Biomass Energy Conversion

C.J. Kobus, Ph.D.

Thanks to Roger Samson (REAP-CANADA) for many of these slides

www.reap-canada.com
Biomass

- Biomass is any living organism, plant, animal, etc.
- $40 \times 10^{12} \text{ W}$ out of the $174,000 \times 10^{12} \text{ W}$ incident on the earth from the sun goes into photosynthesis
  - $0.023\%$
  - this is the fuel for virtually all biological activity
  - half occurs in oceans
- Compare this to global human power generation of $13 \times 10^{12} \text{ W}$, or to $0.6 \times 10^{12} \text{ W}$ of human biological activity
- Fossil fuels represent *stored* biomass energy
Photosynthesis

- Typical carbohydrate (sugar) has molecular structure like: \([\text{CH}_2\text{O}]_x\), where \(x\) is some integer
- Refer to this as “unit block”: \(\text{C}_6\text{H}_{12}\text{O}_6\) (glucose) has \(x=6\)

Photosynthetic reaction:
\[
x\text{CO}_2 + x\text{H}_2\text{O} + \text{light} \rightarrow [\text{CH}_2\text{O}]_x + x\text{O}_2
\]

\[
1.47 \text{ g} \quad 0.6 \text{ g} \quad 16 \text{ kJ} \quad 1 \text{ g} \quad 1.07 \text{ g}
\]

Carbohydrate reaction (food consumption) is photosynthesis run backwards
- 16 kJ per gram is about 4 Calories per gram
- Basically a “battery” for storing solar energy
Photosynthetic efficiency

- Only 25% of the solar spectrum is useful to the photosynthetic process
  - uses both red and blue light (reflects green), doesn’t use IR or UV
- 70% of this light is actually absorbed by leaf
- Only 35% of the absorbed light energy (in the useful wavelength bands) is stored as chemical energy
  - the rest is heat
  - akin to photovoltaic incomplete usage of photon energy
- Net result is about 6%
### Realistic photosynthetic efficiency

<table>
<thead>
<tr>
<th>Location</th>
<th>Plant Production (g/m² per day)</th>
<th>Solar Energy Conversion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Maximum</td>
<td>71</td>
<td>5%</td>
</tr>
<tr>
<td>Polluted stream (?!?)</td>
<td>55</td>
<td>4%</td>
</tr>
<tr>
<td>Iowa cornfield</td>
<td>20</td>
<td>1.5%</td>
</tr>
<tr>
<td>Pine Forest</td>
<td>6</td>
<td>0.5%</td>
</tr>
<tr>
<td>Wyoming Prairie</td>
<td>0.3</td>
<td>0.02%</td>
</tr>
<tr>
<td>Nevada Desert</td>
<td>0.2</td>
<td>0.015%</td>
</tr>
</tbody>
</table>
How much biomass is available?

Two estimates of plant production in book come up with comparable answers:

- $10^{17}$ grams per year
- 320 grams per $m^2$ averaged over earth’s surface
- consistent with $40 \times 10^{12}$ W photosynthesis

U.S. annual harvested mass corresponds to 80 QBtu

- comparable to 100 QBtu total consumption

U.S. actually has wood-fired plants: 6,500 MW-

- worth

in 1992, burned equivalent of 200,000 barrels of oil per day
# Bioenergy background

## Feedstocks
- Forest residue
- Black liquor
- Ag residues
- Grains
  - corn/soybeans/rapeseed
- Urban wastes
  - MSW, wood, cooking grease
- Energy crops
  - grasses
  - trees

## Energy forms
- Heat
- Power
- Fuels
  - ethanol
  - biodiesel
  - hydrogen
Biomass Feedstocks
Resource is Prevalent and Widespread

Wood Residues
- Sawdust
- Wood chips
- Wood waste
  - pallets
  - crate discards
  - wood yard trimmings

Agricultural Residues
- Corn stover
- Rice hulls
- Sugarcane bagasse
- Animal waste

Energy Crops
- Hybrid poplar
- Switchgrass
- Willow
Bioenergy use

2004 US Energy Consumption 105 EJ

- Oil: 42.8 EJ
- Nat gas: 24.8 EJ
- Coal: 21.8 EJ
- Nuke: 8.7 EJ
- Hydro: 3.0 EJ
- Bio: 3.0 EJ
- Renew: 2.9 EJ

