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## ABSTRACT

*Lignocellulosic biomass is seen as an attractive feedstock for future supplies of renewable fuels, reducing the dependence on imported petroleum. However, there are technical and economic impediments to the development of commercial processes that utilise biomass feedstocks for the production of liquid fuels such as ethanol. Significant investment into research, pilot and demonstration plants is ongoing to develop commercially viable processes utilising the biochemical and thermochemical conversion technologies for ethanol. This paper reviews the current status of commercial lignocellulosic ethanol production and identifies global production facilities.*

## INTRODUCTION

Escalating petroleum prices and the threat to fuel security are strong drivers in the search for sustainable fuel alternatives. Increasing evidence that rising carbon dioxide levels are contributing to global warming, and the growing consumer demand for environmentally-friendly energy solutions have also added to the attractiveness of biofuels.

Governments around the world have recognised the role that biofuels will play in a renewable fuels portfolio and have introduced minimum targets for their implementation in the future [1].

Lignocellulosic biomass is seen as an attractive feedstock for renewable fuels, particularly ethanol. Lignocellulosic feedstocks include agricultural residues, wood, municipal solid waste and dedicated energy crops which have significant advantages over first generation feedstocks for ethanol production. The net energy balance of lignocellulosic ethanol, in terms of energy in/energy out, has been shown to be significantly lower than ethanol produced from sugarcane and starch feedstocks [2]. Additionally, life-cycle emissions of green house gases are reported to be 50-85% lower for lignocellulosic ethanol than those from gasoline, with corn ethanol providing a 25-40% reduction [2,3].

Lignocellulosic ethanol presents a means of satisfying demand for ethanol without further pressuring food supply. Marginal land, not suitable for food crops can be used, with less intensive use of water and fertilisers. Production of cellulosic ethanol can also utilise 'waste materials' such as agriculture and forest residues as feedstocks.

## TECHNOLOGIES

Lignocellulosic biomass can be converted to ethanol using either a biochemical or thermochemical platform.

### Biochemical conversion

In biochemical conversion the plant fibre is separated into its component parts; cellulose, hemicelluloses, and lignin hence the term lignocellulosic or cellulosic ethanol. The cellulose is then further broken down to simple sugars that are fermented to produce ethanol. Typically the process is carried out in four stages (Fig. 1):

1. Physical or chemical pretreatment of the plant fibres to expose the cellulose and reduce its crystallinity,
2. Hydrolysis of the cellulose polymer, with enzymes or acids, to simple sugars (glucose),
3. Microbial fermentation of these simple sugars to ethanol, and
4. Distillation to produce 99.5% pure alcohol.

Lignin is a byproduct of this process, and can be used as a boiler fuel or processed into specialty chemicals. Hydrolysis and fermentation can be conducted simultaneously in one stage but simultaneous saccharification and fermentation (SSF) is yet to be implemented commercially since the optimal conditions for hydrolysis are different to those for fermentation and improved micro-organisms are necessary.

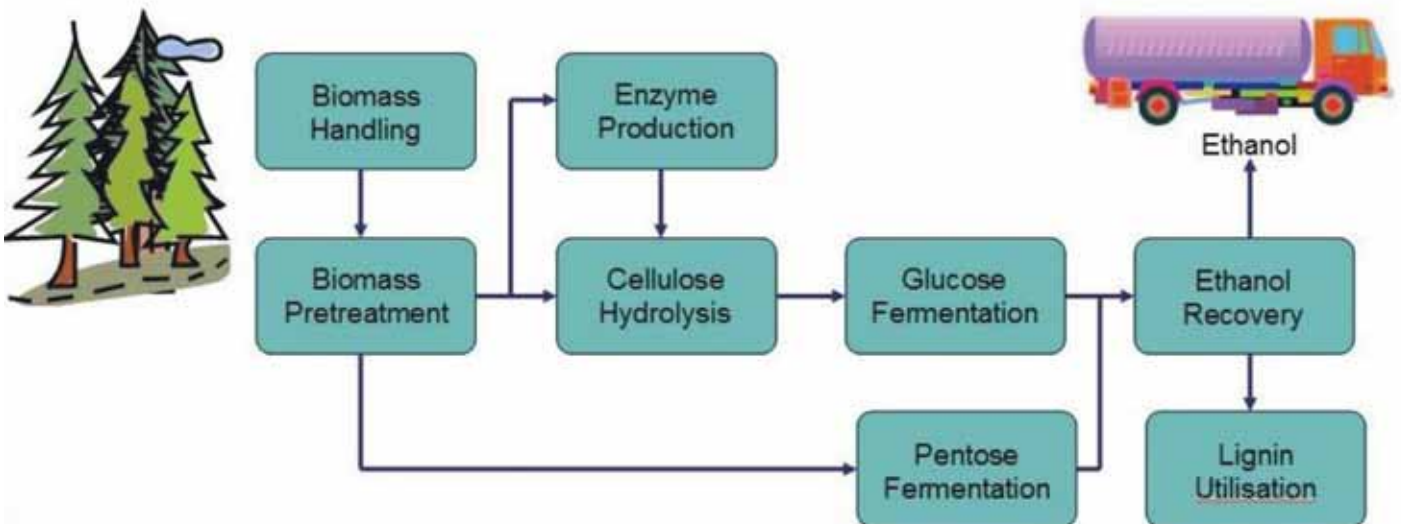


Figure 1: Schematic of a biochemical cellulosic ethanol production process [4].

