Chapter 16
Developing Energy Crops for Thermal Applications: Optimizing Fuel Quality, Energy Security and GHG Mitigation

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Abstract Unprecedented opportunities for biofuel development are occurring as a result of increasing energy security concerns and the need to reduce greenhouse gas (GHG) emissions. This chapter analyzes the potential of growing energy crops for thermal energy applications, making a case-study comparison of bioheat, biogas and liquid biofuel production from energy crops in Ontario. Switchgrass pellets for bioheat and corn silage biogas were the most efficient strategies found for displacing imported fossil fuels, producing 142 and 123 GJ/ha respectively of net energy gain. Corn ethanol, soybean biodiesel and switchgrass cellulosic ethanol produced net energy gains of 16, 11 and 53 GJ/ha, respectively. Bioheat also proved the most efficient means to reduce GHG emissions. Switchgrass pellets were found to offset 86–91% of emissions compared with using coal, heating oil, natural gas or liquid natural gas (LNG). Each hectare of land used for production of switchgrass pellets could offset 7.6–13.1 tonnes of CO_2 annually. In contrast, soybean biodiesel, corn ethanol and switchgrass cellulosic ethanol could offset 0.9, 1.5 and 5.2 tonnes of CO_2/ha, respectively.

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The main historic constraint in the development of herbaceous biomass for thermal applications has been clinker formation and corrosion in the boiler during combustion. This problem is being overcome through plant selection and cultural techniques in grass cultivation, combined with advances in combustion technology. In the coming years, growing warm-season grasses for pellet production will emerge as a major new renewable energy technology, largely because it represents the most resource-efficient strategy to use farmland in temperate regions to create energy security and mitigate greenhouse gases.

Keywords Combustion · bioheat · biomass · net energy balance · grass pellets · switchgrass · energy crop · greenhouse gas · thermal energy · energy security · biomass quality · perennial

Acronyms & abbreviations

Bioheat:	biomass use for thermal applications
C_3:	cool season
C_4:	warm season
Cl:	Chlorine
GHG:	greenhouse gas
K:	Potassium
LNG:	liquefied natural gas
N:	nitrogen
RET's:	renewable energy technologies
Si:	Silica
WSG:	warm season grass

16.1 Introduction

In most industrialized countries, thermal energy represents the largest energy need in the economy. Thermal energy is used for space and water heating in the residential, commercial and industrial sectors, low and high temperature process heat for industry, and power applications. Thermal energy can also be used for cooling applications. Rather than supporting biomass for simple thermal applications such as direct heating applications industrialized countries have currently placed emphasis on researching and providing subsidies for more technologically complex innovations such as large industrial bio-refineries. However, governments in industrialized nations who have identified the need to develop biofuels for energy security and greenhouse gas mitigation should look more closely at thermal applications for biomass to fulfill these needs. This review therefore examines energy security in section one, identifying opportunities to grow energy crops on farmland in eastern Canada as a means to collect solar energy and convert it into useful energy products

for consumption. The greenhouse gas (GHG) mitigation potential of switching from fossil fuels to various biofuels produced from energy crops is also examined. Section two then overviews recent advances in the emerging agricultural industry growing grasses for bioheat, identifying opportunities and challenges in advancing this technology for commercial applications in temperate regions of the world.

16.2 Energy Crop Production for Energy Security and GHG Mitigation

Since the Arab oil embargo in the 1970s there has been considerable interest in North America in growing both conventional field crops and dedicated energy crops for bioenergy as a means to enhance energy security. The long-term decline in farm commodity prices has also created significant interest in using the surplus production capacity of the farm sector as a means to produce energy while creating demand enhancement for the farm sector. This decline in farm commodity prices, due to innovation in plant breeding and production technology, is accelerating the likelihood that large quantities of biomass energy from farms could penetrate energy markets currently dominated by fossil fuels.

One of the strongest drivers for biofuel development is the GHG mitigation potential of energy crops to produce solid, liquid and gaseous biofuels to replace fossil fuels in our economy. With the increased use of grain crops for liquid biofuels, the past two years have seen a rise in both the demand and price for farm commodities. Also increasing however, are concerns over other important social issues such as the potential for bioenergy to compete with food security, and problems with soil erosion and long-term soil fertility. The production and utilization of crops residues as a global biofuel sources has recently been reviewed (Lal, 2005). The main conclusions were that the most appropriate use of crop residues is to enhance, maintain and sustain soil quality by increasing soil organic matter, enhancing activity and species of soil fauna, minimizing soil erosion and non-source pollution, mitigating climate change by sequestering carbon in the pedosphere, and advancing global food security through enhancement of soil quality. It was recommended that efforts be undertaken to grow biomass on specifically dedicated land with species of high yield potential, suggesting that 250 million hectares (ha) globally could be put into production of perennial energy crops.

The increasing biodiversity loss from agricultural landscapes through crop intensification is also a major environmental concern. The rapid development of liquid biofuels in the tropics in the past decade has also caused significant harm to biodiversity through the conversion of forests into agricultural production. Resource efficient, rather than resource exhausting, bioenergy crop production strategies need to evolve with a priority placed on de-intensification of farm production through the use of perennials and utilization of existing marginal farmlands. This approach would to a much greater extent avoid the biofuel conflicts with food crop production and biodiversity that are now occurring with using annual food crops as biofuels.

To achieve the objective of resource efficient biomass production we must examine some of the basic factors influencing biomass accumulation:

1. There are two main photosynthetic pathways for converting solar energy into plant material: the C_3 and C_4 pathways. The C_4 pathway is approximately 40% more efficient than the C_3 pathway in accumulating carbon (Beadle and Long, 1985).
2. C_4 species use approximately half the water of most C_3 species (Black, 1971).
3. In temperate climates, sunlight interception is often more efficient with perennial plants because annual plants spend much of the spring establishing a canopy and also exhibit poor growth on marginal soils.
4. Some species of warm season grasses are climax community species and have excellent stand longevity (which also results in decreased economic costs for establishing perennial crops through decreased expenditures for seeding, tillage etc.).
5. C_4 species of grasses contain less N than C_3 species and can be more N-use efficient in temperate zones because the N is cycled internally to the root system in the fall for use in the following growing season (Clark, 1977).

It is apparent that the optimal plants for resource-efficient biomass production should be both perennial and C_4 in nature.

16.2.1 Perennial and Annual Energy Crops

In North America, the warm continental climate has produced a diversity of native warm season (C_4) perennial grasses that have a relatively high energy production potential on marginal farmlands. In the more humid zones, these species include switchgrass (*panicum virgatum*), prairie cordgrass (*spartina pectinata*), eastern gamagrass (*tripsacum dactyloides*), big bluestem (*andropogon gerardii vitman*) and coastal panic grass (*panicum amarum A.S. hitchc.*). In semi-arid zones and dry-land farming areas, prairie sandreed (*calamovilfa longifolia*) and sand bluestem (*andropogon hallii*) are amongst the most productive species. All of these species are relatively thin stemmed, winter hardy, highly productive and are established through seed.

Switchgrass was chosen as the model herbaceous energy crop species to concentrate development efforts on in the early 1990s by the U.S. Department of Energy. It had a number of promising features including its moderate to high productivity, adaptation to marginal farmlands, drought resistance, stand longevity, low nitrogen requirements and resistance to pests and diseases (Samson and Omielan, 1994; Parrish and Fike, 2005).

