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Review

The biorefining opportunities in Wales: Understanding the scope for building a sustainable, biorenewable economy using plant biomass

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ABSTRACT

There are many factors influencing the current global interest in the biorefining of biomass feedstocks to produce a wide variety of extracts, fuels and chemicals. Identifying renewable sources of target molecules currently produced from fossil fuels is one of these, which will ultimately have a positive impact on climate change. Another driver is identifying potential uses for land masses, where a low GDP is affecting communities in those areas. From a UK perspective, a decline in total income generated from farming in Wales has had a detrimental impact on many communities right across the Principality.

There is a considerable body of data to argue that with effective land use and the use of a range of enzymic and chemical processing technologies, the utilisation of lignocellulosic biomass as feedstock for a biorefining industry would result in both social and economic regeneration of these rural communities.

In order to create a sustainable biorefining in Wales, alongside regeneration of the rural economy there is a requirement for expansion of the high technology skill base, in areas such as chemistry, biotechnology and engineering.

The key to developing this sustainable and economically viable biorefining industry within Wales and ultimately in the UK is based on several technical issues which need to be addressed. These include ensuring that the feedstocks can be grown on marginal land which will not therefore compete with traditional food crops, the need to create local supply chains linking regions together, but which can also feed into the rapidly expanding networks of biomass-based industrial activity in other areas of the UK, and ensuring that the existing transport infrastructure can absorb this increase in activity.

This paper will consider the options for large scale biorefining of high sugar perennial ryegrasses in Wales, as a model for producing sustainable, bulk quantities of chemicals, including biofuels.

Keywords: Green biorefineries; Plant biomass; Agriculture and food production; UK/Welsh Assembly Government Policy on renewables

Contents

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1. Introduction

There is increasing concern about the impact that chemicals, fuels and energy obtained from fossil based feedstocks (i.e. natural gas, coal and oil) are having on the earth's environment, particularly in view of the increasing demand from rapidly expanding industrial nations such as India and China. There are several issues surrounding the continued utilisation of these fossil fuels. These include the fact that reserves are finite and non-renewable; the increased global warming potential when these materials are combusted to provide energy and the security of supply of these commodities exported from certain world regions may not be reliable in the future. As the levels of fossil fuels diminish, then more inaccessible and remote areas of the earth's subterranean and marine environments are being actively explored in the search for new reserves, often to the detriment of the physical landscape as well as the delicately balanced ecosystems in these areas.

Accurate estimates of remaining world oil reserves are difficult to produce and vary depending on the source, but as part of the EIA's (Energy Information Administration, providing official energy statistics from the US Government) 'Assumptions to the Annual Energy Outlook 2009', it was stated that OPEC producing countries hold about 70% of the world's estimated total reserves in 2008; in excess of 927 billion barrels (EIA, 2009). An additional report by the US Geological Survey indicated that there may be up to 90bn barrels of oil in Arctic regions (United States Geological Survey, 2008), although there are potential environmental issues that would need to be addressed before accessing these reserves.

What is apparent is that with the increasing volatility in the price of crude oil, alternative, renewable feedstocks from which key chemicals, fuels and energy sources can be isolated are required in the longer term, in order to maintain both current demands and facilitate future worldwide industrial expansion.

One renewable source of all of these materials is plant material (biomass) and there is increasing research activity surrounding the use of plant based feedstocks in industrial processing, as a source of these key commodities (NNFCC, 2007). This has led to the concept of biorefining in order to produce targeted end products for the petro/chemicals industry. A biorefinery is, according to one definition published by the American National Renewable Energy Laboratory, 'a facility that integrates biomass conversion processes and equipment to produce fuels, power and chemicals from biomass. The biorefinery concept is analogous to today's petroleum refineries, which produce multiple fuels and products from petroleum' (www.nrel.gov/biomass/biorefinery.html). In reality this means that, depending on the plant feedstock used and following mechanical processing and either enzymatic conversion, or chemical modification, a broad spectrum of materials can be produced from biomass in order to maximise the financial gain from the conversion. There is a hierarchy of value for the various products that can be obtained from biomass, including extracts with pharmaceutical applications (e.g. the cancer drug taxol from the bark of the Pacific yew—Patel, 1998), platform chemicals such as organic acids from fermentation (Willke and Vorlop, 2004), biofuels (e.g. FAME following chemical transformation of plant oils and bioethanol from biomass fermentation—Huber et al., 2006), energy sources (e.g. syngas and bio-oil produced by pyrolysis—Huber et al., 2006) and fibre residues that have applications in biocomposite materials, for example in the automotive and building industries (Fowler et al., 2006).

There are several factors to be considered when using plant biomass as an alternative to fossil fuels. These include consistency of supply (some plant crops are seasonal and the levels of active molecules required for biochemical transformation may vary during the growing season); the optimisation of mechanical fractionation in order to maximise the quantities of active molecules released for further downstream processing and the impact that change of land use has on going from food to biofuel crops, for example. The technologies required for processing biomass are wide ranging, and in the early stages of development when compared to those developed for processing fossil fuel based feedstocks, such as fractional distillation (cracking). The variety of expertise required in order to exploit biomass as a viable source of base commodities is also diverse and requires a multidisciplinary approach.

This paper will focus on the use of terrestrial plant biomass as feedstocks for a biorefining industry across Wales, although it is important to note that marine biomass (e.g. algae and seaweeds) is also another potential, bulk source of key commodities (The Royal Society, 2008). This paper will also consider the issues surrounding the implementation of a national biorefining strategy across Wales and how this would integrate with agriculture, food production, the environment and current industrial activity in the region.

2. Policy drivers for change to a biomass-based economy

The Kyoto Protocol (United Nations, 1998) is one of the most potentially influential agreements in moving to a world economy which would use biomass as one of the alternatives to fossil fuels. This protocol is part of the International Framework convention on climate change, with the primary objective of reducing green house gas emissions. In May 2008, 182 parties ratified this protocol, including 36 developed countries (plus the EU as a party in its own right) and have made a commitment to reduce green house gas emissions to the levels specified for each of them in the treaty. Included in this list of countries were 137 developing nations which have ratified the protocol, including Brazil, China and India, but have no obligation beyond monitoring and reporting emissions.

In May 2007, the Department for Environment Food and Rural Affairs published a UK biomass strategy, which focused on potential applications of biomass for energy and transport (Defra, 2007). The report acknowledged the central role of biomass in complying with the EU target of 20% renewable energy by 2020, and also the proposed UK target of at least 60% cuts in carbon dioxide emissions by 2050. In addition, this document links into the Renewable Transport Fuel Obligation (RTFO) published in consultation form in February 2007 and introduced in April 2008, which is part of the UK Government's Energy White paper and which seeks to deliver 5% of transport fuels from biofuels by 2010 (BERR, 2007).

The Biomass Strategy report outlined several issues surrounding the use of biomass, not least of which how biofuels production could impact on food production through land use change, by replacing food based crops with those such as rapeseed, for biofuel manufacture. A United Nations framework document on the use of biomass for energy/fuel production also highlighted these concerns, with regards to how the cultivation of biofuels crops (such as palm oil) could, without careful management, push up world food prices, endangering the already unstable food supply chain in many developing regions of the world, which in turn could have dangerous effects on many millions of people already suffering from malnutrition (United Nations, 2007).

A report by The Renewable Fuels Agency (Gallagher, 2008) recommended that the RTFO 5% target be pushed back to 2013, because not enough is known about the wider social and environmental issues surrounding the intensive push towards biofuels production. The report advocates that any future agricultural expansion of crops for biofuels use is directed to suitable idle or marginal land. In addition, the report states that the balance of evidence suggests that current policies relating to biofuels production will lead to net green house gas emissions and loss of biodiversity through habitat destruction. This includes the effects arising from the conversion of grassland to cropland'. One of the most significant conclusions from this report was that biofuels could only contribute to a net saving in green house gas production, if significant emissions from land use change are avoided and appropriate production technologies are employed.

From a UK perspective a report published by Defra investigated the impact of biofuels pricing on the commodities markets. The increasing pressure from biofuels production on prices for crops such as cereals, oilseed and sugar could be affected by several short term (e.g. adverse weather conditions impacting on harvesting and speculative investment trading on the world commodities market) and longer term (a growing trend for increased worldwide consumption of these crops as well as increasing oil prices affecting agricultural production costs) trends (Defra, 2008a). Another report published at the same time by Defra on the cost-effectiveness of biofuels discussed the implications of rising oil prices on the economic viability of the current generation of biofuels. The report concluded that current costs associated with biofuels production are too high to make them cost-effective, apart from bioethanol derived from sugar cane (Defra, 2008b). However, as crude oil prices increase rapidly, it is likely that these fuels will become competitive. The point at which this is the case is dependent on the particular biomass feedstock used.