2003 World Energy Consumption 470 EJ

- Oil: 162 EJ
- Nat gas: 98 EJ
- Coal: 98 EJ
- Renew: 55 EJ
- Fuelwood: 55 EJ
- Bio: 55 EJ
- Hydro: 27 EJ


- 4 EJ power & heat
- 8 EJ fuels
- 28 Tg of bio-based chemicals

World estimates of technical bioenergy potential based on IPCC land-use scenarios (M. Hooijwik et al. 2005)

<table>
<thead>
<tr>
<th></th>
<th>2000 all</th>
<th>2050 Biobased</th>
<th>2100 biobased</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (PWh/yr)</td>
<td>15</td>
<td>63-132</td>
<td>98-225</td>
</tr>
<tr>
<td>Liquid Fuels (EJ/yr)</td>
<td>142</td>
<td>171-361</td>
<td>217-613</td>
</tr>
</tbody>
</table>
## Multiple Factors in Biomass Use

<table>
<thead>
<tr>
<th>Land</th>
<th>Feedstocks</th>
<th>Technologies</th>
<th>Output</th>
<th>Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current cropland</td>
<td>Grains &amp; Feed</td>
<td>Planting, Harvesting, Management</td>
<td>Food/Feed</td>
<td>Fiber/Pulp</td>
</tr>
<tr>
<td>Forest land</td>
<td>Seed</td>
<td>Harvesting, Management</td>
<td>Solid Wood Products</td>
<td></td>
</tr>
<tr>
<td>Rangeland and Pastures</td>
<td>Hardwoods</td>
<td>Materials Handling</td>
<td>Chemicals/Products</td>
<td></td>
</tr>
<tr>
<td>Fallow land CRP</td>
<td>Seed</td>
<td>Chemical/Thermal/Mechanical</td>
<td>Polymers</td>
<td></td>
</tr>
<tr>
<td>Marginal land</td>
<td>Stalks/leaves</td>
<td>Gasification</td>
<td>Fertilizer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trees</td>
<td>Combustion</td>
<td>Pesticides</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hardwoods</td>
<td>Pulping</td>
<td>Textiles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Softwoods</td>
<td>Grinding, cutting, sawing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short rotation</td>
<td>Spinning</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trimmings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grasses</td>
<td>Switchgrass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row Crops</td>
<td>Sugar cane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-consumer Waste</td>
<td>Bagasse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>Stalks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Animal Residues</td>
<td>Fiber Crops</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cotton</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sisal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Row Crops</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Post-consumer Waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Animal Residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Demolition Wood</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Animal Residues</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Markets
- Fiber/Pulp
- Solid Wood Products
- Polymers
- Fertilizer
- Pesticides
- Textiles
- Electricity
- Heat
- Combined Heat/Power
- Ethanol
- Methanol
- Biodiesel
- Biogas
- Hydrogen
- Synthesis gas
- Hydrocarbons
Biomass Electric

- Direct combustion – 7500 MWe installed capacity
- Cofiring (wastes) – demonstrations
- Biomass gasification combined cycle (energy crops) – in development
- Regrowing biomass (energy crops) results in very low or zero net CO₂ emissions
- R&D: ash chemistry and deposition, advanced gas turbine technologies

Biomass for bioenergy will transition from a one product to a multiproduct industry

Early 1900’s and before

- Heat

Late 1900’s

- Heat
- Electricity
- Ethanol from corn
- Charcoal

Mid 2000’s

- Heat
- Electricity
- Ethanol
- Biogas
- Other fuels
- Charcoal
- Chemicals
- Plastics
- Fertilizer
- Pesticides
“Future History” Perspective

Petroleum Refining

Emergence: First half of the 20th century

Imperative: Industrialization

Advances in organic chemistry

- Fossil fuels
- Petrochemicals
- Chemical Engineering

Biomass Refining

Emergence: First half of the 21st century

Imperative: Sustainability

Advances in Biotechnology

- Biofuels
- Biochemicals
- Power
- Feed
- Biocommodity Engineering

Oil → Biomass
Biomass Attributes

- Renewable
- Connected to farming - economics
- Multiuse - food, shelter, energy, materials
- Environmental concerns include land and water use, fertilizer and other nutrient requirements
- Naturally diffuse and distributed - harvesting and transport and distribution are important

\[ \text{CO}_2 \xrightarrow{\text{Photosynthesis}} \text{plant} \xrightarrow{\text{Conversion}} \text{CO}_2 \]

