ISSUES IN BIOENERGY DEVELOPMENT IN WESTERN CANADA

Ewen Coxworth
Saskatoon, Saskatchewan
November 2005

Revised February 2006

Chapter 1. Overview of Biomass Energy Issues.

This review paper examines some of the criticisms leveled by Pimentel and Patzek (2005) and others at ethanol production from grains, grasses and wood, and looks at possible solutions for western Canada to the issues they raised. This present report discusses ethanol produced from grain or from lignocellulosic raw materials, such as sawdust, bark, perennial grass hays or crop residues. The main emphasis is on ethanol made from small grains, such as CPS wheat, since most ethanol plants in western Canada are, or are planned to be, grain based. However, the major resources for production of large amounts of biofuels are lignocellulosic raw materials, such as forest residues and crop residues.

Some of the criticisms of Pimentel and Patzek were directed at corn grain production systems in the USA and conversion of corn grain into ethanol and distillers grains and solubles (DDGS), based on USA data. Criticisms of ethanol production from lignocellulosic raw materials, such as wood and grasses, were also based on American technology. Canadian situations and potential solutions to problems may be different than in the USA.

In their study, Pimentel and Patzek (2005) criticized biofuels on a number of issues:

1. Energy efficiency and the use of fossil fuels to produce renewable energy.

Pimentel and Patzek calculated that if one included all the energy inputs going into the production of ethanol and biodiesel, these two biofuels consumed more fossil fuel energy in their production than was gained as renewable energy.

This present report (in Chapter 2) focuses on ethanol produced from wheat grain, since most of the ethanol plants in production, under construction, or planned for western Canada are based on fermentation of grains, such as CPS wheat. The present study includes all the energy inputs included in Pimentel and Patzek's analysis (theirs was based on corn grain as the raw material), some of which have not been included in other analyses.

The present study evaluates a number of ways to improve the energy efficiency of grain production and processing. The study also tests methods to increase the proportion of renewable energy used to produce grain and to process it into ethanol and co-products.

The results of these analyses of ethanol produced from high starch-content wheat, such as CPS wheat, are presented in Chapter 2.

2.Other issues related to production of biofuels.

2.1. Environmental effects.

As well as the energy budget issues, Pimentel and Patzek (2005) criticized liquid biofuels, such as ethanol, on the basis of their environmental impacts. These negative impacts included air pollution, water pollution and soil erosion. These issues are discussed later in this chapter (Chapter 1)(see sections 19 and 20).

2.2. Food versus fuel

Pimentel and Patzek (2005) addressed the food versus fuel issue and felt it was unethical to use potential foods, such as grains and oilseeds, to produce liquid fuels in a world with many hungry people. The responses of different organizations and individuals are reviewed later in this chapter (see section 14 of this chapter).

2.3. Economic benefits to farmers.

Pimentel and Patzek (2005) indicated that farmers had received little economic benefit from the development of ethanol production from corn in the USA. In western Canada, there may be opportunities to utilize crop rotations that would improve the net income from the wheat when used as a raw material for ethanol production.

In the present study, some initial calculations on producing CPS wheat after alfalfa in the rotation, or in long-term zero tillage fields with increased soil fertility, found that the net income from growing CPS wheat was greatly increased compared to growing CPS after a cereal or in fields that had not had increased soil fertility. These results are described in Chapter 2.

2.4. Economic costs.

Finally, Pimentel and Patzek (2005) calculated that the total economic costs of liquid biofuels were substantially more than the gasoline or diesel fuel they were supposed to compete with or supplement. They did conclude that direct use of waste biomass, such as sawdust, or grass hays (such as switchgrass hays grown in eastern Canada or the USA), for direct heat energy applications (e.g., as pelleted solid fuels) seemed more economically and environmentally acceptable.

Other studies will be needed to examine if improved methods of crop production and processing into ethanol and co-products can reduce the economic cost of ethanol production in western Canada. Examples of improved methods of ethanol production are described in Chapter 2, in terms of their effects on reducing the energy costs of ethanol production. These may have economic benefits as well.

3. Goals for improved production and utilization of biofuels for transportation applications.

Methods and strategies to provide solutions to the problems raised by Pimentel and Patzek (2005) can be framed as a set of twelve objectives or goals for renewable fuels used in transportation and produced from agricultural and forestry raw materials (Figure 1).

Figure 1. Twelve goals for transportation fuels produced from agriculture and forest raw materials.

Ensure more renewable energy is produced than fossil fuel inputs used	Reduce GHGs from fuel production and use compared to gasoline or diesel fuel	Reduce GHG emissions from agriculture
Integrate with other renewable energy options	Improve the fuel efficiency of all types of vehicles (less fuel needed per km driven)	Sequester CO_2 out of the atmosphere where possible (soils, trees, deep underground)
Improve the economic competitiveness of renewable fuels cf. gasoline or diesel fuel	Improve farmers' incomes	Minimize potential food versus fuel conflicts for raw materials or land
Reduce air pollution	Reduce water pollution	Reduce soil erosion and improve soil fertility

GHGs = greenhouse gases; CO_2 = carbon dioxide.

4. Responses to Pimentel and Patzek's criticisms.

Chapter 1 of this study reports briefly on solutions provided by other studies to many of the criticisms raised by Pimentel and Patzek (2005), including studies on liquid fuel production from agricultural raw materials. Chapter 2 looks at possible strategies to reduce fossil fuel use in ethanol production from agricultural raw materials in western Canada. The focus is on identifying methods to maximize the reduction in fossil fuel consumption (compared to gasoline) by production of ethanol from grain. Methods to reduce fossil fuel consumption (per unit of ethanol produced) are being used in most of the new production plants under construction or planned.

Several recently published reviews on large scale production of liquid biofuels deal with a number of the issues raised by Pimentel and Patzek (2005)(see for example Greene et al., 2004; IEA, 2005; Lovins et al., 2004; $(S\&T)^2$, 2005). These reviews are used as sources of information and references in the present study.

David Morris of the Institute for Local Self-Reliance has recently published a detailed response to the criticisms raised in Pimentel and Patzek's article (Morris, 2005). Morris's article has also been used in the present report as a source of information about recent developments in the production and use of ethanol.

There is general agreement in these and other studies that large volume ethanol production, to meet a large fraction of the liquid fuel needs of a region, will need to be based on conversion of lignocellulosic raw materials, such as crop residues (where it is environmentally acceptable to remove a portion of them from the land), waste wood and bark, rather than grain.

5. Differences between Canada and the USA with regard to renewable liquid fuels development.

Canada and the USA are in very different situations with regard to the fossil fuel resources to produce liquid fuels for transportation uses.

Canada has large reserves of oil sands and heavy oil, although reserves of conventional light crude oil are declining (see Nikiforuk, 2005, for a recent review). However, significantly more energy is required to produce gasoline and diesel fuel from these unconventional sources of crude oil than is required to produce these transportation fuels from conventional crude oil; hence greenhouse gas emissions are larger also.

The USA imports large amounts of crude oil from all over the world, including Canada. The USA has a much greater need to find domestic sources of liquid fuels to replace imported crude oil.

On the other hand, Canada has signed the Kyoto Agreement and has committed to reducing greenhouse gas emissions; the USA has not signed the Kyoto Agreement. Thus there is greater motivation for Canada to find renewable fuels which reduce greenhouse gas emissions and to improve the efficiency of use of fossil fuels to reduce greenhouse gas emissions.

6. Energy budgets and greenhouse gas reductions from use of ethanol produced from grain or lignocellulosic raw materials, such as wood and straw.

The negative energy budgets for ethanol produced from grain, grass hays or wood calculated by Pimentel and Patzek (2005) are in contrast to most other recent energy analyses, which calculated positive energy balances, i.e., more renewable energy was produced than fossil fuel energy consumed. The International Energy Agency (IEA) has recently published a book on biofuels (IEA, 2005) which reviews the differences between various studies. Recent Canadian studies on the energy balance and greenhouse gas reduction for ethanol produced from corn grain in Ontario, wheat grain in western Canada, and wood, straw and perennial grasses have been reported by Levelton et al. (1999, 1999b), $(S\&T)^2$ (2003) and $(S\&T)^2$ (2005). All these Canadian studies found positive energy budgets, i.e., more ethanol renewable energy was produced than fossil fuel energy consumed.

6.1. Energy credits for the co-products from grain fermentation.

These studies took into account the energy credit for the fermentation co-product of grain, i.e., the dried distillers grain and solubles (DDGS), which are used for animal feed. The amount of DDGS produced from CPS wheat is actually greater (380 kg/tonne of wheat) than the amount of ethanol (370 litres or 292 kg/tonne of wheat). The fermentation process concentrates the energy formerly present in the starch content of the wheat into the fuel ethanol. The protein, oil, fiber and some of the vitamins and minerals originally present in the wheat are still retained in the DDGS and can be used for animal feed.

The DDGS replaces products such as soybean meal and corn or barley in the animal ration. Since it takes fossil fuel-based energy to produce these other animal feeds, the DDGS receives a credit for replacing the energy which otherwise would have been expended for these other feeds.

The economics of producing ethanol from grain depend strongly on having markets for all the DDGS produced.

The most recent study of the energy budget and greenhouse gas emissions for ethanol produced from wheat in western Canada also included an energy credit from capturing carbon dioxide (given off during the fermentation process). This was used this to replace carbon dioxide produced using fossil fuel energy to capture carbon dioxide emitted from other industrial processes which burn fossil fuels ((S&T)^2, 2005). It takes more energy to capture and purify carbon dioxide produced from fossil fuel combustion processes than it does from capture of carbon dioxide produced during fermentation of grain carbohydrate. Thus capture of carbon dioxide from the fermentation of grain receives an energy credit if this carbon dioxide replaces carbon dioxide produced from fossil fuel combustion.

Two industrial processes are likely to be replaced by carbon dioxide (CO_2) captured from grain fermentation systems. These industrial processes are (a) CO_2 generated from hydrocarbon fuels without using the combustion process for anything but CO_2 production, and (b) recovering CO_2 from boiler stack gas from combustion of fossil fuels, such as natural gas. In the latter case, the gas contains only relatively small amounts of CO_2 compared to the concentrated stream available from the grain fermentation process. Thus energy costs to recover the gas are higher in the stack gas situation. In both cases, the CO_2 produced from the grain fermentation process should receive an energy credit.

The (S&T)^2 2005 report describes the energy credit for CO_2 captured from fermentation processes as follows:

"There are many CO_2 plants operating today that burn a fuel (diesel, natural gas) and recover the CO_2 with the monethanolamine (MEA) process…… Due to the economics, these plants are usually part of another process such as an oil refinery or power plant, where the CO_2 would otherwise be wasted."

“The CO_2 is absorbed by an amine solution, some thermal energy must be used to regenerate the CO_2 and some power is required to move the exhaust gases through the scrubbing system. This energy input can be avoided if a concentrated CO_2 gas stream such as that available in an ethanol plant is used. Ethanol plants that capture the CO_2 that then displaces CO_2 generated from combustion facilities and captured by a MEA process will effectively displace energy consumption from these plants and this displaced energy should be credited to the ethanol production cycle.”

Carbon dioxide captured during grain fermentation could also be sequestered in geological formations, such as old oil fields. This sequestration would provide a major greenhouse gas credit for the ethanol produced in conjunction with this removal of carbon dioxide from the atmosphere (see for example Figure 3.13 in Reddy et al., 1997). Carbon dioxide released by the fermentation process has been recently fixed by living plants to produce the grain which was fermented. Its release back into the atmosphere just completes this carbon fixing and release process. There is no net increase in the CO_2 in the atmosphere.

In contrast, release of CO_2 by combustion of fossil fuels releases into the atmosphere this GHG gas which had been sequestered as hydrocarbons deep underground for millions of years. This results in a net increase in this GHG into the atmosphere which causes global warming.

The amount of CO_2 produced during grain fermentation is quite large. About 0.72 kg of CO_2 is released for every litre of ethanol produced from CPS wheat. Thus the potential greenhouse gas credit to ethanol if the carbon dioxide were to be sequestered would be significant.

6.2. Including all the energy costs of producing ethanol and DDGS from grain fermentation.

Pimentel and Patzek did include the energy and economic costs of a number of inputs into liquid biofuels production not included in other analyses. These inputs included the:

1. energy costs of machinery production and repair,
2. labour energy costs,
3. energy required to produce seed for seeding,
4. energy required to provide water and to treat sewage in the ethanol plant.

In the present analysis, these costs have been included. Later discussion in this chapter discusses methods to reduce some of the extra energy costs associated with water provision and treatment.

6.3. Ethanol production from lignocellulosic raw materials such as sawdust or straw

6.3.1. Ethanol production via fermentation routes.

Lignin produced in the processing of lignocellulosic raw materials into ethanol can be used as a fuel to run the process. In the case of ethanol production by fermentation routes from lignocellulosic raw materials such as wood, straw or perennial grasses, a residue consisting mainly of lignin is left after fermentation. This residue is burned to produce the heat and electricity which is needed in the process. Thus only small amounts of fossil fuels are required to effect the conversion of a solid biomass raw material into a liquid fuel suitable for running a vehicle. While more energy is required to run the process than is returned as ethanol, much of this energy is the renewable by-product (lignin) of the process.

The net effect is that greenhouse gas emissions due to fossil fuel consumption are low in the whole process. This result is due to the fact that the CO_2 which has been converted into lignin is recently fixed CO_2 and doesn't result in a net increase in CO_2 in the atmosphere. In contrast, CO_2 released by the combustion of gasoline or diesel fuel does increase atmospheric CO_2, since the crude oil from which these fuels are derived has been sequestered deep underground for millions of years. Thus the use of fuel ethanol, produced from these types of biomass raw materials, greatly reduces greenhouse emissions compared to combustion of fossil fuels. This topic is reviewed in a recent report from the International Energy Agency (IEA)(IEA, 2005).

Canadian technology, based on a process for converting lignocellulosic raw materials by fermentation into ethanol, has been developed by the Canadian company Iogen. The calculated greenhouse gas reductions for ethanol produced from corn stover, wheat straw or grass hay were in the order of 57% to 68% compared to gasoline (Levelton et al., 1999b; $(S\&T)^2$, 2005).