2.1. The production of bulk and speciality chemicals from biomass

The production of platform chemicals from biomass is another potentially huge market. A study on biobased chemicals in Wales and adjacent regions in England, with good transport infrastructure links into the Principality, indicated that the market for these materials could be as much as £560 million, which is 25% of the UK total (CI-KTN, 2008). However, there are currently no fiscal incentives or legislative drivers to encourage industry to produce chemicals from biomass, unlike the production of power and biofuels. Such incentives may be important in the early-stage development of new markets for biobased materials from biomass, by encouraging companies to make the change to both manufacturing and consuming sustainable products. The production of sustainably derived transport fuels is influenced by the RTFO as previously discussed and electricity production from renewables is subsidised through ROCs (renewable obligation certificates) and LECs (climate change levy certificates) which are designed to facilitate the change from fossil based to sustainable energy sources (www.ofgem.gov.uk/Sustainability/Environment/Renewable).

There are several reports which have been published relating to the production of chemicals from biomass. One of the most comprehensive of these is the final report from the BREW project, co-ordinated by Utrecht University, Netherlands, which focused on the application of white biotechnology (i.e. the industrial scale fermentation or enzymatic conversion) to the production of a range of chemicals from biomass (The BREW project, 2006). The report examined in detail the economic, technical and environmental issues surrounding the production of 21 key chemicals. The broad conclusion of the report was that the manufacture of these chemicals from biomass is currently possible with existing technology, but the main issue to address was the economics of using these different technologies. As expected, as the price of oil increases, then the use of white technology becomes economically viable and a range of scenarios with differing oil and sugar prices was presented in order to illustrate this (see Section 3.3.4.2). Another report (US Dept. of Energy, 2004) focused on twelve platform chemicals that can be produced from sugars by either biological or chemical conversions. The selection of these molecules from an initial list of 300 was based on synthetic utility, market potential and technical complexity involved in manufacture. The chemicals identified included a range of organic acids such as succinic, aspartic, glutamic and levulinic and 3-hydroxypropionic as well as compounds such as glycerol and sorbitol. These chemicals were viewed as key platforms, from which a large number of commercially important, secondary derivatives could be prepared. Another review focused on the chemical (including the catalytic) conversion of biomass to a range of value-added chemicals (Corma et al., 2007). This included the conversion of carbohydrates, vegetable oils, animal fats and terpenes into a variety of value-added bulk and speciality chemicals. The review focused on environmentally friendly catalytic technologies that could substitute older, mineral acid or base conversion processes. The broad conclusions were that with the rapid technological advances, future catalytic design for biomass conversion could focus on multi-site systems using both transition metal complexes and enzymes, in order to telescope multi-stage processes, thereby reducing the need for costly intermediate stage separations.

An additional report published by NEXANT, on behalf of the NNFCC [National Non Food Crops Centre (NNFCC, 2008a)] investigated the opportunities for the UK from the conversion of biomass to bulk and speciality chemicals, using fermentation technology. It listed 48 potential target platform molecules based on their 'market attractiveness' and 'technical feasibility', following an assessment of the current status of commercial development, capital investment required, complexity of the conversion process, access to required technology and environmental considerations. This assessment resulted in the identification of four important process streams:

i. *Bioethylene production with a combined low/high density polyethylene facility*, for use in the plastics sector (injection moulding, film, fibre and extrusion applications).
ii. *Integrated succinic or fumaric acid production with 1,4-butanediol, tetrahydrofuran and gamma-butyrolactone*. These are all important platform chemicals which are crucial to the downstream production of hundreds of other chemicals for the pharmaceuticals, polymers, adhesives and lubricants sectors.
iii. *3-Hydroxypropionc acid to acrylic acid*. An important intermediate in solvents, coatings and paint based applications.
iv. *Methyl methacrylate (MMA) and polyhydroxyalkanoates (PHAs)*. MMA is used as a monomer the manufacture of a wide range of polymers for use in the building, automotive and glazing sectors. PHAs are a family of natural polymers produced by the fermentation of sugars and lipids with medicinal applications as non-woven fabrics, films, fibres and coatings due to their biodegradability.

The majority of these reports identified the same groups of target molecules as being crucial to the development of biobased chemicals from plant material.

The current expectation, from the review work published to date, is that the future products developed from commercial biorefining processes will include chemicals with established market requirements, such as ethanol, butane-1,4-diol, 3-hydroxypropionic acid, polyethylene and methyl methacrylate. This was reinforced in a white paper on biomass-based chemicals produced by the FROPTOP (From Renewable Platform Chemicals to Value-Added Products) group. This is a specialist interest group bringing together UK Academic, Industrial and Business expertise in the area of renewable chemicals. The report concluded that 'One of the most important future markets for biomass-based chemicals will be the existing speciality chemicals market. Industry prefers to use chemicals already known to them and which have a proven safety track record' (FROPTOP, 2009).

The utility of using sugars isolated from plant feedstocks extends beyond the production of ethanol by fermentation to include other higher value chemicals. For example, fructans (polymers of D-fructose) are becoming increasingly important as artificial sweeteners. Hydrolysis of the polymer to yield fructose, followed by further downstream chemical processing yields hydroyxmethylfurfural, which is an important intermediate in the production of chemical platforms such as tetrahydrofuran and levulinic acid. Hydrogenation of fructose affords mannitol and sorbitol, which are also high volume chemicals used as sweeteners.

It is apparent that there are potential opportunities for producing key commodities, including biofuels, energy and platform chemicals from biomass. Central to the successful exploitation of these opportunities will be identifying suitable biomass feedstocks that can be cultivated, harvested and processed in a sustainable way.

3. Biorefining in Wales

3.1. *The Welsh policy framework for change*

Wales has a population of around 2.94 million people and the total land surface comprises nearly 2.1 million ha, of which some 80% is devoted to agriculture. The remainder consists of forestry and woodland (12%) and urban and miscellaneous land (8%) (Welsh Assembly Government, 2007a,b).

The industrial landscape in Wales has changed drastically over the last 100 years. The start of the 20th century saw the emphasis on coal and steel in the south (Rees, 1978) and slate in the north (Richards, 1995), with the transport of these commodities from key ports also giving rise to a strong maritime industry. These traditional heavy industries have since declined and have been replaced by tourism and public services, which are now the main employers in Wales. The landscape, particularly in Mid-Wales lends itself to agriculture. However, in more recent times the contribution of this activity to the economy in this region has diminished somewhat. These changes in commercial outputs are also mirrored in the manufacturing sector, where traditional heavy industries have been replaced with lighter manufacturing including the electronics, components and technology sectors (House of Commons Welsh Affairs Committee, 2009).

Despite this, a report commissioned by the Royal Society of Chemistry, which looked at the chemical science intermediate sized business sector, indicated that Wales has the highest proportion of companies growing in this area anywhere in the UK (Royal Society of Chemistry, 2007). In Wales, out of all the companies that responded to the survey carried out as part of this report, 20% were involved in bioscience/biotechnology.

Since 1999, devolution in Wales has resulted in the country being administered by the Welsh Assembly Government (WAG), based in the capital Cardiff. In parallel with the UK government, WAG has been developing its own policy with regards to the production of chemicals, energy and fuel from renewable sources.

Figures published (Welsh Assembly Government, 2005) indicate that, in terms of relative prosperity in Wales, the GDP (Gross Domestic Product) per head of population is considerably lower than both the UK and European Union averages (90% of the EU25 figure in 2002). However, this report also concluded that these figures do not take into account other factors such as employment, earnings and household disposable incomes, which all affect 'quality of life'.

It is however apparent that following a decline in the traditional heavy industries in Wales, some regions have experienced an economic downturn in recent decades. Certain, predominantly rural areas, including North West and Mid-Wales and the valleys of South Wales have been badly affected by this downturn. These areas have a GDP below 75% of the EU average and are known as convergence (formerly Objective 1) regions (Welsh European Funding Office, 2007). They are some of the poorest areas in the EU and are eligible to receive financial support through a range of funds, in order to facilitate economic and social regeneration.

