TROTTIER ENERGY FUTURES PROJECT

Working Paper

BIOFUELS

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Introduction

Biofuels play a small but significant role in Canada's transportation fuel mixture, and this role is driven entirely by policy. The country's current renewable fuel regulation (RFR) was enacted in 2010 as part of the Canadian Environmental Protection Act (Bill C-33). The RFR mandates an average of 5% renewable content in gasoline and 2% renewable content in diesel fuel (Sorda 2010). This translates to demand of 2.1 billion litres (Bl) of ethanol and 585 million litres (Ml) of biodiesel production(Evans 2013). The mandate initially included a 2% renewable content requirement for heating distillate oil (fuel oil), but this requirement has been removed through an amendment to the Act on the fear that additional costs would be unreasonable for homeowners and small business (Canada Gazette 2013). Thus, the RFR focuses almost exclusively upon road transportation and industrial uses of biofuel.

In some provinces, separate mandates for renewable fuel content have been enacted. For gasoline, these mandates range from 5% renewables (Ontario, Alberta, British Columbia) to 7.5% (Saskatchewan) and 8.5% (Manitoba). For diesel oil, they range between 2% (Manitoba, Alberta, Saskatchewan) and 4% (British Columbia) (Evans 2013). The introduction of provincial mandates essentially ensures that fuel sold in these jurisdictions include a renewable component. The federal RFR, which seeks an average renewable content across the entire country, would naturally see greater amounts of renewable fuel blended in areas where biofuels can be easily produced. More detail on mandates by province is provided in Section 2.

Fuel ethanol production capacity for 2013 was estimated to be about 1,785 Ml in 2013, and an additional which is about 4% higher than 2012 levels (Evans 2013). Actual production statistics are not readily available. Greenfield Ethanol has reported running plants above nameplate capacity by 2-5% in certain cases (Greenfield Ethanol 2014), and so it may be assumed that regular operation between 95-105% is not unusual. At the same time, not all ethanol produced at these facilities is classified as fuel ethanol; for example, Greenfield Ethanol reports producing 103-133 Ml of fuel ethanol and an additional 60-90 Ml of industrial alcohol at their Chatham facility. About 78% of fuel ethanol is produced from corn, primarily in Ontario and Quebec; the remaining 22% is sourced from wheat and is primarily produced in the three Prairie provinces. Cellulosic ethanol is only produced in small quantities from wood waste and municipal solid waste and is being developed by Enerkem.

It may be assumed that consumption of ethanol is now (approximately) at the level dictated by the blend mandates in various provinces and by the federal RFR. The gap between Canadian production capacity and the fuel levels required under the RFR is about 315 Ml of ethanol. While biofuel trade data is not tracked, the USDA estimates that 1.1 billion litres of ethanol were imported in 2013; it is not clear that all ethanol imported is used for transportation purposes (Evans 2013). Canada also exports some ethanol, but this is expected to slow (Evans 2013).

Biodiesel production capacity for 2013 is estimated at 464 ML, but production is estimated to reach 646 ML in 2014. The most prevalent feedstock is canola, which is currently supplying about 35% of all biodiesel production. Other feedstocks include soybean, tallow, and recycled vegetable oils. The gap between the RFR and current production capacity is about 121 Ml of biodiesel. While data is not tracked, the USDA assumes that both import and export of biofuels is happening across the different regions of Canada, and that transfer of stocks is happening between different provinces; while imports to Canada are expected to level out, exports may rise as demand increases in the USA (Evans 2013).

Section 1: Energy Sector Description

As described in the introduction, policies related to biofuels in Canada are found at the federal and provincial level and are part of a suite of tools that promote biofuels and bioenergy. Biofuel-related policy also exists at the municipal level in Canada, with at least five major municipalities identifying biofuels as a significant component of future energy mix (St Denis and Parker 2009). Biofuel production currently lags behind levels required by the federal mandate. With anticipated shortfalls of 315 Ml ethanol and 121 Ml biodiesel, there is still some room for development in either the conventional ethanol and biodiesel sector, or in the emerging biofuels sector (Evans 2013). There is interest in shifting future biofuel production to advanced fuels sourced from non-food feedstocks, but to date there has been little support in terms of policy instruments that would drive commercial investment into these technologies (Mabee and Saddler 2010).

It is important to place biofuels within the context of the larger bioenergy sector in Canada. There are currently 39 cogeneration plants in pulp and paper mills and sawmills across Canada, with generation capacity estimated at 1,349 megawatts (MW) of electricity and 5,331 MW of thermal energy (Bradley and Bradburn 2012). There are also 16 independent biomass-to-electricity facilities capable of producing an additional 465 MW of electricity, and 8 community-based wood-to-heat plants with the capacity to produce more than 10 MW of heat (Bradley and Bradburn 2012). Finally, Canada has about 39 operational wood pellet plants with a capacity approaching 3.3 million tonnes per year, although reported production is about 50% of this capacity as of 2013 (Aguilar, Hartkamp et al. 2012, Bradley and Bradburn 2012). Canada has seen a decline in biomass-to-energy share of the nation's total primary energy supply, from about 4% in 2007 to about 2% in 2009, largely due to shutdowns in the forest sector. As such, Canada now uses much less biomass for energy than many other countries, including Sweden, Finland, and the USA (Aguilar, Hartkamp et al. 2012). There is potential to either restore this generation capacity, or to direct feedstocks that are no longer used for energy to biofuel production.

Policy is the key driver behind biofuel development, both in Canada and in other nations. It can be argued that the prevalence of corn-based ethanol in the USA is primarily driven by tax credits, mandates and imports (de Gorter and Just 2010). Since 2012, the USA has seen the removal of the excise tax exemption for ethanol and the withdrawal of tariffs designed to restrict ethanol imports; while it is difficult to say exactly what the long-term impacts of these changes will be, but the last two years of production statistics indicate that growth in the US ethanol sector has flattened (IEA Bioenergy 2014). In Canada, the EcoENERGY for Biofuels Program (approximately C$1.5 billion) provided ethanol manufacturers an incentive of as much as C$0.06 per litre; this program has been closed and the existing support to producers will end in 2017 (Natural Resources Canada 2014). Other significant sources of support for infrastructure for both conventional and advanced biofuels over the past few years include the Sustainable Development Technology Canada NextGen Biofuels Fund (C$500 million), the ecoAgriculture Biofuels Capital Initiative (C$200 million), and the Agri-Opportunities Program (C$135 million) (Evans 2013). While the biofuels sector has received significant support, it has also provided significant benefit, contributing an estimated $2 billion annually to the Canadian economy in 2010 (Doyletech Corporation 2010). It is unknown what impact the expiry of ongoing funding programs will have on Canada's biofuel sector.