6.3.2. Gasification routes to ethanol

Ethanol and other renewable fuels can also be produced by gasification of lignocellulosic raw materials, such as wood or straw. In these technologies, gasification produces a mixture of hydrogen and carbon monoxide called synthesis gas. By choice of catalyst, this synthesis gas can be converted into ethanol, methanol or synthetic gasoline or diesel fuel (IEA, 2005). Some of the raw material is burned to produce the heat energy required to convert the rest of the raw material into ethanol or other renewable fuel. Thus the processes use mainly renewable energy to convert a solid (wood, straw or hay) into a liquid fuel. The reduction in greenhouse gas emissions by using these fuels in internal combustion engines for transport, compared to burning fossil fuels, was 60% or more, according to various studies summarized in the IEA report (IEA, 2005).

It should be noted that most studies of the potential of biomass to provide a significant fraction of world's future transportation fuels or electricity assume that gasification processes are employed (see for example Berndes et al., 2001).

A gasification process combined with Fischer-Tropsch catalysis conversion of the synthesis gas to ethanol and higher alcohols is being developed by the Saskatchewan Research Council and other organizations, for a possible ethanol production plant at

Nipawin, Saskatchewan (Sulatisky, 2005; Nipawin Biomass Ethanol New Generation Co-operative, Ltd., briefing memo, December, 2004). The process and concept were first proposed by Hutchence (1999, 2001). Hutchence also conducted the initial discussions with local organizations. This led to the concept of a new generation co-op to develop the process and commercialize the ethanol production. The economic structure of a new generation co-op was chosen to improve the economic benefits to local farmers and local investors, including local First Nations bands and local municipalities. The process would use sawdust and other forestry waste products, plus flax straw produced by local farmers. Some 75 million litres of ethanol would be produced from 150,000 tonnes (dry basis) of sawdust and flax straw. Sulatisky (2005) has calculated that using ethanol produced by this process would reduce greenhouse gas emissions by 77%, when used in an 85% ethanol:15% gasoline blend transportation fuel.

A similar gasification/Fischer-Tropsch synthesis to ethanol have been described more recently by Lovins et al. (2004, Technical Annex to Chapter 18). The process described by Lovins et al. is based on a new technology developed by Pearson called the Pearson Gasification Process (Pearson, 2001). In this process, biomass raw materials, such as wood waste, bagasse or rice hulls, are first gasified in the presence of high temperature and pressure steam to generate a mixture of carbon monoxide and hydrogen. Plants can be smaller than plants using conventional gasification with oxygen since capital costs of an air separation plant to produce oxygen are avoided (Pearson, 2001). The synthesis gas is cleaned before being sent to the catalyst unit where it is converted into ethanol, plus small amounts of other longer chain length alcohols (such as propanol and butanol). Un-reacted synthesis gas is recycled to the reactor for conversion into alcohol. Distillation separates the fuel ethanol from the small amounts of other alcohols. These other alcohols may have industrial markets.

6.4. Western Canada situation.

Grain-based ethanol production.
Integration with livestock production.
Use as part of a strategy to reduce GHG emissions from livetock production.

Pimentel and Patzek's criticisms were mainly directed at production of ethanol from corn grain in the United States. However, conditions may be very different in western Canada. There may be possibilities to reduce the energy costs of ethanol production here and also to reduce the negative environmental impacts of ethanol production. Cropping systems appear to be possible for western Canada which would improve farmers' net incomes and also reduce the energy costs of the raw materials for bioprocessing (see Chapter 2).

Cropping systems that involve use of zero and minimum tillage practices have been shown to reduce soil erosion by keeping standing stubble present most of the time. Small grains such as wheat are not wide row-spacing crops like corn and thus have less erosion risk potential. Leaving stubble standing from the previous crop also traps snow to enhance soil moisture, reduces moisture loss from the soil, creates a favorable microclimate for the growing crop and enables more continuous cropping. This in turn can increase soil organic matter. Over time this may lead to build up of soil fertility and reduced needs for fertilizer (Lafond, 2003).

Inclusion of a forage legume in the rotation can lead to a reduced need for nitrogen fertilizer, reducing the energy costs of the crop following the legume, and improving net economic returns for the farmer (this is also discussed in Chapter 2).

A new method for biogas and bio-fertilizer co-production by anaerobic digestion of livestock manure, called Integrated Manure Utilization System (IMUS) has been developed in Alberta by Li (Li, 2005)(MacArthur, 2005)(see also http://res2.agr.ca/initiatives/manurenet/en/hems/ecoamu_main.html). Anaerobic digestion of feedlot manure produces two products: biogas (mainly methane) and a digested manure from which a solid bio-fertilizer can be recovered. This solid bio-fertilizer can be transported further than the manure slurry produced by previous biogas systems. In Chapter 2 the potential of coupling this system with a grain-based ethanol production plant is examined. The biogas could be used to provide the heat energy requirements of the ethanol plant. Biogas capture and use would reduce the methane emissions from the manure produced in the feedlot.

The distillers grain and solubles (DGS) produced as a co-product from grain fermentation would be fed in the wet state (no need for drying) to the cattle in the feedlot. It is known that feeding wet DGS to cattle improves their rate of gain and reduces methane eructation.

All these effects would reduce the GHG emissions from the cattle and from the ethanol plant, since biogas would replace natural gas as the energy source for ethanol production. The potential energy budget benefits for ethanol production by this integrated process are examined in Chapter 2.

Methane emissions from eructation by ruminant animals (“burping cows”) and methane emissions from untreated manure are major sources of GHG emissions from the livestock industry. Integration of ethanol production with livestock production has the potential to reduce both these sources of GHGs.

7. Biofuels and improved efficiency of energy use in vehicles.

The use of biofuels to reduce greenhouse gas emissions can be compared to technologies which achieve greater energy use efficiency in various economic activities as a means to reduce greenhouse gas emissions. An example would be improving the fuel efficiency of cars and trucks. A recent study by the Union of Concerned Scientists in the USA found that low cost improvements in a hypothetical sports utility vehicle (SUV) could significantly improve the fuel efficiency and safety of such a vehicle (Friedman et al., 2003). The cost of saving a tonne of greenhouse gases by improving the fuel efficiency of the SUV (in the range of US$7 to $33) appeared from this study to be much less than saving a tonne of greenhouse gases by using ethanol made from grain, for example, where the IEA estimates that saving a tonne of carbon dioxide costs about US$300/tonne of carbon dioxide equivalents saved (IEA, 2005). The IEA study estimated that advanced methods of producing ethanol from lignocellulosic sources might reduce greenhouse gas emissions at a cost of about US$100/tonne of greenhouse gases.

A reviewer has noted that these comparisons were done when the price of crude oil was considerably lower (e.g. $20-40/barrel) than the price in the last year (in the range of $50-60/barrel). Comparisons of the cost of reducing GHGs by use of biofuels needs to be updated frequently to provide a current comparison.

It should be noted that these two routes to reducing greenhouse gas emissions are complementary; i.e., the more we make vehicles more fuel efficient, the lower the cost of fuel needed per unit distance driven, and the less land is needed to produce the fuel (such as ethanol) required to drive a vehicle a stated distance (this issue is discussed in detail in Greene et al., 2004).

Given the substantial reductions in rates of GHG emissions believed necessary for stabilization of world GHG levels, improvements in vehicle fuel efficiency alone are unlikely to be sufficient in the transportation sector. More generally, for all energy use in the economy, it has been recognized that a combination of energy efficiency improvements and switching to zero or low emission energy sources will be necessary in the coming century to lower rates of GHG emissions to a level that is consistent with stabilization of world emission levels to a point which poses an acceptable risk to climate change.

Ethanol from lignocellulosic raw materials is not yet in commercial production, so the potentially significant impact on reducing GHG emissions is still some years away. In contrast, methods to improve the fuel efficiency of vehicles are coming into general application commercially now. These technologies can also reduce air pollution from vehicles. Thus the immediate strategy for Canada would appear to be to apply various economic strategies to speed up the sales of vehicles, regardless of type, which reduce GHG emissions. These fiscal strategies are described in some detail in Lovins et al. (2004).

An advantage of renewable fuels, such as ethanol, is that the gains from emission reductions can be achieved relatively quickly by introduction of an ethanol mandate. Fuel efficiency standards and higher efficiency vehicles can take ten to fifteen years to achieve most of their emission reduction potential since older vehicle are replaced slowly over time.

8. Other Renewable Sources of Energy for Transportation Applications:

Wind energy potential and hydrogen derived by electrolysis of water using wind-derived electricity

Other renewable fuels may offer opportunities for rural western Canada also. A recent study of hydrogen production by electrolysis of water using wind-derived electricity, coupled with use of the hydrogen in a fuel cell powered vehicle, concluded that hydrogen so produced at good wind energy sites and used as an energy source in fuel cell-powered vehicles, was almost cost competitive with gasoline used in internal combustion engines (Jacobson et al., 2005). Other studies have concluded that hydrogen derived by electrolysis of water using wind generated electricity was considerably more expensive than hydrogen produced from natural gas via a reformation process coupled with CO_2 sequestration (e.g. Jaccard, 2005).

A study of world wind energy potential found that good wind energy sites might be able to produce a world total of about 72 TW of electricity (2270 EJ)(Archer and Jacobson, 2005). This is a very large amount of electrical energy, equivalent to the energy contained in all the net primary production of land biomass in the world (Vitousek et al., 1986), and much higher than the world's total energy consumption at the present time (about 400-450 EJ). For comparison, domestic demand for energy in Canada was about 11 EJ in 2001 (Environment Canada, 2003).

Shewchuk (2005) has estimated that the wind energy potential (as electricity) in Saskatchewan south of Saskatoon is in the order of 15,000 MW. The income generation potential for farmers having good wind sites on their land could be substantial. Lovins et al. (2004) calculated that USA farmers could obtain $US 50-80 per acre per year new net income from wind energy royalties at good wind energy sites in the USA.

The first application of wind energy is to produce electricity for the grid. In the future, hydrogen generation via electrolysis of water may be a possibility. Jacobson et al. (2005) propose that this hydrogen should be used in fuel cell-powered vehicles to reduce air pollution in urban areas. Conventional thinking is that hydrogen powered fuel cell technology used in vehicles is still far more expensive than gasoline powered internal combustion engines for transportation applications and wide-spread application in vehicles is still very far away (e.g., Keith and Farrell, 2003). However, one UK-based company, Intelligent Energy (www.intelligent-energy.com) has stated that it is planning to produce a fuel cell powered motorcycle for about $US 6,000 starting in 2006 (Dunlop, 2005). The company is also working on a reformer which could transform biofuels (such as ethanol) into hydrogen for use in fuel cell-powered applications. The company estimated that this would add about $US 1,500 to the cost of the motorcycle.

Hydrogen derived by electrolysis of water, using wind-generated electricity, is not affected by drought as are all routes to transportation fuels from biomass. Droughts may become more frequent and more severe as global warming affects the prairie region of Canada (Munro, 2005). Thus it seems wise to devote some research and development resources to methods to produce transportation fuels from non-biomass, renewable and/or carbon neutral sources.

9. Multiple energy sources for the future.

One conclusion is that there is no one silver bullet solution to the world's future energy needs, but that a combination of many different options need to be considered. Michael

Pacheco, director of the National Bioenergy Center, part of the National Renewable Energy Laboratory in Golden, Colorado, stated “We’re going to need everything we can get from biomass, everything we can get from solar, everything we can get from wind. And still the question is can we get enough?”(quoted by Parfit, 2005).

10. The biorefinery concept.

One way to address the issue of competing uses for biomass raw materials is to consider biofuels production as part of the activities of biorefineries, also called regional processing centres. These biorefineries could produce a variety of products. The agricultural biorefineries could produce (as well as ethanol) feed for animals, food for people, fertilizers (such as from the lignin portion of lignocellulosic biomass) and carbon dioxide for various food and industrial markets, including enhanced oil recovery and sequestration of carbon dioxide. Some of these are already being produced, but there may be new uses for some of these which could expand their markets. Forest biorefineries could produce fiber products (e.g., pulp and paper), as well as ethanol. It should be noted that existing ethanol plants in Canada already produce feeds for livestock.

Some projections of future food needs for the whole population of the planet are pessimistic that food needs can be met, given the potential negative effects of mining of ground water supplies and climate change effects on water supplies and crop yield reductions due to higher temperatures (e.g., Brown, 2004). Grain-based biorefineries in western Canada could shift in the future to producing more food products, such as wheat gluten and wheat flour, and produce ethanol only from the poorer quality starch-enriched flour fraction. This is basically what the Permolex biorefinery in Red Deer, Alberta, is doing already.

11. Some bioproducts may reduce energy consumption and green house gases emissions more than biofuels.

Improving the energy efficiency of human activities, such as heating a home or driving a car, usually costs less than fossil fuels to provide the same energy service (Lovins and King, 2003). These, in turn, at the present time, are usually less costly than renewable fuels.

There are a number of applications of biomass products where these materials save considerable amounts of energy (i.e., improve energy efficiency) and reduce GHG emissions. Calculations indicate that these uses of biomass save much more energy than using the same raw materials to produce energy. Less biomass raw materials are needed to achieve the same savings in energy and GHG emissions, thus placing less stress on ecosystems and using less land to achieve the same savings. Examples include:

11.1. Using waste paper-based cellulose insulation to reduce energy needs in a home.

The Dumont home in Saskatoon, Saskatchewan, is probably the best-insulated home in the world (Dumont, 2000). This large house has very thick walls insulated with 7.26

tonnes of cellulose insulation obtained from waste paper. This home has about two-thirds more insulation than the average home in Saskatoon. This extra insulation (4.9 tonnes) was estimated to save about 25 GJ of space heating energy requirements per year.

How does this compare with using the same extra waste paper cellulose to produce fuel pellets to heat the home, using a very energy efficient (80%) close coupled gasifier-combustion furnace? My estimate is that the net space heating value of these biomass pellets would be about 78GJ. Thus the energy savings of using this material as insulation equals the fuel value in 3.1 years. The lifetime of the insulation would be at least 31 years, probably much more. Thus using the cellulose as insulation is at least ten times as effective as using it to provide heat.