The published Science Policy for Wales (Welsh Assembly Government, 2006) reflects this need for assistance and will seek to address three keys issues, which are health, a low carbon economy and social/economic renewal. In addition, the Renewable Energy Route Map for Wales (Welsh Assembly Government, 2008a) stresses the need to move away from traditional fossil fuels and the associated problems with carbon dioxide emissions and increased global warming potential and move to a low carbon economy. The utilisation of biomass is one of the preferred options to achieve this along with other forms of renewable energy such as wind and tidal power. However, the route map states that the growth of specific crops or plants as renewable feedstocks for industrial processes and the resultant change in land use that this could involve does have potential drawbacks. These include the competition with traditional food crops such as cereals, the impact on rural ecosystems as a result of intense cultivation techniques, and the effects this could have on soil quality/drainage, flood risk and the increased levels of fertilisers required.

3.2. *Agriculture in Wales*

Wales typically has heavier rainfall, a greater proportion of upland areas and more marginal quality soils than England. This has resulted in a greater dependency on livestock farming than most other areas in the UK, requiring a large percentage of land devoted to the cultivation of grassland as a feed source. The total land mass in Wales utilised for agriculture is 1.7 million ha, with 60% of this land over 150 m and 27% over 300 m above sea level. The topography of Wales, along with the comparatively poor soil quality and climatic conditions mean that the majority of land is not suited to the production of food crops and there is no significant scope for increasing current levels of production for this reason. The predominant cereal crops in Wales are wheat and barley, although recent statistics indicate that between 1996 and 2006 the amount of arable land in Wales decreased from 211,000 to 164,000 ha (Welsh Assembly Government, 2007c). This was probably due to decreased competitiveness with other arable farming regions in the UK, because of input costs and reduced market prices. A report commissioned by the National Non Food Crops Centre (NNFCC, 2008b) reinforced this and showed that the main centres for UK food crop production are in the Midlands, East/South East England (wheat) and North East/South East Scotland (barley) (see Fig. 1).

When put into context with other agricultural land usage in Wales, arable land accounts for 10% (∼164,000 ha) with permanent grassland (62%), rough grazing (25%), woodland (3%) and other land (1%) accounting for the remainder (Welsh Assembly Government, 2007b).

In terms of livestock farming, in Wales, it is generally accepted that since the 1970s, this sector of the industry has suffered a general downturn (Welsh Assembly Government, 2008c), with recent Foot and Mouth and Bluetongue outbreaks having had a further impact. In the period 1996–2006, there was a significant decrease in the number of holdings in Wales with livestock. During this period, the total labour engaged on holdings also decreased from 64,000 to 56,000 people (Welsh Assembly Government, 2007c). These figures do not take into account the jobs lost in associated sectors such as agricultural machinery, feed suppliers and animal welfare, which rely heavily on farming for an income. The total income from

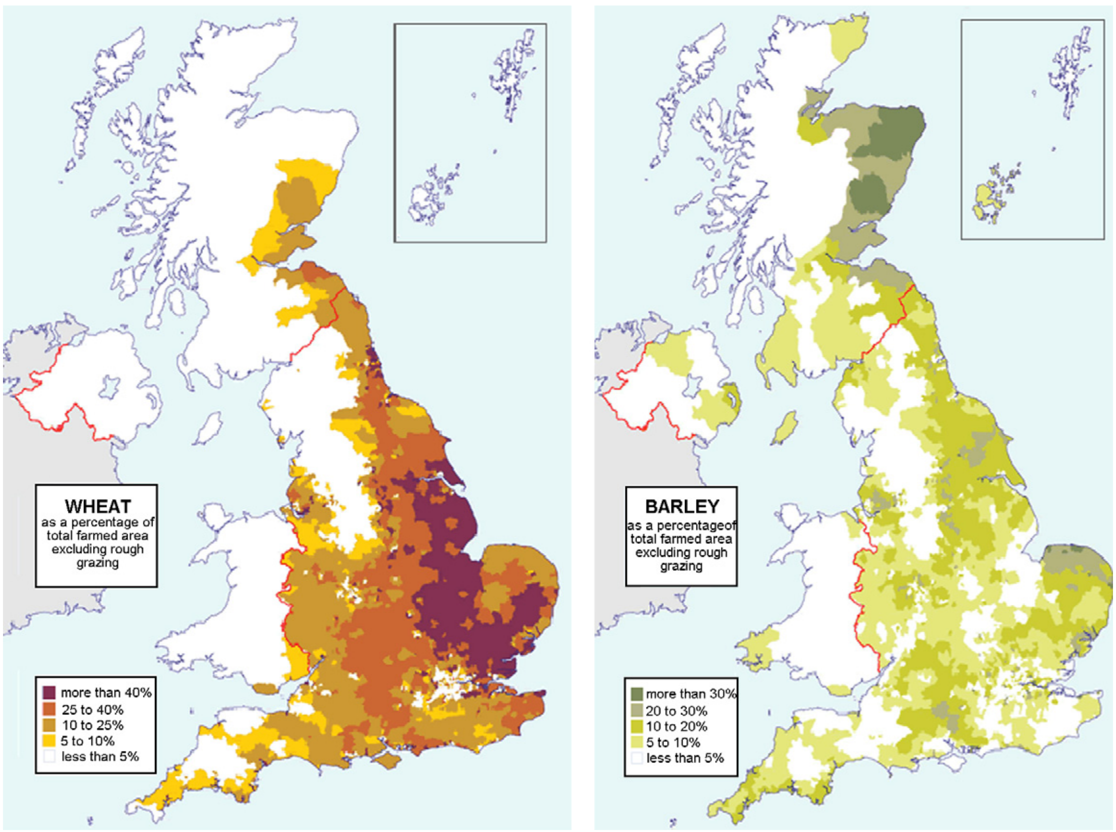

Fig. 1 – Food crop production (wheat and barley) in the UK (NNFCC, 2008b).

farming in Wales also decreased by £5.4M from 2006 to 2007 (Welsh Assembly Government, 2008b), although this figure was affected by the levels of subsidies paid to farmers.

The debate therefore should not necessarily be whether Welsh agriculture is currently in decline, but whether it is sustainable in its current form for the future. It is generally accepted that average farming incomes are low when compared to the rest of society, particularly in Wales and do not reflect the inputs in terms of capital, skill and labour. This has had a profound effect on farming communities in the Convergence Regions of Wales.

A report on the future of agriculture in Wales (Welsh Assembly Government, 2007d) concluded that these problems should be addressed in a number of ways, including connecting with the market, delivering environmental goods and services and helping to sustain rural economies. The success of this vision will depend on collaboration, local empowerment and innovation through rejuvenation of the affected rural communities. This will require further diversification of farming practices in Wales, not just in order to protect existing jobs, but to encourage expansion of the rural economy through the creation of new jobs.

A major priority for Wales is identifying ways to facilitate both social and economic regeneration in these rural communities (Welsh Assembly Government, 2008c). These include improving the competitiveness of the agriculture (and forestry) sectors, by identifying new high value products, processes and technologies. This will almost certainly involve using the general principles of biorefining to add value to waste products generated by the forestry industry, as well as producing new products from plant material. This was acknowledged in a Welsh bioenergy consultation document (Welsh Assembly Government, 2009) which stated that 'by utilising co-products from one process into another, an integrated production system can increase the production efficiency and benefit from economies of scale to make biobased products cost competitive'. Improving the environment and enhancing the quality of life in rural areas through the diversification of the rural economy are also considered to be central to this plan.

The creation of jobs in the 'green sector', which establish a link between economic development and environmental protection and social wellbeing, is seen as crucial to this (Welsh Assembly Government, 2008e). This is in response to recent changes in consumer demands for green products, and the resultant impact this has had on both shareholders and stakeholders in Wales. One of the ways in which both the greening of existing jobs and the creation of new opportunities could be achieved is enabling businesses in Wales to exploit developing low carbon technologies, such as clean manufacturing processes. This would include aspects of biorefining.

The question is can the future of the agriculture in Wales be secured through diversifying into other areas of activity such as biorefining, whilst allowing the more traditional areas such as livestock farming to continue?

3.3. *The potential for creating a biorefining based industry in Wales*

3.3.1. *Feedstock selection*

There is a variety of crops grown in Wales that could potentially be used for large scale conversion to a range of biobased products.

Cereal and oilseed crops are cultivated primarily in areas of South/South West Wales and were discounted as potential bulk sources of biomass in Wales for a variety of reasons. The climatic conditions in Wales do not favour the large scale cultivation of these crops and because food/animal feed production is a priority for farmers, it is important not to displace or compete with this type of existing activity. This is because although livestock numbers have decreased in Wales in recent years, cereal crops remain important dietary supplements for livestock. In addition, input costs for these crops are relatively high and much of the agricultural land in Wales is of only marginal fertility and not suitable for large scale cereals production. Table 1 shows the yields from typical cereals crops grown in Wales.

