Transportation Fuels from Biomass via IH^2 Technology

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Presented by CRI Catalyst Company

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Agenda

- Introduction to CRI and GTI
- IH^2 Technology Overview
- Economics
- Deployment

Technology Heritage - CRI Snapshot

- Evolution of Shell Catalyst Business with > 45 year history
- Global business headquartered in Houston
- Business Units
  - EO
  - ECS
  - Performance Products (CRI KataLeuna)
  - Upstream & Renewables
- Research Facilities
  - STCA 1000 staff using > 80,000 m^2 building space
  - SBL > 70 staff using ~3 acre temporary site, to relocate to 40 acre campus
  - STCH (Westhollow) 1200 staff using > 1mln sq.ft. building space
- Manufacturing Facilities in US, Germany, Belgium
- CRI and GTI have Joint Development and Commercial agreements in place

Technology Heritage - GTI Snapshot

- Not-for-profit gas research & services organization with a 70 year history
- Capabilities that span the natural gas value chain
- Energy Solutions
- Facilities
  - 18 acre Chicago campus
  - 28 specialized labs totaling 200,000 sq ft
- Staff of 250
- >1,200 patents
- >750 products taken to market

Offices& Labs

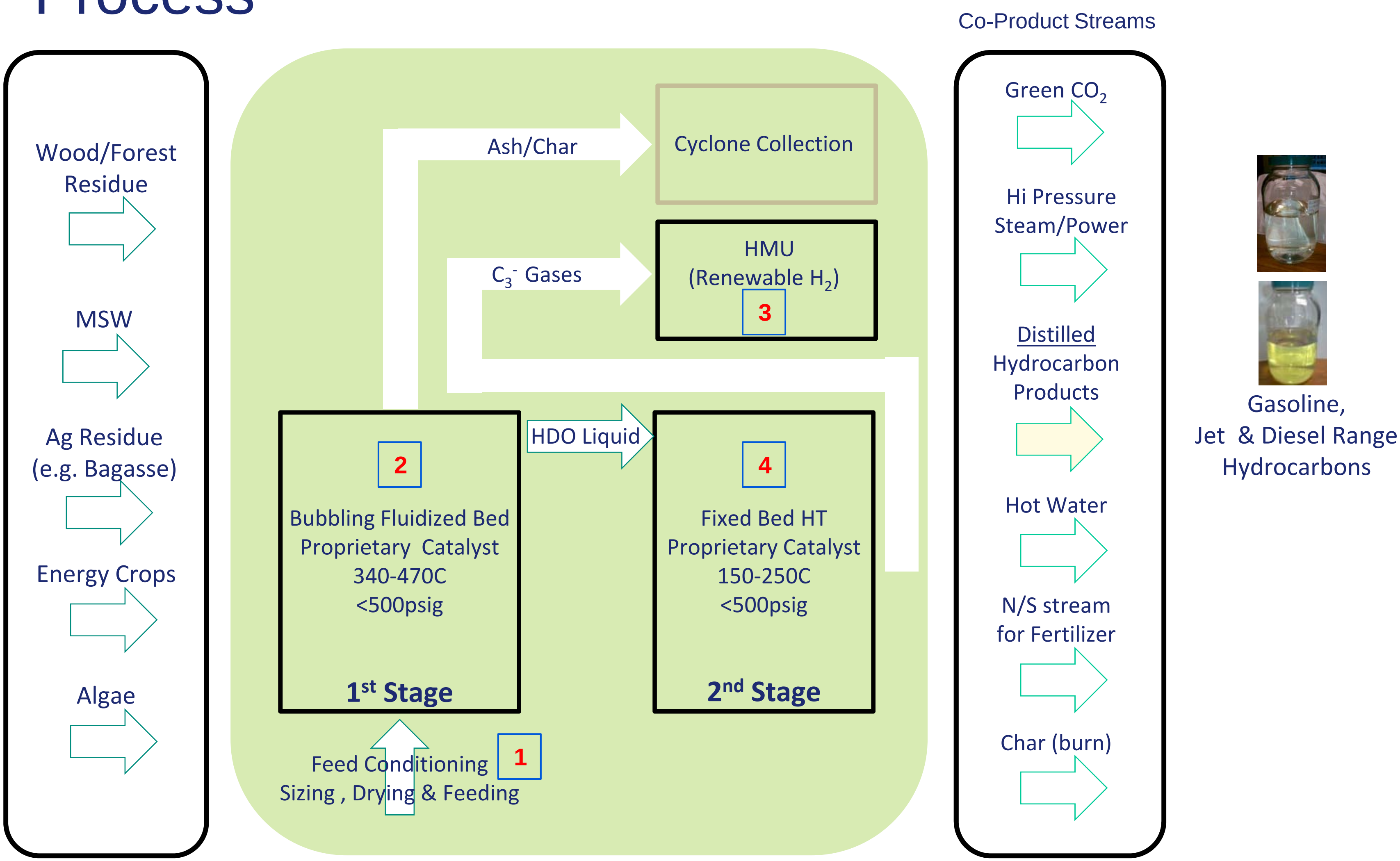
Pilot Scale Gasification Campus

Energy & Environmental Technology Center

Design Principles

- Produce fungible hydrocarbon fuel/blend stock from a broad range of inedible/residual biomass feed at low cost
- *Require* no infrastructure other than road/rail transport into and out of the production. Can be integrated with existing mills or refineries for even better economics
- Have minimal unsustainable impact on the surrounding environment

IH^2 Process



Co-Product Streams
Wood/Forest Residue
MSW
Ag Residue (e.g. Bagasse)
Energy Crops
Algae
Ash/Char
Cyclone Collection
C_3^- Gases
HMU (Renewable H_2)
3
HDO Liquid
2
Bubbling Fluidized Bed
Proprietary Catalyst
340-470C
<500psig
1^{st} Stage
4
Fixed Bed HT
Proprietary Catalyst
150-250C
<500psig
2^{nd} Stage
Feed Conditioning
Sizing , Drying & Feeding
1
Green CO_2
Hi Pressure Steam/Power
Distilled Hydrocarbon Products
Hot Water
N/S stream for Fertilizer
Char (burn)
Gasoline, Jet & Diesel Range Hydrocarbons