Useful Energy
To economically provide large amounts of renewable energy from biomass we must:

- As efficiently as possible capture solar energy over a large area
- Convert this captured energy as efficiently as possible into a convenient and low cost end use application

SO WHAT ARE OUR OPTIONS?
Canada’s Surplus Wood Residues (1990-1998) (Hatton 1999)
C3 vs C4 Plants as Biomass Crops

C3 Plants
- Greater chilling tolerance
- Tolerant of imperfectly drained soils
- Utilizes solar radiation effectively in spring and fall

C4 Plants
- Responsive to warming climate
- Greater water use efficiency
- Utilizes solar radiation effectively at high temperatures
- Modest levels of ash
Water as a factor limiting yield

- Ontario and Quebec receive 1000 mm/yr
- Assumption that 40% of water is available for crop growth: 400 mm/yr
- Assume C4 species use 20 mm/tonne
  - Assume C3 species use 40 mm/tonne
- Maximum yield C4 species: $\frac{400}{20} = 20$ tonnes
- Maximum yield C3 species: $\frac{400}{40} = 10$ tonnes
Introduction to switchgrass

Fast growing warm season perennial grasses have been identified as ideal candidates for biomass fuel production due to their high net energy yield per hectare and low cost of production.

Switchgrass (*Panicum virgatum*), is an ideal biomass energy source because of its moderate to high productivity, stand longevity, high moisture and nutrient use efficiency, low cost of production and adaptability to most agricultural regions in North America.

Switchgrass has an energy output to input ratio of approximately 20:1 and can typically produce 185 GJ of energy per 10 tonnes of biomass from land that is often of marginal crop producing value.

Switchgrass can be densified into a pelletized biofuel and used for space heating purposes with a close couple gasifier pellet stove. This energy pathway was evaluated with support from Natural Resources Canada.
Desirable Characteristics of Switchgrass as a Biomass Crop

- Moderate to high productivity
- Low maintenance
- Tolerates acidic soils
- Stand longevity
- Low NPK requirements
- Moisture efficient
- Soil restoring properties
Economics of Switchgrass Production

- Fall harvesting: $41-57 CDN/tonne
- Spring harvesting: $46-68 CDN/tonne

**Pie Chart: Economic Cost Breakdown for Fall Switchgrass Production**
- Harvest and transport: 46%
- Fertilization: 16%
- Land rent: 29%
- Establishment: 3%
- Labour: 5%
- Misc: 1%
Native Range of Selected C4 Grasses

PRAIRIE SANDREED (CALAMOVILFA LONGIFOLIA)

SWITCHGRASS (PANICUM VIRGATUM)
# Farmland in North America and Potential for Biofuel Production

<table>
<thead>
<tr>
<th>Land use</th>
<th>Millions of Hectares</th>
<th>Area for biofuel production* (million ha)</th>
<th>Potential perennial grass production** (million tonnes)</th>
<th>Solar energy collected (Billions GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>68</td>
<td>9.5</td>
<td>55.8</td>
<td>1.03</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>377</td>
<td>52.4</td>
<td>425</td>
<td>7.86</td>
</tr>
</tbody>
</table>

*Estimated 13.9% land converted to bioenergy grasses

**Assumed hay yields of 5.9 tonne/ha in Canada, 8.1 tonne/ha U.S.
Comparative Costs of Hay Prices vs. Residential Heating Costs in Manitoba

![Graph showing the comparative costs of hay prices versus residential heating costs in Manitoba. The graph includes lines for hay, electricity, heating oil, heating oil, and natural gas, with data points for the years 1988 to 2002.](image-url)
Modernizing the Bioenergy Heat Production Chain

- Energy crop
- Pellet fuel
- Stove Boiler
- Heating Cooking
**PFI Pellet Fuel Quality Standards**

- Premium (<1% ash) vs. Standard (3% ash)
- Density: 40 pounds per cubic ft.
- Dimensions: Maximum 1.5 inches in length
  - Diameter ¼ or 5/16 in.
- Fines: Maximum 0.5% by weight
- Chlorides: Maximum 300 ppm
Biomass quality of switchgrass as a combustible biofuel

The formation of clinker is a concern when combusting herbaceous feedstocks such as switchgrass pellets.

Overwintering switchgrass reduces the potassium and chlorine content which improves overall biomass quality. Switchgrass biomass quality is also better when grown on sandy soils.