### Thermochemical conversion

Thermochemical conversion transforms the lignocellulosic feedstock into carbon monoxide and hydrogen (syngas) by partial combustion (Fig. 2). These gases can be converted to liquid transportation fuels or commodity chemicals by catalytic or biological pathways. The biological process converts carbon monoxide to ethanol using a non-yeast fermentation microorganism (eg *Clostridium ljungdahlii*).

Alternatively, the syngas can be fed to a catalytic reactor where the carbon monoxide and water are combined via a metal-catalysed process to produce ethanol, other higher alcohols and liquid fuels (Fischer-Tropsch liquids). Gasification is important because lignin, which constitutes about 25 – 30% of cellulosic biomass, is also converted to syngas.

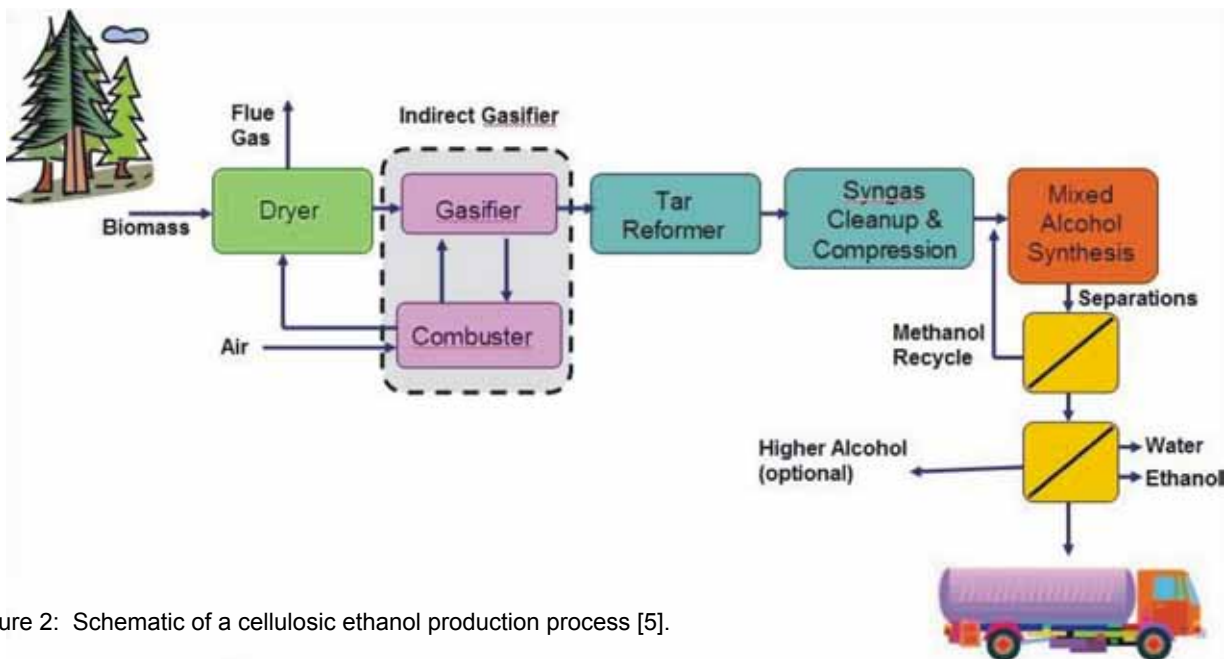


Figure 2: Schematic of a cellulosic ethanol production process [5].

## CURRENT STATE OF TECHNOLOGIES AND TECHNICAL CHALLENGES

### Biochemical

**Pretreatment** - the usefulness of cellulose as a feedstock has been limited by its rigid structure and difficulty to breakdown into simple sugars. Cost-effective pretreatments are needed to liberate the cellulose from the lignin/hemicellulose matrix and reduce its crystallinity. Pretreatments of increasing severity are needed as feedstock recalcitrance increases from nonwoods (agricultural residues) to hardwoods to softwoods.

Many pretreatments are currently being explored, ranging in chemistries from very acidic to mildly alkaline, such as dilute acid, ammonia fibre expansion (AFEX), wet oxidation, organosolv, steam explosion. The ideal pretreatment must also minimise the formation of degradation products that can inhibit the subsequent hydrolysis and fermentation processes.