11.2. Using flax fibre as reinforcement in plastic components in vehicles.

Flax fibre is being used in Europe to provide fiber reinforcement in plastic composites in cars, such as floor panels (Schoenmaeckers, 1997). A direct GHG reduction occurs because flax fibre requires less energy for manufacture than the glass fibre it would replace. An indirect GHG reduction occurs because the flax fibre is lighter than glass fibre. This results in a lighter vehicle which consumes less fuel.

11.3. Using bio-based polymers to make high performance plastic composites which could halve the weight of a car and greatly improve its fuel efficiency.

The Rocky Mountain Institute has investigated how the fuel efficiency of vehicles could be greatly increased by integration of methods to make the vehicles much lighter with application of more fuel efficient power sources (Brylawski, 1999; Lovins, 2003). One of the more promising methods to reduce the weight, without compromising safety, is to use advanced plastic composites to replace steel in various auto body components.

Studies in Europe and the USA are investigating the use of biomass raw materials, such as vegetable oils, to synthesize polymers to produce plastics, which could be used in plastic composites in vehicles (Coxworth and McEwen, 2004; CARC-BIOCAP Canada, 2003). A plastic composite-bodied SUV would use about 244 kg more plastic than a similar-sized steel-bodied SUV, but weigh about half as much (Lovins, 2003; see also www.hypercar.com). If combined with a gasoline-electric hybrid drive power system, Coxworth and McEwen (2004) estimated that the vehicle would save 1520 L of fuel per year (20,000 km driving distance per year) compared to a conventional steel-bodied conventionally powered SUV. The energy savings and GHG reduction were estimated to be between one and two orders of magnitude more than using the same vegetable oil to produce liquid fuel, such as biodiesel.

12. Costs and supplies of fossil fuels.

Renewable energy must compete with fossil fuels in the market place. At the present time, many of the environmental costs from fossil fuel production and use are not accounted for in the present economic costs. These externalities include the negative effects from increases in GHGs in the atmosphere and air pollution costs. Thus the full social costs of fossil fuels are not expressed in the present economic costs as paid by the consumer. If these externalities were included in the fossil fuel costs then the costs of the renewable energy sources would be more competitive with the fossil fuels sources. This assumes that the renewable energy source does in fact reduce greenhouse gas emissions and other pollutants.

In addition, fossil fuels are used in the production of biomass raw materials and fossil fuels are used in the processing of these materials into liquid fuels and co-products. What are the prospects for the price and availability of fossil fuels in Canada in the future?

Costs.

According to Statistics Canada, the costs of all goods used in the economy has risen about 30 percent since 1992 (Statistics Canada, quoted by Royston and Pulfer in Canadian Business, 2005). In contrast, all energy products have risen in price about 130%, while natural gas prices have risen by about 240%. Thus for every $1.00 spent in 1992 we now pay $1.30 for all goods and services, $2.30 for energy products and $3.60 for natural gas. This consumer price index survey was taken before the two recent hurricanes in the Gulf of Mexico caused a further short term spike in natural gas and gasoline and diesel fuel prices.

Patricia Mohr, vice-president of Scotia Economics, expects natural gas prices to stay in the range of US$9 per million BTUs (about US$9.50/GJ) for several years more (Mohr, quoted by Barnes, 2005). She also predicts crude oil prices may stay in the range of US$ 60/barrel.

One of the outcomes of these increases in fossil fuel prices is that we need, for economic reasons, as well as greenhouse gas reduction reasons, to reduce the amount of fossil fuels required to produce agricultural and forestry raw materials used for food, feed and fibre, as well as for industrial applications, and reduce the fossil fuel energy required to process such biomass raw materials into biofuels and co-products. The efficiency of use of fossil fuels for production of these raw materials also needs to be improved.

Agriculture is very vulnerable to increases in the price of fossil fuels and products produced from them, such as nitrogen fertilizer. Agriculture is also a large consumer of fossil fuel products, such as diesel fuel. In 2001, agriculture in Canada consumed 11.1% of all diesel fuels; in Saskatchewan, agriculture consumed 44.1 % of all diesel fuel used in the province (Statistics Canada, 2001).

Supplies.

An analysis of the Canadian and world situation with regard to production and use of fossil fuels was given in a recent issue of Canadian Business (Nikiforuk, 2005). Some of the conclusions of this analysis, based in part on the studies of David Hughes of the Geological Survey of Natural Resources Canada, are as follows:

(a) The world is not running out of oil, but it is running out of cheap crude oil. Hughes estimated that world oil production will climb to 87 million barrels a day by 2008 to 2010, and then falter. Prices will continue to rise.

(b) Canada's oil sands won't make a lot of difference to world supply, partly because they are expensive to develop (both in energy and economic senses). In an optimistic scenario, oil sands might produce about 4% of world oil supply by 2010. Much of Canada's future natural gas supplies might be consumed just as energy and hydrogen sources for development of the oil sands. Woynillowicz et al. (2005) estimate that natural gas demand for oil sand extraction and upgrading could rise from about 0.75 billion cubic feet per year in 2004 to about 5.5 billion cubic feet a year by 2030

(c) World supplies of natural gas are large, but North American supplies of conventional natural gas are low, about four % of world supplies. There could be a North American shortfall (over domestic production) of 42% by 2025. Coal-bed methane and liquefied natural gas from overseas might help, but are unlikely to make up the shortfall. There are significant environmental problems with coal-bed methane development, and liquefying natural gas takes substantial amounts of energy (from 15 to 30% of the energy content of the natural gas). One estimate is that global conventional natural gas output will peak about 2025 (Imam et al., 2004).

Alberta supplies of coal bed methane have been calculated to be large, in the order of 538 trillion cubic feet, of which about 167 trillion cubic feet are recoverable with present technology (Duckworth, 2005). For comparison, present annual Canadian production from all sources of natural gas is 6.3 trillion cubic feet, of which 3.6 trillion cubic feet is exported to the USA.

(d) North American supplies of coal are large. However, burning coal releases about twice the CO_2 of burning natural gas per unit of energy produced. Methods to reduce the pollutants released by burning coal are being developed, including methods to sequester the CO_2 released by combustion (Ritter, 2002; Jaccard, 2005). It is interesting that one of the new technologies to produce electricity from coal is supercritical steam gasification followed by combustion of the synthesis gas produced (Gibbins, 2005). This process is similar to the gasification technology being developed for conversion of biomass via synthesis gas into ethanol (Pearson, 2001). This coal gasification process can be combined with separation of the CO_2 produced by combustion and subsequent sequestration of the CO_2 in geological structures, such as old oil fields. These conditions for coal gasification and CO_2 sequestration may exist in southern Saskatchewan, for example.

13. Different routes to ethanol from different raw materials.

It is important to stress again the differences between making ethanol from grain by fermentation and making ethanol from lignocellulosic raw materials such as perennial grasses, crop residues and wood either by fermentation or gasification routes.

Ethanol production from grain is limited by how much ethanol we could make before there were serious conflicts with traditional uses of grain for food or feed, and by limits to how much distillers dried grains and solubles (DDGS), the co-product from making ethanol from grain, could be produced before the market was saturated and the price fell so low as to make ethanol production considerably more expensive.

In contrast, ethanol production from lignocellulosic raw materials has the advantage that raw materials are considerably more abundant and lower in cost. Any scenarios for future world energy supply in which liquid biofuels play an important part, assume that these liquid fuels would be produced from lignocellulosic raw materials (see Berndes et al., 2001).

14. Food versus fuel controversies.

Pimentel and Patzek (2005) raised the issue of whether it was immoral to convert food (corn or wheat grain, for example) into fuel (ethanol) when there are so many poor and starving people in the world.

According to various studies, the solution to this complex problem is not just a matter of sending cheap food produced in North America to poor and starving people elsewhere. About 50% of the hungry people in the world are poor Third World farmers (Polak, 2005). They need income from sale of their own crops to be able to buy food and other needs. Providing their region with imported North American grain that is cheaper than locally produced grain might make it difficult for them to sell their own grain crops. In addition, cheaper sources of grain may be available closer at hand, in a neighboring country not affected by drought, for example.

Norman Borlaug, who received a Nobel Peace Prize in 1970 for his contributions to the development of the Green Revolution, has stated that wealthy countries should continue to send food aid during emergencies, but that the long-range solution is revolutionizing agricultural production, especially among subsistence farmers in developing countries (Polak, 2005).

Simple, low-cost methods to pump water and to use water more efficiently to grow food are described by Polak (2005), based on experience with poor farmers in Bangladesh and elsewhere. Agroforestry systems, based on nitrogen-fixing trees, are being used successfully to increase crop yields and reduce the impact of drought in Africa (Garrity, 2005) and increase crop yields and reduce the need for slash and burn agriculture in rain forests in Central America (Elkan, 2005). Providing better roads, technical and marketing assistance and low-cost loans has greatly improved family income and food supplies for some poor farmers in India, for example (Kripolani, 2005).

Water may become a critically short resource in many regions in the future. Lester Brown has argued that depletion of underground water resources is at least as serious a world problem as depletion of cheap oil reserves (Brown, 2005). This loss of water resources could greatly compromise food production in many countries, particularly when combined with rising temperatures resulting from global warming. He has argued that we need to raise water productivity, cut GHG emissions and stabilize population to avoid major food shortages.

In Canada, the amount of wheat grain which might be diverted from food and feed markets into ethanol and DDGS production is quite small. $(S\&T)^2$ Consultants (2005) estimated that one million tonnes of grain might be converted into ethanol and DDGS per year in the future. This would yield 370 million litres of ethanol and 380,000 tonnes of DDGS feed. This represents only 4.3 % of the average annual total amount (23.1 million tones) of wheat produced normally in Canada (mainly in western Canada) in the period 1997 to 2002. About 700,000 tonnes of wheat would be diverted from export markets, but the domestic market for wheat would increase by over 30%. It is also worth noting that 38% of the wheat diverted into ethanol production is still being used for feed (the DDGS co-product). Thus the loss of feed value is the amount of starch energy that has been converted into ethanol, or 620,000 tonnes (1,000,000 t – 380,000 t). This represents a reduction in the total Canadian wheat production food and feed nutritional value of only 2.7%.

Hutchence (2001) stated that the main food ingredient in short supply in many developing countries is protein. He suggested that gluten might be separated from wheat in Canada and the gluten shipped to developing countries to be combined there with cheap, locally produced starch from various plant sources. This gluten separation could be a processing step conducted at grain biorefineries, with the starch by-product used to produce ethanol for local liquid fuel requirements.

A recent review of various studies on the world potential to produce liquid biofuels for transportation applications found wide differences between studies in the amount which could likely be produced. These differences arose because of different estimates of the land required to provide food and animal feed for a growing world population, to provide fiber and industrial products, to maintain wilderness areas, and finally, what would be left over to grow biomass for energy purposes (IEA, 2005). Total world liquid fuel energy potential from biomass ranged from 12 exajoules (EJ) to over 400 EJ. Present world demand for liquid fuels for transportation is about 60 EJ, but is expected to increase rapidly.

15. Estimates of the total amounts of lignocellulosic biomass resources available in Canada for energy and bio-product applications.

Canada is more of a forest country than an agricultural country. Much of the future potential for production of biofuels would likely use forest raw materials, such as sawdust and bark. Wood and Layzell (2003) calculated that about 98 million tonnes (oven dry basis) of forest residues might be available per year for various energy and bio-product applications, surplus to soil protection and soil fertility requirements. Not included in their estimate was about 24 million tonnes of black liquor solids produced annually in Canada (CARC-BIOCAP, 2003). This material is a by-product from Kraft pulping of wood. It is recycled and burned now to generate heat and electricity for use in the pulp mill and to recover the pulping chemicals. Swedish studies have shown that it is possible to produce substantial amounts of fuel alcohol from this material, using a gasification process to generate synthesis gas followed by conversion to alcohol. This integrated process would still produce steam and electricity for the pulping energy needs of the pulp mill (Berglin, Lindblom and Ekbom, 2002).

In addition, some 18-19 million tonnes of municipal organic residues might be available. Wood and Layzell (2003) estimated that up to 19-20 million tonnes of agricultural residues might also be available, surplus to soil protection and livestock feed and bedding requirements. The amounts of crop residues available would be expected to be considerably less during drought years, however.

Gasification technology would likely be used to produce ethanol (for example) from such materials (see section 6.3.2). The proposed gasification-route ethanol plant at Nipawin, Saskatchewan, would use mainly forest residues. Such raw materials do not compete with food production. They may compete with other uses of forest raw materials, such as particle board made from sawdust or bark.

Countries with large amounts of forest, compared to population, such as Canada and Sweden, may be in a good position to produce large amounts of liquid fuels from biomass resources. Sweden plans to be the world's first oil-free economy, with plans to produce much of the country's liquid fuel needs for transportation from forest biomass resources (Vidal, 2006).

16. Capturing solar energy by photosynthesis compared to other methods.

Pimentel and Patzek (2005) pointed out that plants (by employing photosynthesis) are a poor way to capture solar energy (see also Patzek and Pimentel, 2005). Kheshegi et al (2000) compared sugarcane (used to make ethanol in tropical countries) and corn (used to produce ethanol in the USA and Canada) in terms of the amount of the solar energy captured in the final ethanol:

Sugar cane example:

About 0.93% of the solar energy falling on a hectare of land growing sugar cane is captured as above ground sugarcane material. The final yield of ethanol contains about 0.14% of the original sunlight falling on the field. Compared to gasoline, the reduction in GHG emissions is about 2.08 tonnes of carbon per hectare per year.

The residue from sugar cane, after extracting the cane sugar, is called bagasse. Improved methods of gasification of bagasse, coupled with advanced combined cycle methods to generate electricity, could significantly increase the total amount of useful energy derived from the sugar cane. One estimate is that one MJ of sugar cane dry matter would produce 0.31 MJ of ethanol plus 0.23 MJ of electricity (IEA, 2005, p. 141).

Corn grain example:

About 0.60% of the sunlight falling on the corn field is captured in the above ground corn crop. The final ethanol produced contains about 0.03% of the original sunlight energy falling on the corn field. The potential GHG emissions savings are about 0.32 tonnes of carbon per hectare per year.

