Catalytic Conversion of Renewable Plant Sugars to Fungible Liquid Hydrocarbon Fuels Using the BioForming™ Process

TAPPI, IBBC Session 3: Conversion Pathways
Memphis, TN
October 15, 2009

Andrew Held, Director Process Engineering

© 2009 Virent Energy Systems, Inc.
Virent Introduction

- Company background
- Technology platform and Commercialization
  Gasoline, Jet, Diesel, Chemicals & Hydrogen

Feedstock supply and processing scale

- Feedstock supply
- Virent’s Biorefinery concept
- Scale of Deployment
Virent’s BioForming® Technology

- **Fast and Robust**
  - Inorganic Catalysts
  - Moderate Conditions
  - Industry Proven Scalability

- **Energy Efficient**
  - Exothermic
  - Low Energy Separation
  - Low Carbon Footprint

- **Premium Drop-in Products**
  - Tunable
  - Infrastructure Compatible

- **Feedstock Flexible**
  - Conventional Sugars
  - Non-Food Sugars

Strategic Investors & Partners

© 2009 Virent Energy Systems, Inc.
Virent Energy Systems

- Founded in 2002
- Based in Madison, WI
- 80 Employees
- 20 Pilot Plants in Operation
- Commissioning 10,000 gal/yr plant
- 63,000 sq. ft. facility
  - 35,000 new in 2009
- > $30 MM of Venture Financing
- > $40 MM of Development Funding from Government and Industry
Catalytic vs. Other Routes for Fuel Production

• Orders of Magnitude Higher Productivity than Biochemical

Measure of Productivity: Space Time Yield
(moles reactant per second per cc of reaction volume)

- 10^{-9}
- 10^{-8}
- 10^{-7}
- 10^{-6}
- 10^{-5}

• Tolerant of broader spectrum of feeds
• Produce range of desirable molecules
Biofuel Pathways from Biomass

Biomass

Virent’s BioForming® Process

CH$_{1.4}$O$_{0.6}$

Fermentation

Fischer-Tropsch

CH$_2$

Diesel
Jet Fuel

Ethanol

Methanol
Ethanol

Liquid Fuels

Syngas

CO + H$_2$

Gasification

Pyrolysis

Bio-oils

CH$_{1.6}$O$_{0.4}$

Refrining

Sugars

Hydrolysis

CH$_2$O

Aqueous Phase Reforming

CH$_2$

CH$_3$O$_{0.5}$

Ethanol

Butanol
Hydrocarbons

Gasoline,
Jet, Diesel,
Chemicals,
Alcohols,
Hydrogen

© 2009 Virent Energy Systems, Inc.
<table>
<thead>
<tr>
<th>Hydrocarbons</th>
<th>Gasoline</th>
<th>Jet Fuel</th>
<th>Diesel</th>
<th>Bio-Crude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amyris</td>
<td>Solazyme</td>
<td>Amyris</td>
<td>Sapphire</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solazyme</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LS-9</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Alcohols</th>
<th>Butanol</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gevo</td>
<td>Iogen</td>
</tr>
<tr>
<td></td>
<td>Dupont/BP</td>
<td>Verenium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Codexis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mascoma</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ineos</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coskata</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biological</th>
<th>Non-Biological</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Syntroleum</td>
</tr>
<tr>
<td></td>
<td>(Gasification/FT)</td>
</tr>
<tr>
<td></td>
<td>Choren</td>
</tr>
<tr>
<td></td>
<td>(Gasification/FT)</td>
</tr>
<tr>
<td></td>
<td>UOP</td>
</tr>
<tr>
<td></td>
<td>Ensyn</td>
</tr>
<tr>
<td></td>
<td>Dynamotive</td>
</tr>
<tr>
<td></td>
<td>KiOR</td>
</tr>
<tr>
<td></td>
<td>Ineos</td>
</tr>
<tr>
<td></td>
<td>Coskata</td>
</tr>
<tr>
<td></td>
<td>Clear Fuels</td>
</tr>
<tr>
<td></td>
<td>Range Fuels</td>
</tr>
<tr>
<td></td>
<td>Syntec</td>
</tr>
<tr>
<td></td>
<td>Enerkem</td>
</tr>
</tbody>
</table>
Virent's BioForming® Concept

Biomass Fractionation and Pretreatment

- Lignocellulosic Materials
- Soluble Sugars
- Starches

Process Heat

Lignin → Hydrolysis

Polysaccharides
- C₆ & C₅ Sugars
- Furans
- Phenolics
- Acids

Aqueous Phase Reforming

Hydrogenation

Sugar Alcohols

Base-Catalyzed Condensation

H₂

HDO

Alkanes

ZSM-5

Oligomerization

Alkanes

Dehydration

Alkene Saturation

Aromatics, Alkanes

Hydrogenolysis

C₂⁻ C₆ Oxygenates

C₁⁻ C₄ Alkanes

Alkenes

Hydrogenation

Sugar Alcohols

C₂⁻ C₆ Oxygenates

Alkanes

Gasoline

Kerosene

Jet Fuel

Diesel

© 2009 Virent Energy Systems, Inc.