**Lignin** – As lignin is mainly responsible for lignocellulosic recalcitrance, particularly in softwoods, studies have shown its separation during pretreatment greatly enhances cellulose accessibility and enzyme effectiveness [6]. Pretreatments that minimise lignin redeposition and condensation on the fibre surfaces are favoured. Separation of lignin and production of specialty lignin co-products also has the potential to improve the overall economics.

**Hydrolysis** - Cellulose is broken down into individual glucose units by cellulase enzymes, under mild conditions. Research is ongoing to find cost-effective enzyme systems that produce high sugar yields at accelerated rates and without the formation of inhibitory byproducts. Currently, the per unit cost of enzymes is considered to be a deterrent to the commercial success of the biochemical pathway. Alternative strategies to reduce enzyme cost include the recycling of enzymes and the use of polymers to reduce the binding of enzymes to the substrate [7].

**Fermentation** - The hydrolysate contains both 5-carbon (pentose) and 6-carbon (hexose) sugars. The conversion of pentose sugars into ethanol is less efficient than conversion of hexose sugars. A system of mixed-sugar fermenting microorganisms is required to utilise the full range of sugars present and thus maximise the production of ethanol. Metabolic engineering is on-going to find low-cost, microorganisms capable of C5 and C6 sugar co-fermentation that are also resistant to inhibitors (acetic acid, furfural) that may be present.

### Thermochemical

**Contamination** – various components of the biomass feedstock can cause problems in the gasification and catalytic synthesis stages. Contaminants such as tars and inorganic components (halides, alkalis, ash) present in the syngas can deactivate the catalysts and must be removed prior to catalytic conversion. The formation of tars, and measures to deal with their removal, are significant challenges in biomass gasification. Advances in catalyst preparations are also needed in order to make large-scale biomass to liquid facilities practical.

## ECONOMICS

Both the biochemical and thermochemical pathways require sophisticated processing steps that have higher operating costs and need significant capital investment compared with grain-based ethanol processes. Based on the current state of technology, capital costs for biochemical cellulosic ethanol are estimated to be between US\$4.03 and \$5.60 per US gallon of annual capacity [8, 9]. Operating costs are estimated to be between US\$1.34 and \$1.69 per US gallon, depending upon the assumptions made about feedstock costs, enzyme costs, and the kind of pretreatment to be employed [8,9]. Projected capital costs for future plants employing anticipated improvements in biochemical conversion are estimated to be US\$3.33-4.44 per US gallon ethanol annual capacity with operating costs dropping to US\$0.40-0.89 per US gallon of ethanol (10). The US Department of Energy (DOE) has determined that competitiveness with petroleum can be achieved at an ethanol production cost of US\$1.07/US gallon (in 2002 dollars) and aims to achieve this goal by 2012 [5]. This compares to the production cost of Brazilian sugarcane ethanol of US\$0.81/gal.

Lignocellulosic based ethanol has a further advantage over starch based ethanol in that the feed stock is not commodity based and subject to brokers and trader speculation on pricing. Lignocellulosic based feedstocks avoid the arbitrage that starch-based ethanol is subject to; project developers are better able to forecast and manage feedstock costs reducing project risk. Many starch-based ethanol producers are currently struggling to survive and many may go bankrupt due to the volatile swings in corn, wheat, sugar and ethanol prices.

A recent study of the production of Fischer-Tropsch (FT) liquids from syngas has shown the thermochemical platform to be economically comparable to the biochemical platforms [8].

## CELLULOSIC ETHANOL PLANTS

This section provides brief details on all publically announced bioethanol plants based on lignocellulosic feedstocks. The authors have endeavoured to be comprehensive but do not guarantee all facilities are included. Table 1 summarises all known facilities as of February 2009, and these are shown geographically on Fig. 4.

Table 1: Lignocellulosic Facilities as at February 2009

	Pilot <sup>1</sup> / Demonstration <sup>2</sup>	Commercial <sup>3</sup>
Biochemical	25	9
Thermo Chemical	5	3

Note: 1. Pilot Scale is R&D  
2. Demonstration Scale is <10ML/yr  
3. Commercial Scale is >10ML/yr

### United States

Currently the US has a target of 136,260 million litres per year (ML/yr) of renewable fuels production by 2022. This target is only achievable with a majority of this renewable fuel coming from lignocellulosic material, such as corn stover, wood, switch grass, wheat straw and purpose grown energy crops.