Kheshegi et al. (2000) compare these solar capture efficiencies with photovoltaic efficiencies (solar energy to electricity) of about 15-20% now, with the potential to raise this to about 25% in the future. A consortium led by the University of Delaware is aiming at producing photovoltaic systems with over 50% efficiency of conversion of solar energy to electricity.

Integration of solar-derived electricity into transportation energy requirements.

Renewable electricity produced by such photovoltaic means could be tied into transportation energy needs by the use of e-hydrid vehicles (Romm, 2005). These types of hybrid vehicles would have extra battery storage capacity compared to a conventional hybrid vehicle. They would be plugged into the electricity grid to recharge the batteries while they were parked at the driver's place of work. The office or the factory of the driver's place of work would be equipped with a photovoltaic array to provide the electricity required. The vehicles would be able to travel 30-60 km on battery electrical power alone. For many urban purposes this would constitute a major portion of a daily driving range. Once the battery pack was discharged, the vehicle would switch to a liquid fuel powering the hybrid's internal combustion engine. Romm estimated that such e-hybrids, if they were also flexible fuel vehicles, could travel 800 km on 23 litres of 85% ethanol:gasoline mix (cellulosic-derived ethanol)(2.9 L/100km), plus the electrical energy derived from the photovoltaic array (Romm, 2005). Romm estimated that such vehicles would have one-tenth the GHG emissions of a conventional hybrid vehicle.

Morris (2005) also describes such an electricity-supplemented hybrid vehicle with the potential to reduce the amount of ethanol (for example) required for urban driving by between 40 and 90%.

A reviewer of a draft of this report noted that a litre of ethanol has only about two thirds the energy content of a litre of gasoline (see also Klass, 1998, p. 392). Thus more litres of 85% ethanol:gasoline (E85) fuel would be required to drive a vehicle a given distance than if the vehicle was powered by gasoline alone. Fuel prices would need to reflect this difference in fuel energy per litre.

Engines designed specifically to burn E85 may obtain greater fuel efficiency and power output than this simple comparison of the energy content of a litre of ethanol with a litre of gasoline would indicate. Saab in Sweden is claiming a 15% improvement in fuel efficiency and greater power output (compared to gasoline) for a turbocharged Saab BioPower vehicle running on E85 (Green Car Journal, 2005).

Solar-derived hydrogen.

Sunlight can also be used to photoelectrochemically split water into hydrogen and oxygen (Khan et al., 2002). Using a carbon doped titanium oxide material to capture sunlight and dissociate water into hydrogen and oxygen, Khan et al. (2002) were able to achieve a photoconversion efficiency of 8.35%.

Conclusions.

Such developments could be important sources of energy in the future. They would appear to be of most interest first for countries in areas closer to the equator than western Canada, where sunlight is more evenly distributed around the year. For now, biomass may have advantages in that sunlight is stored as biomass for future conversion into energy and other products. Biomass also produces complex organic co-products to some liquid fuel production systems (e.g., ethanol) which can be used for animal feed (like the DDGS feed produced as a co-product of grain fermentation), for food, or for fibre applications. For example, forest biorefineries could produce ethanol as a co-product to pulp and paper. These co-products are often very important to the overall economics of the ethanol production process.

17. Greenhouse gas emissions from Canadian agriculture. Potential roles for ethanol co-products to reduce greenhouse gas emissions.

The total GHG emissions from all fossil fuel products used in agriculture (whether directly as fuels or indirectly as inputs such as nitrogen fertilizer) was estimated in 1996 to be 25.8 million tonnes of carbon dioxide equivalents, or 3.8% of all emissions from the Canadian economy (Janzen et al., 1998). In addition various microbiological processes occurring in ruminant animals, in decomposition of manures, and emitted from soils, add a further 67 million tonnes of GHGs. The total emitted by agriculture was thus about 93 million tonnes, or roughly 14% of the 670 million tonnes of GHGs (expressed as carbon dioxide equivalents) emitted from the Canadian economy in 1996 (Environment Canada, 2003).

Distillers grains are the co-product produced when grains are fermented to produce ethanol. Numerous studies have shown that inclusion of distillers grains in the diet of ruminant animals improves feed efficiency and hence can reduce methane emissions ("burping cows")(S&T)^2, 2005). Methane emissions (eructation) from cattle, during digestion of feed in the rumen, are one of the main sources of GHG emissions from Canadian agriculture (Jenzen, 1998). Thus this effect of distillers grains on reducing methane emissions from cattle should be given a credit in the total GHG implications of making ethanol from grain. The latest version of the computer program to calculate the GHG savings from production of ethanol from grain takes this effect into account ((S&T)^2, 2005).

Carbon dioxide (CO_2) is a co-product of fermentation processes to produce ethanol. If CO_2 is captured from the fermentation process, it could in theory be carried by pipeline to old oil fields and piped underground to sequester it and improve oil recovery. If this were to be done, the ethanol process would be given a further GHG emission credit, since this CO_2 has been removed from the atmosphere. Fossil fuel-derived CO_2 is already being sequestered by this process at the Weyburn oilfield in southern Saskatchewan.

One recent publication concluded that fossil fuels could continue to be consumed in large amounts in the future, without significant emissions of greenhouse gases, if the fossil fuels were used to produce electricity or hydrogen, with sequestration of the CO_2 emitted (Jaccard, 2005). Hydrogen would be produced by gasification of the fossil fuel source (coal or natural gas) and the CO_2 produced as a co-product captured and sequestered in geological formations, such as old oilfields. Jaccard calculated that hydrogen produced this way would be considerably cheaper than hydrogen produced by electrolysis using electricity generated by nuclear or wind energy sources, and slightly cheaper than hydrogen generated by gasification of biomass (Jaccard, 2005).

Some reviewers of a draft version of this report questioned whether CO_2 capture would be a realistic technology for Saskatchewan or Manitoba ethanol plants due to uncertainties about industrial markets or uncertainties about transportation costs to potential CO_2 sequestration sites. Ethanol plants in Alberta might be close enough to future CO_2 pipelines to justify capture of this gas and sequestration in geological formations. In Chapter 2 the effects of CO_2 capture on ethanol energy budgets are compared to situations without capture of this gas.

18. Economic problems in western Canadian agriculture.

The 2005 and 2006 Planning Guides for Crop Production in Saskatchewan indicated that farmers would lose money growing almost all crops, if all potential costs of crop production were to be taken into account. This was a result of a combination of very low prices for most crops coupled with rising costs for major inputs such as fuel and fertilizer.

Can the development of biofuels such as ethanol improve farmers' incomes? In the USA, Morris (2005) has estimated that 20,000 farmers own shares in ethanol production plants. He estimates that these farmers receive about 50-75 cents per bushel in dividends, on top of the market price. In western Canada, the proposed ethanol plant at Nipawin, Saskatchewan, would operate as a new generation co-op, in which farmers could own shares, and share in the profits.

The other approach is to design and implement cropping systems which would improve farmers' net income, whatever the market, including ethanol plants. Several examples are shown in Chapter 2. For example, growing wheat after alfalfa in the rotation has the potential to greatly reduce nitrogen fertilizer requirements, reduce the energy costs of wheat as a raw material for ethanol and DDGS production, and substantially improve net returns for wheat production.

In another example, Lafond (2003) reported increased yields and higher protein content in wheat grown in a field which had been in continuous cropping using low disturbance seeding from many years compared to a field which had not been in continuous cropping. This yield advantage was achieved without an increase in nitrogen fertilizer requirements. This resulted in a considerable improvement in net economic returns for the long-term continuous cropping field. This result is probably due to increased soil fertility associated with an increase in soil organic matter.

On the same farm it has been found possible to grow field peas without added phosphorous fertilizer on a number of occasions (Lyseng, 2005). This was attributed to a build up in reserves of phosphorous in the soil from previously added fertilizer. Much of the added phosphorous fertilizer was immobilized in the soil and was not available to crops such as wheat. The peas were able to access this phosphorous for plant growth since peas were able to acidify the rhizosphere around the plant roots and make the phosphorous available for uptake by the plant. The cost savings to the farmer were in the range of $9-10/acre ($22-25/ha).

19. Air pollution from production and use of ethanol as a transportation fuel.

Some older corn grain ethanol plants had severe volatile organic compounds (VOC) air pollution problems, but these problems have been largely resolved through proper sizing of pollution control devices (Greene et al., 2004).

There are two sources of air pollution associated with ethanol. These are: combustion of the fuel itself, and the air pollution occurring upstream, in the various steps of grain production and processing prior to ethanol final use. The (S&T)^2, 2005 report describes these two effects.

Use of ethanol in a 10% blend with gasoline reduced several air pollutants compared to burning gasoline without the ethanol additive. Carbon monoxide was reduced by 2.8%, nitrogen oxides (NO_x) were decreased by 0.7%, volatile organic compounds (VOC), ozone weighted, were reduced by 3%, sulphur oxides were reduced by 3% and particulate matter was reduced by 6.2%.

When all the emissions in the production of the grain and the processing operations in the ethanol plant were included, the air pollution totals were actually increased in the case of nitrogen oxides, volatile organic compounds (VOC) and particulate matter. This increase was probably due in part to the diesel tractors and trucks used in crop production and transport.

Greene et al. (2004) describe how modern cars have greatly improved air pollutant emission reduction systems compared to older vehicles. Modern cars can meet very stringent criteria air pollutant reduction standards (substances other than carbon dioxide) without the use of alternative fuels such as ethanol. Increasingly, ethanol may be used mainly to reduce greenhouse gas emissions, with the main criteria air pollutant reduction being achieved by the engine and exhaust system design and operation.

20. Water pollution from the production and use of ethanol.

Fermentation processes, such as are used to produce ethanol from grain, produce large amounts of waste water containing substantial amounts of soluble organic compounds. These could place a serious oxygen demand on waterways (Greene et al., 2004). However, standard waste water treatment technologies can virtually eliminate this problem. Recently constructed corn grain-to-ethanol plants are using a two step process to reduce waste water pollution problems and permit recycling of much of the water used in the process (Green et al, 2004). The waste water is first treated in an anaerobic digester to produce biogas, which can be used to provide some of the thermal energy requirements of the ethanol plant. The water remaining after anaerobic digestion treatment can be further treated and recycled in the plant. About 95% of the treated water can be recycled. Similar processes would be used in ethanol plants based on fermentation processes using lignocellulosic raw materials. The economic value of the biogas produced offsets much of the waste water treatment costs.

Ethanol used in blends with gasoline has both good and bad effects if spills occur in water or on soils (Greene et al., 2004). Ethanol by itself is rapidly biodegraded. But in blends with gasoline the overall effect may be to increase the time it takes for the gasoline to be biodegraded, since the microbial degradation of the ethanol component may deplete available oxygen supply and delay gasoline breakdown. Ethanol can also act as a carrier to extend the distance a solution mixture of gasoline and ethanol might spread. Greene et al (2004) suggest that further research and regulation is needed to reduce these risks from ethanol-gasoline blends.

Chapter 2. Energy Costs of Producing Ethanol and Co-Products from Grains. Methods to Reduce Energy Costs.

1. Objectives of this chapter.

The first objective is to determine the effect of different crop production systems on the energy consumed to produce a tonne of grain and, from this, to determine the energy cost contribution of the grain crop to the final energy cost of producing a litre of ethanol from this grain. Effects tested included (a) growing wheat varieties with higher yields (20% or 30%) and higher starch contents than the hard red spring wheat commonly grown in western Canada, (b) energy savings effects (less nitrogen fertilizer requirements) of growing wheat after a legume in the rotation and (c) yield enhancing and energy savings effects of the build up of soil fertility by continuous cropping with low soil disturbance crop production systems.

The second objective is to determine the effect of different ethanol production systems on the energy costs of producing ethanol and its co-products of dried distillers grains and solubles (DDGS) and recovered carbon dioxide. Effects tested included (a) the gradual improvements in energy efficiency of ethanol production plants since a 2001 survey, (b) energy savings effects of integrating an ethanol plant with an existing heavy oil upgrader enabling the use of waste heat and process steam from the heavy oil upgrader operation to provide some of the energy needs of the ethanol plant, (c) integrating an ethanol plant with a livestock feedlot and a biogas operation using the manure from the feedlot to produce biogas to provide the process heat energy costs of the ethanol plant.

The final objective is to put the grain energy costs and the processing energy costs together to arrive at the complete energy cost of producing ethanol. This would allow us to determine the best methods to produce ethanol from grain so as to reduce the overall energy cost of producing ethanol and maximize the reduction in fossil fuel energy to produce a unit of liquid fuel energy, compared to gasoline.

Present and planned ethanol production in Saskatchewan.

Saskatchewan has a new ethanol production facility under construction beside the Husky Heavy Oil Upgrader plant at Lloydminster. It will produce 130 million litres of ethanol per year plus 134,000 tonnes of dried distillers grains and solubles (DDGS) animal feed (Briere, 2004). In addition, a smaller plant at Weyburn (NorAmera) will produce 25 million litres a year of ethanol, plus 67,000 tonnes of DDGS animal feed. The existing ethanol plant at Lanigan (Pound Maker AgVentures) produces 12 million litres of ethanol per year in the plant integrated with a feedlot. Thus the total potential ethanol production in Saskatchewan will be 167 million litres of ethanol per year. Since the gasoline consumption in Saskatchewan is about 1.65 billion litres per year, this would allow ethanol to be used in a 10% blend with gasoline in the province.

Ethanol produced by fermentation of grains is the main source of fuel ethanol produced in Canada at the present time. Most new plants planned or under construction in Canada are also grain based. These plants should be looked at as grain bioprocessing plants rather than just as ethanol plants. The main products produced now are fuel ethanol, dried distillers grains and solubles (DDGS), used as animal feed, and carbon dioxide. The economics of making ethanol by this route are very dependent on having markets for all the DDGS produced as a co-product. There is some evidence that American markets for this product may becoming saturated (Racz, 2005). Markets for the carbon dioxide produced would also help to reduce the costs of the ethanol.