Miscanthus and short rotation coppice (SRC) are also potential feedstock for biorefining and both can be grown on less fertile land. Miscanthus or Asian elephant grass is a perennial species that produces over 3 m of bamboo-like stems each year. It has a productive lifetime of 10–15 years and is harvested from year 2 onwards, yielding ∼12 t/dm ha year (tonnes dry matter per hectare per year) (Clifton-Brown and Valentine, 2007). The crop is generally harvested in late winter or early spring, leading to reduced yields as well as potential difficulties in accessing material in water-logged fields during this period. However this crop does show promise and there are large scale breeding programmes which will enhance both crop quality and yields.

SRC is harvested every 3 years, from year 2 onwards and trials run in Mid-Wales from 2003 using 15 varieties gave an average yield of ∼10 t/(dm ha year) (Valentine et al., 2007). Again the material is harvested during the winter months, so cultivation on particularly wet land is not ideal, although the crop is suitable for cultivation on both upland and lowland areas and on land where soil fertility is marginal (Welsh Energy Crops Centre). Both miscanthus and SRC are more expensive to establish than arable crops and require a long term commitment from growers in order to receive adequate financial returns.

Another potential biorefinery feedstock is perennial ryegrasses. These grasses have been cultivated in Wales for many generations, using land management and harvesting techniques that many farmers are familiar with. In addition, these grasses do not require the capital investment that other crops

Table 1 – Quantities of grain, oilseed and straw generated in Wales (Welsh Assembly Government, 2007b).

Crop	Area (ha)	Seed yield (t/ha)	Total seed yield (t)	Straw yield (t/ha)	Total straw yield (t)
Wheat	15,524	8.0	124,192	3.5	54,334
Winter Barley	6,985	6.5	45,402	3.0	20,955
Spring Barley	12,144	5.5	66,792	2.5	30,360
Oats	3,901	6.5	25,356	3.5	13,654
Oilseed rape	2,614	3.0	7,842	1.5	3,921
	41,168	–	269,584	–	123,224

do, they could be grown on temporary grassland that was previously cropped for hay or silage and do not require high fertiliser inputs, particularly if co-sown with nitrogen fixing plants such as clover. The climate and marginal soil fertility in many areas of Wales are also ideally suited to grass production on a large scale. Perennial ryegrass (*Lolium perenne*) is the predominant cultivated forage grass species in European agriculture. Other cultivated forage grasses include fescues (*Festuca pratensis* and *Festuca arundinacea*) and to a lesser extent timothy (*Phleum pratense*) and cocksfoot (*Dactylis glomerata*). Although they make up only 6% of the total grass seed usage in the UK, these other species are grown to a greater extent in Northern Europe, because they are more tolerant to abiotic stresses (Humphreys et al., 2006). Perennial ryegrasses achieve the highest levels of grass and livestock production. The nutritional quality of these grasses correlates with non-structural carbohydrate content of which fructan is a major component (Miller et al., 2001). Fructan, a polymer of fructose, is the major reserve carbohydrate in temperate grasses and comprises on average 70% of the water soluble carbohydrate of perennial ryegrass in field conditions (McGrath, 1988). Grass biomass yields are comparable with other crops used in the biorefinery industry. Typically, high productivity perennial ryegrasses yields as much as 15 t/(dm ha year), whilst permanent grassland and rough grazing pasture produce 12 and 6 t/(dm ha year), respectively (Wilkins and Humphreys, 2003).

3.3.2. *Chemical composition of grass and availability of land in Wales for grass cultivation*

The type of soils, topography, hydrology and climate in Wales has created an optimum environment for the growth of temperate grasses and this is reflected in the high proportion of grassland areas (~90% of agricultural land).

Alternative novel high value products from grass biomass will allow farmers the opportunity to diversify into areas of activity outside traditional agriculture. Utilisation of grass as one of the primary feedstocks for a biorefining industry has considerable potential. Characteristics selected for the livestock industry, such as high digestibility, high sugar, low lignin, coupled with low inputs potentially make grasses ideal for biorefining (e.g. production of fine chemicals, polymers, fuels, etc.) with no new knowledge or change in grassland management practice required, whilst maintaining current biodiversity.

In addition to the high levels of sugars in these grasses, they tend to be more efficient in their use of fertiliser than standard varieties, and are highly productive for more than 10 years. It is predicted that co-sowing these grasses with clover to produce mixed swards could reduce the nitrogen input by up to 50% (Morris et al., 2008). The subsequent need for lower amounts of fertiliser per hectare in areas where these grasses are grown is extremely important, not just from an economic perspective, but also because of the reduced impact on the ecology and hydrology of some areas of Wales which are designated as nitrate vulnerable zones (NVZs) (Welsh Assembly Government, 2007e). Moreover, reduced nitrogen application would have a significant effect on green house gas (GHG) emissions because of the high energy demand of the Haber process.

In terms of utilising temperate grasses as bulk feedstocks for a sustainable biorefining industry in Wales, one of the critical factors will be to maximise the levels of available polysaccharides present for downstream processing by fermentation. This can be achieved by the selection of high sugar, low lignin, highly digestible varieties, in combination with effective mechanical processing to fractionate the grass following harvesting. There has been a considerable amount of work carried out in Wales over many years in order to breed high sugar perennial ryegrasses for use as livestock fodder. These breeding programmes, conducted at IBERS, Aberystwyth University have resulted in several new high sugar varieties of ryegrass being developed (e.g. Aberdart and AberMagic). These new types have between 25 and 50% higher levels of water soluble carbohydrates than older varieties, which could potentially be fermented to produce platform chemicals and biofuels (IGER, 2007).

The bulk of this biomass consists of vegetative growth comprising highly digestible leafy material which is composed of approximately 45% cellular material and 55% cell wall components. The cellular fraction contains carbohydrates, protein, lipids, soluble phenolics and nucleic acid. The carbohydrate component consists predominantly of water soluble polymeric fructan (chains of fructose, a C6 sugar), the major storage carbohydrate in temperate grasses, which can comprise up to 35% of the dry matter content in high sugar varieties. The cell wall component is made up of cellulose, hemicelluloses and lignin. Cellulose (25% of dry matter) is an insoluble polymeric carbohydrate consisting of β(1–4) linked glucose (C6 sugar) units, whilst hemicelluloses (20% dry matter) are polymers predominantly made up of the C5 sugars xylose and arabinose (16% dry matter). Grass hemicellulose polymers are crosslinked *via* ferulate bridges (Buanafina et al., 2006). Lignin (4–6% dry weight) is a polymer of various cinnamic alcohols (sinapyl, coniferyl and coumaryl alcohols), which crosslink together in the form of phenylpropane units, and binds covalently to hemicelluloses to form a matrix. The chemistry of the cell wall carbohydrates, cellulose and hemicellulose, and their utilisation is described in detail elsewhere (Kamm et al., 2006). In addition to sugars (polysaccharides), a review on the industrial uses of forage grasses (Fowler et al., 2003) indicated that there are seven additional materials present, with the potential to be exploited in a variety of industrial applications. These include proteins, enzymes, colourants, fatty acids, silica, minerals and alkaloids. The detailed composition of perennial ryegrass is shown in Fig. 2.

In an extensive study carried out by Smit et al. (2008), looking at spatial distribution of grassland productivity and land use in Europe, it was shown that the regions of greatest productivity were in Wales, Ireland, England and the Netherlands. Productivity in these regions ranges from 8 to 11 t/ha in the Netherlands, 7 to 10 t/ha in Ireland, 7 to 10 t/ha in England and 8 to 9 t/ha in Wales. However analysis of the proportion of permanent grassland in these regions shows that Wales has the highest proportion, whilst productive regions in England and the Netherlands have the lowest. Inclusion of modern, high-yielding varieties in non-permanent pasture will undoubtedly account in part for the high productivity observed in these regions. This data implies that there is scope for increasing productivity of Welsh pastures by reseeding permanent pastures. Wales is also at an advantage in comparison to more geographically remote regions such as Ireland which will inevitably have higher transport costs.