Incentives for biomass heat and electricity are found at both federal and provincial levels. Recent federal funding programs include the Pulp and Paper Green Transformation Program (C$1 billion), a program designed to increase energy production in pulp and paper mills across Canada by upgrading recovery boilers. This program funded 98 projects, bringing about 200 MW of electrical power and 150 MW of thermal power capacity online - power expected to create about C$149 million in annual revenues for the pulp and paper industry (Natural Resources Canada 2012). The investments in the Forest Industry Transformation Program (C$100 million) will provide funding for both high-value bioproducts as well as new renewable energy capacity between 2011-2015 (Natural Resources Canada 2014). Provincial funding opportunities for biomass heat or electricity tend to be smaller; for instance, British Columbia introduced the Innovative Clean Energy fund in 2007, which offered C$25 million per year from 2007-10 for new energy projects; this in part engendered development of significant heat and electricity capacity. Similarly, Ontario's Green Energy and Green Economy Act provides a feed-in tariff to support bioelectricity generation, but the rate provided is not competitive with the incentive for wind or solar power and most capital investment has selected those technology options over bioenergy (Mabee, Mannion et al. 2012).

A major driver behind government support for biofuels and bioenergy is the potential for new job creation, something that has been a particular challenge. A recent report indicates that 'green' jobs accounted for 11% of job growth across Canada between March and May 2012 (Evergreen and Canada 2012). Within this study, biofuels and bioenergy are considered a component of 'green' energy – a category that includes other forms of renewables (such as wind, solar, and hydroelectric power) as well as renewable energy services. The problem with these statistics is that they overlook the very important role that indirect employment plays, as biorefining can drive activity both up and down the supply chain. Greenfield Ethanol, the largest biofuel company in Canada, operates a number of plants in Ontario; according to the company's own statistics, corn-based ethanol plants operated by Greenfield generally produce about 10 litres of ethanol per bushel of corn (Greenfield Ethanol 2014), the equivalent of 394 litres per tonne of feedstock. In 2012, Ontario produced 8,599,700 tonnes of grain corn on about 894,000 hectares (Ontario Ministry of Food Agriculture and Rural Affairs 2014). As the average farm size in Ontario was about 99 ha and employs approximately 1.44 operators per farm (Statistics Canada 2011), the labour associated with providing feedstock to Greenfield's operations amounted to at least 4,400 individual jobs in 2012.

Section 2: Base Year Sector Data for existing technologies

Canada has the world's third-largest proven oil reserves, after Venezuela and Saudi Arabia, and is one of the top ten oil exporters in the world. Canada's renewable fuel industry has therefore not been driven from an energy security perspective, but rather from the need to diversify rural economies and to reduce greenhouse gas (GHG) emissions. Major sources of funding for biofuel development include the Program of Energy Research and Development (PERD) within Natural Resources Canada, which provides ongoing support to a number of university and industry-led projects. Also significant is Sustainable Development Technology Canada, which operates two funds - a technology fund ($550 million over 14 years) and a NextGen Fuels fund ($500 million over 8 years). Both of these funds are currently slated to close in 2015. Finally, the government of Canada has supported industry and university research through the research granting councils, most recently providing $25 million to BioFuelNet, a Network of Centres of Excellence dedicated to advanced biofuel research (IEA Bioenergy 2014).

Previous governments have provided more substantial support to biofuels, including a cumulative investment of $2.7 billion CDN into the implementation of the former Climate Change Plan for Canada, which included incentives for the development and use of environmentally friendly technologies including bioethanol. The federal Canadian government provided direct funding for the industry through two rounds of the Ethanol Expansion Program (announced 2003), which in 2004 and 2005 provided a total of $118 million in direct funding for eleven projects. Finally, the Agricultural Bioproducts Innovation Program is a $145 million grant that mobilizes research networks that conduct scientific research projects with a specific focus on developing effective and efficient technologies for an agricultural biomass conversion; evolve beyond bio-fuels production to a sustainable, bio-based economy. The program runs on a multi-year basis.

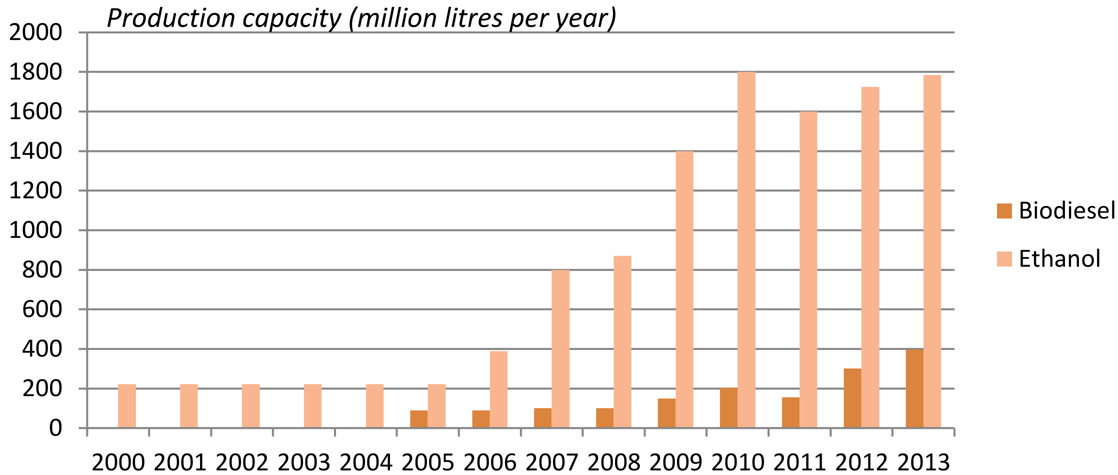
Market development for biofuels

As at the beginning of 2013, there were 16 ethanol and 9 biodiesel plants in operation in Canada, with another 3 biodiesel plants being commissioned and another 1 under construction. Total ethanol production capacity is 1,785 Ml in 2013, while the federal mandate (at 5%) requires an additional 316 Ml of ethanol. There is significant import activity from the US to Canada, which amounted to 1.14 billion litres in 2013; this could indicate blending levels beyond the mandate, but also could be an artifact of the lack of separation between industrial and fuel ethanol. Almost all the ethanol is produced from corn (78%, east) and wheat (22%, west).

Biodiesel capacity of current plants in operation is 464 Ml as of 2014, while commissioning and construction will extend the capacity to 646 million litres. Based on the current federal mandate (2%), an additional 121 million litres of biodiesel is required at the present time, and this number would rise as diesel consumption rises across Canada. Almost all of the biodiesel is produced from canola (in the west) and animal fats (in the east).

Figure 2 illustrates the development of production capacity across Canada. It is clear that ethanol production capacity has leveled off in recent years, while biodiesel production capacity has risen slightly since 2011. As production capacity approaches the mandate levels, future development becomes less likely without new policy impetus or strong market signals.