Table 16.1 illustrates that in Ontario, Canada, C_4 species like corn and switchgrass produce considerably higher quantities of energy from farmland than C_3 crops. The perennial crops were also identified to have the lowest fossil energy input requirements. Overall, prior to any conversion process, switchgrass produces 40% more

Table 16.1 Solar energy collection and fossil fuel energy requirements of Ontario Crops per hectare, adapted from Samson et al. (2005)

Crop	Yield (ODT/ha)	Energy content (GJ/ODT)	Fossil energy used (GJ/ODT)	Fossil energy used (GJ/ha)	Solar energy collected (GJ/ha)	Net energy (GJ/ha)
Canola	1.8[a]	25.0	6.3	11.3	45	**33.7**
Soybean	2.2[a]	23.8	3.2	7.0	52.4	**45.3**
Barley	2.8[a]	19.0	3.9	11.0	53.2	**42.3**
Winter Wheat	4.4[a]	18.7	2.9	12.8	82.3	**69.5**
Tame Hay	4.7[a]	17.9	1.0	4.7	84.1	**79.4**
Grain Corn	7.3[a]	18.8	2.9	21.2	137.2	**116.1**
Switchgrass	9	18.8	0.8	7.2	169.2	**162.0**

[a]OMAFRA, (2007)

net-energy gain per hectare than grain corn and five times more net-energy gain per hectare than canola. It also should be noted that corn yields are based on modern hybrid yields in Ontario while switchgrass yields are based on commercial production of the cultivar cave in-rock, an unimproved cultivar that was collected from an Illinois prairie in 1958. Warm season grasses (WSG's) function well as perennial energy crops because they mimic the biological efficiency of the tall-grass prairie ecosystem native to North America. They produce significantly more energy than grain corn while at the same time requiring minimal fossil energy inputs for field operations and less fertilizers and herbicides.

In industrialized countries, the seed portion of annual grain and oilseed crops became the first feedstock for energy applications. However, whole plant annual crops capture much larger quantities of energy per hectare. In Western Europe, whole plant crops such as maize and rye are now commonly harvested for biogas applications. High yielding hybrid forage sorghum, sorghum-sudangrass and millet, also hold promise as new candidates for biogas digestion (Von Felde, 2007; Venuto, 2007). The major advantage of ensiling is that even in relatively unfavourable weather for crop drying, energy crops can be stored and delivered to the digester year round. This is particularly advantageous for thick stemmed species like maize and sorghum which are commonly difficult to dry in areas receiving more than 700 mm of rainfall annually or have harvests late in the year when solar radiation is declining. In combustion applications, thick stemmed herbaceous species have biomass quality constraints which make them difficult to burn (further discussed in Section 16.3). In warm, humid southern production zones in temperate regions, it may also be difficult to dry the feedstock for combustion applications as the material would be more vulnerable to decomposition. In these situations, crop conversion to usable energy would be facilitated by using a biogas conversion system and storing the crop as silage.

Overall, both thick and thin stemmed whole-plant biomass crops can be successfully grown for biogas applications. Highest biogas yields are achieved when a fine chop and highly digestible silage are used. Conversely, thin stemmed, perennial WSG's have been identified as the most viable means to store dry crops for combustion applications and offer the best potential for improved biomass quality for

combustion (discussed further in Section 16.3). For liquid fuel production such as cellulosic ethanol, the process is more flexible in terms of the moisture content and chemical composition of the feedstock in the production of energy.

16.2.2 Options for Growing and Using Energy Crops for Energy Security in Industrialized Countries

As greater scarcity of fossil fuels occurs in the next 25–50 years, industrialized countries will undoubtedly seek greater energy security from renewable energy technologies (RET's). Countries will increasingly aim to develop bioenergy production and conversion technologies which are efficient at using energy crops grown on both productive and marginal farmland to displace the use of imported fossil fuels. North America, Europe, and China in particular, urgently need to develop effective bioenergy production systems as these areas will become increasingly dependent on importing fossil fuels due to their large economies and declining fossil energy production. While many industrialized countries have imported petroleum fuels from distant producers for many years, the international trade in natural gas use will expand substantially. For example in North America, domestic natural gas production peaked in the United States in 2001 and has declined by 1.7% per year since that time, while in Canada production has been in decline or reached a plateau since 2001. To compensate for declining North American gas production and rising prices, energy intensive natural gas industries have moved offshore and liquid natural gas (LNG) imports have started to come into the United States (Hughes, 2006). LNG imports currently supply approximately 3% of the United States supply and are expected to increase to 15–20% by 2025. Much of this natural gas demand is presently used in thermal applications. For example, the United States relies on natural gas for 20% of its power requirements and for 60% of its home heating requirements (Darley, 2004).

Identifying sustainable bioenergy technologies with a high net energy gain per hectare is essential to reduce imports of natural gas and other fossil fuels into industrialized countries. In particular, there may be opportunities to cost-effectively produce solid and gaseous biofuels in temperate regions to replace high quality fossil fuels in thermal applications. In the past 5 years, petroleum and natural gas prices have increased substantially while thermal coal prices in the world have remained relatively stable. This likely is a function of the changing awareness around supply and demand of fossil fuels. On a global basis, the lifespan of natural gas and oil reserves are less than half that of coal, however many energy analysts foresee a transition from the current global energy economy dominated by petroleum to one where natural gas plays an equally important role. This widening gap between the prices of high-quality fossil fuels like natural gas and petroleum versus coal will make fuels of higher quality ideal candidates for displacement by renewables. Solid and gaseous biofuels could substitute in thermal applications through both heat generation and combined heat and power operations. This is a fitting association as both biomass production and heat demand are relatively disperse, thus biomass could be

produced locally to meet local thermal energy needs sustainably. A key tenet of the concept of the *soft energy path* introduced by Lovins (1977) is that both the scale and quality of energy should be matched appropriately with its end use to create a more sustainable energy supply system.

The growing price difference between coal, natural gas and heating oil suggests that high-quality fossil fuels will be increasingly utilized for high-quality end uses such as transportation fuels and industrial products while lower-quality fuels like coal will be increasingly used for low-end thermal applications. Due to the polluting nature of coal and the increasing emphasis on reducing carbon emissions through taxes and cap and trade systems, there also will be substantial opportunities for biomass to substitute for coal in thermal applications (discussed further in Section 16.2.3). The following section explores the thermodynamics around converting biomass into solid and gaseous products versus their present utilization opportunities as liquid fuels in temperate regions of the world.

16.2.2.1 Opportunities to use Ontario Farmland for Improving Energy Security

This analysis examines present or currently proposed strategies to use biomass derived from farmland in the province of Ontario for generating solid, gaseous and liquid biofuel products. Ontario has a continental climate and cropping patterns that are somewhat similar to other regions in the temperate world including the Great Lake states of Michigan and Wisconsin in the United States, countries in central Europe such as Hungary, and the Northeastern provinces of China. As such, it represents a useful case study for the bioenergy opportunities for continental climates in the temperate world. Ontario produces very limited quantities of fossil fuels. Coal and coal products in Ontario are primarily used for power generation and for large industrial applications, such as the steel and cement industry. Petroleum products are mainly used in the transport sector in Ontario, with some additional use as heating oil. Ontario imports natural gas from western Canada, petroleum from the world market, and coal mainly from the Northeastern United States. Within the next 2–5 years, two LNG terminals on Canada's east coast will begin supplying eastern Canadian energy user's imported liquefied natural gas from either Russia or producers in the Middle East. Declining western Canadian supplies will likely not be sufficient to enable export production to reach Ontario in the coming years. Thus the Ontario economy, which is heavily dependent on natural gas for residential and commercial heating applications and process heat for industry and power generation, will begin to rely on distant foreign natural gas resources.