Demonstration-scale cellulosic ethanol plants are under construction as part of the government's goal to make cellulosic ethanol cost competitive by 2012. The plants cover a wide variety of feedstocks, conversion technologies and plant configurations to help identify viable technologies and processes for full-scale commercialisation. All demonstration plants, which are sized at 10% of a commercial-scale biorefinery, are expected to be operational by 2012. Commercial-scale plants are in the planning stages. Demonstration and commercial plants include:

**Abengoa** - Abengoa is using a US\$76 million DOE grant to produce 42 ML/yr of cellulosic ethanol, in Hugoton, Kansas. The biomass plant will be situated next to a conventional cereal-to-ethanol facility to share feedstocks, including wheat straw and corn stover. Steam explosion pre-treatment will be used prior to enzymatic hydrolysis. The plant will be operational by 2010, and will have the capability of ramping up to 185 ML/yr. Since mid-2007, Abengoa has operated a pilot plant in York, NE using corn stover. 0.08 ML/yr of ethanol can be produced using enzymatic hydrolysis and fermentation of C5 and C6 sugars. Abengoa also has a demonstration scale plant in Spain (Fig. 3).



Figure 3: Abengoa, Castilla, Spain.

**Alico** had partnered with New Planet Energy, LLC to develop and commercialise gasification and biological fermentation of ethanol from syngas. Alico has decided to withdraw from this project. New Planet Energy is planning to move forward and is looking for a site in Florida.

**Alltech**, through its subsidiary Ecofin, is planning to develop a 4 ML/yr corn cob/corn stover and switch grass ethanol demonstration plant in Springfield, Kentucky. The facility will produce other value added chemicals and will have the capability to grow algae for biofuel production. A solid state fermentation process developed by Alltech will be used and the plant is expected to be operational by 2010.

**American Energy Enterprises (AEE)** has proposed construction of a 90 to 190 ML/yr cellulosic ethanol facility in New Milford, Connecticut. American Energy has partnered with two unspecified Bio-technology science companies and a major ethanol engineering company to complete the project. AEE intends to use plant biomass and wood waste as a feed stock for the ethanol facility.

**Bluefire Ethanol** will demonstrate proprietary concentrated acid hydrolysis to convert wood waste, sorted municipal solid waste, rice hulls and other cellulosic material to sugar for fermentation. Production capacity of 72 ML/yr is planned for 2010. Concentrated acid hydrolysis is reported to have high sugar yields (>90%) and can be easily adapted to a variety of feedstocks. Acid recovery and handling have been viewed as barriers to widespread use of this process.

**Coskata** has developed gasification to ethanol conversion technology that includes syngas cleaning, a proprietary syngas fermentation organism and ethanol recovery using per-evaporation.

Coskata claims to be able to produce cellulosic ethanol for less than the DOE benchmark price of US\$1.07/US gallon. The Coskata process has been developed quietly, intentionally keeping a low profile. Coskata developers have been awarded 16 patents and based on Argonne National laboratory analysis

is showing 7.7 times the energy output to energy input. Coskata has backing from GM and Khosla Ventures, they have not received a DOE award, but are planning an 0.16 ML/yr demonstration facility at the Westinghouse Plasma facility in Madison, Pennsylvania. Coskata is developing plans for a 200 to 400 ML/yr commercial scale ethanol facility in parallel with the design of the pilot plant.

**Flambeau River Papers**, Park Falls, Wisconsin, is a sulfite mill looking to implement an integrated biorefinery. The mill is planning to produce sulphur-free Fischer-Tropsch (FT) liquids (diesel and paraffinic waxes) from gasification of 1,000 bone dry ton of biomass (forest residue) per day. (BDT/d) Two stages of FT reactors are planned to convert the syngas to liquid fuel with capacity of about 57 ML/yr. Integration with the pulp and paper mill provides a heat sink for the generated energy.

**Fulcrum-Bioenergy** is developing the Sierra Biofuels Plant to convert 90,000 tons per year of municipal solid waste (MSW) to approximately 40 ML/yr of ethanol. Fulcrum is providing financing, design and construction services for the facility to be located near Reno, Nevada.

The Sierra Biofuels project uses a plasma enhanced gasification to create syngas from MSW and a proprietary catalytic technology to convert the syngas to ethanol.

**ICM** has received DOE funding to construct a 10 ML/yr cellulosic ethanol demonstration plant to be co-located at the existing 190 ML/yr corn-based ethanol plant in St Joseph Missouri. The facility will process a variety of feed stocks, including sorghum and switchgrass as well as corn stover residue. The process utilises biochemical conversion technology - Novozymes are a collaborator – with simultaneous saccharification and fermentation. Significant benefits are to be achieved via integration with the corn-ethanol process and utilization of the vast amounts of carbon dioxide that are given off. ICM intends to have the plant operational by Q4 2010.