Figure 1 - Evolution of Canadian biofuel production capacity, 2000-present (IEA Bioenergy 2014)



The support for ethanol in Canada has been estimated at between C$9.40-11.30/GJ of fuel produced (Laan, Litman et al. 2009). At a HHV of 23.4 MJ/l, this is equivalent to support of C$0.22-0.26/l. Much of this support can be attributed to excise tax exemptions at the federal level (C$0.10/l) and at provincial levels (between $0-0.25/l), although provincial exemptions are slowly being withdrawn (IEA Bioenergy 2014). Support for biodiesel is higher, between C$18.70-25.45/GJ. At a HHV of 35.7 MJ/l, this is equivalent to C$0.67-0.91/l. The calculated level of subsidy per tonne of carbon avoided is between C$90 (for cellulosic ethanol) and C$430 (for corn and wheat-based ethanol),and between C$205 (for recycled oil biodiesel) and $C580 (for canola biodiesel), figures far in excess of market prices for carbon (Laan, Litman et al. 2009).

Ethanol production technologies

Baseline comparator: Gasoline
Baseline level (g CO_2-equivalent/MJ): 86 (Laan, Litman et al. 2009); 86.64 (1995), 88.76 (2015) (O'Connor 2009)
<u>Corn ethanol</u>

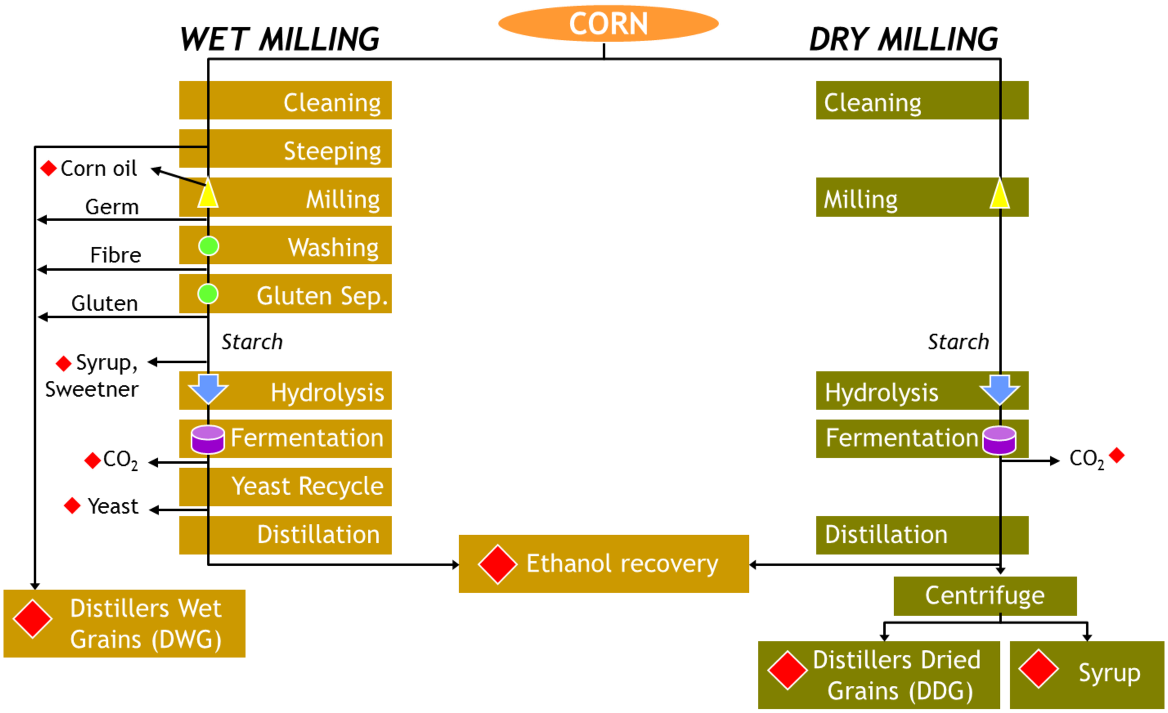
Emission reductions (% below baseline): 26.2% (1995), 39% (2005), 54.9-98% (2015) (O'Connor 2009); 36.5% (2012) (O'Connor 2013); 30-54% (Laan, Litman et al. 2009)
Capacity: 1,392 Ml/year

<u>Wheat ethanol</u>

Emission reductions (% below baseline): 30-53% (Laan, Litman et al. 2009)
Capacity: 393 Ml/year

The biochemical platform is designed to recover intermediate products from biomass. The platform generally enzymatic hydrolysis to release sugars from biomass; the use of enzymes has almost completely replaced acid hydrolysis as enzyme costs can be much lower (REF). Sugar can then be fermented to ethanol or higher alcohols (typically butanol), and the non-sugar components of the biomass can be combusted for energy, or used as the basis for other products. Starchy biomass is an ideal feedstock for bioconversion because it is comprised of a single sugar (glucose), which simplifies process design and complexity (Wyman 2003). The current bioethanol industry in Canada uses the biochemical platform, utilizing agricultural crops and food processing residues which have high starch contents and are relatively homogenous in composition (Pandey, Soccol et al. 2000).

Figure 2 - Wet- and dry-milling flowcharts for ethanol production (created by author)



With starch-rich cereal feedstocks, the two major processes for ethanol production are wet-milling and dry-milling (shown in Figure 2 above). Wet-milling is usually only used with corn; it is a relatively expensive process that uses a steep tank to pretreat corn kernels, which allows the removal of the germ in the centre of the grain to create other high-value products. Fibres are then screened and starch is recovered. The starch can be hydrolyzed using amylase, followed by fermentation using yeast to produce ethanol. Corn-based wet mills produce a range of products including distillers' wet grains, gluten meal and corn oil, in addition to ethanol. By comparison, dry-milling forgoes the soaker pretreatment and instead uses hammermills to reduce cereal grain to a fine meal, which can then be hydrolyzed and fermented to produce ethanol. The solid portion collected after ethanol production is dried and sold as Dried Distillers Grains (DDG), which is a valuable animal feed. Significant developments to the dry-milling process are introducing new, higher-value products such as corn syrup (Semencenko, Mojovic et al. 2013). An overview of wet- and dry-milling is shown in the diagram below. The majority of Canadian ethanol producers, using both corn and wheat, are dry mills. The production efficiency of corn-based ethanol mills is typically in the 390-400 l/tonne range (O'Connor 2009). The production efficiency of wheat-based ethanol mills may be slightly lower, with suggested yields ranging between 331-345 l/tonne (Sosulski and Sosulski 1994, McLeod, May et al. 2010).