Slide 8
Virent’s Sugar to Liquid Fuels Process

H₂ generation → selective deoxygenation → monoxygenates → condensation reactions

\[ 3.58 \text{ C}_6\text{H}_{12}\text{O}_6 \rightarrow \text{C}_{14}\text{H}_{30} + 7.5 \text{ CO}_2 + 6.5 \text{ H}_2\text{O} \]

Hydrocarbon contains 65% of Sugar Carbon & 94% LHV
Virent’s BioGasoline Product

*Premium product with the same components as petroleum derived gasoline*

- **Unleaded Gasoline**: 115,000 BTUs/Gal
- **BioForming BioGasoline**: +120,000 BTUs/Gal
- **Ethanol**: 76,000 BTUs/Gal


© 2009 Virent Energy Systems, Inc.
Virent's BioGasoline Product

Premium product with the same components as petroleum derived gasoline

Cane Sugar and Xylose to BioGasoline

~ 20 liters of sugar derived biogasoline from Virent’s BioForming process.


© 2009 Virent Energy Systems, Inc.
Biogasoline Development

- Fuel production
- Preliminary composition analysis

- Composition analysis
- Standard fuel tests
- Blending
- Preliminary engine tests

- Standard engine tests
- Evaluation of compatibility with next generation engines

- High blend rate potential while maintaining specification compliance
- Fully Fungible Fuels
Virent Energy Systems Overview

Virent Introduction
- Company background
- Technology platform and Commercialization
  Gasoline, Jet, Diesel, Chemicals & Hydrogen

Feedstock supply and processing scale
- Feedstock supply
- Virent’s Biorefinery concept
- Scale of Deployment
Biomass and Plant Carbohydrates

Simple / Fermentable Sugars - Tier I

- **Sucrose**
  - Disaccharide
  - Plant Saps
  - Sugarcane, Sugar beets
  - Hydrolyzed to Glucose & Fructose

- **Glucose**
  - Monosaccharide
  - Found in Plant Starch
  - Corn, Potato, Rice and Tapioca
  - Fermentable
**Biomass and Plant Carbohydrates**

**Polysaccharides - Tier II**

- **Cellulose (44%)**
  - Most abundant naturally occurring substance (main constituent of cell wall)
  - Crystalline
  - Built from Glucose (7,000 – 15,000)
  - Insoluble- Resistant to Hydrolysis

- **Hemicellulose (30%)**
  - Amorphous
  - Built from Multiple Sugar Building Blocks- Primarily Pentoses (500 – 3000)
  - Soluble

- **Lignin (26%)**
  - Glue
  - Rigid Non-carbohydrate Polymer of Benzene Rings

© 2009 Virent Energy Systems, Inc.
• Sugarcane and corn remain large potential feedstocks.
• Cellulosic's provide the opportunity of producing at least 2 X more product (but we are looking forward to updated data!!)
Bioresinry with Virent APR

- Commodity crops
- Ag residues
- Woody materials
- Energy crops
- Oligosaccharides (of C5 & C6 monomers)

Biomass → Fractionation → Pyrolysis → Hydrotreater → Gasoline

- Lignin
- Hydrogen
- Light Ends
- Alcohols
- Benzene
- Toluene
- Xylene

© 2009 Virent Energy Systems, Inc.
Analytical Capabilities

- **Feedstock Analytical Methods**
  - Liquid Chromatography for Sugars, Oligosaccharides*
  - GC –with Sample Derivitization
  - GC-MS for volatile compounds
  - GC-Pyrolysis and Head-space sampling*
  - GC-IR and IR Spectroscopy
  - Acid and Moisture Titrations
  - Inductively Coupled Plasma (ICP)
  - Ion Chromatography*

- **Characterization of poly / oligo / di- & monosaccharides**

- **Quantitation of elements by ICP and Ion Chromatography**

* denotes methods specific to the feedstock analysis.
Sugar Cost Estimating

- Commodity sugar price trends and cost drivers analyzed (results not shown)

- Cellulosic sugars - 15 different cases analyzed
  - 5 biomasses
  - 3 deconstruction & purification processes
Costs are higher than those for conventional sugars; numerous developments needed to make cellulosic sugars cost effective.
Plant 1+ Feedstock Considerations

• Feedstock for Plant 1: Low Cost, Commercially Available, Minimize Technical and Commercial Risk
  – Feedstock of choice depends on geography
  – Vertical Integration Desirable
  – Alignment with Long Term Strategy

• Cellulosic Offers Long Term Promise (> 5 yrs or longer)
  – Near Term- Timing and Pricing Risk appear too high for fast commercial deployment
  – Amenability of Cellulosics for Plant 1 will be Considered.