16.2.2.2 Harvesting Energy from Ontario Farmland for Biofuel Applications: A Case Study

To optimize energy security and GHG mitigation potential from bioenergy, a case study has been developed to compare alternative bioenergy crops and conversion

technologies in Ontario. The comparison crops include soybean, corn, corn silage and switchgrass, which are well adapted to Ontario's warm continental climate summer. The main agricultural zones in the province experience a frost free period typically from mid May to mid to late Sept and about 900 mm of annual precipitation. Soybean, corn and corn silage are commonly grown in Ontario while switchgrass and other native warm season grasses such as big bluestem and coastal panic grass are emerging crops that are native to the region. Switchgrass has been selected to represent the WSG's in the analysis as it has undergone the furthest development of all native grasses for energy use in North America. In Ontario, approximately 500 ha of native grasses are presently under bioenergy production in 2007. It is anticipated that a portfolio of warm season species will be developed as future energy crops, with mixed seedings encouraged to reduce production risks and enhance biodiversity.

As can be seen from Table 16.2, the dry matter production potential prior to processing is highest with the whole corn plant harvested as silage. Switchgrass also produces significant quantities of dry matter and has the added advantage of being able to be grown on marginal farmlands. The yields for switchgrass are estimated to be slightly lower for combustion applications as a delayed harvest technique is used (discussed further in Section 16.3). The net energy gain/ha that results from each energy crop and conversion process is generally highest where whole-plant biomass is used for biogas or bioheat, and lowest where the seed portion of annual crops is used for liquid fuels. From a net energy gain perspective, the two most promising systems for Ontario are corn silage biogas and switchgrass pellets. These technologies have the potential to produce 770–890% more net energy gain/ha than growing grain corn for ethanol. Cellulosic ethanol from grasses is much more efficient than other annual grain or oilseed liquid fuel options for producing net energy gain/ha. However it remains substantially less efficient than direct combustion of energy grasses or corn silage biogas as a means to produce energy from farmland. The energy balance and GHG studies cited in the Tables (16.2 and 16.3), largely omit a full accounting of energy use. For example energy inputs associated with plant construction are generally not included and if these energy inputs were included the results would be less favourable especially for the more capital intensive technologies such as corn and cellulosic ethanol. Bioheat from pellets has a much lower capital investment requirement per unit of renewable energy produced (Bradley, 2006; Mani et al., 2006) and as such a full life cycle analysis would have less impact on its energy balance.

The main problem of cellulosic ethanol is that, even with current technology, less than half of the energy in the original feedstock is recovered in the ethanol. This analysis illustrates that upgrading the energy quality of biomass from a solid form to a liquid form appears to be quite expensive thermodynamically. While advances in cellulosic ethanol technology can be expected in the coming years, the prediction of a technology that would be cost-competitive at $1.00/gallon with gasoline by the year 2000 (Lynd et al., 1991), was and remains far from reality. There are currently no commercial cellulosic ethanol plants using agricultural feedstocks in existence despite the generous subsidies for ethanol production available in North America.

Table 16.2 Harvesting Energy from Ontario farmland for biofuel applications: A case study comparing alternative bioenergy crops and conversion technologies in Ontario

Feedstock	Field Yield[a] (tonnes/ha)	Field Yield[b] (ODT/ha)	Losses (%)[c] H = Harvest S = Storage D = Densification	Net Yield (ODT/ha)	Energy Content of feedstock[d] (units)	Total Energy Production (unit/ha)	Conversion[e] (GJ/unit)	Gross Energy (GJ/ha)	Energy Used in Production[f] (GJ/ha)	Net Energy Gain (GJ/ha)
Biogas (Anaerobic Digestion)										
Corn Silage	–	15.6	15% (H/S)	13.3	500 m³/ODT biogas	6625 m³ biogas	0.0232 GJ/m3	153.7	31.0	**122.7**
Perennial Grass Energy Crops	–	10	20% (H/S)	8.0	400 m³/ODT biogas	3200 m³ biogas	0.0232 GJ/m3	74.2	13.0	**61.2**
Bioheat (Direct Combustion)										
Grain Corn	8.6	7.3	–	7.3	18.8 GJ/ODT Heat	137.2 GJ Heat	–	137.2	21.2	**116.0**
Switchgrass Pellet	–	10	18% (H/D)	8.2	18.8 GJ/ODT Heat	154.2 GJ Heat	–	154.2	12.0	**142.2**
Biofuels										
Grain Corn Ethanol	8.6	7.3	–	7.3	473 L/ODT ethanol	3452.9 L ethanol	0.021 GJ/L	72.5	56.6	**15.9**
Switchgrass Cellulosic Ethanol	–	10	5% (H/S)	9.5	340 L/ODT ethanol	3230 L ethanol	0.021 GJ/L	67.8	15.3	**52.5**

Table 16.2 (Continued)

Feedstock	Field Yield[a] (tonnes/ha)	Field Yield[b] (ODT/ha)	Net Yield (ODT/ha)	Losses (%)[c] H = Harvest S = Storage D = Densification	Energy Content[d] of feedstock (units)	Total Energy Production (unit/ha)	Conversion[e] (GJ/unit)	Gross Energy (GJ/ha)	Energy Used in Production[f] (GJ/ha)	Net Energy Gain (GJ/ha)
Soybean Biodiesel	2.6	2.2	2.2	–	224 L/ODT biodiesel	492.3 L biodiesel	0.03524 GJ/L	17.3	6.8	**10.6**

a Corn and soybean yield is 5 year (2002–2007) average in Ontario (OMAFRA, 2007)

b Assuming that corn grain yield is 47% of total plant yield (Zan, 1998), silage corn field yield is equivalent to 7.3 ODT/ha x 2.13 = 15.6 ODT/ha
10 tonne/ha is average of fall and spring field yields in Ontario (Samson, 2007, Samson et al., 2008b)
Ontario's 5 year average soybean yield is 2.6 tonnes per hectare (at 13% moisture content) which results in 2.2 ODT/hectare.

c Harvest and storage losses for corn silage are 15% (Roth and Undersander, 1995)
Harvest and storage losses for energy grass silage production are estimated at 20% (Manitoba Agriculture, Food and Rural Initiatives , MAFRI)
Harvesting, storage and densification losses for switchgrass pellets are estimated to be 18% of field biomass of mature crops (Girouard et al., 1998; Samson et al. 2008b), net yields of 8.2 t/ha can be considered an average of productive and marginal farmlands.
Fall harvesting losses and storage losses for switchgrass used for cellulosic ethanol are estimated to be 5% (Sanderson et al., 1997)

d Corn silage yields 400–600 m³/tonne (dry matter basis) biogas (Braun and Wellinger, 2005; López et al., 2005)
Grass silage yields 350–450 m³/tonne (dry matter basis) biogas (De Baere, 2007; Berglund and Börjesson, 2006; Mähnert et al., 2005)
Grain corn has an energy content of 18.8 GJ/ODT (Schneider and Hartmann, 2005)
Switchgrass has an energy content of 18.8 GJ/ODT (Samson et al., 2005).
Corn ethanol yields 473 L/ODT (Farrell et al., 2006)
Switchgrass ethanol yield is estimated at 340 litres per ODT (Spatari et al., 2005; Iogen Corporation, 2008)
Soybean biodiesel yields 224 L/ODT (Klass, 1998)

e Biogas energy = 0.0232 GJ/m3 (Klass, 1998).
Ethanol energy = 0.021 GJ/litre (Klass, 1998; Smith et al., 2004)
Electrical energy = 0.0036 GJ/kWh (Klass, 1998)
Methyl ester soybean biodiesel = 0.03524 GJ/litre (Klass, 1998)

f Biogas

The energy used in the production of the corn silage biogas equals the gross methane energy consumed to warm the digester, methane leakage, and the energy used in production and conversion. The methane consumed to warm the digester is 3.5% (Gerin et al., 2008) of the original gross methane produced (3.5% of 153.7 GJ/ha = 5.4 GJ/ha). The energy used in corn silage production and biogas conversion is equivalent 25.6 GJ/ha, this assumes energy production to produce corn silage is the same as corn production in Ontario at 20.59 GJ/ha (see grain corn estimate below), 1% methane leakage (1% of 148.3 = 1.5 GJ/ha (Zwart et al., 2007)), plus 2.5% of energy used for biodigester processing (Gerin et al., 2008) (2.5% of 148.3 GJ/ha = 3.7 GJ/ha). Total input is 5.4 + 25.6 = 31.0 GJ/ha.