Biodiesel production technologies

Baseline comparator: Diesel oil
Baseline level (g CO_2-equivalent/MJ): 89 (Laan, Litman et al. 2009); 88.1 (1995) (O'Connor 2011)
<u>Canola/Rapeseed</u>

Emission reductions (% below baseline): 59.6% (1995), 70.3% (2005), 79.8% (2015) (O'Connor 2011); 30-54% (Laan, Litman et al. 2009)
Capacity: 87 Ml/year (265 Ml under construction)

<u>Soybean</u>

Emission reductions (% below baseline): 51.9% (1995), 62.6% (2005), 70.3% (2015) (O'Connor 2011)
Capacity: 220 Ml/year

<u>Waste oils (animal/vegetable)</u>

Emission reductions (% below baseline): 87-103% (Laan, Litman et al. 2009)
Capacity: 156 Ml/year

Biodiesel production in Canada generally follows the FAME (fatty acid methyl ester) process, which utilizes a relatively simple pathway. Methanol is added to vegetable oils, used cooking oils, or animal fats along with a catalyst. A process of transesterification of free fatty acids and triglycerides produces methyl esters (biodiesel) as well as glycerin; glycerin (often reformed to glycerol) represents about 10% of the raw feedstock by mass. Glycerol is recognized as a potential platform chemical for industrial processing but the world market is currently overstocked with this commodity, which creates problems for new biodiesel producers who have difficulty finding markets. Sarma et al. have explored the production of biohydrogen from glycerol via a two-stage fermentation approach. This research indicates that 1 kg of crude glycerol could produce a theoretical maximum of 45.6 g H_2 (Sarma, Brar et al. 2012).

Smith et al. reported on Canadian feedstocks for biodiesel; for one tonne of soybean, 0.175 t of crude vegetable oil was generated, which was equivalent to 0.164 t of biodiesel (Smith, Janzen et al. 2007). For one tonne of canola, 0.410 t of crude vegetable oil was generated and 0.380 t of biodiesel produced (Smith, Janzen et al. 2007). Thus, the conversion efficiency of the FAME process is about 93-94%.

Other production processes are also utilized in Canada. BIOX uses a patented production process which first uses acid esterification to convert free fatty acids in the vegetable oil, and then uses transesterification to handle the remaining triglycerides (BIOX 2014). This process was first developed at the University of Toronto. Other modified processes for biodiesel include supercritical and subcritical processing, often proposed as a means of handling new feedstocks such as algae (Reddy, Muppaneni et al. 2014).

Section 3: Sector Data for new Technologies

Advanced biofuels may be produced through a biorefining approach, which usually suggests the production of additional coproducts including (potentially) heat and electricity. Development of new advanced biofuel capacity may in part be done by leveraging existing infrastructure and building on established supply chains in Canada's agricultural and forest sectors (Mabee, Gregg et al. 2005, McCormick and Kaberger 2007, Towers, Browne et al. 2007, Gold and Seuring 2011). The forest sector in particular may benefit from development of the biorefinery strategy (Stuart 2006, Browne 2011).

Lignocellulosic ethanol

Baseline comparator: Gasoline
Baseline level (g CO_2-equivalent/MJ): 86 (Laan, Litman et al. 2009); 86.64 (1995), 88.76 (2015) (O'Connor 2009)

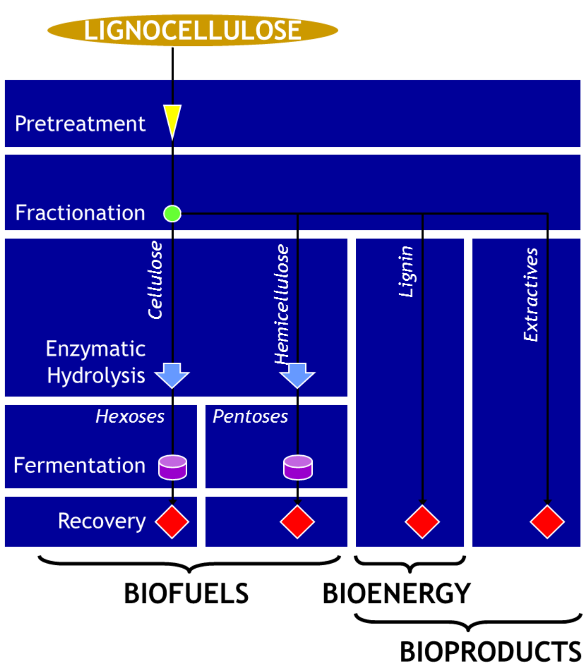
Crop residues (corn stover)

Emission reductions (% below baseline): 82-122% (Laan, Litman et al. 2009); 63.8% (traditional process), 70.7% (hybrid thermochem-biochem process) (O'Connor 2013)
Capacity: 0 Ml/year

Mill residues/wood waste

Emission reductions (% below baseline): 54-63% (Roy and Dutta 2013)
Capacity: 0 Ml/year

Figure 3 - Biochemical production of lignocellulosic ethanol (created by author)



Lignocellulosic ethanol (or cellulosic ethanol) is can be produced through both biochemical and thermochemical means, but the most common platform under development is the biochemical platform. This platform builds off of the existing corn- and sugarcane-based biorefineries and is detailed in Figure 3 at right. In commercializing the biochemical platform for lignocellulosic ethanol, a number of challenges must be overcome as detailed below.

Challenge 1: Feedstock complexity

Unlike starch - a single strand of linked glucose molecules - lignocellulose is a complex of three interwoven polymers, including cellulose (glucose), hemicellulose (both C6 and C5 sugars) and lignin (Sjöström 1993). The complexity of lignocellulose suggests that making lignocellulosic ethanol using the biochemical approach, which combines enzymatic hydrolysis and fermentation, will be more difficult (Wyman 2003). To manage feedstock complexity, the biochemical process includes pretreatment stages that can separate and recover the various components of lignocellulosic biomass, including fibre, carbohydrates, and aromatic compounds from the lignin and extractives; recovery of these materials creates the potential for additional chemical coproducts. Most plans for lignocellulosic ethanol production assume that a portion of the feedstock will be used to generate power for the process, and in some cases additional electricity or heat can be sold through the grid or through a district heating system (Edye, Doherty et al. 2006).

Challenge 2: Facility scale

Recent work suggests that lignocellulose-based ethanol must achieve substantial cost reductions in virtually all unit-components of the biochemical production process (Stephen, Mabee et al. 2012). While very large facilities (~ 1 billion litres of ethanol production per year) might be able to take advantage of economies of scale, the challenge of supplying these facilities with feedstock is enormous. Facilities on this scale would be significantly larger than the average corn-to-ethanol plants (about 150-200 million litres per year), although a few very large corn-to-ethanol facilities do exist (Stephen, Mabee et al. 2010). This work is correlated to at tripling plant size could reduce capital costs by about 40% and operating costs by 15-20%; this study suggests that Canadian plants are typically too small, with only 9 plants in excess of 100 million litres per year of capacity, and that future investment by government should focus on expanding plant size, and on promoting cellulosic biofuels (Mukhopadhyay and Thomassin 2011). Ultimately, such a policy would lead to fewer, larger facilities; for the most part this would lead to increased transport costs related to feedstock deliveries, although appropriate plant siting could optimize costs of getting the final product to market.