In 2006, permanent grassland accounted for 62% of the agricultural area in Wales, which equated to ~1million ha, with a further 409,000 ha of rough grazing and 180,000 ha of common grazing land. A further 10% was assigned to land classed as suitable for growing arable crops. The majority of this land was composed of temporary grassland (133,000 ha), with 63,000 ha of cropped land being used for the production of fodder and

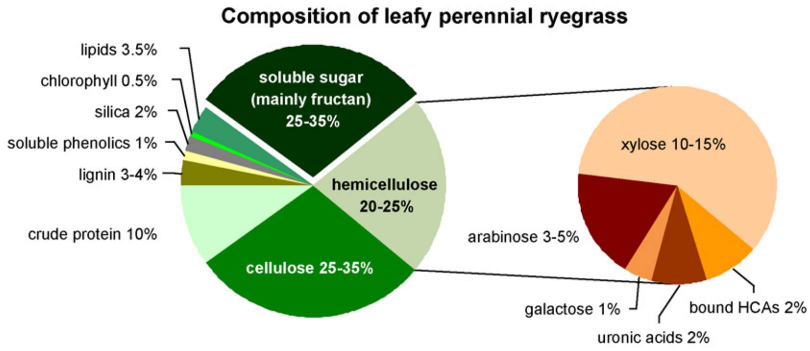

Fig. 2 – Composition of perennial ryegrass (IBERS, Aberystwyth University).

cereal crops. The main areas of arable land in Wales are located in the South and South West, whilst Mid- and North Wales contain a higher proportion of permanent, common and rough grazing land which is unsuitable for arable crop production. The total area of both arable and grassland in Wales between 1999 and 2006 is shown in Fig. 3.

3.3.3. *The green biorefinery as a model for manufacturing downstream products from grass*

The majority of commercial biorefineries currently operating are known as first generation, i.e. they utilise part of the plant as a primary source of material for the biorefining activity (CI-KTN, 2007). First generation processes utilise readily fermentable sugars and starch, in microbial transformations. An example of this type of process is carried out at the NatureWorks facility (Nebraska, US) which uses maize cob (high in starch) as a source of sugar from which lactic acid is produced by fermentation. This is then converted to polylactic acid which has many uses in the bioplastics sector (NNFCC, 2008c; Gruber et al., 2006).

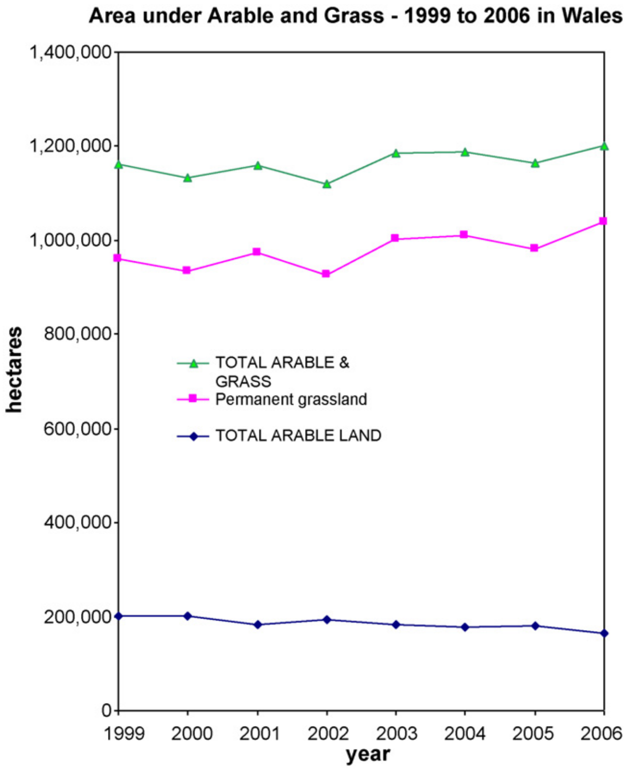

Fig. 3 – Arable and grassland areas in Wales 1999–2006 (Welsh Assembly Government, 2007b).

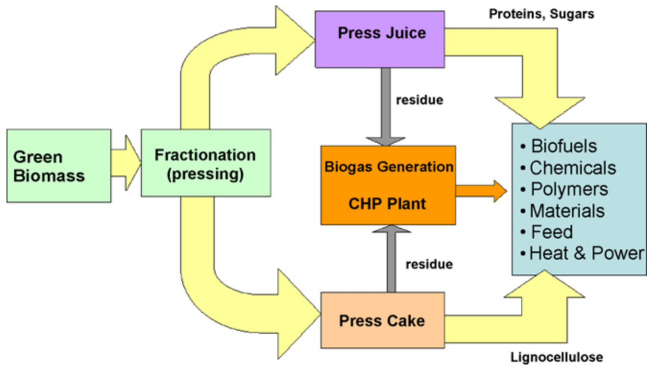

Fig. 4 – The green biorefinery for processing green biomass (NNFCC, 2007).

It is generally accepted that in order for biorefining from plant feedstocks to become sustainable, then technologies utilising the whole plant, including the bulk fibre fraction are required. Second generation processes are currently in development to release the sugars and other molecules 'locked up' in the lignocellulosic fraction. These technologies include steam, acid, alkali and enzymic treatments to produce fermentable sugars which can then be used in microbial biotransformations to produce a range of chemicals (Kamm et al., 2006). Optimised fermentation of the sugars derived from the lignocellulosic fraction, and storage sugars following enzyme hydrolysis, requires organisms that can ferment C5 and C6 sugars.

There are several current models for how biorefineries might work, based on the types of feedstocks used (NNFCC, 2007). Fig. 4 shows how one of these, a second generation green biorefinery for the processing of green biomass, might operate in the future. This type of biorefinery would be suited to the processing of grass biomass in Wales and involves the initial separation of the grass juice from the lignocellulosic fraction. Using this processing strategy, high sugar perennial ryegrass would ideally be processed on farm to give a sugar-rich juice, which would be fermented locally, and a stable highly digestible fibre. The stability of the fibre means that this material can be stored and used to keep a central plant running throughout the year. Removal of most of the liquid by juicing makes the fibre cheaper to transport. The sugar-rich juice, which also contains soluble proteins and essential minerals would ideally be fermented on farm. The type of fermentation would depend on the products required, for example, anaerobic digestion for the production of methane, or fermented to produce bulk chemicals such as lactic acid. The products could be extracted at a local co-operative. An infrastructure to facilitate this would need to be developed.

The fibre produced following juicing can be converted to fermentable sugars using a cocktail of commercial enzymes. This fibre also has a range of alternative uses, including animal feed (because of its high protein content), as reinforcement in biocomposite materials for a range of applications, or used as fuel for a combined heat and power (CHP) source for the biorefinery. The range of processing technologies available to fractionate process and extract the green biomass has been reviewed recently (Kamm et al., 2006), but the key point to note is that in order for such a process to be sustainable and economically viable, the biorefinery must extract the maximum value from the biomass by producing a broad spectrum of products, in much the same way as oil refineries operate currently, using crude oil as a feedstock. In this way, the value chain of different products discussed previously would be created, which would maximise the economic efficiency of the process.

One of the concerns in assessing the economic viability of biorefining in Wales is the relative bulk of biomass in comparison to crude oil, which will obviously impact on transportation costs and other logistical factors including storage of material prior to processing. Biomass has a narrow, annual harvest period in comparison to the year round feedstock requirements for a biorefinery and so storage will form a crucial part of any facility in Wales. The main considerations for biomass storage are to ensure that material remains dry, in order to prevent degradation with the resulting loss in yield of material for downstream refining, and also dry matter loss if storage temperatures are too high. The key factor in reducing biological changes in the biomass is to ensure low moisture content (<15%) of the stored material, which in Wales would preclude outside storage of material prior to processing. Increasing the bulk density of feedstock in order to reduce transport and storage costs, by baling material will also impact on the viability of the overall process (Hess et al., 2007).

It will therefore be important to ensure that as much on-farm processing as possible takes place prior to transporting to central refinery facilities. Whilst the ability of farmers to harvest, fractionate and process grass on-site, in order to lower production costs, will be limited because of the many varied skills required to achieve this, a compromise solution may be to use regional biomass processing facilities (RBPs), or cooperatives. A model for how such units might work is presented in Fig. 5.

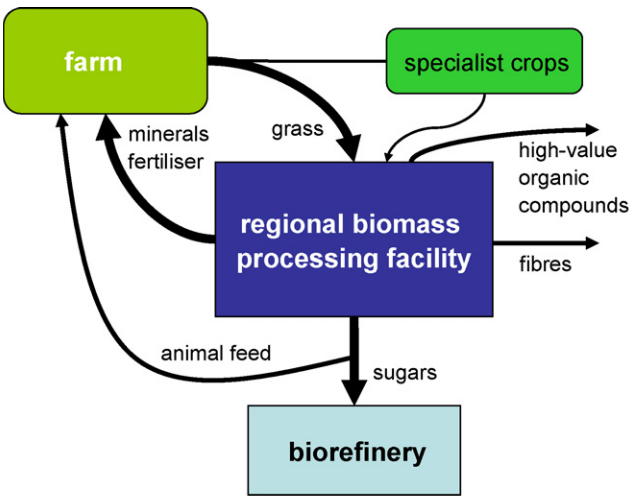

Fig. 5 – The concept of a regional biomass processing facility (CI-KTN, 2008).