The energy used in the production of the switchgrass silage biogas equals the gross methane energy consumed to warm the digester plus the energy used in production and conversion. The methane consumed to warm the digester is 3.5% (Gerin et al., 2008) of the original gross methane produced (3.5% of 74.2 GJ/ha = 2.6 GJ/ha). The energy used in switchgrass production and biogas conversion is equivalent 10.4 GJ/ha, comprised of 7.9 GJ/ha for switchgrass production (Samson et al., 2000), 1% methane leakage (1% of 71.6 = 0.7 GJ/ha (Zwart et al., 2007)), plus 2.5% (Gerin et al., 2008) of energy used for biodigester processing (2.5% of 71.6 GJ/ha = 1.8 GJ/ha). Total input is 2.6 + 10.4 = 13 GJ/ha.

Bioheat

The energy input for corn production in Ontario has been estimated to be 2.9 GJ/ODT (Samson et al., 2005) which assuming a field yield of 7.3 ODT/ha equals 21.17 GJ/ha.

The energy input for switchgrass pellets is 12 GJ/ha, based on field energy inputs of 7.9 GJ/ha and 4.1 GJ/ha for pellet processing and marketing (Samson et al., 2000).

Biofuels

The energy output:input ratio for corn ethanol is 1.28:1 (Wang et al., 2007), this results in an energy input of 72.5/1.28 = 47.9 GJ/ha.

The energy output:input ratio switchgrass cellulosic ethanol is 4.44 (average of Lynd, 1996; Sheenan et al., 2004; Lynd and Wang, 2004), this results in an energy input of 67.8/4.44 =15.3 GJ/ha.

The energy output:input ratio for soybean biodiesel is 2.56:1 (average from Hill et al., 2006, and Sheenan et al., 1998), this results in an energy input of 17.3/2.56 = 6.8 GJ/ha.

Table 16.3 Net GHG offsets from various bioenergy technologies through fuel switching applications for fossil fuels in Ontario, Canada

Fossil Fuel Traditional Use		Renewable Alternative Fuel Use		Net offset emissions including N_2O	
Energy Type	$kgCO_{2e}$/GJ	Energy type	$kgCO_{2e}$/GJ	($kgCO_{2e}$/GJ)	%[h]
Gasoline Transport	99.56[a]	Corn Ethanol	62.03[c]	21.13[h]	21
		Cellulosic Ethanol	23.40[b]	76.16[b]	77[g]
Diesel Transport	98.54[a]	Soybean Biodiesel	36.36[d]	49.73[h]	50
		Canola Biodiesel	28.77[d]	57.09[h]	58
Coal	93.11[a]	Switchgrass Pellets	8.17[e]	84.94	91
		Wood pellets	13.14[f]	79.97	86
		Straw pellets	9.19[f]	83.92	90
Heating Oil	87.90[a]	Switchgrass Pellets	8.17[e]	79.73	91
		Wood pellets	13.14[f]	74.76	85
		Straw pellets	9.19[f]	78.71	90
Liquefied Natural Gas	73.69[i]	Switchgrass Pellets	8.17[e]	65.52	89
		Wood pellets	13.14[f]	60.55	82
		Straw pellets	9.19[f]	64.5	88
Natural Gas	57.57[a]	Switchgrass Pellets	8.17[e]	49.40	86
		Wood pellets	13.14[f]	44.43	77
		Straw pellets	9.19[f]	48.38	84

[a]Natural Resources Canada, (2007)

[b]Emissions estimated from cited GHG savings

[c]EIA, (2006)

[d](S&T)^{2}Consultants Inc., (2002)

[e]Samson et al., (2000)

[f]Jungmeier et al., (2000)

[g]Average from Wang et al., (2007), and Spatari et al., (2005)

[h]Samson et al., (2008a)

[i]LNG imported from Russia into North America estimated to have 28% higher GHG emissions then North American NG production due to methane leakage and energy associated with Russian pipelines, LNG liquification, ocean transport and heating during re-gasification (Heede, 2006; Jaramillo et al., 2007; Uherek, 2005)

Biogas production from energy crops represents a more thermodynamically efficient option than converting plant matter into liquid fuels. Considering the case of corn silage, 500 m^3 of biogas can be produced from one tonne of feedstock (Table 16.2) which is equivalent to 11.6 GJ/ODT or 61.7% conversion efficiency. In contrast with current projected cellulosic ethanol product yields of 340 l of ethanol (Iogen Corporation, 2008), 7.1GJ/tonne of energy is recovered, a 38% conversion efficiency. In Germany, there has been significant scale-up of energy crops grown for biogas applications. In 2006, there were an estimated 3500 biogas digestors in the country that were mainly operating on energy crops such as corn silage, rye silage, and perennial grasses as well as manure and food processing wastes (House et al., 2007).

Some of the main problems facing the cellulosic ethanol industry are: (1) a chronic underestimation of feedstock procurement costs required by farmers in industrialized countries to make the technology viable on a large-scale; and

(2) projected commercial plant construction costs have risen dramatically, especially those for stainless steel and skilled labour costs. The economics now favour larger plants, with most plants foreseen to have a feedstock requirement of one million tonnes per year or more. Considering the increasing depletion of fossil energy resources in industrialized countries projected for the future, it may be difficult for such large amounts of affordable biomass to be procured and transported to bioethanol plants, especially when they are competing with local biogas and bio-heat plants that are more thermodynamically efficient and have significantly lower processing and transport costs. A centralized biogas digester producing 3 MW of thermal energy or a 50,000 tonne per year bioheat pellet plant have much smaller land area footprints than a 700,000 tonne per year cellulosic ethanol plant. The land area to be planted, based on the switchgrass yields in Table 16.2, would be 6000ha and 75,000ha for a switchgrass pellet and cellulosic ethanol plant respectively. If 1 in 4 ha surrounding the cellulosic ethanol plant was planted to switchgrass, the plants feedstock supply would be drawn from a land area covering 300,000 ha and stretch out a radius of 310km from the plant. The economic premium offered to produce liquid biofuels as a substitute for gasoline may not be sufficient to recover the large thermodynamic loss required for production and conversion of solid plant matter into liquid fuel in these large biorefineries. It is, by comparison, more efficient to use whole-plant biomass in pellet or biogas form to substitute for natural gas. As such, in temperate regions of industrialized countries, which are densely inhabited and have high local demands for heat and power, bioheat and biogas are the technologies likely to succeed if there is any level of parity in the government incentives applied to bioheat, biogas and liquid biofuels.

16.2.3 Greenhouse Gas Mitigation from Bioheat and Other Biofuels Options

With increasing concern about global climate change, it is of paramount importance that cost-effective emission reduction strategies evolve from producing bioenergy from farmland in industrialized countries. Efforts to import biofuels from tropical countries to date have resulted in rapid deforestation of native forests for palm oil production, particularly in Malaysia and Indonesia. Sugar cane cultivation for ethanol production is now expanding into traditional grazing lands in countries like Brazil, causing the cattle industry to expand into tropical forests. While certification systems may evolve for sustainable importation of tropical biofuels into industrialized countries, it is essential that effective domestic strategies are developed in industrialized countries to reduce the need for these imports. Developing nations in the tropics will themselves require large volumes of biofuels for their internal needs, further increasing the pressure on industrialized nations to become energy self-sufficient.