• Low Cost Feedstock via Partnership Being Pursued
Virent Energy Systems Overview

Virent Introduction
- Company background
- Technology platform and Commercialization
  Gasoline, Jet, Diesel, Chemicals & Hydrogen

Feedstock supply and processing scale
- Feedstock supply
- Virent’s Biorefinery concept
- Scale of Deployment - A brief comparison of processing scale between selected biorefinery industries and petroleum refinery industry

© 2009 Virent Energy Systems, Inc.
Energy Usage – for context

Petroleum Crude Oil Uses

- Gasoline, 47%
- Distillate, 20%
- Jet Fuel, 10%
- Petrochem, 3%
- Resid, 7%
- Asphalt, 3%
- Other, 10%

2008 U.S. Energy Consumption

- Stationary - Coal, 23%
- Stationary - Nat. Gas, 24%
- Stationary - Nuclear, 8%
- Stationary - Hydro, Solar, Wind, Geothermal, 3%
- Existing Biomass, 4%
- Other - Fossil, 0%
- Petro - Other, 8%
- Petroleum - Liquid Fuels, 9%

Data from DOE/EIA Report 0383(2009).

~ 100 Quad BTU is typical from 2006 to 2008.

© 2009 Virent Energy Systems, Inc.

Data from DOE/EIA Report 0383(2009) and other EIA information.
Energy Usage - continued

- DOE ‘Billion ton biomass study’ in 2005 targeted ~30+% replacement of annual Petroleum consumption by 2030.

Illustration using 2008 Energy usage and 2030 biomass projection for Liquid Fuels

- We use a lot of Energy!!
The following is a comparison of typical processing scale across several biomass supplied industries:

<table>
<thead>
<tr>
<th>Industry</th>
<th>Nominal Capacity</th>
<th>Feedstock Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn dry grind</td>
<td>100,000,000 gal/yr EtOH</td>
<td>2,370 corn</td>
</tr>
<tr>
<td>Corn wet mill</td>
<td>200,000 bu/day</td>
<td>5,079 corn</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>16,000 MT/day</td>
<td>16,000 cane</td>
</tr>
<tr>
<td>Oil refining</td>
<td>280,000 barrels/day</td>
<td>38,859 oil</td>
</tr>
<tr>
<td>Wood pulp</td>
<td>396,000 tons/yr</td>
<td>2,460 wood</td>
</tr>
</tbody>
</table>

Two significant factors affecting production capacity:
- Number of actual annual operating days
- Dry weight % of feedstock at the plant gate
Scale of deployment — current ‘biorefineries’

Data from various public sources, see slide titled ‘Data Sources’.
Current ‘biorefineries’ with U.S. petroleum

Data from various public sources, see slide titled ‘Data Sources’.

- Decatur, IL (ADM)
  450,000 bu/d

- Brunswick, GA (GP)
  936,000 short ton/yr pulp

- Mini Casia, ID
  (Amalgamated) 17,000 tbd

- Clewiston, FL (US Sugar)
  26,500 tcd

- Baytown, TX (ExxonMobil)
  557,000 bbl/d

- US refineries
- Selected US pulp mills
- US Corn wet mills
- US Cane mills
- US Cane mills
- US Beet sugar mills

© 2009 Virent Energy Systems, Inc.
Current ‘biorefineries’ with petroleum

Data from various public sources, see slide titled ‘Data Sources’.

© 2009 Virent Energy Systems, Inc.
Current and future biorefineries

Data from various public sources, see slide titled ‘Data Sources’. Slide 29

Throughput [tonnes/day]

Number of mills or refineries

© 2009 Virent Energy Systems, Inc.

US refineries

Largest refineries outside US

Selected US pulp mills

US Corn wet mills

US Cane mills

US Beel sugar mills

USDA Ag residue, current - sustainably removable

USDA Forest products current

USDA - agricultural materials - biomass currently available from agricultural lands - processing requires **nine 50,000 tpd plants**

USDA - forestry materials - forestry residues, thinnings and urban wood waste - processing requires **five 50,000 tpd plants**

Paraguana Refining Complex, VZ 940,000 bbl/d

Baytown, TX (ExxonMobil) 557,000 bbl/d

Decatur, IL (ADM) 450,000 bu/d

Brunswick, GA (GP) 936,000 short ton/yr pulp

Mini Casia, ID (Amalgamated) 17,000 tbd

Clewiston, FL (US Sugar) 26,500 tcd

© 2009 Virent Energy Systems, Inc.
Deployment Advantage

Leveraging Today’s Assets.

Mills  Refineries  Infrastructure

Maximizing Tomorrow’s Investment.

BIOFORMING
PROCESS

Deconstruction  Biomass Handling  Cellulosic

© 2009 Virent Energy Systems, Inc.
Energy Usage

Biomass Supply
   – USDA-DOE 2005, “Biomass for a Bioenergy and Bioproducts Industry:
     The Technical Feasibility of a Billion-Ton Annual Supply”

Processing Plant Sizes
   – Petroleum - Oil and Gas Journal (via wikipedia)
   – Wet corn mills - http://www.energystar.gov/ia/business/industry/LBNL-
     52307.pdf , p. 80
   – Cane and beet sugar - http://www.sugartech.com/index.php
Thank you!

Director Process Engineering
Virent Energy Systems
3571 Anderson St.
Madison, WI 53704
Office: 608.237-8614
andrew_held@virent.com
www.virent.com