1.1. Effect of crop rotations and crop selection.

In the present study, different crop rotations to grow CPS wheat were tested to determine the effect of these cropping systems on the energy cost of growing the wheat raw material for the ethanol plant. Legume crops grown before a cereal crop are known to help reduce nitrogen fertilizer costs for the cereal and frequently increase the cereal crop yields. The study estimated the effect this would have on the energy output:input ratio, i.e., how much renewable energy (ethanol) was produced in comparison to the fossil fuel energy required to grow the crop and convert it into ethanol and co-products.

For ethanol produced from grain, the usual co-product is distillers dried grains and solubles (DDGS), which is used as an animal feed. It would replace other ration ingredients, including energy sources, such as corn or barley, and protein sources, such as soybean meal or canola meal. These alternative ration ingredients require fossil fuels for their production. In the displacement method of crediting DDGS (used in the studies reported in this report) the energy costs of the ration ingredients replaced by DDGS are deducted from the total energy costs of producing the grain and processing it to give the net energy costs of producing ethanol.

In addition, crop breeding might produce grain crops which had a higher yield than the current CPS wheat varieties, which have about a 20% yield advantage over hard red spring wheat. The study estimated the effect that a CPS wheat, or another high yielding cereal crop, would have on energy budgets for ethanol production, if the yield advantage of this new crop was 30% higher than hard red spring wheat. This would indicate a crop breeding goal for the future.

Gasoline production requires considerable fossil fuel consumption to extract the oil or oil sand from the ground and refine it into gasoline and other products. In addition, gasoline itself is made entirely from fossil fuels. In contrast, ethanol is made from biological raw materials produced using solar energy, assisted by fossil fuels required to grow the crop and convert it into ethanol and other co-products. The net reduction in total fossil fuel consumption when ethanol replaces gasoline would be represented by the equation:

(Gasoline fossil fuel content + fossil fuel energy to produce it) – (fossil fuel energy required to produce ethanol + co-products – fossil fuel energy credit for co-products) = net reduction in fossil fuel energy.

This net reduction in fossil fuel consumption by replacing gasoline by ethanol was measured for various combinations of crop production systems and processing systems.

Different crops rotations and CPS wheat yields (compared to hard red spring wheat) were tested for their effects on the total reduction in fossil fuel consumption.

Effects of processing conditions:

1.2. Effects on energy savings by integrating an ethanol plant with the Heavy Oil Upgrader.

The Husky ethanol plant at Lloydminster is reported to have access to excess steam and waste heat from the oil upgrader operations and an energy cogeneration system, which will be used to reduce the heat energy requirements of the ethanol operation (Pratt, 2005). This study estimated the effect of a 33% reduction in the amount of natural gas required. One person consulted, familiar with the oil industry, felt that this was a reasonable potential saving.

1.3. Effect on total fossil fuel energy consumption to produce ethanol of integrating a biogas plant with an ethanol operation and a feedlot.

The Pound Maker AgVenture ethanol plant at Lanigan is integrated with a feedlot. A new process for production of biogas and biofertilizer has been developed in Alberta (MacArthur, 2005) and might be applicable to the ethanol-feedlot operation. The effect of replacing natural gas with biogas on the total fossil fuel requirements to produce ethanol was examined.

1.4. Energy effects of capturing carbon dioxide (CO_2) and selling it to replace fossil fuel derived carbon dioxide.

The most recent study on the energy savings and GHG reduction of replacing gasoline with ethanol derived from western grain assumed that all the CO_2 evolved during grain fermentation was captured and sold into industrial markets to replace CO_2 manufactured directly or indirectly from combustion of fossil fuels ($(S\&T)^2$, 2005). The effect of not capturing this grain fermentation-based CO_2 was also examined in the present study. Some reviewers doubted whether the capture and sale of CO_2 would be carried out at plants in western Canada. Therefore the effects of not capturing this gas were also examined.

1.5. Recovery of human food products from grain prior to fermentation to produce ethanol.

There may be markets in the future for human food products produced by these grain biorefineries as well as the production of fuel ethanol and cattle feed materials. Permolex is producing such human food products at its plant in Red Deer, Alberta. The present study looked only at the by-product DDGS being used for animal feed. Production of human food products from bio-refineries may become more economically important in the future if grain prices rise again.

2. Energy analyses of ethanol and co-products produced from grain raw materials.

The energy costs of grain production and of processing the grain into ethanol plus DDGS and/or without captured carbon dioxide are reported separately so one can measure (1) the effects of methods to reduce the energy costs of grain production on final ethanol energy costs and (2) the effects on energy costs of methods to reduce the energy costs of processing.

All energy data in this study are reported in higher heat values (HHV) to be consistent with Zentner et al. (2004).

2.1. Energy costs of grain production in Saskatchewan.

Detailed energy and economic analyses of spring wheat production at Indian Head, Saskatchewan, have recently been published by R. Zentner and his co-workers (Zentner et al., 2004; Zentner et al., 2002). This set of cropping systems was chosen for a number of reasons to represent Saskatchewan grain production and to test various methods to improve the energy efficiency and improve the economics of grain production:

1. The rotation study was run at Indian Head, Saskatchewan, for twelve years (1987-1998), including years with drought as well as years with good growing conditions. Thus average yields over the years are representative of different growing conditions.

2. An economic analysis has been done to measure the riskiness of different rotations, crops, and tillage methods, and the effect of differing costs of production and different prices for crops.

3. A detailed energy analysis has been done, including the energy costs associated with machinery production and repair. These energy costs have not been included in some Canadian and American energy studies on production of ethanol from grain. Pimentel and Patzek (2005) criticized these studies for this omission.

4. The site is in the Thin Black soil zone east of Regina and is representative of a large portion of the grain producing region of the province.

5. Previous crop rotation experiments at Indian Head included rotations including brome-alfalfa hay. New studies at Indian Head are examining methods to reduce harvesting costs, such as the use of a header-stripper to quickly harvest grain and chaff and leave all the straw standing. These studies could be included in future analyses on how to reduce the energy and economic costs of grain production.

6. A further three-year study at Indian Head (2000-2002) examined the energy costs and returns and nitrous oxide emissions of three crops, spring wheat, flax and canola, grown in rotation with zero tillage. Three fertilizer rates and two sources of nitrogen fertilizer were compared, plus the effects of several methods of applying nitrogen fertilizer.

7. Farm results near Indian Head have shown the beneficial effects of long term continuous cropping with low soil disturbance on crop yields and quality (Lafond, 2003). These results have implications for reducing the energy and economic costs of grain production. These results can be modeled for their effects on the energy costs of ethanol production.

The rotations studied at Indian Head in the 1987-1999 period for their energy and economic effects included spring wheat, winter wheat, flax and field pea grown in three different rotations and managed using three tillage methods: conventional tillage, minimum tillage and zero tillage.

Crops included in the Indian Head rotations did not include CPS wheat, which is likely the wheat type that would be used for ethanol production. It was assumed that CPS wheat would have a yield 20% higher than hard red spring wheat, the type used in the Indian Head study. Both yield increases of 20% and 30% of CPS wheat over hard red spring wheat have been used in the Saskatchewan Crop Planning Guide for various years. Most of the calculations in the present study were done using a 20% yield increase; a 30% yield increase was also tested for its effect on energy budgets.

Energy costs of inputs into crop production.

Energy coefficients for inputs used in agriculture in western Canada have been published by the Canadian Agricultural Energy End-Use Data and Analysis Centre (CAEEDAC)(Nagy, 1999). These were the energy coefficients used by Zentner et al. 2004). Some coefficients have been changed since that study was done to reflect energy changes in the manufacture of inputs (Nagy, 2000). The present study includes those changes.

Energy inputs to manufacture herbicides were decreased by 27% to reflect recent improvements in the energy efficiency of products of the petrochemical industry.

The energy costs to make gasoline and diesel fuel have been increased to reflect the growing proportion of heavy oil and oil sands tar used to make these fuels in Canada, and the increased energy costs to transform these raw materials into refined petroleum products. This increases the energy input for diesel fuel (energy content of the fuel plus the energy cost to make it) from 43.99 MJ/L to 46.44 MJ/L, and increases gasoline energy costs from 39.61 MJ/L to 42.19 MJ/L. For diesel fuel, the energy content of the fuel is 38.96 MJ/L, the energy cost to make it is 7.48 MJ/L. For gasoline, the energy content of the fuel is 34.78 MJ/L, the energy cost to make it is 7.41 MJ/L.

The energy costs to manufacture and repair machinery have decreased in recent years. These costs have decreased about 23 to 25% for tractors and combines and about 36% for other machinery. A reduction of 25% was assumed for all farm equipment in the present study.

Energy is used to produce the grain used for seed in crop production. In the energy analyses carried out by Zentner et al. (2004), the amount of grain used for seeding (135 kg/ha) was deducted from the total yield of grain obtained. This method was also employed in the present study. For the present analyses, an energy cost of 7.2 MJ/kg wheat seed was added, based on results published by Nagy (1999). This amount accounts for the energy costs of wheat seed production.

Labour costs were not included in the energy analyses conducted by Zentner et al. (2004). Opinion varies on how much energy should be counted for human labour used in crop production (e.g., see Fluck, 1992). For the present study, the same value as used by Pimentel and Patzek was employed (170 MJ/hour). Data on the labour costs for spring wheat production at Indian Head were given in Zentner et al. (2002)(1.22 person hours/ha) and were used in the present study.

The main nitrogen fertilizer used for spring wheat production in the Indian Head study was urea. This is a more energy expensive fertilizer than anhydrous ammonia. The ratio of anhydrous ammonia to urea used in Saskatchewan is about 40:60. The nitrogen fertilizer energy costs in the Indian Head study were adjusted to make the model more representative of average Saskatchewan use by including 40% anhydrous ammonia and 60% urea as the nitrogen fertilizer mix used in typical wheat production in Saskatchewan. The extra fuel and machinery energy costs for banding anhydrous ammonia were included in the overall fuel and machinery costs of wheat production.

Fuel costs used by Zentner et al. (2004) included fuel cost for all field operations, heavy trucks for hauling inputs to the field and hauling grain to the local elevator. Light truck energy costs for driving the farmer to and from the field and for other grain production uses were also included (10,000 km per year for farm business).

The energy costs for transporting the wheat from the farm to the processing plant were the same as those employed by $(S\&T)^2$ (2005).

2.2. Energy costs of processing grain into ethanol, DDGS and captured carbon dioxide.

The natural gas and electricity energy costs of processing wheat into ethanol and DDGS were the same in the base case as those reported by $(S\&T)^2$,(2005). These results were obtained by modifying the results of a 2001 survey of ethanol produced from corn grain dry milling plants in the USA (Shapouri, Duffield and Wang, 2002) to reflect the lower yields of ethanol and higher yields of DDGS from fermentation of wheat. It was assumed that ethanol plants based on wheat would use more natural gas and electricity than a corn based plant due to the lower ethanol yield (370 L/tonne) compared to corn grain (395

L/tonne) and the higher amounts of DDGS which needed to be dried (380 kg/tonne compared to 295 kg/tonne).

Pimentel and Patzek (2005) also included energy costs for water purification, stainless steel, steel and cement used in the construction of the plant, and sewage treatment. In total these extra energy costs added 0.802 MJ per litre of ethanol produced. These extra costs were included in the present study. Some of these energy costs may have been included in the corn grain-to-ethanol survey, and double counting may have resulted. More detailed studies should check this issue.

$(S\&T)^2$ (2005) suggested that a 2% per year reduction in the amounts of natural gas and electrical power needed in a processing plant seemed reasonable to reflect recent rates of improvement in the energy efficiency of modern ethanol plants. In the present study a 10% reduction in these costs (since the survey was done in early 2001) was tested for the effect on the energy costs of ethanol production.

The energy costs in the present study for natural gas and electricity include factors to account for the energy costs of extracting the natural gas from the ground, removal of impurities such as hydrogen sulfide, and transport to the ethanol plant. Electricity energy costs include the energy costs of producing electricity from coal and other fuel raw materials. Fossil fuel energy costs of electricity production in this study were based on Saskatchewan conditions, in which about 75% of the electricity is generated from coal. Energy costs for electricity would be much lower in Manitoba, where most electricity is generated from hydropower.

The distillers dried grain and solubles (DDGS) are assumed to replace corn grain and soybean meal in cattle rations (dairy or beef)($(S\&T)^2$, 2005). The most recent analyses assumed that carbon dioxide would also be captured and used to replace carbon dioxide (CO_2) produced from fossil fuel combustion processes. Thus the credits are for both DDGS and CO_2. (In most cases, this present study assumed that CO_2 was not captured.)

The data in the above report were reported as BTUs consumed per BTU of ethanol delivered. Translated into MJ per 23.52 MJ of ethanol (the HHV of one litre of ethanol), the DDGS and carbon dioxide from wheat are given a credit of 4.005 MJ/L of ethanol produced. In comparison, the DDGS and carbon dioxide from corn grain fermentation are given a credit of 3.335 MJ/L of ethanol produced and delivered (smaller amounts of DDGS per litre of ethanol produced). For cattle rations in western Canada, it might be more appropriate to compare DDGS with (for example) barley grain and canola meal. For this present study, the credit for DDGS and carbon dioxide byproducts from wheat grain fermentation is left at 4.005 MJ/L of ethanol. To this energy credit was added a factor of 10% to account for the energy costs of producing the energy inputs into production of corn grain and soybean meal and fossil fuel-based carbon dioxide capture. Thus the total energy credit for the co-products was 4.40 MJ/L of ethanol produced. It was estimated that the energy credit for the DDGS alone (the situation if no CO_2 was captured and sold) would be 2.58 MJ/L of ethanol produced.

3. Results of energy analyses of crop production options and processing improvement effects on the energy costs of ethanol production from wheat.

3.1. Energy costs of CPS wheat. Effects of crop rotations, use of manure and different yield advantages of CPS wheat over hard red spring wheat.

a) CPS wheat following another cereal in the rotation.

The energy costs of spring wheat production are shown in Table 1. Wheat was grown on cereal stubble in a continuous cropping system.