An important driver for the development of bioenergy will be the economic competitiveness of various technologies as greenhouse gas mitigation strategies. Thus,

it is important that the economics of various solid and liquid biofuels options be compared. There are several factors which are fundamental to the economic competitiveness of various agricultural biomass production and conversion chains to reduce greenhouse gases effectively including:

1. optimizing the amount of energy produced from each hectare of marginal and arable farmland (explored in Section 16.2 above);
2. the net GHG offset provided by displacing a GJ of fossil fuels used for a particular application with a renewable energy for the same application (fuel switching); and
3. the cost of production of the processed bioenergy product relative to the fossil fuel it is displacing.

The net offsets from various bioenergy technologies through fuel switching applications for fossil fuels in Ontario, Canada are summarized in Table 16.3. The net GHG offsets are highest with switchgrass pellets (86–91%), moderate with soybean biodiesel (50% offset) and low with corn ethanol (21%). The low GHG offsets from corn ethanol is confirmed by two recent analyses in the United States which determined the GHG offset potential of corn ethanol to be 15% (Farrell et al., 2006) and 19% (Wang et al., 2007) respectively in the current state of the industry.

The reason for the high offset potential of switchgrass pellets is that they require modest amounts of energy for switchgrass feedstock production and pellet processing. As well there is no change of physical state that occurs, so nearly all of the energy content of the grass is available in a pellet form. Switchgrass production also has no significant landscape emissions as N_2O emissions are low for perennial grasses and the soil carbon sequestered is expected to offset the low amounts of N_2O emissions that occur (Adler et al., 2006). Soybean biodiesel (or canola biodiesel) represents a moderately efficient offset potential because the liquid fuel production process is not energy intensive and the crop has moderate energy inputs and N_2O emissions in North America (Samson et al., 2008a). Each GJ of soybean biodiesel produced displaces approximately half the GHG emissions of diesel fuel. However it still represents a largely ineffective approach to mitigate greenhouse gasses from farmland in temperate regions, as the soybean yield is low and the oil content in the soybean seed is low. With soybean oil being a high quality vegetable oil selling for premium prices in 2007–2008 around $1000/tonne, biodiesel is far from being an economically viable biofuel unless heavily subsidized.

The reasons for the low offset potential of corn are: (1) the technology relies heavily on carbon intensive fuels such as coal and natural gas for processing; (2) corn is an energy intensive annual crop to produce; (3) there are relatively high N_2O losses from each hectare of corn production, which has a strong impact on overall emissions; and (4) comparatively low amounts of energy are captured in the field and converted into a final energy product. In the province of Ontario, Canada, the combined federal and provincial incentives in 2007 amounted to 16.8 cents per litre of ethanol produced (or $8.00 CAN/GJ assuming an energy value of 0.021GJ/litre). With only 21.13 kg CO_{2e} offsets per GJ of fuel, it takes 47.3 GJ of ethanol to offset one tonne of carbon dioxide. This is equivalent to a subsidy of $379 (CAN) (Samson

et al., 2008a) (1 \$CAN = \$1 USD in October 2007). Even larger federal and state subsidies are available for promoting corn ethanol production in certain states in the United States.

The main advantage of cellulosic ethanol from switchgrass over corn ethanol is that the heat and power for plant processes are provided by lignin, a by-product in cellulosic ethanol processing. Cellulosic ethanol results in a moderately high offset potential of 76.5% compared to the use of gasoline. Nevertheless this use of lignin causes a parasitic impact on the net GHG mitigation per ha that can be provided in comparison to using the grass for other bioenergy applications. With relatively modest volumes of energy recovered from each tonne of biomass of 340 l ethanol/tonne, the technology on a per hectare basis represents only a moderately efficient approach at using farmland to mitigate greenhouse gases. The technology can be best categorized as having a medium energy output per hectare and a moderate to high GHG offset when displacing fossil fuels. Overall, Table 16.4 illustrates that using Ontario farmland to produce switchgrass ethanol has the potential to offset approximately 5,164 kg CO_{2e}/ha tonnes of GHG emissions. It is significantly superior to corn ethanol and soybean biodiesel if current commercialization problems can be overcome.

From Table 16.4, it can be observed that corn ethanol and soybean biodiesel cannot be considered effective greenhouse gas mitigation policies with less than 1,500 kg CO_{2e}/ha offsets. Per hectare, corn ethanol has modest energy production and poor net GHG offsets, while per hectare soybean biodiesel has a poor liquid fuel output and only a moderate GHG offset. This analysis demonstrates that solid biofuels represent a highly promising means for Ontario to mitigate greenhouse gases, particularly compared with liquid fuel options. Figure 16.1 graphically represents these findings.

The advanced boiler technology currently available to burn pellets offers the same combustion efficiency as natural gas combustion appliances (Fiedler, 2004). When switchgrass pellets are used to displace coal, the highest overall GHG displacement potential can be achieved at 13,098 kg CO_{2e}/ha. The lowest GHG

Table 16.4 Evaluation of different methods of producing GHG offsets from Ontario farmland using biofuels

Feedstock	Gross Energy (GJ/ha)	Fossil Fuel Substitution	Net GHG emission offsets kgCO$_2$e/GJ	Total GHG emission offsets kgCO$_2$e/ha
BioHeat				
Switchgrass Pellets	154.2	Coal	84.94	**13098**
Switchgrass Pellets	154.2	Heating Oil	79.73	**12294**
Switchgrass Pellets	154.2	Liquefied Natural Gas	65.52	**10103**
Switchgrass Pellets	154.2	Natural Gas	49.4	**7617**
Biofuels				
Switchgrass Cellulosic Ethanol	67.8	Transport gasoline	76.16	**5164**
Grain Corn Ethanol	70.6	Transport gasoline	21.13	**1492**
Soybean Biodiesel	18.2	Transport diesel	49.73	**905**
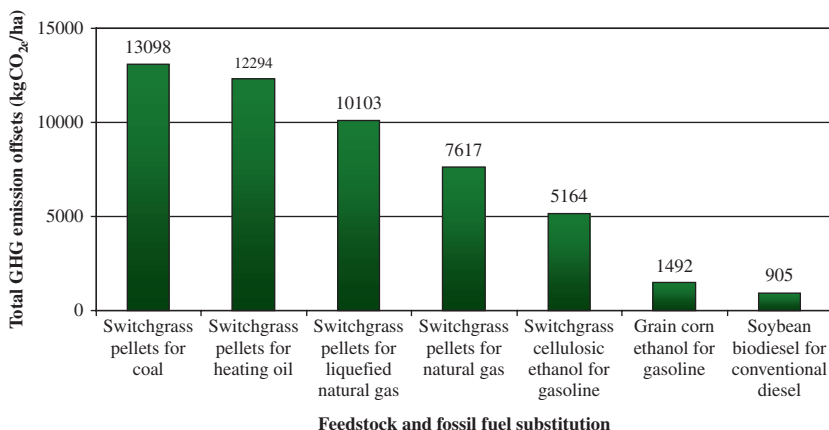
Fig. 16.1 Evaluation of different methods of producing GHG offsets from Ontario farmland using biofuels