Spring harvested switchgrass has an ash content of approximately 3-3.5%. It has an energy content of 19.2 GJ/tonne, only 3% lower than wood and 7% greater than wheat straw.

The densification of switchgrass into fuel pellets eases the combustion and handling problems normally associated with the bulky nature of biomass.
Production and economics of switchgrass pellets

In terms of pelleting, switchgrass behaves similarly to alfalfa, and it is significantly easier to pellet than hardwood or softwood fibre sources.

The use of switchgrass as a pelleting material can reduce pellet production costs by increasing the throughput of a 150HP pellet machine to 6.9-10.9 tonnes/hr compared to 3.1 for hardwood and 4.5 for softwood.

Switchgrass is an economically attractive feedstock as it requires minimal drying compared to wood.

Switchgrass pellets can be produced in closer proximity to more densely populated areas than can wood fuel pellets, thus reducing transportation costs and making bulk handling more feasible.
Summary of preliminary feedstock production costs ($CDN/tonne)$^a$

<table>
<thead>
<tr>
<th></th>
<th>Wood pellet costs</th>
<th>Projected switchgrass pellet costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock</td>
<td>$34.35</td>
<td>$46-$68</td>
</tr>
<tr>
<td>Drying</td>
<td>$11.93</td>
<td>$0</td>
</tr>
<tr>
<td>Direct Pelleting Costs</td>
<td>$59.00</td>
<td>$25.29-39.33</td>
</tr>
<tr>
<td>Bagging</td>
<td>$19.25</td>
<td>$19.25</td>
</tr>
<tr>
<td>Total cost</td>
<td>$124.53</td>
<td>$90.54-$126.58</td>
</tr>
</tbody>
</table>

$^a$Direct pelleting costs are based on:
30 lbs./hr/HP (177.6 kg/hr/MJ) for wood residues
45-70 lbs/hr/HP (266 – 414 kg/hr.MJ) for switchgrass
The Dell-Pointe Pellet Stove

This close coupled gasifier pellet stove was designed to efficiently burn moderately high ash fuels and feed grains.
Combustion performance of switchgrass fuel pellets

Dell-Point Technologies (Blainville, QC), in partnership with the Natural Resources Canada Advanced Combustion Laboratory, has developed a close couple gasification pellet stove with an overall efficiency of 81-87%.

The stove design is such that a lower operating temperature exists in the bottom of the gasifier where the first stage of the combustion occurs. The ash is slowly augered out allows the ash to remain in the auger fall through the grate into the ash pan, thus reducing clinker production.

Burning switchgrass provided an efficiency of 82%-84% when tested by the CANMET combustion laboratory.

Grains (including rye, barley, oats, wheat and corn) are now also being burnt Dell-Pointe Stove.

Particulate levels from switchgrass combustion were greater than those obtained for wood, with peak levels of 2.5 g/hour at the high range setting. However, the values were well below the 7 g/hour EPA limit for pellet stoves.
Reducing heating costs and CO$_2$ emissions with switchgrass biofuel pellets

In North America, biomass energy from grass pellets and crop residues could play an important role in reducing the economic and environmental costs associated with fossil fuel use.

The rising price of heating oil and natural gas will increasingly make the replacement of these fuels with biomass energy more financially attractive to consumers.

The bottom line is that relative to heating oil systems, switchgrass pellets have the potential to reduce fuel heating costs and greenhouse gas emissions by approximately 30% and 90% respectively.
Fuel costs and CO$_2$ emissions associated with home heating in S.W. Quebec

- **Home heating cost ($Cdn)**
  - Electricity
  - Heating oil
  - Natural gas
  - Bagged wood pellets
  - Bulk switchgrass pellets

- **CO$_2$ emissions (kg)**
  - Bagged wood pellets
  - Bulk switchgrass pellets

- **Cost of heating home**
- **Emissions of CO2**
Assumptions:

**Electricity** has an energy content of 3.6 MJ/kWh, a delivered fuel value of 6.87 cents/kWh, a CO₂ loading value of 52.2 kg CO₂/GJ and is converted at 98% efficiency. Approximate Canadian electrical mix: 63% hydro-power, 15% nuclear, 16.5% coal, 3% oil, 2% natural gas.

**Heating Oil** has an energy content of 0.0382 GJ/l, a delivered fuel value of 46.01 cents/l, a CO₂ loading value of 81.8 kg CO₂/GJ, and is converted at 82% efficiency.