**Mascoma** has a demonstration plant (0.8-1.9 ML/yr) at Griffiss Technology Park, Rome, NY, evaluating multiple feedstocks including hardwood. Biochemical technology, based on thermophilic bacteria is used. A simple pretreatment step precedes a low-cost cellulose hydrolysis and fermentation Consolidated Bioprocessing stage (CBP). The plant has had a phased start up from June 2008. Mascoma is also planning a 151 ML/yr commercial development in Michigan by early 2011 using the biochemical process.



Figure 4: Global and Lignocellulosic Ethanol Facilities

Legend:		Biochemical	
Thermochemical			
★	Pilot / Demonstration	●	Pilot / Demonstration
☆	Commercial	○	Commercial

The Wisconsin Rapids pulp and paper mill will be the site for a biomass gasification plant producing 18 ML/yr of FT liquids from bark, slash and unmerchantable forest residue procured within a 110 kilometre radius of the mill. The gas fraction from the FT reactor will be burnt in the lime kiln and power boiler, and the excess energy generated from the FT reactor will be used in the mill. Construction of the plant is planned for 2010 with startup in 2011.

Red Shield Environmental (RSE) has received a DOE award of up to US\$30 million for the development of a wood based cellulosic ethanol demonstration plant to be implemented at the Old Town Maine Pulp mill. RSE is partnering with University of Maine to commercialise the production of ethanol from hemicellulose extracted during kraft pulping. The integrated ethanol plant is expected to produce 8.4 ML/yr from 80 BDT/d of hemicellulose extract.

Pacific Ethanol is a leading producer of ethanol in the US, and is partnering with BioGasol from Denmark to develop a 10 ML/yr demonstration plant to produce bioethanol from wheat straw, hardwood chips and corn stover. The plant will be co-located at the site of Pacific Ethanol's existing corn-based ethanol facility in Boardman, Oregon.

The BioGasol process utilises proprietary process technology developed at its pilot facility at the Denmark Technology University in Copenhagen. The process includes a pre-treatment using a combination of steam explosion and wet oxidation, enzymatic hydrolysis and C6 and C5 sugar fermentation. Biogas (methane) is produced from anaerobic digestion of the organic material remaining in the process effluent. Completion of the demonstration plant is scheduled for Q4 2009 with expansion to commercial scale by 2012.

Poet is also nearing completion (early 2009) of a US\$4 million pilot-scale cellulosic ethanol facility in Scotland, South Dakota. Poet is collaborating with DuPont to convert corn stover to ethanol at Poet's Emmetsburg, Iowa plant. 95 ML/yr of ethanol will be made from corn cobs alongside 378 ML/yr from corn, starting in 2011. DuPont has been developing genetically modified strains of the bacteria for conversion of wood sugars and high-efficiency fermentation technologies.

Pure Energy & Raven BioFuels have partnered to develop two cellulosic ethanol projects, which are each in various stages of development:

- A 125 ML/yr plant based on wood waste is being developed in Mississippi and will produce furfural in addition to ethanol.
- A memorandum of understanding has been signed with the Kamloops Indian Band in British Columbia. Biomass suitable for supporting a 26 ML/yr ethanol facility is part of the MOU. Furfural, Hydroxymethyl Furfural, lignin cake will also be produced as part of the process. The PureEnergy Process uses dilute acid hydrolysis with separate C5 and C6 fermentation.

**Range Fuels** is building the largest commercial plant in the USA in Soperton, Georgia. The site, already under construction, was to produce 76 ML/yr by the end of 2009, but now aims for 38 ML/yr by 2010 before ramping up to 378 ML/yr. This plant uses novel gasification technology producing syngas and then mixed-alcohol synthesis with metal catalysts for ethanol production. Challenges exist with significant proportions of tars from biomass as feedstock, compared to fossil fuels.

**Verenium** is operating a 5.5 ML/yr demonstration facility in Jennings, Louisiana. The demonstration plant is located adjacent to Verenium's existing integrated cellulosic ethanol pilot plant that has been operational since 1999 and capable of processing about 2 t/d of biomass. Demonstration plant commissioning is underway. A wide range of feedstocks will be used, including bagasse and energy cane initially, and wood chips, grasses and agricultural residues later. The Verenium process uses dilute acid steam explosion, liquid/solid separation, followed by separate C5 and C6 sugar fermentation. Proprietary enzymes are used for the saccharification of cellulose. Verenium, together with partner BP, has announced the plans for construction of the first commercial-scale facility in Highlands, Florida. The Highlands facility will use bagasse, energy cane and hardwood to produce 136ML/yr of ethanol in 2012 using steam explosion pulping followed C5 and C6 fermentation with proprietary organisms.

Virent has developed a technology referred to as 'bioforming' which allows for direct production of gasoline, kerosene and diesel hydrocarbons from cellulosic material. A demonstration plant is being planned for Orange County, New York.