emission potential of switchgrass pellets is at 7,617 kg CO_{2e}/ha when they are used to displace natural gas. When switchgrass pellets replace imported LNG from Russia, approximately 10 tonnes of CO_{2e}/ha is abated. From Ontario's perspective, an effective policy strategy for GHG mitigation would clearly be to replace foreign imports of LNG and coal with domestically produced pellets within the province. A \$2(CAN)/GJ incentive for switchgrass pellet producers would cost an average of \$24, \$31 and \$40/tonne of CO_2 offset to displace the use of coal, liquefied natural gas and conventional gas, respectively. In contrast, Ontario has combined federal and provincial wind energy incentives of \$15.28/GJ (6.5 cents/kWh), soybean biodiesel incentives of \$5.68/GJ (20 cents/L) and corn ethanol incentives of \$8.00/GJ (16.8 cents/litre). The corresponding costs of these offsets are \$50, \$98 and \$379/tonne CO_{2e} for wind, biodiesel and corn ethanol, respectively (Samson et al., 2008a). Two other recent studies also found that with carbon taxes under \$100/tonne, bioheat is considerably less expensive GHG offset strategy than producing liquid fuels in temperate regions (Grahn et al., 2007). To create more effective use of taxpayers' money in reducing GHG emissions, policy makers need to understand the offset potential of the various technologies and create mechanisms to allow GHG reduction to happen competitively within the marketplace.

Another problematic example exists with energy crop use for biogas systems, which is currently strongly supported as a RET in Germany. Energy crop biogas systems appear to be facing several challenges in being an efficient GHG mitigation technology. Few detailed studies have been completed but there appears to be some identified limitations. When examining only energy related GHG emissions, power generation from energy crop biogas is a highly effective GHG mitigation technology compared to using fossil fuels for power production (Gerin et al., 2008). However, two GHG emission problems have been identified with energy crop biogas for power generation which are methane leakage from digesters (estimated at 1%) and the

high N_2O emissions associated with maize cultivation (Crutzen et al., 2007). In one preliminary study from Western Europe there was no net GHG benefit from maize silage biogas because of these two aforementioned problems (Zwart et al., 2007). It is likely the use of deeper rooted and more nitrogen efficient annual crops such as sorghum or perennial species such as highly digestible warm season grasses may help reduce GHG emissions from feedstock production. As well, energy crop cultivation in less humid regions would reduce the N_2O loss problem. New design features of digesters and larger centralized biogas digesters may help reduce methane losses that are currently occurring. Energy crops used in biogas digesters in the future will likely play an important role in providing GHG friendly thermal energy for combined heat and power applications. However, presently only manure biogas digesters have been found to have positive impacts on GHG mitigation (Zwart et al., 2007). If governments created incentives for RET's based on their actual GHG mitigation efficient approaches to reduce emissions would be likely be stimulated and more efficient progress in mitigating GHG's would be realized through bioenergy technologies.

16.3 Optimization of Energy Grasses for Combustion Applications

From the previous analysis it is evident growing energy grasses for bioheat represents the most outstanding option for using one hectare of farmland to produce renewable energy and mitigate GHG's from an agricultural production system. If energy crop grasses are to evolve as a major new RET for energy security and GHG abatement for the industrialized world, it is imperative that considerable research and development efforts to expand this opportunity be undertaken. Historically, the major limitation to the development of grasses for bioheat applications has been the difficultly associated with burning energy grasses efficiently in conventional biomass boilers. In particular, the relatively high alkali and chlorine contents of herbaceous plants are widely known to lead to clinker formation and corrosion of boilers. These biomass quality problems have resulted in slow commercialization of grass feedstocks as agro-pellets for use in small scale boilers (Elbersen et al., 2002; Obernberger and Thek, 2004). Despite this, the problems with burning grasses have now become reasonably well understood and constraints are being resolved through several strategies. Plant selection and breeding together with delayed harvest management can be used to reduce the chlorine, alkali and silica content in native grasses, reducing clinker formation and corrosion in boilers. Utilizing advanced combustion systems which are specifically designed to burn high-ash; herbaceous fuels can also reduce problems with ash accumulation in burners (Obernberger and Thek, 2004). However, high-ash fuels can still pose major convenience issues, particularly when used in pellet stoves and small scale boilers. Strategies to lower the ash content and the undesirable chemical elements in grasses are essential if commercial markets are to be fully developed.

16.3.1 Improving Biomass Quality for Combustion

The most serious biomass quality problem with herbaceous feedstocks is the alkali and chlorine content in the feedstock material, which has potential for fouling and corroding boilers during combustion (Passalacqua et al., 2004). Particulate emissions are strongly related to fuel type, and specifically, to the content of aerosol-forming compounds such as potassium (K), chlorine (Cl), sodium (Na), sulphur (S) and even lead and zinc in the fuel (Hartmann et al., 2007). Using fuels that are low in the "dust critical" elements K, Cl, Na and S is of particular importance for achieving high-quality biomass fuels and lowering particulate emissions during biomass combustion. The major factors affecting the level of aerosol-forming compounds are fertilization practices, choice of species, stem thickness, time of crop harvest, relative maturity of the cultivar, and the level of precipitation in a region (Samson et al., 2005; Samson, 2007). Chlorine is particularly problematic as it increases the ash-sintering effect of fuels containing potassium and makes these elements migrate from the fuel bed to the boiler walls, forming clinkers (Godoy and Chen, 2004). The nitrogen content of feedstocks has little impact on the efficiency of the combustion process but burning high-N fuels is undesirable from an environmental standpoint as this contributes to NO_x pollution. However, delayed harvest switchgrass has relatively low N contents that are comparable to wood (Samson et al., 2005; Adler et al., 2006). Reducing the moisture content of feedstocks to below 15% is also important as this eases storage problems from decomposition and can reduce or even eliminate the need to dry materials before pelletizing them.

16.3.1.1 Nutrient Management

Both potassium and chlorine are known to be effectively leached out of thin-stemmed grasses in humid climates. As potassium is water soluble, the potassium content in plants can decrease appreciably following senescence of materials during the end of growing season, particularly if significant rainfall occurs during this period. Prairie ecology studies have also demonstrated that potassium in unharvested material is efficiently recycled into the soil over the late fall and winter (Koelling and Kucera, 1965; White, 1973). Kucera and Ehrenreich, (1962) in Missouri found potassium content of native prairie plants to decline from 1.34% K_2O in mid-June, to 0.63% by mid-September, and to 0.05% by the end of November. Koelling and Kucera (1965) found the average potassium content of big bluestem in the Missouri prairies to decrease from 1.28% K_2O in July, to 0.33% in September, and to 0.13% in November. Over-wintering further reduced levels to 0.07% by May the following year. It is also of interest to note that native prairie materials likely have significantly earlier maturity dates (and hence time for fall leaching) than purpose grown energy grasses. In Quebec, Cave-in-Rock switchgrass harvested in early October was found to contain 0.95% potassium, while over-wintered switchgrass harvested in mid-May was found to contain just 0.06% potassium (Goel et al., 2000). In the case of potassium, it appears that harvesting in the fall at least several weeks after materials senesce, or alternately harvesting over-wintered material, provides significant

reductions in the potassium content of feedstocks. Chlorine is also highly water soluble in herbaceous biomass feedstocks (Sander, 1997). Like potassium, the chlorine content of perennial grass feedstocks is reduced if a late-season or overwintering harvest management regime is practiced. Burvall (1997) found an 86% reduction in chlorine content of reed canarygrass when it was over-wintered in Sweden.