The estimated net yield of CPS wheat, assuming a yield 20% higher than the hard red spring wheat used in the study, was 2,522 kg/ha. The energy costs of production for a tonne of CPS wheat were therefore 3.433 GJ/t. The ethanol yield was assumed to be 370 L/t ((S&T)^{2} ,2005). Thus the energy costs of the wheat component of the total energy costs to produce a litre of ethanol were 9.28 MJ/L.

Wheat following another cereal in the rotation represents probably the highest energy cost way to produce CPS wheat in the rotation. Fertilizer nitrogen (N) rates were higher in the minimum and zero tillage systems than in the conventional tillage system, since they retained more soil moisture than the conventional tillage system, and more N was tied up in the straw and other residue cover of the minimum and zero tillage systems. Thus the yield potential was higher and nitrogen fertilizer rates were higher to try and capture this extra yield potential (Zentner et al., 2002).

Table 1. Energy costs of spring wheat production at Indian Head, Saskatchewan (derived from Zentner et al., 2004). Minimum tillage, cereal stubble crop example.

Input item	Amount of input	Energy costs (MJ/ha
Seed	135 kg/ha @ 7.2 MJ/kg	972
Fertilizer nitrogen	76 kgN/ha	4772
Fertilizer phosphorous	10.9 kg P/ha	104
Fertilizer potassium and sulfur	~ 5 kg potassium/ha and 6 kg sulfur/ha	42
Herbicides		569
Machinery		333
Fuels and lubricants	37.3 L diesel fuel/ha	1640
Labour	1.22 hours/ha @ 170 MJ/ha	225

Total energy costs of production of CPS wheat in a grain rotation = 8657

Inclusion of seed energy costs and the energy costs for labour increased the energy costs of grain production by 13.8%.

Minimum tillage systems are used in all the examples shown in this present study, since this represents close to the average tillage system used on Saskatchewan farms. In all the minimum tillage systems studied at Indian Head, minimum tillage was done shortly before the crop was to be seeded, using a sweep cultivator operating at slow speed to minimize soil disturbance and leave as much standing stubble as possible.

b) Energy costs of CPS wheat in the rotation following a pulse crop.

Nitrogen fertilizer rates for wheat following pea in the rotation were 70 kg N/ha, slightly lower that for wheat following wheat (76kg N/ha). In addition, yields were higher (2864 kg/ha estimated CPS wheat yield at a 20% yield advantage to hard red spring wheat, net to seed cost for seeding) probably due to legume and rotation benefits to yield. The total energy costs were 8195 MJ/ha. Thus the energy costs per tonne of wheat were 2.861 GJ/t. With an estimated ethanol yield of 370 L/t, the energy cost of the wheat component of total energy costs of ethanol were 7.732 MJ/L. It should be noted that the energy costs of pea production are included under that crop only and are not debited to the following crop, such as CPS wheat.

Recent research studies in North Dakota indicate that inclusion of pea could have a useful place in cattle rations, particularly for weaned calves (Anderson, reported by Pratt, 2005). Use of field pea in cattle rations also improved the taste quality of the beef. New uses for field pea in western Canada might also improve the market price for field pea, which has been very low this year (2005).

c) Energy costs of CPS wheat in the rotation following alfalfa.

Studies by Entz et al. (1995) at the University of Manitoba at Winnipeg found that spring wheat grown after alfalfa in the rotation required only 17% as much nitrogen fertilizer as spring wheat following spring wheat in the rotation. Earlier studies at Indian Head, Saskatchewan, also found that nitrogen fertilizer requirements for wheat following brome-alfalfa hay in the rotation were low. In the present study, it was assumed that nitrogen fertilizer requirements were reduce to 17% of requirements of spring wheat following a cereal in the rotation. Yields were assumed to be the same as wheat following pea in the rotation, similar to the results at Winnipeg. Yields of CPS wheat were assumed to be 20% higher than hard red spring wheat. Other studies in Manitoba found that weed populations were lower in wheat which followed alfalfa in the rotation, compared to wheat following an annual crop (Ominski, 1999). For the present study, it was assumed that the energy costs for herbicides were one half those of wheat following an annual crop in the rotation.

Energy costs of producing CPS wheat following alfalfa were calculated to be 4371 MJ/ha. CPS yield (net to seed cost) was estimated to be 2864 kg/ha. Thus energy costs per tonne of CPS wheat were 1.526 GJ/ha. With an estimated ethanol yield of 370 L/tonne, the energy costs of the grain component of ethanol energy costs were 4.124 MJ/L.

It should be noted that inclusion of alfalfa in rotation would apply only to those areas of western Canada where there was sufficient moisture to compensate for the soil moisture depletion effects of alfalfa in the rotation. This would include the Black, Moist Black and Grey soils regions of western Canada.

For the drier areas of western Canada, annual legume hays or a biennial forage legume, such as sweet clover, may be of more interest. They would have less moisture depletion effects than alfalfa and may be easier for farmers to fit into rotations than perennial alfalfa. For example, fenugreek (*Trigonella foenum graecum* L.) looks promising as an annual legume hay. Studies at Lethbridge, Alberta, have found that mature fenugreek hay had nutrient content and digestibility similar to early-cut alfalfa hay (Mir et al., 1993). Named varieties have been developed (Acharya, quoted by Raine, 2005). It is highly drought tolerant, but also responds well to irrigation. Annual legume forage crops may reduce soil moisture content less than alfalfa, and would be more suitable to the drier areas of the prairies than alfalfa.

Long term experiments with organic crop rotations containing legume hays and application of aged cattle manure were found in Pennsylvania to similarly increase annual crop yields, reduce energy costs for crop production and increase soil organic matter (Pimentel et al., 2005). Thus there are different routes to reducing the energy costs of crop production. Common factors appear to include continuous cropping, use of legumes where possible and recycling of nutrients (such as application of manure).

It should be noted that studies in Manitoba on the benefits of inclusion of alfalfa hay in the rotation (e.g., Entz et al., 1995) did not include the effects of applying the manure produced by the animals feeding on the alfalfa hay back to farm fields. This would be expected to further reduce nutrient requirements and reduce energy costs of crop production.

d) Energy costs of CPS wheat production with 20% of the nitrogen fertilizer requirements provided by manure.

An earlier energy and GHG emission analysis of ethanol produced from western Canada CPS wheat included an estimate of 20% of the nitrogen fertilizer requirements being provided by manure ($(S\&T)^2$, 2005). The CPS production model shown in Table 1 was used in the present study. Some 20% of the nitrogen fertilizer requirements were assumed to be provided by manure. Energy costs for labour, fuel and machinery were increased slightly to account for the extra costs of manure hauling and application.

Total energy costs were reduced to 7853 MJ/ha, compared to 8657 MJ/ha with no manure application (see Table 1). Yield of CPS wheat was assumed to be the same (2522 kg/ha). Energy costs for the manure application scenario were 3.114 GJ/t and energy costs for the wheat portion of the energy costs of ethanol production were reduced to 8.416 MJ/L.

e) Energy costs of CPS wheat produced from land which has been in long-term direct seeding.

Lafond has reported that spring wheat grown on farm land (near Indian Head) which had been in 20+ years of direct seeding had a 22% yield increase compared to a field which was in the first year of direct seeding, using the same rate of nitrogen fertilizer on both fields (Lafond, 2003). The wheat also had a higher protein content when produced on the long-term direct seeding field. Other evidence indicated that the long-term direct seeding field had been treated with crop rotations and more continuous cropping, which would also be expected to increase soil organic matter and soil fertility (Lyseng, 2005).

In this present calculation, it was assumed that CPS wheat would also have a 22% higher yield in the long-term direct seeding field. Net yield of CPS wheat was estimated to be 3053 kg/ha. Using the same rate of nitrogen fertilizer as used in the crop rotation studies at Indian Head (see Table 1), the energy costs of producing CPS wheat was 2.836 GJ/tonne. The energy cost of the wheat production component of ethanol production was 7.665 MJ/L.

f) Summary of the effects of different cropping systems on the energy cost of CPS wheat used for ethanol production.

Table 2 summarizes the effects described in the previous section of this report. Also included is the estimated effect of CPS or other types of wheat having a 30% yield advantage over hard red spring wheat instead of the 20% yield increase used in the previous examples.

Table 2. Energy costs of the grain component of ethanol produced from CPS wheat. Effects of crop rotation and yield increase of CPS wheat compared to hard red spring wheat. Indian Head rotations, minimum tillage.

Rotation or treatment	Yield CPSW compared to HRSW (%)	Grain cost component of ethanol production (MJ/L)
W-CPSW	120	9.278
W-CPSW	130	8.540
W-CPSW (20% manure)	120	8.416
W-CPSW (long-term ZT)	120	7.665
P-CPSW	120	7.732
P-CPSW	130	7.114
A-CPSW	120	3.919
A-CPSW	130	3.604

W = spring wheat or winter wheat, CPSW = CPS wheat following another crop in the rotation, P = field peas, A = alfalfa, HRSW = hard red spring wheat

3.2. Energy costs of transporting grain to the processing centre, conversion into ethanol, DDGS and captured CO_2, and costs of storing and transporting the ethanol to the delivery point.

The main energy costs for conversion of wheat grain to ethanol and DDGS are natural gas, used for process heat energy in converting wheat starch into sugars, for distillation of the fermented material to recover the ethanol, and for drying the wet distillers grains and solubles to produce dried material for sale off site. A survey was conducted in 2001 of American dry mill plants producing ethanol and DDGS from corn grain (Shapouri et al., 2002). Average energy costs for natural gas were 11.2 MJ/L ethanol. Electricity costs were 0.1175 kWh/L ethanol. Corn produces more ethanol per tonne of grain and less DDGS per tonne than does CPS wheat. Therefore, the energy costs for ethanol produced from CPS wheat grain were estimated to be 11.98 MJ/L for natural gas and 0.30 kWh/L for electricity ($(S\&T)^2$, 2005). These energy costs need to be adjusted to account for the energy costs to produce and deliver natural gas (HHV X 1.188) and for conversion of coal and other energy sources into electricity (kWh X 8.95 MJ/kWh in Saskatchewan). This raised the total energy costs for natural gas to 14.23 MJ/L and electricity costs to 2.69 MJ/L. Other energy costs to convert CPS wheat grain into ethanol, DDGS and captured carbon dioxide are shown in Table 3. The costs for water purification and delivery, sewage treatment, and the steel and cement used to manufacture the ethanol plant are taken from the study of Pimentel and Patzek (2005). These energy costs have not been included in most other studies.

D. O'Connor of $(S\&T)^2$ Consultants reported to me that modern grain ethanol plants are now using advanced sewage treatment methods, and are able to recycle much of the water used (O'Connor, 2005). This would be expected to reduce some of the energy costs for water supply and treatment. For the present analyses, Pimentel and Patzek's data have been left in the analyses, with the expectation that the actual energy costs for this budget item will be less.

Table 3. Energy costs for conversion of CPS wheat into ethanol, DDGS and captured CO_2. Base case scenario.

Energy input for ethanol and DDGs production	Energy costs in MJ/L of ethanol produced
Natural gas	14.23
Electricity	2.69
Ammonia	0.34
Water (40 L per L of ethanol)	0.378
Stainless steel	0.050
Steel	0.050
Cement	0.034
Sewage treatment	0.290
Total	18.062

A very small amount of diesel fuel (0.0002 MJ/L of ethanol produced) is used for mobile equipment around the ethanol plant, but this is omitted in this study. Additional costs include the energy required to transport the CPS wheat to the ethanol plant (0.15 MJ/L) and the energy costs to distribute and store the ethanol (0.294 MJ/L) and dispense the ethanol (0.066 MJ/L). These costs also include the capture of carbon dioxide for sale.

Thus the total energy costs for ethanol production, outside of the energy costs of producing the grain, were 18.572 MJ/L of ethanol.

a) Energy costs for ethanol produced from CPS wheat grown after another cereal crop in the rotation.

For CPS wheat produced on cereal stubble, with minimum tillage (Tables 1 and 2), the energy costs of production were 9.278 MJ/L. Thus the total energy costs for the ethanol production system were 27.85 MJ/L. From this total needs to be deducted the energy credit for the DDGS and carbon dioxide captured to replace fossil fuel-derived carbon dioxide (4.40 MJ/L). This leaves a total of 23.45 MJ/L for the fossil fuel energy costs for producing ethanol. Since the HHV of ethanol is 23.52 MJ/l, the output to input ratio is 1.003:1. One MJ of ethanol requires 0.997 MJ of fossil fuel energy for its production.

Thus ethanol produced this way consumes nearly as much fossil fuel energy as renewable energy is produced. But ethanol is being used to replace gasoline. Gasoline requires 0.28 MJ of fossil fuel energy to produce 1.00 MJ of gasoline energy to power a vehicle ($(S\&T)^2$, 2005). This energy cost includes the energy required to pump the crude oil out of the ground, refine it into gasoline and transport the gasoline to the filling station. Thus ethanol produced this way requires 22.1% less fossil fuel energy ((1.28 - 0.997)/1.28 X 100) than gasoline to provide one MJ of liquid fuel energy.

This is the worst case scenario. This study now looks at methods to improve the energy efficiency of producing ethanol from CPS wheat.

b) Effect of a legume in the rotation before CPS wheat.

Combining the data in Table 3 with the data in Table 2, and using a 20% yield increase of CPS wheat compared to HRS wheat, the energy output:input ratio of ethanol produced from CPS produced after field pea was 1.074. The ratio for ethanol produced from CPS wheat following alfalfa in the rotation was 1.30:1.

c). Effect of not capturing carbon dioxide on energy budgets.

Some ethanol plants may not capture carbon dioxide released during fermentation of the grain. The credit for replacing carbon dioxide produced from fossil fuel consumption with fermentation based carbon dioxide would be lost. It was estimated that this reduced the co-product credit from 4.40 MJ/L to 2.58 MJ/L. The effects on the energy output:input ratio and the reduction in fossil fuel consumption from replacing gasoline with ethanol are compared in Tables 4, 5 and 6.

d) Effect of reducing the amount of natural gas and electricity required in the processing plant.