This type of facility would allow farmers to transport grass and other crops, following initial on-farm processing to a regional 'hub' where the biomass could be further fractionated into fermentable sugars, fibres and high protein material that could be used as animal feed. The sugars generated could then be transported to a much larger central biorefinery facility for the production of high volume, lower value chemicals previously discussed. In addition to the production of these bulk chemicals, there may also be the potential to use RBPs to produce high value, low volume performance chemicals from other 'specialist' plant feedstocks for use in the pharma- or nutraceuticals industry. An example of this type of chemical is the Alzheimer's drug galanthamine which is currently extracted from daffodils grown in Mid-Wales (www.alzeim.org).

There are several obvious benefits to using this type of RBP facility. These include a reduction in transport, processing and storage costs, through biomass densification; the ability to homogenise different types of biomass supplied by individual farmers to produce a bulk feedstock with a more consistent composition and also reduced capital expenditure costs through the creation of these regional cooperatives.

A full analysis of on-farm and regional biomass grass processing in Wales is still required in order to determine the most viable route forward, but a response from the Royal Society of Chemistry, following a Royal Society call for evidence on biofuels development, cited an example of demonstration grass biorefinery in Germany. Studies from the 25,000 t green biorefinery facility located at Brandenberg indicated that the transport of biomass over distances >30 km was uneconomic, implying that this 'model would seem to favour production of biofuels (and other products) in close proximity to where the feedstock is grown' (Royal Society of Chemistry, 2006).

3.3.4. *The commercial viability of a grass biorefinery in Wales*

3.3.4.1. Grass production costs and land requirements for biomass cultivation. Table 2 shows the production costs and yields of perennial ryegrass, currently grown as a silage crop for animal fodder, over a range of intensity scenarios. Although the yields for grass across these different scenarios range from ∼9 to 12.7 t/ha, previously quoted figures indicate that in Wales, up to 15 t/ha yields are possible. This reflects the climatic conditions in Wales which are suited to the cultivation of grass.

Trials using some of the new high sugar grasses developed at IBERS, Aberystwyth University indicate that yields of 18 t/dm ha year, or greater are possible.

A feasibility study published by the Chemistry Innovation-Knowledge Transfer Network, in collaboration with Bangor and Aberystwyth Universities, examined one possible scenario for establishing a biorefining based industry in Wales, using grass as a bulk feedstock (CI-KTN, 2008). It was noted that in the period between 1999 and 2006, the levels of temporary grassland in Wales decreased from ∼130,000 to ∼100,000 ha, with a decrease in total arable land from ∼200,000 to 163,000 ha. (Welsh Assembly Government, 2007b). This was due to reduced competitiveness with other arable regions of the UK and higher input costs (e.g. fertiliser). The study concluded that if stocking densities of this grade of land were returned to the levels observed in the late-1990s, then an additional 50,000 ha of land would be released for grass cultivation. Using the average dry matter yield from the three scenarios presented in Table 2, this could potentially result in

Table 2 – Production costs for perennial ryegrass as a silage crop (ABC guides, 2007).

	Low intensity (£/ha)	Medium intensity (£/ha)	High intensity (£/ha)
Establishment cost	32	32	32
Annual fertiliser (kg/ha)	170N:60P:160K	275N:80P:250K	365N:100P:320K
Annual fertiliser cost[a]	143	224	292
Total annual costs	175	256	324
Fresh yield (t/ha)			
1st cut	20–22	23–25	22–24
2nd cut	8–10	13–14	13–14
3rd cut	–	–	9–10
Total fresh yield	35–42	45–51	52–58
Dry matter yield (t/ha)	8.9	11.0	12.7
£ per tonne dry matter	19.8	23.2	25.6

[a] Fertiliser costs are based on 2007 data; costs have increased significantly during 2008.

∼550,000 t of dry grass being generated as a resource for a central biorefinery. Using the figure of 18 t/ha, then in theory this could produce over 900,000 t/ha of dry grass. In addition to the 50,000 ha of land created through restocking, a recent report by the Assembly Government in Wales (WAG, 2008c, Axis 2) stated that there is an additional 600,000 ha of available land that is suitable for growing biomass for energy conversion. If a percentage of this was used for grass cultivation, then yields of dry grass *per annum* in excess of 1 million t could, in theory, be achieved.

The output of a commercial scale biorefinery is likely to be in excess of 100,000 t pa (see Section 3.3.4.3), but how does this relate to the quantities of grass that could be produced in Wales?

More detailed studies are required in order to determine the likely fermentation yields using sugars produced from grass in Wales, but by comparison it is known that 0.385 t of anhydrous ethanol can be produced from 1 t of sugar (Fleay, 2006). Using high sugar ryegrass as the model, it was assumed that 40% of the available sugars could be fermented to produce a range of platform chemicals. Based on a water soluble carbohydrate content of 25% (see Fig. 2), this would require 1 million t pa of dry grass as a feedstock, which would result in a potential output capacity of 100,000 t pa. This is in accordance with the potential grass yields using 50,000 ha of recovered temporary grassland as discussed above.

In terms of comparison with previous UK based studies on the processing of green biomass, a report that assessed the potential for establishing a grass biorefining facility in England was published by Agros Associates in 2004 (NNFCC, 2004). As well as identifying potential products that could be extracted from grass and their associated markets, this study attempted to assess potential sources of grass, volumes required and possible locations for a biorefinery facility.

The potential site chosen for the theoretical study was in Northern England between the large urban areas of Bradford, Keighley and Ilkley. This area was 500 km^2 (50,000 ha), containing ∼20,000 ha of agricultural land used for both livestock and grass conservation. The grassland area was composed of 12,410 ha of permanent and 1,400 ha of temporary grassland and for the study, an assumption was made that 10% of this area could be withdrawn from hay, silage and grazing without any major effect on the livestock market. This gave a total yield (based on 10 t/ha of dry matter per annum) of 13,550 t. The report stated that additional sources of grass could be obtained from domestic recycling of green waste (300 t dry matter) and grass clippings from golf courses in the region (54 t dry matter), as well as the potential for an extra 300 t pa from municipal/school sports pitches in the region. The study suggested that by establishing a biorefinery close to the centre of the Bradford Council area, all the grass required would be produced within a 10 mile distance from this processing facility. A dry matter weight of ∼14,000 t would equate to 56,000 t of fresh material (based on 25% dry matter yield) and following fractionation and extraction, it was estimated that a range of products would be generated from this, including fibre (3300 t pa), protein (2100 t pa), soluble sugars (∼1000 t pa), polysaccharides (∼3000 t pa), amino acids (210 t pa) and chlorophyll (21 t pa).

Following an assessment of the annual processing costs for this pilot plant facility (∼£265,500) and potential revenue streams generated (∼£550,000), the broad conclusions from the study were that the concept of a biorefinery based on mixed herbage was both technically and financially viable. The increasing pressure for industrial end users to obtain materials from renewable sources and the existing niche markets for some products already extracted from grass were also cited as positive indicators for establishing such a facility. The report did however note that there were some barriers to overcome, including the requirement for better market information on specialist chemical sectors in order to guide the selection of potential products from grass and the lack of technical information in the public domain on the likely yields and quality of chemicals that could be produced from green biomass.

3.3.4.2. *Sugar production costs from perennial ryegrass.* From the preceding discussion, it can be seen that theoretically Wales has access to sufficient quantities of biomass to supply a commercial green biorefinery, but an assessment of the likely sugar production costs from grass is of central importance in assessing the viability of such a facility.

As shown in Table 2, the production of ryegrass for silage as animal fodder ranges in cost from £20 to £26 which, in turn, gives a cost per tonne of sugar in the harvested grass of £83–£108. Fig. 2 shows that perennial ryegrass is composed of 25–35% water soluble carbohydrate (WSC), which is predominantly fructan. In making an assessment of the cost of isolating the fermentable sugar that could be produced from grass and utilised in a biorefinery, the lower figure of 25% WSC content was used, along with an assumption that 80% of the available sugars could be isolated using a combination of fibre cake pressing and hot water extraction. A UK study on the use

Table 3 – Scenarios for the production of biobased chemicals from biomass in Europe until 2050 (The BREW Report, 2006).