16.3.1.2 Harvest Management and Cultivar Selection

Despite the benefits that overwintering can provide, letting grasses remain unharvested through the winter can also reduce the eventual biomass yield obtained in the spring. In Southwestern Quebec, spring-harvested switchgrass yields were found to be approximately 24% lower than that of fall-harvested switchgrass (Goel et al., 2000). This loss was due likely to both the late season translocation of materials to the root system in winter (Parrish et al., 2003), and the physical loss of material, mainly from leaves and seed heads during the winter season (Goel et al., 2000). Compared to fall harvested material, spring-harvested switchgrass lost 4% of dry matter from the stem component, 11% from leaf sheaths, 30% from leaves and 80% from seed heads (Goel et al., 2000). Field observations have indicated that when the material is completely dry in late winter and early spring, the majority of breakage losses occur during storm events. As well, some decomposition occurs in the field when material lodges in late summer and early fall and plants come into contact with the soil.

A new delayed harvest technique was assessed in the spring of 2007 in Ontario by REAP-Canada (Samson et al., 2008b) to minimize winter breakage and spring harvest losses from feedstocks, while maintaining the benefits of nutrient leaching that are associated with overwintering. Under this system, the material is mowed into windrows in mid-November and directly baled off the windrow in the spring. Results to date are promising as yields were 21% higher than spring mowed and harvested material. The fall mowing technique also caused faster spring drying of windrowed material, but recovery of material below 10% moisture was achieved in early May in both systems. Finally, the fall mowing technique encouraged earlier soil warming and than spring mowed areas, promoting earlier regrowth of the switchgrass.

Selecting for increased stem and leaf sheath content and developing warm season grass varieties that more efficiently retain their leaves through the winter could help reduce overwintering losses. Another strategy that has proven effective to reduce potassium and chlorine content in feedstocks is to utilize earlier-maturing warm season grass varieties that senesce earlier in the fall (Bakker and Elbersen, 2005). Early maturity enables a more extended period between senescence and late fall harvest for nutrients to be leached from the stem material. Thin stemmed grasses have also been identified to have higher nutrient leaching potential compared than thicker stemmed grasses. Lowland switchgrass cultivars with tall, moderately coarse stems, such as Alamo and Kanlow have been found to be moderately higher in K and Cl than upland switchgrass with short, fine stems at the end of the season (Cassida et al., 2005). The average outer diameter of lowland ecotypes of

switchgrass has been found to range from 3.5 mm (Igathinathane et al., 2007) to 5 mm (Das et al., 2004) and to have a stem wall thickness of approximately 0.7 mm (Igathinathane et al., 2007). The problem of biomass quality appears to be even more serious in miscanthus than switchgrass. Thick stemmed miscanthus ecotypes are known to have high potassium and chlorine contents, especially when combined with late maturity (Jørgensen, 1997). Comparatively, the average stem diameter of miscanthus is 8.8–9.2 mm, with a stem wall thickness of 1.3–1.5 mm (Kaack and Schwarz, 2001). No biomass quality reports from Europe could be identified which indicated miscanthus sinensis giganteus was able to reach the minimal biomass quality targets of 0.2% K and 0.1% chlorine for power generation in Denmark outlined by Sander (1997). Thick stems also make it more difficult to dry material. REAP-Canada identified that even in fall harvested upland switchgrass, while most plant components had moisture contents below 15%, the stems still tended to retain significant moisture (Samson et al., 2008b). Spring harvesting of material can enable bales to be collected below 12% moisture. The low moisture content of grasses at spring harvest is a significant advantage that grass energy crops hold over woody energy crops. The moisture content of willows at harvest for willows can be 50%. High moisture woody materials can use 21% of the raw material to provide energy for the drying process if made into pellets (Bradley, 2006). Spring harvested grasses thus have a major biomass quality advantage for pellet processing because of the dryness of the material.

Overall, grass pellets appear to represent the most promising solution to the strong international growth in demand for fuel pellets, a growth that cannot be met with supplies of wood residues forecast for the future. Many combustion issues have now been resolved in replacing wood pellets with grass pellets. Research indicates native warm-season grass pellets grown in North-eastern North America can approach a comparable content of aerosol forming compounds as that found wood residue pellets. However, the overall ash content of grass pellets typically remains considerably higher than wood. Wood residue pellets of highest quality are sold as premium grade when they achieve less than 1% ash. Typically, the European market trades wood pellets with 0.6% ash in this category (Obernberger and Thek, 2004). However, grasses harvested in North-eastern North America are generally in the 3-5% ash range (Samson et al., 2005). Even higher contents of ash are experienced in switchgrass growing regions with less favourable rainfall to evaporation ratios such as western Canada (Jefferson et al., 2004) and the Western United States (Cassida et al., 2005).

16.3.1.3 Impacts and Management of Silica

Silica levels in grasses must also be reduced if grass pellets are to enter into the high-end residential wood pellet market that currently has products trading in Europe at approximately $250/tonne. Producing fuels with lower silica levels has many benefits. Low silica containing fuels have higher energy contents, reduce abrasion on metal parts such as pellet dies during the densification processes, and improve convenience in reducing ash removal requirements. When burned in pellet appliances,

high-ash grass pellets with high silica contents can also produce a low-density ash that retains the shape of the former pellet. As an example, consider that the bulk density of reed canary grass ash has been assessed to be half that of wood ash (Paulrud, 2004). Thus the residual ash leftover after burning grass pellets in the 3–5% ash range can take up to 10–20 times the volume of the ash from burning 0.6% ash wood pellets. To burn 3–5% ash grass pellets, ash pans will need to be modified in smaller appliances to create larger ash collecting areas. Combustion units burning high-ash grass pellets will require more frequent cleaning and may experience increased operational problems such as automatic shutdown of the combustion appliance if the ash builds up into the combustion chamber. Conversely, silica is generally not a problematic element for commercial combustion boilers. Paulrud et al., (2001), working with reed canary grass, found that the relative content of K and Ca in the ash was more important for agglomeration and clinker formation than the silica content. High-ash agro-pellets (approximately 5% ash) with low to moderate levels of aerosol forming compounds are readily burned in most coal boiler technologies and greenhouse producers in Canada are now installing multifuel boilers capable of burning both coal and agro-pellets.

A comprehensive strategy will be required to reduce the silica content of grasses to make them more convenient for combustion applications and to improve their energy content. The understanding of silica uptake into the plant is improving amongst agronomists and plant breeders. The main cultural factors which appear to have potential to reduce the silica content are: soil type, production region, photosynthetic cycle of the biomass crop and the choice of grass species and variety. The main breeding strategies to reduce silica content include increasing the stem to leaf ratio of the species and reducing silica transport into the plant. As well, fractionation of plant components can help create lower silica containing feedstocks.

The translocation and deposition of silica in plants is heavily influenced by the soluble levels of silica in the soil, present as monosilicic acid or $Si(OH)_4$ (Jones and Handreck, 1967). Clay soils have higher monosilicic acid levels than sandy soils, and therefore produce feedstocks with higher silica levels. A Scandinavian study found silica levels in reed canarygrass to be highly influenced by soil type; reed canarygrass had silica levels of 1.3%, 1.9% and 4.9% on sandy, organic, and clay soils, respectively (Pahkala et al., 1996). In Denmark, high silica contents in wheat straw were strongly correlated with clay contents of soils (Sander, 1997). A main difference in silica content between perennial grass species can also be the photosynthetic mechanism of the grass and the amount of water being transpired by the plant. Warm season (C_4) grasses on average, use half as much water as C_3 grasses per tonne of biomass produced (Black, 1971). The decreased water usage reduces the uptake of silicic acid and decreases the ash content of the plant.