One of the most recent studies in Canada on the energy balance and greenhouse gas emissions reduction potential of ethanol produced from CPS wheat was reported by

(S&T)^2 consultants for Natural Resources Canada ((S&T)^2, 2005). They concluded that rapid improvements in the energy efficiency of grain ethanol plants were being achieved. They suggested a 2% per year reduction in the natural gas and electricity requirements of an ethanol plant was reasonable. For the present study it was assumed that a 10% reduction in natural gas and electricity requirements was achieved since 2001 by modern plants compared to the amounts shown in Table 3. This modern plant would have a natural gas requirement of 12.807 MJ/L of ethanol and an electricity requirement of 2.421 MJ/L of ethanol. These costs include the energy costs of production of these final energy inputs into ethanol production. The total non-grain costs of ethanol production would be reduced to 16.882 MJ/L of ethanol.

Table 4 shows the effects of combining improving the energy efficiency of the ethanol plant by 10% and the effect of different methods of producing the grain used as the raw material.

Table 4. Energy efficient ethanol production plant. Effects on the final energy output:input ratio of different methods of growing CPS wheat used as the raw material and different yield benefits of CPS wheat compared to HRSW. Reduction in total fossil fuel consumption when 1 MJ ethanol replaces 1 MJ gasoline. Data in parentheses = no carbon dioxide capture.

Rotation	Yield of CPSW cf. HRSW (%)	Energy output:input ratio	Reduction in fossil fuel consumption when 1 MJ ethanol replaces 1 MJ gasoline (%)
W-CPSW	120	1.08:1 (1.01:1)	27.7 (22.3)
W-CPSW	130	1.19:1 (1.03:1)	34.4 (24.1)
P-CPSW	120	1.16:1 (1.07:1)	32.7 (26.9)
P-CPSW	130	1.20:1 (1.10:1)	34.9 (28.8)
A-CPSW	120	1.43:1 (1.29:1)	45.4 (39.5)
A-CPSW	130	1.46:1 (1.31:1)	46.5 (40.5)

W = another cereal in the rotation, CPSW = CPS wheat following another crop in the rotation, P = peas, A = alfalfa, HRSW = hard red spring wheat.

e) Effect of using excess steam and waste heat from a nearby oil refinery/upgrader operation to reduce the heat energy requirements of a grain ethanol plant.

Husky Energy is constructing a large ethanol plant beside its heavy oil upgrader plant at Lloydminster, Saskatchewan (Briere, 2004; Pratt, 2005; www.huskyenergy.ca). The ethanol plant will produce 130 million litres per year. Pratt (2005) reported that the plant is able to capture excess steam and waste heat from its upgrader, and from the co-generation facility producing steam and electricity, to use in the ethanol production process. For the present study it was assumed that these energy sources would reduce the natural gas requirements of the ethanol process by one third. An energy efficient plant was assumed with 10% less natural gas and electricity requirements than ethanol plants built before 2001, such as was described in the previous section of this report. For the Husky plant it was assumed that the natural gas requirements were reduced to 8.58 MJ/L of ethanol and the electricity requirements were 2.421 MJ/L. These energy costs include the energy coefficients to account for the energy required to produce and deliver the energy input. The total energy costs for all ethanol production and delivery costs, except the energy to grown the grain crop, were reduced to 12.653 MJ/L of ethanol.

The effects of different methods to produce the CPS grain input, when combined with this energy efficient, energy-integrated plant, are shown in Table 5.

Table 5. Energy efficient, energy-integrated ethanol production plant. Effects on the energy output:input ratio of different methods of growing CPS wheat and different yield benefits of CPS wheat compared to HRSW. Reduction in total fossil fuel consumption when ethanol replaces gasoline. Data in parentheses = no carbon dioxide capture.

Rotation, CPS wheat after another crop	Yield of CPS wheat compared to hard red spring wheat (%)	Output:input ratio, ethanol energy produced compared to fossil fuel energy used	Reduction in total fossil fuel consumption when 1 MJ ethanol replaces 1 MJ gasoline (%)
W-CPSW	120	1.36:1 (1.23:1)	42.6 (36.4)
W-CPSW	130	1.40:1 (1.26:1)	44.2 (38.2)
P-CPSW	120	1.47:1 (1.32:1)	46.9 (40.9)
P-CPSW	130	1.53:1 (1.37:1)	48.9 (42.9)
A-CPSW	120	1.93:1 (1.68:1)	59.5 (53.5)
A-CPSW	130	1.98:1 (1.72:1)	60.5 (54.7)

Symbols the same as in Table 4 (q.v.).

It should be noted that there is no assumption that all CPS wheat coming into the processing plant would be produced by any one of the rotations shown in Table 4 or 5. Some combination of these crop production systems, plus possible others, would actually happen. Data shown in Tables 3, 4, 5 and 6 do indicate the energy efficiency implications of different crop rotations and yield benefits (CPS compared to hard red spring wheat) on the final ethanol energy balance.

f) Energy costs of ethanol produced by an energy efficient plant coupled with a feedlot and a biogas plant using feedlot manure as the feedstock.

Saskatchewan already has one ethanol plant integrated with a feedlot, the Pound Maker AgVentures operation near Lanigan, Saskatchewan. This operation feeds all the distillers solids and solubles in the wet state to the animals in the feedlot. Thus the thermal energy requirements for drying these co-products are avoided. According to Wang et al. (1997) drying the distillers solids and solubles consumed about 30% of the thermal energy requirements of a grain-to-ethanol production facility. For an energy efficient ethanol plant, such as described in a previous section of this report, eliminating the drying costs for the co-product would reduce the natural gas requirements to 8.965 MJ/L of ethanol.

A new method of producing biogas and a solid bio-fertilizer from solid manure has been developed in Alberta (MacArthur, 2005; http://www.jpcs.on.ca/biodiversity/ghg/project_reports/ab-4.html; http://res2.agr.ca/initiatives/manurenet/en/hems/ecoamu_main.html). The process is called Integrated Manure Utilization System (IMUS). Manure is first treated in an anaerobic digestion system to produce biogas, which can be used for various thermal energy purposes. The treated slurry remaining after manure digestion is separated into liquid and solids. Nutrients are recovered from the liquid and added to the solids to produce a solid biofertilizer. The liquid portion after nutrient removal is now reusable water, which can be recycled in the system. All products from the system have to have economic value for the system to be economically attractive. For the present study, the question is: can such a biogas/biofertilizer system be integrated with a grain-to-ethanol plant to reduce energy and economic costs for the integrated systems?

For the present study, it was assumed that enough biogas was produced to meet the thermal energy needs (8.965 MJ./L of ethanol) of the ethanol plant. The energy costs of the IMUS system were not available for the present project. It was assumed, as a working model, that the fossil fuel input energy (materials, power to run pumps, and truck fuel needs to haul manure to the biogas plant) amounted to one half of the energy of the biogas output, net to the credit for the biofertilizer. Thus the fossil fuel energy costs for the biogas to run the thermal energy needs of the ethanol plant would be 4.483 MJ/L of ethanol. When energy costs for hauling grain to the plant, and energy costs for ethanol distribution, storage and dispensing were included, the total non-grain fossil fuel energy costs were 8.261 MJ/L.

It would be expected that an ethanol plant integrated with a biogas plant and feedlot would not have any sewage treatment energy costs. The IMUS process does include technology to recycle water from the digested manure from the anaerobic process.

An earlier analysis of biogas production from manure in the USA calculated that the net energy gain (as biogas) would be 30.5%, after deducting operating energy costs and energy depreciation factors for the steel and concrete in the biogas plant and operating equipment (Giampietro and Pimentel, 1990). This analysis was based on earlier research data on biogas production from the 1970s. It was assumed for the present study that the net energy efficiency of production of biogas had improved by 2005 to a net energy gain of 50%.

Table 6 shows the energy costs of producing ethanol from this integrated system when the energy costs of producing the CPS grain in different rotations are included. It was assumed that an ethanol plant integrated with a feedlot would not be large enough to warrant CO_2 capture.

Table 6. Energy output:input ratio of ethanol produced from grain when using an integrated ethanol plant/biogas/feedlot system. Effects of crop rotations, different yield benefits of CPS wheat compared to hard red spring wheat, and use of manure

as a fertilizer. Reduction in total fossil fuel consumption when ethanol replaces gasoline. Situation with no carbon dioxide capture.

Crop rotation or manure use	Yield of CPSW compared to HRSW (%)	Energy output:input ratio	Reduction in total fossil fuel consumption when 1 MJ ethanol replaces 1 MJ gasoline (%)
W-CPSW	120	1.59:1	51.0
W-CPSW	130	1.65:1	52.7
W-CPSW (20% manure N)	120	1.67:1	53.1
P-CPSW	120	1.75:1	55.5
A-CPSW	120	2.45:1	68.1

Symbols in Table 6 are the same as in previous Tables 3, 4 and 5.

4. Examples of cropping systems which increase farmer net income as well as reducing energy costs of the grain produced.

This present study has not examined in detail methods to improve farmer income using cropping systems which reduce the fossil fuel energy costs of the grain produced. Several examples are worth pointing out:

Growing CPS wheat after alfalfa in the rotation.

Studies by Martin Entz and his students at the University of Manitoba found that little nitrogen fertilizer was required for wheat grown after alfalfa. The Crop Planning Guide for the Black soil zone of Saskatchewan for 2005 was used to estimate reduce costs and improved net income for CPS wheat grown on stubble after alfalfa in the rotation compared to CPS wheat grown after another cereal in the rotation. Nitrogen fertilizer costs were assumed to be reduced to 17% of those otherwise required for CPS wheat grown after a non-legume annual crop. Herbicide costs were assumed to be reduced by one half for the alfalfa-CPS wheat rotation (benefits of a forage crop in the rotation). Overall production costs were reduced to \$322/ha, compared to \$392/ha for CPS wheat grown after another annual cereal crop in the rotation. With CPS wheat crop yield assumed the same (no yield gain or loss for wheat after alfalfa), the net income in the CPS wheat after alfalfa system was \$7/ha, compared to a loss of \$63/ha in the CPS wheat after a cereal in the rotation system.

Growing CPS wheat in a long-term zero tillage crop production system.

Results obtained by Lafond (2003) on a farm in the Indian Head area were tested for their potential effect on costs of CPS wheat production. A 22% yield increase was assumed, the same as found by Lafond for hard red spring wheat in the comparison trial conducted.

Using the Crop Planning Guide for 2005 for the Black soil zone, this yield increase would increase net income to $5/ha, compared to a loss of $64/ha if these long-term soil fertility benefits could not be achieved.

The farmer in this study has also found that he can grow peas without phosphorous fertilizer some years on these high fertility soils on his farm. This saves him some $22-25/ha (Lyseng, 2005).

5. Conclusions.

Ethanol produced from CPS wheat required less fossil fuel for its production than the gasoline it would replace as a fuel. In most cases, substantially more renewable fuel was produced (ethanol) than fossil fuel was required to produce it.

In all cases examined, less fossil fuel was consumed if ethanol replaced gasoline. This has positive implications for a reduction in GHG emissions when ethanol replaces gasoline. Other studies have confirmed this reduction in GHG emissions.

Inclusion of a legume in the crop rotation before CPS wheat, or application of manure to replace some of the nitrogen fertilizer required, reduced energy costs of producing the wheat. This also reduced the energy costs of producing ethanol.

Methods to improve the energy efficiency of the ethanol plant, particularly when integrated with utilization of excess heat energy from a heavy oil upgrader, substantially reduced the fossil fuel costs of ethanol production. This analysis was based on an assumption of the actual energy savings of one-third at the ethanol plant.

Integration of an energy efficient ethanol plant with a feedlot and a biogas/biofertilizer production unit gave significant reductions in energy costs of ethanol production. An estimate of the net energy savings of biogas produced in a modern biogas operation was used in these analyses. It would be helpful to have the actual energy budget for future analyses.

Combinations of energy efficient crop production with energy efficient ethanol production facilities gave further improvements in the renewable energy status of ethanol produced from grain in western Canada.

These ethanol production systems need to be tested for their GHG reduction potential, using a model such as GHGenius modified so it can include all the inputs energy sources used in the present study.

The economic benefits/implications of these various crop production and ethanol production systems need to be investigated. More methods to improve the income of farmers providing raw materials to the processing centre need to be found and implemented. Methods to integrate a livestock operation with a number of neighboring grain farms are starting to be implemented by several livestock operations in western

Canada. This has the potential to be beneficial to all co-operating farms. It allows grain farms to integrate forage legumes in their crop rotations, for example. This arrangement needs to be investigated further.

The carbon credits of some of these systems could be substantial. This should be investigated.

Other types of energy savings by employing ethanol as a transportation fuel may be applicable:

- Some oil refineries may be able to reduce the energy use intensity of certain refinery operations if ethanol is used to provide some of the octane requirements of the gasoline:ethanol blend.
- In addition, the fuel efficiency of engines employing an 85%:15% blend of ethanol:gasoline may be significantly improved compared to gasoline alone if the engine is specially redesigned to take advantage of the different properties of the ethanol fuel. This would give the ethanol component a further energy credit.

These types of energy savings need to be investigated.

In times of greater world food shortages in the future, and higher grain prices, many ethanol production plants based on grain feedstocks should be able to add processing steps to produce human food products (for example, wheat gluten and high quality wheat flour) and produce ethanol from the poorer quality wheat starch fractions.

6. References to both chapters.

Archer, C.L. and Jacobson, M.Z. 2005. Evaluation of global wind power. Journal of Geophysical Research. 110: D12110, doi: 10.1029/2004JD005462, 2005. 20pp.

Barnes, A. 2005. Energy prices drive index to record high. Globe and Mail, October 26, p. B16.

Berglin, N., Lindblom, M. and Ekbom, T. 2002. Efficient production of methanol from biomass via black liquor gasification. TAPPI (Technical Association of the Pulp and Paper Industry) Fall Conference & Trade Fair.

Berndes, G., Azar, C., Kaberger, T. and Abrahamson, D. 2001. The feasibility of large-scale lignocellulose-based bioenergy production. Biomass and Bioenergy 20: 371-383.

Brethour, P. 2005. Alberta firms studying ways to ship, sell CO_2. Globe & Mail, September 20, p. B3.