Challenge 3: Process selection

At the current time, there is no single option for lignocellulosic ethanol production that is proven commercially. In terms of Canadian research and development related to the biochemical process, the focus has moved towards pretreatment of lignocellulosics, and the substrate characteristics that control the effectiveness of enzymatic hydrolysis (Chandra, Bura et al. 2007). A number of pretreatments are considered in the Chandra review, two of which are being championed by Canadian companies – steam pretreatment (Iogen) and organosolv pretreatment (Lignol). The organosolv process uses ethanol under high pressure and temperature to isolate lignin and cellulose. Combining organosolv pretreatment with enzymatic hydrolysis on mixed softwood feedstocks, Pan et al. were able to achieve 90% conversion of cellulose to ethanol (Pan, Arato et al. 2005). Organosolv seems well suited to lignocellulosics feedstocks, and fibre size has been shown to play a relatively minor role in the effectiveness of organosolv pretreatment (Del Rio, Chandra et al. 2012). Steam pretreatment has also been shown to be an effective biomass pretreatment, particularly with hardwoods (Sims, Mabee et al. 2010). One unique application might apply steam explosion to wood pellet production; recent work by Kumar et al. suggests that using steam pretreatment prior to pelletization results in a pellet feedstock that can be easily hydrolyzed without the need for further pretreatment, and with relatively little loss of hemicellulose fraction (Kumar, Tooyserkani et al. 2012).

Lignocellulosic ethanol champions

A number of Canadian 'champions' for the biochemical pathway are currently active. They include the following players:

- Greenfield Ethanol, Canada's largest conventional ethanol producer, created a new technology spin-off company (G2Bio) which is focused on developing new technologies including cellulosic ethanol production. Greenfield's research and development has also tested new membrane technologies which will have application in both conventional and advanced biofuel facilities (Cote, Noel et al. 2010). Greenfield Ethanol is also undertaking a joint venture with Enerkem (next section).
- Iogen was at one time Canada's largest advanced biofuel company, and was an early leader in demonstrating biochemical pathways to liquid fuels. The company built itself up with strategic partners including Petro Canada and Royal Dutch Shell, and for a time had ambitious plans to build a very large straw-based biorefinery in western Canada, but in 2012 was forced to restructure and is currently focusing on developing projects in Brazil in conjunction with the Raízen Group. Iogen's technology will be co-located with sugarcane-to-ethanol facilities owned by Raízen, capitalizing on existing infrastructure and focused on processing bagasse to add capacity to their current 2.2 billion liters of sugarcane-based ethanol annually (Lane 2012). Iogen currently has about 110 workers at their Ottawa headquarters and demonstration plant (OBJ Staff 2012).
- Lignol Innovations is a Burnaby-based company that has a proprietary organosolv pretreatment technology, a solvent based pre-treatment technology that was originally developed by a subsidiary of General Electric and piloted in New Brunswick. This approach to pretreatment is unique in that it is capable of isolating lignin with useful properties, although no clear lignin-based bioproducts pathway has been established or demonstrated.
- In March 2009, KL Energy Corporation of South Dakota and Prairie Green Renewable Energy of Alberta announced their intention to develop a cellulosic ethanol plant near Hudson Bay, Saskatchewan. The Northeast Saskatchewan Renewable Energy Facility will use KL Energy's modern design and engineering to produce ethanol from wood waste.

Thermochemical biofuels

Baseline comparator: Diesel oil
Baseline level (g CO_2-equivalent/MJ): 89 (Laan, Litman et al. 2009); 88.1 (1995) (O'Connor 2011)
<u>Synthetic diesel (Fischer-Tropsch fuels)</u>

Emission reductions (% below baseline): 113% (O'Connor 2013)
Capacity: 0 Ml/year

<u>Methanol/Ethanol</u>

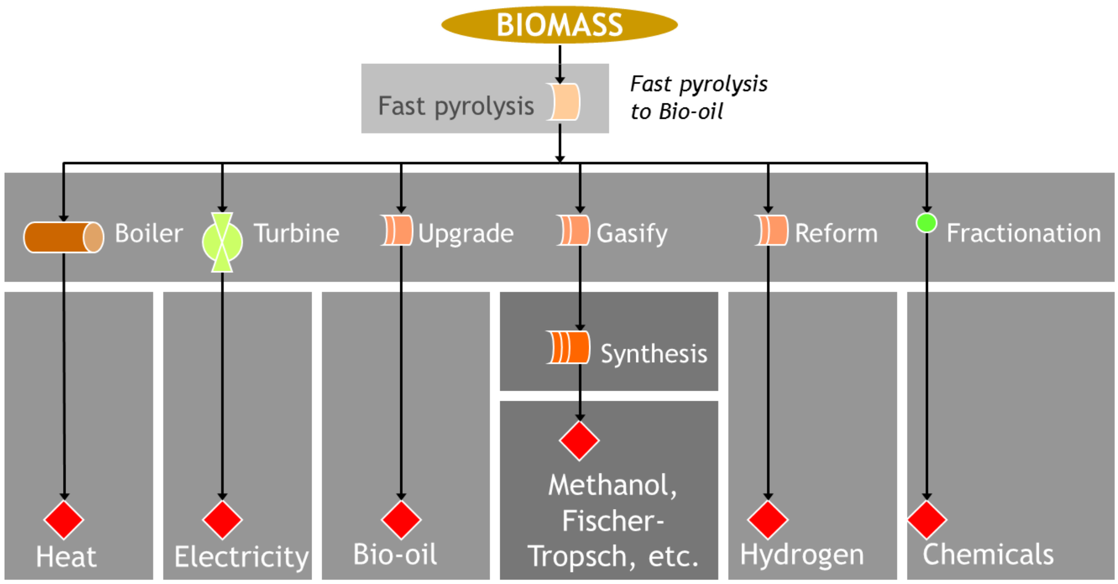
Emission reductions (% below baseline): unknown
Capacity: 0 Ml/year (32 Ml/year expected + 38 Ml/year planned by Enerkem)

<u>Green Gasoline</u>

Emission reductions (% below baseline): 43.1-97.9% (O'Connor 2013)
Capacity: 0 Ml/year

The thermochemical platform utilizes pyrolysis in the absence of complete or partial oxygen to process biomass and create products including synthesis gas (syngas), bio-oils, and solid char. These products can be recovered and further processed into products including fuels, chemicals and plastics, with a portion of the product stream used to generate energy supporting the process (Zhong and Wei 2004). The most commonly explored product from the thermochemical platform is a synthetic diesel substitute which can be derived from lignocellulose (Sims, Mabee et al. 2010), although a range of fuel products are possible. Because a great deal of heat is released during the process, a major product of these facilities will be heat and/or electrical power. One potential coproduct of the thermochemical platform is production of biomass char, which suggests a pathway for long-term carbon sequestration; this has been investigated in Canada using switchgrass as a feedstock (Pilon and Lavoie 2011). Figure 4 details the elements of the thermochemical platform, although it should be noted that configuration of process elements can vary dramatically between different facilities.