Factor	Scenario		
	1. **Low** Unfavourable to development of biobased chemicals	2. **Medium** Moderately favourable to development of biobased chemicals	3. **High** Very favourable to development of biobased chemicals
Oil price	Up to $30 barrel	Up to $66 barrel	Up to $83 barrel
Rate of technology development	Low-technology remains the same	Future technologies from 2040	Future technologies from 2020
Bio-feedstock cost	€400/t sugar	€200/t sugar	€70/t sugar
Chemicals market	0% pa growth	1.5% pa growth	3% pa growth
Subsidies	None	None	1–5% of product value

of sugar beet as an industrial biorefining feedstock indicated that isolation of 90% of soluble sugars was possible, by slicing the root and immersing the beet in water at 70°C for 100 min (NNFCC, 2007b). By factoring in additional costs for both pressing and hot water extraction carried out on a local basis (i.e. on-farm), an approximate cost for 1 t of sugar in a dilute liquor was £120–£150 (CI-KTN, 2008).

Further analysis is required in order to consider the benefits of transporting this liquor to a regional biomass processing hub, or central biorefinery location following extraction, or pressing, extracting and concentrating prior to transportation. Logistical considerations will form an important part of this analysis, particularly in view of the marginal transport infrastructure in many rural areas of Wales.

Given the theoretical cost of £120–£150/t of sugar from perennial ryegrass, how does this relate to the potential viability of a commercial biorefinery in Wales?

A comprehensive study that examined the potential viability of manufacturing biobased chemicals from biomass and relating this to both the cost of crude oil and sugar was published in 2006 (The BREW project, 2006). This investigated three scenarios for the production of chemicals from biomass in Europe, up to 2050. These scenarios ranged from low crude oil/high sugar costs (1) to high crude oil/low sugar costs (3) with an intermediate scenario between the two extremes (2). Factors such as the availability of subsidies, rate of technology development and growth in the chemicals markets were also considered (see Table 3). Given the theoretical cost of sugar production from perennial ryegrass grown in Wales, of £120–£150/t, then this would fit into scenario 2, where the production of biobased chemicals is moderately viable, with a crude oil price of $66 per barrel. However, given the increasing volatility in the crude oil price (reaching a high of $146 per barrel in July 2008), the production of biobased chemicals is likely to become increasingly favourable.

3.3.4.3. Comparison with existing and planned UK based biofuel production facilities. In order to be economically viable, the output for a commercial biorefinery in Wales is likely to be in the region of 100,000 t pa, which is in line with the minimum output capacities of currently operating biofuels plants. This is feasible, as discussed in Section 3.3.4.1.

A feasibility study examined the potential for establishing a UK based biorefinery for the production of poly lactic acid (PLA). In this proposal, PLA would be produced from lactide monomer, which is itself produced from lactic acid (LA). LA would be made by fermentation of dextrose derived from starch, obtained by milling feed wheat grown in the UK. In order to be commercially viable, it was predicted that the output of such a biorefinery would need to be 132,000 t of PLA *per annum* (NNFCC, 2008c), which would require >490,000 t pa of wheat.

There is currently only one commercial bioethanol plant which is operational in the UK and this is run by British Sugar at Wissington, Norfolk. This currently produces ~55,000 t pa of bioethanol, using 7 million t pa of sugar beet as the feedstock, but this is supplemented by a range of value-added products including recovered topsoil, stone, and lime—by products as soil improvers and a range of graded sugar products (NNFCC, 2007b).

There are however several operational biodiesel plants in the UK and other planned bioethanol production facilities for the UK (NNFCC, 2009). Operational biodiesel plants in the UK include the 100,000 t pa Greenergy plants an Immingham that utilise waste vegetable oil and the 250,000 t pa Biofuels Corporation facility at Wilton that uses palm, soya and rapeseed oils. There are several planned bioethanol plants for the UK which will all use wheat as the primary feedstock. These include two at Immingham (Abengoa, 400,000 t pa and Bioethanol Ltd., 200,000 t pa) and facilities at Hull (Vivergo, 320,000 t pa) and Wilton (Ensus, 315,000 t pa). Construction of the last two plants started in 2007.

There are a large number of biorefinery initiatives in Europe based on a range of different feedstocks. A detailed review is outside the scope of this paper, but of these, a number use grass as a feedstock as well as immature cereals, legumes and sugar beet. These grass based biorefinery initiatives are located in Ireland, Belgium, Austria, Poland, Germany, and the Netherlands. They use grass either fresh or as a silage to produce a range of products such as organic acids, insulation materials, high value chemicals and alcohols (Van Ree and Annevelink, 2007).

3.4. *Issues affecting the implementation of a national biorefining strategy in Wales*

To summarise, there is a range of challenges which will need to be addressed before a sustainable biomass-based industry economy can be created in Wales. These include:

- Identifying materials that have commercial value and that should be isolated and purified prior to any chemical or biological transformation of the bulk biomass.
- Identifying key platform chemicals and extractives that can be produced from these feedstocks and developing the large scale technology to manufacture them.
- Identifying potential end users and market requirements for bioderived chemicals.
- The need to identify suitable non-food crop(s) and the expertise to cultivate, harvest, store and process material.

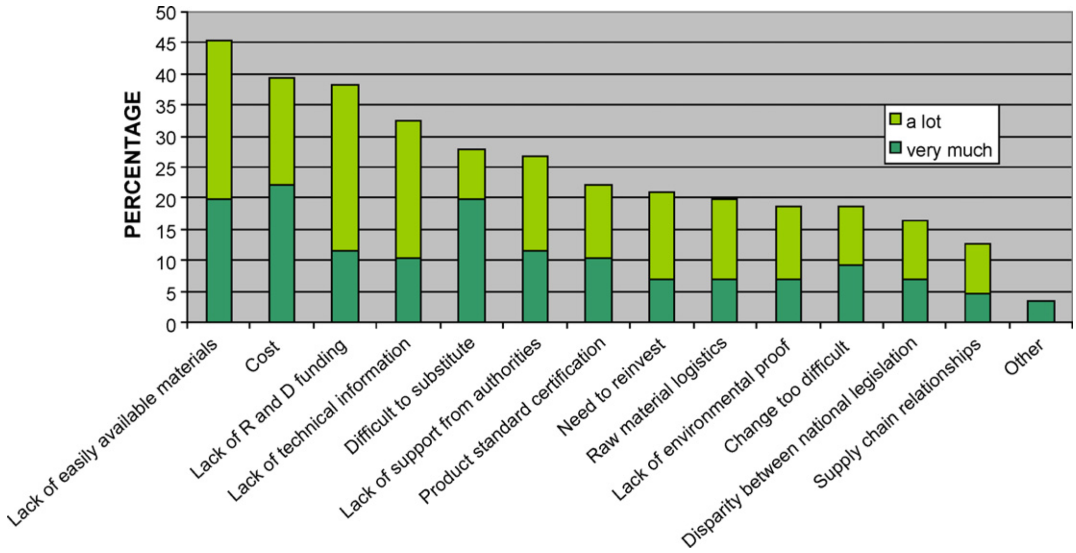

Fig. 6 – Perceived or encountered barriers to the greater use of renewable feedstocks for sustainable materials (Elias et al., 2003).

- Matching the potential feedstocks to land areas to ensure that they do not compete with existing food crops, or result in change of land use, with the associated problems of reduced soil quality/drainage, etc.
- Formation of regional partnerships encompassing a wide range of expertise including biomass producers (farmers) biochemical processors (academic and industrial experts) and end users (industrial customers).

High sugar perennial ryegrasses have potential as bulk feedstocks for a biorefining industry in Wales, because they have been cultivated on marginal land for many generations. Consequently continued cultivation for this use would not compete with arable crops for food production, because those crops require land of higher fertility with lower annual rainfall and higher average temperatures than are generally found in many of the marginal upland areas of Wales.

There is concern at the moment, particularly with regards to the cultivation of particular crops for biofuels production, about the potentially negative impact that this change of land use could have on the environment. This includes issues such as reduced soil fertility because of nutrient leaching, soil erosion with large areas of land being ploughed and reduced levels of drainage due to soil compaction (Defra, 2008c). These concerns are currently being investigated in Wales by organisations such as CALU (Centre for Alternative Land Use, Bangor University, www.calu.bangor.ac.uk), the Wales Biomass Centre (Cardiff University, www.walesbiomass.org) and the Welsh Assembly Government (AEG Energy and Environment, 2008). If the decision is taken to increase the levels of production of these grasses, then it will not be necessary for large areas of land to be ploughed in order to reseed with the high sugar varieties, because of techniques such as slot seeding. This involves cutting narrow slots in the area for cultivation, with minimal land disturbance and introducing the new seeds into this slot. There is minimal ground preparation required prior to sowing, except a short cut of the existing grass and this technique is suitable for land masses of marginal fertility (Rural Development Service, 2004). There are technical challenges to overcome, not least of which may be harvesting these crops in wet upland areas where the slope gradient exceeds 15° and conventional harvesting techniques may not be appropriate.

