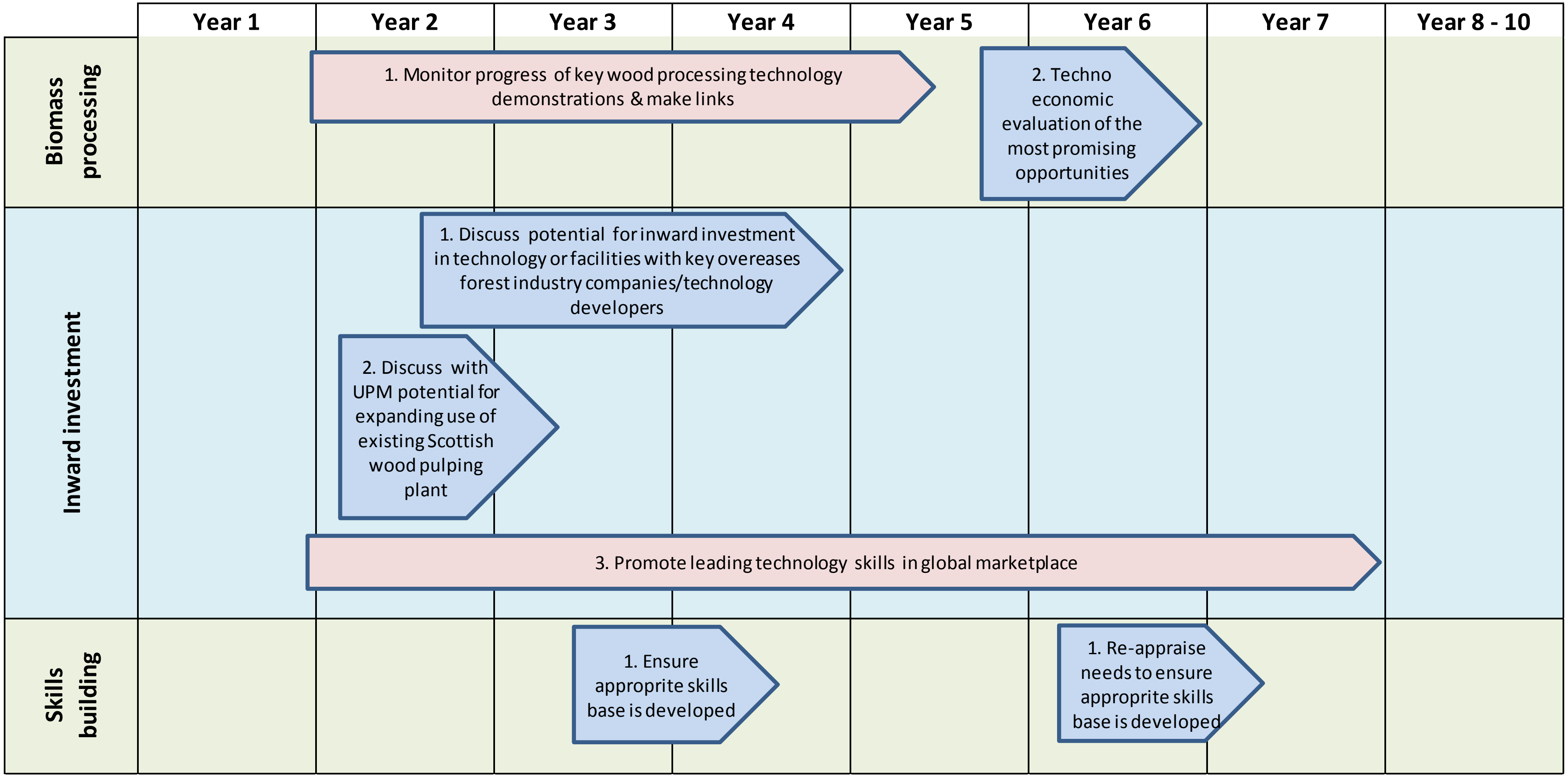
3	Support initiatives to secure access to, or to develop relevant pilot scale plants	Scottish Enterprise
Increasing feedstock availability		
1	Detailed mapping of available forest resource arisings (sawmill residues and forest harvest residues) to identify the most promising sites for industry development using Scottish wood resources	Scottish Enterprise and Forestry Commission Scotland
2	Promote initiatives to increase biomass collection and improve logistics, including collection of forest harvest residues (e.g. fact finding tours and demonstrations)	Scottish Enterprise and Forestry Commission Scotland
3	Support initiatives to encourage private woodlands to increase wood and forest residue resources	Scottish Enterprise and Forestry Commission Scotland
Biomass processing		
1	Monitor the progress of key wood-processing technology developments in the temperate forest industry sector to identify the most promising for Scotland's forest resource. Scotland needs to build links with the relevant company interests.	Scottish Enterprise
2	Technoeconomic evaluation – economic models need to be developed for the most promising opportunities to assess cost effectiveness and competitiveness for Scottish forest wood resources	Scottish Enterprise to fund
Inward investment		
1	Work with key technology leads in the temperate forest industry to ascertain interest working with, or locating in Scotland and working in joint ventures.	Scottish Enterprise and inward investment teams
2	Investigate with UPM the potential for expanding on current mechanical pulping processes in Scotland, exploiting UPM's interest in developing wood processing for chemicals.	Scottish Enterprise
3	Promote Scotland's academic and SME skills in the global market place for technology solutions to deliver a growing global bio-based economy	Scottish Enterprise and Invest UK
Skills building		
1	Ensure an appropriate skills base is being developed to support industry development	Scottish Enterprise, Chemicals Scotland and IBiolC

A timeline for the above actions is given below. This forms a roadmap for the specific exploitation of forest resources to serve the Scottish chemical sector. This compliments the recently published more generic Biorefinery Roadmap for Scotland.

This roadmap presents a number of actions that serve to broadly drive forward the development of bio-based chemicals in Scotland. With the resources available it has been possible to identify the characteristics of those opportunities that offer the greatest benefits and likelihood of success in a Scottish context, reflecting the current feedstock and infrastructure in Scotland. While this identified a number of limitations on domestic development, this should be seized as an opportunity to develop a vision that looks beyond Scotland's borders to develop international partnerships to deliver on Scotland's aspirations to take advantage of the rapidly developing industrial biotechnology sector and the opportunities this could offer.

Figure 9. (1 of 2) Timeline for actions – pink highlights are the highest priority actions




Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8 - 10
Biomass processing
1. Monitor progress of key wood processing technology demonstrations & make links
2. Techno economic evaluation of the most promising opportunities
Inward investment
1. Discuss potential for inward investment in technology or facilities with key overeases forest industry companies/technology developers
2. Discuss with UPM potential for expanding use of existing Scottish wood pulping plant
3. Promote leading technology skills in global marketplace
Skills building
1. Ensure approprite skills base is developed
1. Re-appraise needs to ensure approprite skills base is developed

NNFCC

NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and bio-based products.

NNFCC, Biocentre,
York Science Park,
Innovation Way,
Heslington, York,
YO10 5DG.

Phone: +44 (0)1904 435182
Fax: +44 (0)1904 435345
E: enquiries@nnfcc.co.uk
Web: www.nnfcc.co.uk