## Canada

The Canadian government has set its sights on a target of 5% renewable fuel in gasoline by 2010 and 2% renewable fuel in diesel by 2012. To support this, the federal government has established funding of C\$550 million dollars for pilot plants and process development and pre-commercial development, with a further C\$500 million for demonstration scale facilities and to assist with bridging the gap between development and commercialization of cellulosic ethanol technologies. Facilities under construction or planned [11] include:

**Enerkem, Westbury** - A 5 ML/yr cellulosic ethanol plant is under construction by Enerkem in Westbury, Quebec. The plant will use thermal gasification and catalysis technology to produce ethanol and methanol from treated wood waste (end-of-life cycle power poles). Construction of the syngas island was completed in December 2008 and is currently being commissioned. The methanol and ethanol production modules are to be added early 2009. The Enerkem thermochemical process yield is 360 L/t wood waste. Enerkem has partnered with GreenField Ethanol, a corn ethanol producer, to commercialise the Enerkem technology. A 36 ML/yr ethanol/methanol plant is planned in Edmonton, Alberta, utilising sorted municipal solid waste.

**logen, Ottawa** - Since 2004, logen has operated a demonstration-scale plant in Ottawa producing 2.5 ML/yr of ethanol from 30 t/d agricultural residues, including wheat, oat and barley straw. The technology can also be used successfully with hardwoods, but not softwoods. A modified steam explosion pretreatment is used to liberate the cellulose, followed by enzymatic hydrolysis and fermentation of both C5 and C6 sugars. Ethanol yields of 340 L/t of fibre, are reported. Lignin is separated and used to generate process steam and electricity. logen has partnered with Shell since 2002. logen's first 90ML/yr commercial plant is planned for Birch Hill, Saskatchewan, an area with sustainable supplies of straw and green residues. The availability of straw, combined with government support, were key factors in this decision. This will be first facility to take advantage of the NextGen Biofuels fund. logen has 'suspended' its 68 ML/yr plant in Shelley, Idaho.

**Lignol** has commissioned a pilot plant using the biochem-organosolv process, capable of producing 0.1 ML/yr of ethanol, at their research facilities in Vancouver, BC. The Alcell technology, originally developed by General Electric and Repap Enterprises, uses a solvent-based pretreatment and produces ethanol and High Purity Lignin (HP-L<sup>TM</sup>) from hardwood and softwood residue. Lignol recently announced that it is suspending development of the previously announced Grand Junction, Colorado demonstration facility. Lignol had partnered with Suncor Energy to build a 10 ML/yr cellulosic ethanol plant. The company is examining other alternatives for US\$30 million dollar DOE grant that it has received.

Details of facilities under construction or planned in the rest of the world are discussed below:

## South America

Brazil is today producing ~ 40% of the world's ethanol from sugar cane. Yields vary from 6,600 – 7,500 L/ha which means production costs half those of US corn-based ethanol processors. Therefore, there has been relatively low interest in second-generation bioethanol. However, recent studies made by Brazilian National Development Bank (BNDES) together with FAO show that when fermenting bagasse and sugar cane the ethanol yield could reach 13,000 L/ha.

**Dedini, Sao Paulo, Brazil** - The sugar and ethanol co-operative Copersucar is supporting the Dedini S/A Indústrias de Base pilot plant using Rapid Hydrolysis (DRH). The pilot plant started operations in 2007 and can produce 1.81 ML/yr. The process uses an initial pretreatment with organic solvents followed by dilute acid hydrolysis and fermentation stages. C5 and C6 sugars are separated from lignin using an acid wash. Dedini claims a 30% increase in ethanol yields for a sugar-based ethanol plant with integration of the bagasse conversion process. Dedini, the world's biggest producer of sugar cane ethanol, expects start-up of its first commercial scale plant in 2012.

**Chile** targets producing second-generation bioethanol from forest biomass within the next five years. Bioenercel is one of the two consortiums created for this development work. It has a five-year budget of US\$7 million and is supported by the Chilean government, two public universities as well as pulp and paper companies Arauco, CMPC and Marisa. Bioenercel is not only supposed to develop and adapt technologies but also create necessary infrastructure for bioethanol production. The current laws in Chile require that, before the year 2020, 10% of the fuel used by cars will be replaced by bioethanol or biodiesel.

## Europe

**Abengoa, Spain** - Abengoa Bioenergy has been operating a biomass-to-ethanol pilot plant since the end of 2007 at the Biocarburantes Castilla y León grain-ethanol plant in Babilafuente, near Salamanca in Spain. 5 ML/yr are produced from wheat and barley straw using enzymatic hydrolysis (glucose). A steam explosion pretreatment stage, from SunOpta, is currently being installed and will start up early 2009. In the second phase, it is intended to separate the lignin and pentose sugars as co-products. (See also Abengoa in United States section).