In addition to concerns about the environmental issues surrounding land management, a review highlighted some of the potential problems that could affect temperate grasslands across Europe, in response to global atmospheric change (Sousanna and Luscher, 2007). It was noted that whilst elevated atmospheric carbon dioxide concentrations will, to some extent, reduce the vulnerability of pasture and forage production to climatic variation and change, there are a number of sub-optimal environmental and soil conditions that could ultimately make the conservation of grassland stocks increasingly difficult. One of these is the fact that whilst elevated CO_2 concentrations tend to reduce the sensitivity of grassland to low levels of precipitation, the result is progressive nitrogen limitations on plant growth. This could be alleviated through significant external input of nitrogen, by increased use of mineral fertiliser or nitrogen fixing legumes.

One of the other major challenges in assessing the potential sustainability of a biorefining based industry in Wales, is an understanding of the economics of the whole process from sourcing and cultivating seeds through to harvesting, storage and processing of the fractionated biomass, extraction/purification of end products, followed by transportation to customers. A scoping study investigating bioproducts in Wales (Elias et al., 2003), focused on the potential impact that the use of sustainable biorenewables would have on companies across the region. In assessing the concerns of companies regarding the use of renewable materials, the main issues were lack of readily available materials, their cost and the lack of available funding for research and development in this area (see Fig. 6). Any national biorefining strategy implemented across Wales would need to address these concerns as a matter of priority.

Another factor to consider within Wales is whether the existing transport infrastructure can cope with the expansion in biorefining capacity that would be required in order to ensure long term sustainability of a biomass-based economy. Fig. 7 (Packwood, 2008) shows the key transport links in Wales. It can be seen that the rail and road links between England and Wales are good in both the north and south of the Principality, particularly so in South Wales with good motorway access. Transport networks between North and South Wales

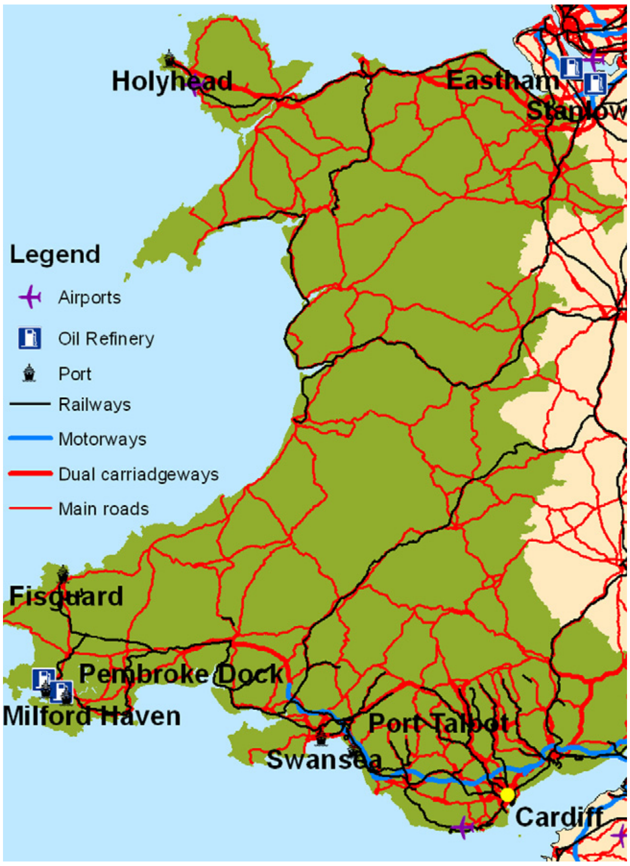

Fig. 7 – Transport infrastructure map of Wales (Packwood, 2008).

however are more limited and roads offer the main means of freight movement. These limited transport links between North and South Wales reflect the geography of the region, as well as traditional areas of economic development. This issue will be addressed as part of WAGs integrated transport/freight strategy (Welsh Assembly Government, 2008d). Wales has a number of sea ports, which provide good marine links with other nations, and are particularly important for oil, steel, fishing, agro-economy and leisure use. The West Wales and the Valleys area have four ferry ports. These are at Holyhead, Fishguard, Pembroke Dock and Swansea. In addition, Milford Haven and Port Talbot provide deep berthing facilities. Additionally, there are smaller port facilities in North Wales located at Penrhyn and Mostyn.

Allied to a good transport infrastructure is the requirement to access the engineering technologies currently in use at oil refineries, in order to ensure that the biorefining of biomass has a sustainable future. Wales has two existing oil refinery locations at Milford Haven and Pembroke in the South West. North Wales would potentially have good access to refineries located at Eastham and Stanlow in England. Biomass feedstocks are generally low density materials and will therefore be costly to transport in harvested form. Consequently, on-farm or regional, downstream processing of biomass must be maximised, before large scale fermentation or chemical modification that would take place in central refinery locations.

Key to the success of this strategy will be the creation of regional and ultimately national networked supply chains consisting of producers (farmers), processors and industrial end users.

3.5. *The future for biorefining in Wales*

There is currently a growing industrial demand for alternative biobased, renewable feedstocks which could ultimately be part of the solution for replacing fossil fuels as a source of chemicals, fuels and energy. This demand is being driven by a combination of customer requirements for renewable sources of these commodities which have a reduced impact on the environment and also increased legislation and regulation which requires companies to reduce their GHG emissions, and focus more on sustainability and renewable materials.

There are several challenges in using biomass as the raw material for a biorefining based industry in an analogous way to the use of crude oil in the petrochemical refineries. Central issues include efficient land management to ensure consistent biomass supplies which are tailored to the specific climate, soil fertility and hydrology of the different regions of the UK; suitable bio/chemical processing technologies to facilitate production, extraction and purification of these commodities and an efficient transport infrastructure for the movement of raw materials and products around the UK and abroad.

What is apparent is that for biorefining to fulfil many of the UK government and EU targets on renewability for key commodities, then the different regions of the UK will need to work together in a coordinated programme of activity so that the feedstocks and products generated in each region complement each other.

For example, a recent feasibility study commissioned by a consortium of academic and industrial partners in NE England investigated the sustainable use of wheat for the production of biofuels, platform chemicals and energy (CI-KTN, 2007). Indeed, four refineries producing bioethanol from wheat are currently planned or being built in this region, because of the close proximity to the cereal crop growing areas (NNFCC, 2008b). However, it is clear that there will be increasing future pressure on the wheat crop in this region, for the competing production of these different commodities. It is not yet clear whether the planned expansion in biorefining capacity can be supported by current or even proposed increases in crop production (NNFCC, 2008d). It is feasible that complementary activities taking place in Wales using high sugar perennial grasses could supplement a UK requirement for biobased products manufactured from sustainable sources of biomass.

In doing so, it is anticipated that not only will inward investment in Welsh biorefining initiatives be forthcoming, but this will also facilitate economic and social regeneration of the rural communities in the convergence regions.

4. Concluding remarks

The preceding discussion indicates that Wales has potential access to at least 900,000 t of dry matter using high sugar perennial ryegrass grown on 50,000 ha of recovered temporary grassland. This could be used in a commercial scale biorefinery with a potential output of ~100,000 t pa and with predicted sugar production costs of £120–£150/t from this grass. This fits into a scenario which is moderately favourable for the production of biobased chemicals, given the current crude oil price, but this will undoubtedly become more favourable as oil prices increase in the future. However, there are clearly a number of challenges that need to be addressed before a more definitive assessment of quantitative feedstock requirements could be made. These include optimising fermentation technology in order to produce a range of microbial organisms that can be used to selectively ferment different chemicals; careful choice of target products for the biorefinery; the logistics considerations (including upgrading costs for regional transport infrastructure); the capital cost implications of creating a network of regional processing hubs, or cooperatives linked to central biorefinery locations and a full environmental impact assessment of any large scale biorefining activity.

The challenge will be to create a framework which will facilitate the change to a coordinated economy for the UK based on renewable technologies, of which biomass conversion would be part, before access to current fossil fuel reserves runs out. Given these pressures, it is likely that commercial second generation biorefining facilities will need to be operating in Wales within the next 10 years.

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