Briere, K. 2004. Ethanol plants get boost. Western Producer, Feb. 19, p. 3.

Brown, L. 2004. Outgrowing the Earth: The Food Security Challenge in an Age of Falling Water Tables and Rising Temperatures. (see http://www.earth-policy.org/Books/Out/).

Brylawski, M. 1999. Uncommon Knowledge: An Automobile Platform Sharing's Impact on Advanced Technologies. Rocky Mountain Institute, Snowmass, Colorado 81654-9199. See also www.rmi.org.

CARC-BIOCAP Canada. 2003. An Assessment of the Opportunities and Challenges of a Bio-Based Economy for Agriculture and Food Research in Canada. Canadian Agri-Food Council, Ottawa, Ontario K1A 0C6. Available at www.crac-crac.ca.

Coxworth, E. and McEwen, T. 2004. Reducing Greenhouse Gas Emissions from the Transportation Sector: Role for Bio-Products. An appendix to the CCFIA Position Paper 3: An Assessment of the Opportunities and Challenges of a Bio-Based Economy for Agriculture and Food Research in Canada. Available at www.carc-crac.ca.

Duckworth, B. 2005. Controversy arises between developers and landowners as a resource dawns. Western Producer, December 13, pp. 10-11.

Dunlop, N. 2005. New fuel cell motorcycle has rider green with ENV. Saskatoon Star Phoenix, September 2, p. E4.

Elkan, D. 2005. The rainforest saver. Ecologist, February issue, pp. 56-63.

Entz, M. et al. 1995. Carbon released by manufactured inputs in prairie agriculture. Chapter 5 of Volume 2 of Study of the Effects of Cropping and Tillage Systems on Carbon Dioxide Released by Manufactured Inputs to Western Canadian Agriculture: Identification of Methods to reduce Carbon Dioxide Emissions. E. Coxworth et al., Report to H.H. Janzen, Agriculture and Agri-Food Canada, Lethbridge, Alberta.

Environment Canada. 2003. Canada's Greenhouse Gas Inventory. 1990-2001. Report catalogue number En49-5/5-9-2-2001E. Environment Canada, Ottawa, Ontario K1A 0H3.

Fluck, R.C. 1992. Energy of Human Labor. Chapter 3. Energy in Farm Production (R.C. Fluck, editor). Elsevier, Amersterdam, Netherlands. Volume 6 of Energy in World Agriculture.

Friedman, D., Nash, C.E. and Ditlow, C. 2003. Building a Better SUV: A Blueprint for Saving Lives, Money and Gasoline. Report from the Union of Concerned Scientists, see www.ucsusa.org.

Fromm, J.J. 2005. A future of E-hybrids, not fuel cells. Green Car Journal Fall Issue, p. 21. See also www.greencar.com.

Garrity, D. 2005. This time, Africa gets a real hand up. Globe and Mail, September 25, p. A15.

Giampietro, M. and Pimentel, D. 1990. Alcohol and biogas production from biomass. Critical Reviews in Plant Science 9 (3): 213-233.

Gibbins, J. 2005. Power-plant design should prepare for carbon capture. Nature, p. 912. Gibbins is with the Energy Technology for Sustainable Development Group, Imperial College, London, UK SW7 2AZ.

Green Car Journal. 2005. Saab 9-5 Biopower, p. 40.

Greene et al. 2004. Growing Energy: How Biofuels Can Help End America's Oil Dependence. Natural Resources Defense Council Report, 78 pp. See www.nrdc.org.

Hutchence, K. 1999. Saskatchewan and the Ethanol Energy Economy: A Strategic Background Study to Support R&D Proposals on Ethanol and Fuel Cells. Saskatchewan Research Council Report Publication No. P-110-432-C-98. Saskatchewan Research Council, Regina, SK S4S 7J7.

Hutchence, K. 2001. Ethanol Plus: Saskatchewan and the Biomass Industries. Saskatchewan Research Council Report No. P-110-539-C-01. Saskatchewan Research Council, Regina, SK S4S 7J7.

IEA, 2005. Biofuels for Transport: An International Perspective. International Energy Agency, Paris, France. 210 pp.

Imam, A., Startzman, R.A. and Barrufet, M.A. 2004. Multicyclic Hubbert model shows global conventional gas output peaking in 2019. Oil & Gas Journal, Aug. 16. pp. 20-28.

Jaccard, M. 2005. Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy. Cambridge University Press, Cambridge, UK. See also www.cambridge.org.

Jacobson, M.Z., Colella, W.G. and Golden, D.M. 2005. Cleaning the air and improving health with hydrogen fuel-cell vehicles. Science 308: 1901-1905.

Janzen, H.H., Desjardins, R.L., Asselin, J.M.R. and Grace, B. 1998. The Health of Our Air: Toward Sustainable Agriculture in Canada. Publication 1981/E. Agriculture and Agri-Food Canada, Ottawa, Ontario K1A 0C5.

Keith, D.W. and Farrell, A.E. 2003. Rethinking hydrogen cars. Science 301: 315-316.

Khan, S.U.M., Al-Shahry, M. and Ingler, W.B. Jr. 2002. Efficient photochemical water splitting by a chemically modified n-TiO_2 . Science 297; 2243-2245.

Kheshegi, H.S., Prince, R.C. and Marland, G. 2000. The potential of biomass fuels in the context of global climate change: Focus on transportation fuels. Ann. Rev. Energy Environ. 25: 199-244.

Klass, D.L. 1998. Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press, San Diego, CA, USA.

Kripalani, M. 2005. India's untold story. Business Week, August 22/29, pp. 132-133.

Lafond, G.P. 2003. Long-term direct seeding effects: can we measure them and are they economically important? Prairie Steward No. 37, winter issue, pp. 1, 18. Available from the Saskatchewan Soil Conservation Association, Indian Head, Sask. S0G 2K0.

Levelton Engineering, $(S\&T)^2$ Consulting, Inc. and J.E. & Associates. 1999. Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Ontario. Report to Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5.

Levelton Engineering. 1999b. Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Canada: Lignocellulosic Residues. Report to Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5.

Li, X. 2005. Personal communication to E.C. October 26, 2005. See also a report of Dr. Li's research at http://www.jpcs.on.ca/biodiversity/ghg/project_reports/ab-4.html.

Lovins, A.B. 2003. Twenty Hydrogen Myths. Rocky Mountain Institute, Snowmass, Colorado 81654-9199. See also www.rmi.org.

Lovins, A.B. et al. 2004. Winning the Oil Endgame. Rocky Mountain Institute, Snowmass, Colorado, USA 81654-9199. See page 164. See also www.rmi.org and www.oilendgame.com . Technical Annex to Chapter 18 is called Biofuels and Biomaterials.

Lovins, H. and King, W. 2003. Boom, Bust, and Efficiency. Chapter 8 in Fueling the Future (editors A. Heintzman and E. Solomon). Anansi Press, Toronto, Ontario, Canada..

Lyseng, R. 2005. Zero T leads to zero P in pulses. Western Producer, September 8, p. 57.

MacArthur, M. 2005. Feedlot turns manure into energy. The Western Producer, May 12, 2005.

Mir, P.S., Mir, Z., and Townley Smith, L. 1993. Comparison of the nutrient and in situ degradability of fenugreek (*Trigonella foenum-graecum*) and alfalfa hays. Can. J. Anim. Sci. 73: 993-996.

Morris, D. 2005. The Carbohydrate Economy, Biofuels and the Net Energy Debate. Published by the Institute for Local Self-Reliance, Minneapolis, MN 55414, USA. See www.ilsr.org.

Munro, M. 2005. Prairies facing shortage of water, scientists warn. Saskatoon Star Phoenix, November 17, p. A13.

Nagy, C.N. 1999. Energy Coefficients for Agriculture Inputs in Western Canada. Canadian Agricultural Energy End-Use Data Analysis Centre, University of Saskatchewan, Saskatoon, SK S7N 5A8.

Nagy, C.N. 2000. Energy and Greenhouse Gas Coefficients for Inputs Used in Agriculture. Canadian Agricultural Energy End-Use Data and Analysis Centre, University of Saskatchewan, Saskatoon SK S7N 5A8.

Nikiforuk, A. Mythoilogy: eight wrong ways to think about the future of energy. Canadian Business, January 17. see www.canadianbusiness.com/shared/print.jsp?content=20050117_64724_64724

O'Connor, D. 2005. Personal communication to E. Coxworth,

Ominski, P.D., Entz, M.H. and Kenkel, N. 1999. Weed suppression by M*edicago sativa* in subsequent cereal crops: a comparative survey. Weed Science 47: 282-290.

Parfit, M. 2005. Future Power: Where Will the World Get Its Next Energy Fix? National Geographic, August issue, pp. 2-31.

Patzek, T.W. and Pimentel, D. 2005. Thermodynamics of energy production from biomass. Accepted for publication in Critical Reviews in Plant Sciences. 91 pp.

Pearson, S.R. 2001. The manufacture of synthesis gas and ethanol from biomass using the Pearson thermo-chemical steam reforming and catalytic conversion process. Proceedings of the 5th Biomass Conference of the Americas. Available from the National Renewable Energy Laboratory, Golden Colorado.

Pimentel, D., Hepperly, P., Hanson, J. Douds, D. and Seidel, R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. BioScience 55 (7): 573-582.

Pimentel, D. and Patzek, T.W. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybeans and sunflower. Natural Resources Research 14 (1): 65-75.

Polak, P. 2005. The big potential of small farms. Scientific American, Special Issue on Crossroads for Planet Earth, September, 2005, pp. 84-91.

Pratt, S. 2005. Peas could fill gap in cattle feed. Report on the research studies of V. Anderson of North Dakota State University. Western Producer, October 27, 2005, pp. 1,2.

Pratt, S. 2005b. Lloydminster ethanol plant to open in 2006. Western Producer, October 20, p. 12. See also www.huskyenergy.ca.

Racz, V. 2005. Comments at an Ethanol Research Update meeting on August 24, Saskatoon, SK.

Raine, M. 2005. Forage crop comes with a licorice twist. Report on research studies by S. Acharya, T. McAllister and S. Basu at the Agriculture Canada Research Centre at Lethbridge, AB and the University of Lethbridge. Western Producer, September 29, p. 17.

Reddy, A.K.N., Williams, R.H. and Johansson, T.B. 1997. Energy After Rio: Prospects and Challenges. United Nations Development Program, 1 United Nations Plaza, New York, NY 10017, USA.

Romm, J.J. 2005. A future of e-hybrids, not fuel cells. Green Car Journal, Fall, p.21.

Royston, L. and Pulfer, R. 2005. Under pressure: traditional energy supplies are increasingly vulnerable. But what are the alternatives? Canadian Business, September 15-25, pp. 31-32.

Ritter, S.K. 2002. Cleaner future for fossil fuels. C & EN (Chemical and Engineering News) October 7, 2002, pp. 30-31.

$(S\&T)^2$. 2003. The Addition of Ethanol from Wheat to GHGenius. Report to Office of Energy Efficiency, Natural Resources Canada, Ottawa, ON K1A 00E4.

$(S\&T)^2$. 2005. Ethanol GHG Emissions Using GHGenius: An Update. Report to Office of Energy Efficiency, Natural Resources Canada, Ottawa, ON K1A 0E4.

$(S\&T)^2$ .2005b. Biodiesel GHG Emissions Using GHGenius: An Update. Report to the Office of Energy Efficiency, Natural Resources Canada. Ottawa, ON K1A 0E4.

Saunders, D. 2005. Stopping starvation is like solving Rubik's Cube. Globe and Mail, September 10, p. F3.

Schoenmaeckers, B. 1997. Dutch CO_2 reduction plan completed. Change 38/September-October pp. 14-15. Published by RIVM/NRP, Bilthoven, The Netherlands.

Shapouri, H., Duffield, J.A. and Wang, M. 2002. The Energy Balance of Corn Ethanol: An Update. Agricultural Economic Report Number 614, United States Department of Agriculture, Washington , DC, USA.

Shewchuk, S. 2005. Personal communication to E.C. Shewchuk is at the Saskatchewan Research Council, Saskatoon, SK.

Solatisky, M. 2005. A Preliminary Investigation of Afforestation to Reduce Greenhouse Gas Emissions in Electrical and Ethanol Production. Saskatchewan Research Council Publication No. 11858-1C05.

Statistics Canada. 2001. Quarterly Report on Energy Supply and Demand.

Vidal, J. 2006. Sweden plans to be the world's first oil-free economy. Guardian/UK, February 8th issue.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H. and Matson, P.A. 1986. Human appropriation of the products of photosynthesis. BioScience 36 (6): 368-373. See also Vitousek, P.M., Mooney, H.A., Lubchenco, J. and Melillo, J.M. Human domination of earth's ecosystems. Science 277: 494-499.

Wang, M., Saricks, C. and Wu, M. 1997. Fuel-Cycle Fossil Energy Use and Greenhouse Gas Emissions of Fuel Ethanol Produced from U.S. Midwest Corn. Centre for Transportation Research, Argonne National Laboratory, Argonne, Illinois, USA.

Warnyka, B. 2005. You can use corn distillers as a protein source. Grainews, October issue, pp. 1,17.

Wood, S. M., and Layzell, D. B. 2003. A Canadian Biomass Inventory: Feedstocks for a Bio-Based Economy. BIOCAP Canada Foundation, Kingston, Ontario K7L 3N6.

Woynillowicz, D., Sverson-Baker, C. and Raynolds, M. 2005. Oil Sands Fever: The Environmental Implications of Canada's Oil Sands Rush. Pembina Institute, Drayton Valley, AB T7A 1S7. See also www.pembina.org.

Zentner, .P., Lafond, G.P., Derksen, D.A. and Campbell, C.A. 2002. Tillage method and crop diversification: effect on economic returns and riskiness of cropping systems in a Thin Black Chernozem of the Canadian Prairies. Soil & Tillage Research 67: 9-21.

Zentner, R.P., Lafond, G.P., Derksen, D.A., Nagy, C.N., Wall, D.D. and May, W.E. 2004. Effects of tillage method and crop rotation on non-renewable energy use efficiency for a Thin Black Chernozem in the Canadian Prairies. Soil & Tillage Research 77: 125-136.