**Chemrec, Pitea, Sweden** – Chemrec has developed a gasification process to convert pulp mill black liquor (BL) to liquid fuels including ethanol. A BL gasification development plant in Pitea, Sweden is located next to the Smurfit Kappa Kraftliner mill and the research institute ETC. The gasifier uses pressurized oxygen and is capable of gasifying 20 t BLS/d, producing a synthesis gas that requires little cleanup. A commercial-scale BL liquor gasification plant has been operating at Weyerhaeuser's New Bern mill in the US since 1996, and was rebuilt in 2003 increasing capacity to 300 t BLS/d (Fig. 5). Integration of a BL gasifier allows mills to produce liquid fuels and increase recovery capacity. At the New Bern mill the unit provides 15% of the mills BL recovery capacity.



Figure 5: Weyerhaeuser, New Bern, USA

**SEKAB, Ornskoldsvik, Sweden** – SEKAB, in conjunction with Etek Etanolteknik AB, has been operating a bioethanol pilot plant since 2004 at its Domsjo industrial site. The feedstock is pine wood chips, but other biomass such as bagasse, wheat and corn stover, energy grasses and recycled waste can be used. The plant has a maximum wood capacity of 2 BDT/d and ethanol production of 0.14 ML/yr. The process is based on multi-stage weak acid hydrolysis, a detoxification stage prior to fermentation, and separation of lignin using a membrane filter. Recent work has focused on improving the ethanol yield using pentose-fermenting microorganisms. For cost reasons, enzymes are not used. Scale-up of this technology is planned for 2010-11 with the construction of a development facility of 6 ML/yr and a 120 ML/yr commercial plant in 2014, utilising wood waste and sugarcane bagasse.

**Stora Enso, Varkaus, Finland** - Plans have been announced to build a demonstration gasification plant at the research centre at Varkaus mill for the production of biofuels from wood residues. This is a joint venture between Stora Enso Oyj and Neste Oil Corporation.

**UPM Kymmene, Finland** – Finnish pulp and paper company UPM Kymmene and renewable fuel supplier Lassila and Tikanoja are testing bioethanol production from the pulp-based waste created by the paper industry. During the pilot tests ethanol and energy were produced from commercial and industrial waste, such as paper, cardboard and wood. By developing waste processing units, energy company St 1's biofuel division intends to produce 70 ML/yr of bioethanol by the end of 2011. St 1 already has two commercial plants operating using food industry waste as raw material.

**Elsam, Denmark** - A cellulose-to-ethanol pilot plant is located with an Elsam power plant in Odense, Denmark. Agricultural residues are used as feedstocks to a biochemical process. The Integrated Biomass Utilisation System (IBUS) is used to research synergies between the straw-to-ethanol and the conventional grain-to-ethanol process, and the co-production of lignin for co-firing.

Trials include evaluation of thermophilic bacteria to simultaneously ferment C5 and C6 sugars. The pilot plant has the capacity to process 1 t/hr of wheat straw.

**Choren, Freiburg, Germany** - Choren is one of the world's leading biomass gasification companies. A biomass-to-liquids (BTL) commercial plant was constructed in 2008, in Freiberg, Germany (Fig. 6). Shell's Fisher-Tropsch gas-to-liquids technology is used to produce 16.5 ML/yr of FT liquids. Feedstock includes wood chips, recycled wood and agricultural wastes. The process consists of a slow pyrolysis stage producing a char that is broken down and injected into the lower part of the gasification chamber, facilitating a reaction with the hot gases and production of a tar-free synthetic combustion gas. The syngas then feeds a FT chamber to produce biodiesel. Choren plans to build the world's first full-scale BTL plant in Schwedt, Germany, producing 270 ML/yr of synthetic biofuel [2].



Figure 6: Choren, Freiburg, Germany

**DONG Energy, Denmark** started construction (Sept 2008) of a demonstration plant at the Kalundborg coal fired power station. The principal purpose of the demonstration plant is to show that DONG Energy's second-generation technology can be applied on a large scale, and can be integrated with a power station. The plant capacity will be 5.4 ML/yr of ethanol from 4 t/hr of straw biomass per hour.

**BioGasol** is constructing a 5 ML/yr demonstration plant in Denmark, called the BornBioFuel (BBF) project. The plant, located on the island of Bornholm, will demonstrate the potential of the Biogasol technology (see Pacific Ethanol) to produce ethanol from a diverse mixture of biomass, including local available agricultural residues and other low cost cellulosic feedstocks. Construction of BBF has already started and the first ethanol will be produced from this plant in early 2009.

**TMO Renewables, Guildford, UK** - The UK's first cellulosic ethanol demonstration facility has been built using biochemical conversion which incorporates their unique thermophilic bacterium for fermentation at 60-70°C. Feedstocks that can be processed include agricultural waste, wood chips, paper and municipal waste.