Within warm season grasses, water use per tonne of biomass produced is highest in regions which have a low rainfall to evaporation ratio, and where biomass crops are grown on marginal soils (Samson et al., 1993; Samson and Chen, 1995). A combination of these conditions may explain some of the higher values obtained by a survey from the United States reporting switchgrass ash contents of 2.8–7.6% (McLaughlin et al., 1996). Regions with a rainfall to evaporation ratio greater than

100% would be expected to have substantially lower ash contents than short grass prairie regions where the rainfall to evaporation ratio is 60%. This is illustrated in analysis from Quebec and Western Europe where silica levels of lower than 3% are commonly obtained in overwintered materials. Plant species have widely differing levels of silica. By comparing the speed of silica uptake with that of water uptake, three modes of silica uptake have been suggested by Takahashi et al., (1990). These modes are active (higher than water uptake), passive (similar with water uptake) and rejective (slower than water uptake). However, Van Der Vorm (1980), found no evidence of passive uptake. A gradual transition was found between metabolic absorption to metabolic exclusion which depended on the silica concentration. In all species examined, including 3 monocots (rice, sugar cane and corn), there was preferential absorption at low concentrations and exclusion at high concentrations (Van Der Vorm, 1980). As silica uptake by rice is significantly higher than other agronomic species, considerable efforts and achievements have been made in understanding and characterizing the process. This now has included molecular mapping studies of the silica transport mechanism (Ma et al., 2004). It may be possible that some reductions in the silica content of warm season grasses could be made in warm season grass breeding programs by reducing silica transport into the plant. It should however be noted that sugar cane and rice plant breeders are currently trying to increase the content of silica in these species because silica plays an important role in reducing plant stresses, increasing resistance to diseases, pests, and lodging, and decreasing transpiration (Ma, 2003).

Silica is mainly deposited in the leaves, leaf sheaths and inflorescences of plants (Lanning and Eleuterius, 1989). Lanning and Eleuterius (1987) working in Kansas prairie stands found switchgrass silica contents to be lowest in stems and higher in leaf sheaths, inflorescences and leaf blades. Silica levels are suggested to have evolved to be high in inflorescence structures to prevent the grazing of seed heads. Due to the low stem silica content, the overall silica concentration of grasses decrease as the stem content increases. Pahkala et al., (1996) examined 9 different varieties of reed canarygrass and found varieties to range from 2.3% to 3.2% silica content, with the lower silica containing varieties having a higher biomass stem fraction. Thus, selection for increased stem content is desirable for improving biomass quality for combustion purposes. This is demonstrated in Table 16.5 where stems had on average 1.03% ash and leaves had 6.94% ash. The impact of ash content on the energy content of the feedstock is evident as the leaves also contained approximately 6% less energy than stems. Stems contained on average 19.55 GJ/ODT which is 98% of the average energy content of high quality wood pellets of 20 GJ/ODT (Obernberger and Thek, 2004).

The differences in silica content between the various components of grasses has been known for more than 20 years. It also appears there are substantial inherent differences between the silica contents of warm season grass species. Two of the 3 main tallgrass prairie species in North America are big bluestem and switchgrass. The overall silica content of big bluestem may be amongst the lowest of the native North American grasses. In studies of plants harvested from a native prairie,

Table 16.5 Energy and ash contents (%) of spring harvested switchgrass (Samson et al., 1999b)

Component	Sandy Loam Soils Spring 1998	Clay Loam Soils Spring 1998	Average
Switchgrass Ash Contents (%)			
Leaves	6.20	7.67	6.94
Leaf sheaths	2.46	3.67	3.04
Stems	1.08	0.98	1.03
Seed heads	2.38	n/a	2.38
Weighted Average:	**2.75**	**3.21**	**2.98**
Switchgrass Energy Contents (GJ/ODT)			
Leaves	18.44	18.38	18.41
Leaf sheaths	19.19	18.27	18.73
Stems	19.41	19.69	19.55
Seed heads	19.49	n/a	19.49
Weighted Average:	**19.11**	**19.07**	**19.09**

relatively low silica contents of 0.29, 1.69, 2.08, and 2.89% were reported for the stems, leaf sheaths, inflorescences and leaves, respectively. In contrast, switchgrass averaged 1.03, 3.89, 3.41 and 5.04% for stems, leaf sheaths, inflorescences and leaves, respectively (Lanning and Eleuterius, 1987). As switchgrass is known to grow in wetter zones in the prairies, the higher levels of silica found may be a result of where the plants were collected within the prairie remnant. Big bluestem is known to have the additional advantage of having a high percentage of its dry matter in the stem fraction and a smaller inflorescence than native ecovars of switchgrass. Typically, the stem fraction of mature native big bluestem ecovars (e.g. cultivars not selected for forage quality) is approximately 60% of the above ground biomass, while in upland switchgrass ecovars the stem typically comprises 45–50% of the biomass in mature plants (Boe et al., 2000; Samson et al., 1999a). Further analysis of species and components of grasses as well as cultivars of grasses is required to more effectively understand how to reduce silica levels.

In the search for low silica herbaceous feedstocks for the pulp and paper industry, there has been considerable research and commercial development in Scandinavia on fractionation technologies to separate the low silica containing stems from the other plant components (Pahkala and Pihala, 2000; Finell et al., 2002; Finell, 2003). Several approaches to dry fractionation have been developed and integrated into commercial straw pulping facilities in Denmark (Finell et al., 2002). The basic process of disc mill fractionation developed by UMS A/S in Denmark is overviewed by Finell (2003) and includes keys steps of bale shredding with a debaler, hammer milling, disc milling, pre-separation (separating leaf meal and internode chips) and then a final sifting to further refine the accepted fraction of internode chips for pulping. In the case of reed canary grass, typically 40–60% of the plant could be recovered for pulping applications with the residual material used as a commercial pellet fuel (Finell, 2003).

This technology can also be applied to the fractionation of warm season grasses to developing fuels for use in the residential and commercial pellet markets. Fractionation of stems from species such as big bluestem would produce pelletized fuels in the range of 1% ash if the feedstock was grown on sandy soils in regions with a favourable rainfall to evaporation ratio. The higher-ash leaf, leaf sheath and inforescence material could then be used as a high-ash commercial pellet fuel for larger-scale thermal applications.

16.4 Outlook

This review supports other recent studies that have found energy crop development for thermal energy applications holds significant potential for industrialized nations as a means to create energy security and clean energy through GHG mitigation. From an energy security standpoint, it appears that the conversion of whole plant biomass from annual C_4 grasses into biogas or bioheat represent the most promising energy production technologies available. With current understanding of the GHG mitigation issue, direct combustion applications of perennial grasses to displace coal, natural gas and heating is the leading strategy to use farmland to mitigate greenhouse gases. The large N_2O emissions associated with the cultivation of corn in humid temperate climates impairs the effectiveness of corn as a feedstock to produce low GHG loading gaseous and liquid biofuels. In this respect, more research on N-efficient annual crops and higher digestibility perennial biogas species could help strengthen the GHG mitigation potential of biogas from energy crops in the future. In the case of bioheat from grasses, the research challenges ahead include the improvement of biomass quality to develop pellet fuels with low contents of silica and aerosol-loading elements.

Some of the largest hurdles to overcome in the emergence of second generation bioenergy technologies are not technological issues, but rather policy barriers. Governments have a major influence on which crops and technologies are scaled up for commercialization through the use of incentives or subsidy programs. It would be highly recommended to encourage policies to avoid picking technology winners in the development of energy security and greenhouse gas mitigation technologies from RET's. Rather, governments should encourage results-based management approaches to address policy issues and examine means to create parity in incentives in the green energy marketplace. This could include the creation of carbon taxes, green carbon incentives, CO_2 trading systems or incentives per GJ of energy produced. Both progressive policy and technology development need to be developed together for renewable energy to work for environmental protection and energy security in industrialized nations.

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