Figure 4 - Thermochemical-based fuel production platform (created by author)



Challenge 1: Process technology
Pyrolysis (so called at temperatures between 240-700°C, and often described as gasification at temperatures >700°C) is often referred to as a 'robust' technology that can be used to process heterogeneous feedstocks ranging from wood through agricultural residues and even pre- or post-consumer waste, although in practice managing an industrial-scale process with heterogeneous fuels can be challenging (Demirbas 2003, Yaman 2004).

Challenge 2: Process economics
Creating a financially viable model for thermochemical conversion has been challenging. For example, Range Fuels had a plan to build a 380 Ml per year plant in Georgia, USA using softwood feedstocks. Unfortunately the process economics of the plant did not meet expectations, and the firm declared bankruptcy. This particular plant has been assumed by Lanzatech, which is now in the process of starting up the Soperton facility as the 'Freedom Pines' biorefinery. Another major thermochemical failure was the Choren plant in Germany, which was developed in partnership with Royal Dutch Shell. At the present time, no large-scale thermochemical-based plants based on biomass are in operation and so process economics remain a challenge.

Challenge 3: Facility scale
No synthetic fuel plants have yet been constructed using wood as a feedstock, so it is difficult to anticipate the ultimate scale of these operations. Most thermochemical technologies require

deployment on a large scale in order to gain necessary economies of scale; gasification facilities using natural gas as a feedstock often are built in the 1-1.2 billion litres per annum, a scale significantly larger than average ethanol plants, but smaller than existing oil refineries (Spath and Dayton 2003, Faaij 2006, Stephen, Mabee et al. 2012). Thermochemical or cracking technologies can also be used on non-cellulosic feedstocks. Work has been carried out on vegetable oil sludge, a residue that is produced in vegetable oil processing facilities

Challenge 4: Selecting process and products
As with the biochemical pathway, the thermochemical pathway can follow a number of routes and deliver a range of fuel products, in addition to a synthetic biodiesel.

- *Potential product 1 - Biohydrogen for fuel:* In the future biohydrogen could become a major energy source (if coupled with fuel cell technology). One study evaluated the economics of converting biomass to bio-oil, and then to biohydrogen; this study suggested that carbon credits on the order of C$133/t CO_2-e (for wood) and C$356/t CO_2-e (for wheat straw) would be required to make this process competitive with natural gas at C$5/GJ (Sarkar and Kumar 2010).
- *Potential product 2 - Biohydrogen for electricity:* It has been suggested that biohydrogen could be used in conjunction with other renewables such as wind to create dispatchable renewable power systems (Sanchez, Abad et al. 2011). This assumes that stationary power sources that can utilize hydrogen, such as large fuel cells, become economic. Such a process remains at very early stages. A recent study considered the economic feasibility of employing gasification technology in northwestern Ontario to generate electricity, and found that the estimated price for biomass-to-electricity would range between C$0.062 and $0.064/kWh (Upadhyay, Shahi et al. 2012), significantly above the current price for electricity in Ontario but not far out of line with the price offered for other renewables in the province (Mabee, Mannion et al. 2012).
- *Potential product 3* - Methanol/ethanol: It is possible to reform syngas to methanol and then to build ethanol as a product. Enerkem has chosen this pathway and is building two facilities which use this approach - one in Edmonton (32 Ml/year) which should be online in 2014, and one in Varennes (38 Ml/year).
- *Potential product 3 - Green gasoline:* A cracking catalytic reaction, which utilizes a silica source derived from rice husks as a catalyst, is shown to be an effective alternative to pyrolysis in liberating biofuel from vegetable oil residues; indeed, a range of products including liquefied petroleum gas, gasoline, light and heavy cycle oils were recovered from the cracking process (Le, Tran et al. 2011), with 'green gasoline' providing 42.4% of outputs. The advantage of this approach is that higher energy products can be liberated from the feedstock.

Thermochemical process champions
Major Canadian companies in the thermochemical area include

- Enerkem, founded in 2000 by members of its current management team and developers of a combined pyrolysis/gasification technology for processing a variety of biomass feedstocks. It currently employs almost 150 people and runs projects in both Canada and the United States. The company has a Canadian biorefining project under development in Alberta that when complete will produce about 36 million litres of ethanol per year (plus an unspecified amount of methanol); by using municipal solid waste as a feedstock, the company has improved the financial viability of the project. A second major project is underway in Varennes, Quebec, in conjunction with Greenfield Ethanol. The Enerkem process at Varennes will share facilities with the existing Greenfield plant and add 38 Ml/year capacity to that operation.

- Another major player, Ensyn, uses pyrolysis to generate bio-oil; this Ontario-based company recently received a major investment from a Brazilian pulp and paper company. Bio-oil is a notoriously unstable product and is unsuitable for direct use in transportation, but could be a useful feedstock for electricity production.

Other biofuel pathways

Many pathways for advanced biofuel production are being investigated around the world. Three relatively recent developments are described below. Of these, one in particular (unconventional fermentation of sugars) seems to have very high potential GHG reductions - indeed, could lead to increased GHG sequestration compared to baseline measurements.

- *Potential pathway - Unconventional fermentation:* One pathway of particular interest is the use of modified organisms to convert C6 sugars, taken from sugarcane or from processed corn, directly to hydrocarbons. One company involved in developing this process is Amyris through joint ventures with Total and Cosan; it should be noted that after a quick start-up, Amyris has backed off sole development of industrial-scale projects due to difficulties in achieving comparable results to their lab findings. Laboratory scale results suggest that GHG savings might exceed 150%, or a 50% increase in capture compared to traditional diesel (O'Connor 2013).
- *Potential pathway - Hydrothermal liquefaction:* Hydrothermal liquefaction (processing biomass in water at temperatures around 375°C) can be used to convert biomass to a heavy organic liquid often referred to as biocrude, which can then be refined through catalytic hydro-de-oxygenation, which increases the hydrogen ratio and produces a fuel that can be blended with diesel. It has been suggested that a reduction in GHG's by up to 70% can be achieved with this type of process (O'Connor 2013).
- *Potential pathway - Hybrid bio-thermal processes:* The production of biofuels can be carried out by combining elements of the thermochemical and biochemical platforms. The resulting platform can take a variety of forms; for example, biomass gasification can be followed by an unconventional fermentation stage. One champion of this approach is Coskata. Analysis of this type of pathway suggests a potential reduction in GHG emissions of 70.7% (O'Connor 2013). Alternatively, biomass can be converted to sugars using pretreatment and enzymatic hydrolysis, and sugars can then be catalyzed to produce fuels. One champion of this approach is Virent Inc. Analysis of this type of pathway suggests a potential reduction in GHG emissions of 82.5% (O'Connor 2013). Of the two processes, the former (thermochem-biochem) is better detailed in the literature and the data presented is likely to be more accurate for this process.

Most likely emerging biofuels

Of the advanced biofuels described in this section, three have been selected for additional analysis and modeling in the Trottier Energy Futures Project. These are (1) cellulosic ethanol, (2) synthetic diesel (Fischer-Tropsch fuel), and (3) Bio-oil (pyrolysis oil). Modelling parameters suggested for each of these fuels follow in Table 1 below.