## Japan, Australasia, Asia

**BioEthanol Japan** - The BioEthanol Japan plant in Osaka Prefecture has capacity of 1.4 ML/yr and had plans to boost production to 4 ML/yr in 2008. Wood construction waste is used as feedstock and technology from Verenium, the key element of which is a genetically engineered *Escherichia coli* bacteria that can ferment both C6 (hexose) and C5 (pentose) sugars, is used.

**Honda-RITE, Japan** - collaboration between Honda and RITE (Research Institute of Innovative Technology for the Earth) aims to initially develop laboratory scale production of cellulosic ethanol using biochemical process, with scale up to pilot plant size envisaged.

**Marubeni, Saraburi, Thailand** – A 3 ML/yr cellulosic ethanol plant was opened in late 2008 co-located with a sugarcane-ethanol plant (Marubeni and Tsukishima Kikai Co Ltd). The sugarcane bagasse will be the primary feedstock and Verenium's process technology will be used.

**China Resources Alcohol Corporation, China** - CRAC is the second largest ethanol producer in China and has been operating a cellulosic ethanol pilot plant in ZhaoDong City, since 2006. Corn stover feedstock is processed using SunOpta's modified steam explosion technology followed by enzymatic hydrolysis.

CRAC's goal was to install 6 ML/yr of cellulosic ethanol capacity by the end of 2007 and 1,250 ML/yr by 2012, the most ambitious target in the world.

**Mission NewEnergy, India** – A pilot plant of 0.07 ML/yr cellulosic ethanol utilises agricultural waste (wheat/rice/corn/barley straw, and in the future *Jatropha Curcas*, an oil-seed tree) using a novel hydrolysis process. Lignin is separated from the cellulose and hemicellulose prior to hydrolysis, which is conducted without the use of any enzymes. Yields of 500 L/t of feedstock are reported which is 36% more efficient than competing cellulosic ethanol technologies. A commercial scale plant is planned.

**Ethtec, Australia** - Ethtec, a Willmott Forests subsidiary, is currently constructing a pilot plant for cellulosic ethanol production at the NSW Sugar Milling Co-operative Harwood Mill and Refinery near Maclean in northern NSW. The plant will use hydrolysis and fermentation technology developed in collaboration with the University of Southern Mississippi and the University of New South Wales. The process uses 'induced phase separation' for recovery of ethanol eliminating the need for conventional distillation, significantly improving the energy balance of the process and reducing the environmental impact of the distillery. It is planned to use wood residues (including pine), bagasse and other biomass for the production of ethanol.

**Pure Power, Singapore** – Pure Power has purchased the NZ-based BioJoule lignocellulosic conversion technology for the production of bioethanol, natural lignin and xylose. The intended feedstock is the wood crop *Salix*, a variety of willow. A unique washing process is used to preserve and recover the lignin which can be used in paints, glues, resins and other phenolic chemicals which are currently derived from petroleum. It is estimated that 80% of the overall revenue will be derived from the lignin and xylose by-products

**LanzaTech, New Zealand** – This start-up energy company has demonstrated the microbial conversion of carbon monoxide into ethanol. The company envisages that the process can be retrofitted to any industrial facility to generate ethanol from the carbon monoxide component of high volume waste flue gases. Scaling-up of the technology is planned.

**Scion, Rotorua, New Zealand** – The Lignocellulosic Bioethanol Initiative is a collaboration between Scion, Verenium, Carter Holt Harvey, BP and Beca AMEC that is developing a biochemical route using softwoods for ethanol production. A pilot plant is being developed.

## SUMMARY

Substantial investment is occurring in conversion technologies and in determining the most economic, practical and cleanest technology for the production of cellulosic ethanol. Pilot plants have successfully demonstrated the production of ethanol from feedstocks, such as agricultural waste, but the conversion of wood waste, particularly softwoods, continues to be more challenging.

It is likely there will be no single preferred conversion technologies for the production of cellulosic ethanol, but rather technologies appropriate for specific feedstocks. For example, the high ash content of many straws may prohibit their utilisation in the gasification pathway, but these feedstocks show high conversion yields using enzymatic hydrolysis technologies.

Construction of the first large-scale demonstration facilities is underway. The success of these plants in demonstrating a cost-effective sustainable conversion process for ethanol will open the way to the commercialisation of second generation biofuels. Significant reductions in operating costs are needed to achieve the goal of producing cellulosic ethanol for less than US\$1.07/US gallon. The availability and cost of raw materials will determine the size of the plant – more expensive biomass will require larger facilities in order to offset the cost of the investment. The availability of financing, particularly the willingness of governments to share in the scale-up risks with private industry, will also be critical to commercialisation. Co-location with existing infrastructure and facilities, such as power plants, grain-ethanol plants, pulp and paper mills, where various synergies can be achieved, has many advantages over stand-alone plants.

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