**Natural Gas** has an energy content of 0.0375 GJ/m³, a delivered fuel value of 47.85 cents/m³, a CO₂ loading value of 50.6 kg CO₂/GJ, and is converted at an average efficiency of 85%.

**Bagged Wood Pellets** have an energy content of 19.8 GJ/tonne, a delivered fuel value of $207/tonne, a CO₂ loading value of 5.3 kg CO₂/GJ, and are converted at 82% efficiency.

**Bulk Switchgrass Pellets** have an energy content of 19.2 GJ/tonne, a delivered fuel value of $172/tonne, a CO₂ loading value of 5.3 kg CO₂/GJ, and are converted at 82% efficiency. All delivered fuel values include taxes of 7% GST and 7.5% TVQ.

Heat estimates made for a new detached 2000 sq. foot home with a heat requirement of 100 GJ. The analysis does not include capital costs associated with equipment.
Switchgrass production and pelleting: Energy analysis

Pellet conversion facilities are much smaller (200 tonne/day) than other large biomass processing industries (1500 tonne/day), and thus can be located in closer proximity to the site of switchgrass production.

If 5% of the landscape is converted to switchgrass and a harvestable yield of 10 tonne/ha is obtained, switchgrass can be sourced within a 20 km radius of a pelleting plant, versus a 60 km radius for a large industrial user.

This shorter radius would reduce the energy used in delivery by approximately 2/3. Due to the difference in hauling differences, the total energy cost of switchgrass production for a large industrial user is estimated to be 0.91 GJ/tonne, while that of a pellet plant is 0.79 GJ/tonne.
Energy inputs and outputs associated with switchgrass as a pelleted biofuel

<table>
<thead>
<tr>
<th>Process</th>
<th>GJ/tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgrass establishment</td>
<td>0.028</td>
</tr>
<tr>
<td>Switchgrass fertilization and application</td>
<td>0.460</td>
</tr>
<tr>
<td>Switchgrass harvesting</td>
<td>0.231</td>
</tr>
<tr>
<td>Switchgrass transportation</td>
<td>0.072</td>
</tr>
<tr>
<td>Pellet mill construction</td>
<td>0.043</td>
</tr>
<tr>
<td>Pellet mill operation</td>
<td>0.244</td>
</tr>
<tr>
<td>Management, sales, billing and delivery of pellets</td>
<td>0.193</td>
</tr>
<tr>
<td>Total Input Energy</td>
<td>1.271</td>
</tr>
<tr>
<td>Total Output Energy</td>
<td>18.5</td>
</tr>
<tr>
<td>Energy Output/Input Ratio</td>
<td>14.6</td>
</tr>
</tbody>
</table>
## Net Energy Gain and Land Use Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Switchgrass fuel pellets</th>
<th>Co-firing switchgrass with coal</th>
<th>Switchgrass cellulosic ethanol and electricity</th>
<th>Grain corn ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass yield per hectare (ODT)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>6.5</td>
</tr>
<tr>
<td>Direct biomass energy yield (GJ/ha)</td>
<td>185</td>
<td>185</td>
<td>185</td>
<td>136.5</td>
</tr>
<tr>
<td>Energy yield after conversion (GJ/ha)</td>
<td>175.8</td>
<td>58.3</td>
<td>73.0 (67.2 ethanol + 5.8 electricity)</td>
<td></td>
</tr>
<tr>
<td>Energy consumed in production &amp; conversion (GJ/ha)</td>
<td>12.7</td>
<td>11.1</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td><strong>Net energy gain (GJ/ha)</strong></td>
<td><strong>163.1</strong></td>
<td><strong>47.2</strong></td>
<td><strong>57.1</strong></td>
<td><strong>21.4</strong></td>
</tr>
</tbody>
</table>
Conclusions

Converting switchgrass into heat, using close coupled gasifier stoves and furnaces, is proposed as the biofuel system with the greatest potential to produce useful net energy from agricultural land and to displace oil imports with the least government intervention.

This energy transformation pathway appears to accurately fit the definition of a ‘soft energy path’, due to its following characteristics:

- It is powered by a renewable source of energy
- It provides power sources which are multiple, small-scale and local, rather than few, large-scale and distant
- It is a flexible and comparatively low technology system, facilitating its understanding and utilization
- Is matched in terms of both scale and energy quality to its end-use application.