Table 1 – Modelling parameters for selected advanced biofuels (various sources as noted)

Input-output variables	Cellulosic ethanol	Synthetic biodiesel	Bio-oil	Unit
Fuel output	0.14[A] 0.31[B] 0.36[A]	0.16[A] 0.42[A]	0.48[E] 0.66[E]	GJ/GJ feedstock
Process heat	0.30[B]	0.42[D]	0.24[B]	GJ/GJ feedstock
Process electricity	0.10[B]	0.10[D]	0.04[B]	GJ/GJ feedstock
Net electricity output	0.03[B,C] 0.14[B,C]	0.03[B,D] 0.14[B,D]	0.03[B,E] 0.12[B,E]	GJ/GJ feedstock
Capital costs (various residues)	$4.52[F] $6.69[F] $12.41[G] $30.93[H]	$3.88[I] $5.44[I]	$2.97[J] $4.19[J]	$/GJ/year *(20-year loan, 8.5% cost of capital)*
Operating costs (estimated)	$1.71 $2.53	$1.47 $2.06	$1.12 $1.59	$/GJ/year

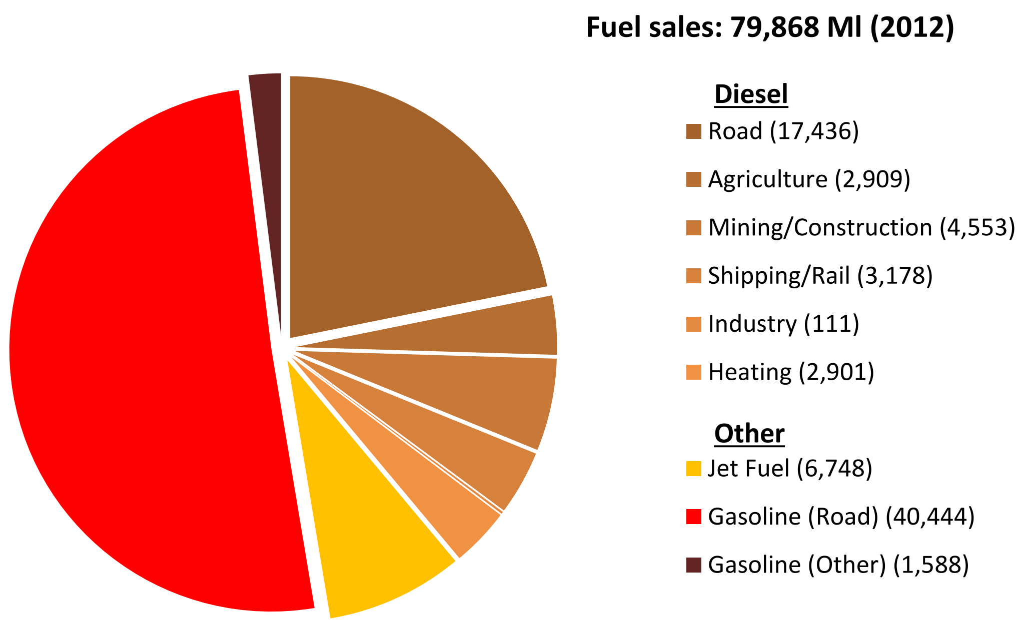
[A] Mabee et al 2006
[B] Liebbrandt et al 2011
[C] Karlsson, Gustavsson 2003
[D] Manganaro et al 2011
[E] Carpenter et al 2014
[F] Stephen et al 2013
[G] http://www.chemicals-technology.com/projects/poet-ethanol/
[H] http://www.chemicals-technology.com/projects/abengoa-cellulosic-ethanol-biorefinery/
[I] Lehmann, Joseph 2009
[J] http://petrowiki.org/Gas_to_liquids_(GTL)

Section 4: Demand projection rationale

The primary demand driver for biofuels in Canada is policy. As discussed in the Introduction, the current renewable fuel standard operated by the federal government includes a 5% renewable fuel mandate for the national gasoline pool (in effect as of December 15, 2010) as well as a 2% renewable fuel mandate for diesel oils (in effect as of July 1, 2011 with full implementation on July 1, 2013) (Evans 2013). The final biodiesel mandate includes a permanent exemption for diesel heating oils (Canada Gazette 2013). Both mandates are volumetric not energetic; thus one litre of renewable fuel substitutes for one litre of petro-based product.

Canada's fuel markets are shown in Figure 5 below. Current levels of gasoline consumption will require 2.1 billion litres (Bl) of ethanol (or another renewable substitute), while diesel consumption (less heating oil) would require 585 million litres (Ml) of biodiesel production (Evans 2013). Canada's jet fuel market is large, with sales of almost 6.8 billion litres in 2012.

Figure 5 - Total Canadian fuel sales, 2012 (Evans 2013, Statistics Canada 2013)



Canada's provincial mandates are shown in Table 2 (gasoline) and Table 3 (diesel) below, as well as 2012 levels of road sales for gasoline and diesel fuels. Note that Canadian provinces have not opted to dictate localized production of biofuel; thus provincial capacities need not be linked to local blend requirements. Taken as a whole, these mandates represent the 'floor' on biofuel demand in Canada, pending any policy change.

Table 2 - Renewable fuel standards and gasoline sales by province, 2012 (Evans 2013, Statistics Canada 2013, IEA Bioenergy 2014)

Region	Gasoline (Road) Sales (Ml)	Renewable Fuel Standard (%)	Volume Required (Ml)	Ethanol Production Capacity (Ml)
Canada	**40,444**	**5% [I]**	**2,022**	**1,786**
Alberta	6,002	5% [I]	300	82 [VI]
British Columbia	4,349	5% [I]	217	-
Manitoba	1,478	8.5% [II]	126	130
New Brunswick	1,070		-	-
Newfoundland and Labrador	700		-	-
Northwest Territories	41		-	-
Nova Scotia	1,175		-	-
Nunavut	35		-	-
Ontario	15,576	5% [III]	779	1,104
Prince Edward Island	204		-	-
Quebec	8,342	[IV]	417	125 [VII]
Saskatchewan	1,404	7.5% [V]	105	195
Yukon	69		-	-

[I] From 2010 [II] From January 2008 [III] From 2007

[IV] A 5% target (not mandate) for cellulosic ethanol blends was originally set for 2012. This target has not been met.

[V] From 2005

[VI] Enerkem's Edmonton facility will add 32 Ml of MSW-based cellulosic ethanol, likely in 2014/15; Mascoma's proposed Drayton Valley facility could add 80 Ml of wood-based cellulosic ethanol

[VII] Includes 5.48 Ml of cellulosic ethanol capacity at Enerkem`s demonstration facilities. Enerkem`s proposed Varennes facility would add 38 Ml of MSW- and residue-based cellulosic ethanol (in conjunction with GreenField Ethanol)

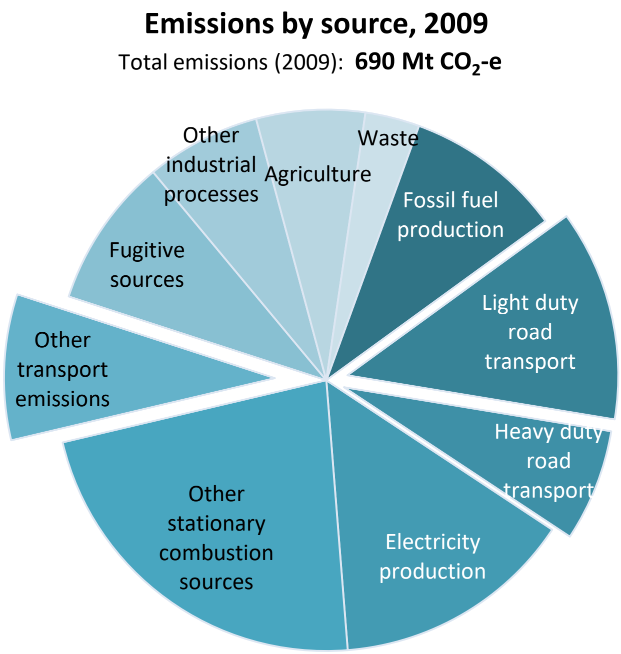
Table 3 - Renewable fuel standards and diesel sales by province, 2012 (Evans 2013, Statistics Canada 2013, IEA Bioenergy 2014)

Region	Diesel Oil (Road) Sales (Ml)	Renewable Fuel Standard (%)	Volume Required (Ml)	Biodiesel Production Capacity (Ml)
Canada	**17,436**			
Canada (Other diesel sales, less heat)	***10,751***	**2% [I]**	**564**	**464**
Alberta	4,054	2% [II]	81	67 [III]
British Columbia	1,762	4% [I]	70	21
Manitoba	778	2% [II]	16	-
New Brunswick	427		-	-
Newfoundland and Labrador	267		-	-
Northwest Territories	93		-	-
Nova Scotia	367		-	-
Nunavut	10		-	-
Ontario	5,044		-	296
Prince Edward Island	41		-	-
Quebec	3,127		-	60
Saskatchewan	1,404	2% [I]	28	20
Yukon	60		-	-

[I] From 2012 [II] From 2010 [III] Includes a 1 Ml demonstration facility as well as the Kyoto Biofuels 66 Ml plant (which started up in November 2013). The Archer Daniels Midland plant planned for Lloydminster would add 265 Ml of biodiesel capacity.

Section 5: Recommendations

Figure 6 - Canada's emissions by source, 2009 (Environment Canada 2011)



Canada's greenhouse gas emissions rose from 590 Mt to 690 Mt of CO_2-equivalents between 1990 and 2009. The emissions associated with transport rose at a fairly significant rate. Where population has grown by 25%, heavy duty road transport emissions rose by 54%, light duty road transport rose by 27%, and other transport emissions rose by 20% over this period. Altogether, these sectors represent 190 Mt of CO_2-e in 2009, or 27.5% of Canada's total GHG emissions. An 80% reduction in these emissions would require us to shrink each sector significantly, with a target of about 30 Mt across heavy-duty, light-duty, and other transport emissions.

Reducing these emissions through the application of biofuels (and other alternative forms of energy) is one option to explore. Three opportunities are identified:

1. Emissions from heavy duty road transport have risen the fastest since 1990 of all sectors identified above. This is a significant problem for Canada and the application of biofuels can help address. Strategy:
    a. Increase uptake of conventional biodiesel from 2%. Even at baseline conditions this will reduce emissions compared to reference case diesel by between 50-60%.
    b. Promote improved agricultural techniques and better fertilizer manufacture techniques to push emission reductions associated with canola and soybean-based biodiesel into the 70-80% range.
    c. Focus on lignocellulosic (wood and crop)-based biodiesel options that can provide much greater GHG emission reductions than conventional biodiesel, in some cases exceeding 100% (i.e. moving to a GHG sink). Recommended biofuels: synthetic biodiesel (Fischer-Tropsch fuel), bio-oil (pyrolysis oil)
2. Emissions from light-duty road transport have risen faster than population growth and should be addressed. Strategy:
    a. Consider scenarios with increased public transit powered through heavy-duty (diesel) fuels or through electricity.
    b. Compare trade-offs between increasing cellulosic ethanol production and shifting to a diesel-based fleet in order to avoid competition for feedstocks.
    Recommended biofuel: cellulosic ethanol
3. Emissions from other transport, including marine and aviation, are significant. Jet fuel use is unlikely to decrease without a price signal (i.e. carbon price, etc.); biojet not yet viable.

Section 6: Summary of perspectives

Key findings of this working paper:

1. Biofuel development in Canada has entirely been dependent upon policy signals from the federal, and to a lesser extent provincial governments. At the current time there is no indication that new signals will be given in the form of increased mandates or new incentive programs, and production levels currently in place are almost sufficient to cover domestic requirements. Thus it can be said that biofuel production in Canada will stagnate in the short term without a new impetus for production.
2. The bioenergy sector in Canada is small but growing. There are a number of options being explored by Canadian industry and by governments, including the development of cogeneration in the pulp and paper sector, the commissioning of biomass-to-electricity facilities in many provinces, and the increasing production of wood pellets (largely for the export market). While uses of biomass for various energy production systems is currently limited, growth in any of these sectors will mean increased competition for feedstocks (to be explored in the feedstock paper).
3. The number of jobs created by the biofuel sector, while not the primary focus of this paper, is significant - but is largely invisible as many of these jobs would be classified as 'retained', in terms of farmers being able to keep their farms, etc.
4. It is often said that carbon taxes will provide the impetus required for biofuel development. However, the limited development in biofuels seen to date is due to support or incentive levels which translate into carbon prices between C$90-430 (for ethanol) and C$205-580 (for biodiesel). These numbers are far in excess of 'market' prices for carbon and suggest that a simple carbon tax will not be able to drive major development of biofuels in the future.
5. The opportunity to reduce GHG emissions will improve as biofuel technologies develop. It may be possible to 'green' existing corn, wheat, canola and soybean-based processes to reach 80-90% reductions under baseline values.
6. Canada's emissions are growing fastest in heavy transport sector. Thus a preference should be given to biodiesel options as these fuels have the best chance of addressing this fast-growing sector. In addition, the ability of other transport sectors to reduce emissions is either technologically limited (for aviation) or may be better served through electrification (for light transport).

Data gaps:

1. Very little good data is available on pricing for biofuels. The author continues to work to fill these gaps.
2. Aviation biofuels have not yet been documented. The pathways for aviation biofuels are beginning to be better understood, and a subsequent version of this paper may include more details on this important area.

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