Differentiators

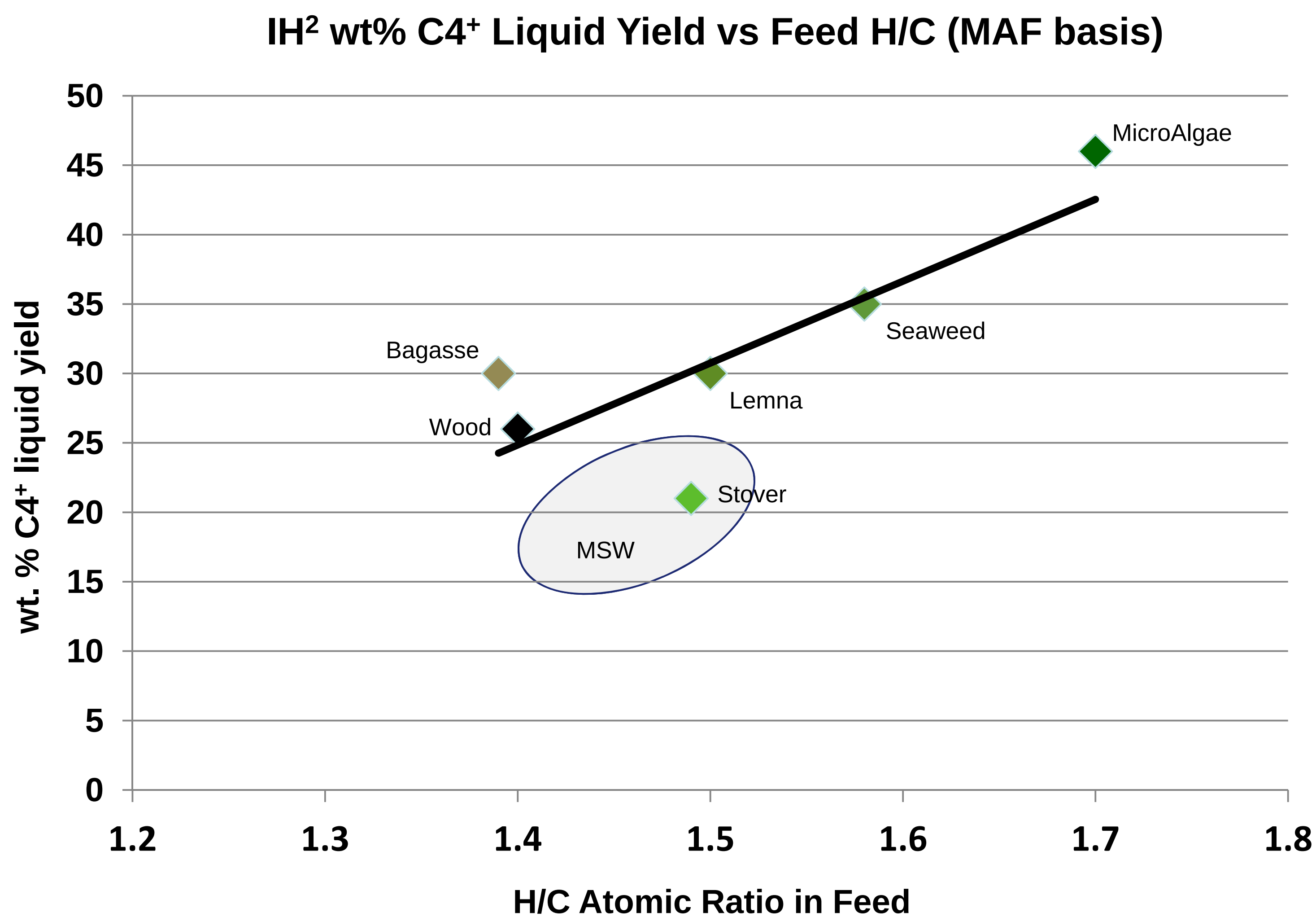
- Feedstock flexibility with yields 67-157 gal/dry, ash-free ton of feed
- Energy recovery >72% (wood, commercial scale, 45% moisture)
- Attractive economics
  - Low capex (low pressure system, non-corrosive materials, simple process)
  - Low opex (predominated by feed cost)
  - Fully profited manufacturing costs under $2.00/gal at 2000mt/d scale
- Both stages exothermic, able to export steam or electricity
- Fungible, high purity hydrocarbon product
  - High energy density (i.e. 18 kBTU/lb)
  - Replaces ‘whole barrel’ gas/jet/diesel with *same molecules* as fossil fuels
  - O below detection limit
- Self-sufficient internal “green” H_2
  - Eases logistical constraints
  - >94% GHG reduction (Professor David Shonnard, MTU)
- Integrates existing technologies for fast implementation
- Proprietary CRI catalysts play critical role

1^{st} Gen Liquid Yields and Feedstock Flexibility

Parameter	UoM	Wood	Parabel Lemna	Aquaflow MicroAlgae	Bagasse	Blue Marble Seaweed	Corn Stover
Feed Carbon Content	wt%	49.7	46.3	43.1	43.1	34.0	40.2
Feed Hydrogen Content	wt%	5.8	5.8	6.1	5.0	4.43	5.0
Feed oxygen content	wt%	43.9	35.7	20.4	35.3	23.6	35.7
Feed nitrogen content	wt%	0.11	3.7	6.5	0.34	4.6	1.0
Feed sulfur content	wt%	0.03	0.3	0.7	0.10	1.9	0.05
Feed ash content	wt%	0.5	8.2	23.1	16.2	29.4	18.1
Feed H/C atomic ratio		1.40	1.50	1.70	1.39	1.56	1.49
C_4^+ liquid yield (MAF)	wt%	28	30	46	30	35	21
(Gasoline/Diesel)	wt/wt	62/38	65/35	50/50	76/24	76/24	62/38
C_4+ liquid yield	Gallons/ton	92	100	157	100	119	67
Product Oxygen		b d l	b d l	b d l	b d l	b d l	b d l
Product TAN	mg KOH/g	<0.05	<0.05	<0.5	<0.05	<0.05	<0.05

b d l = below detection limit

Liquid Yields and Feedstock Flexibility



Approach

- Initial focus upon motor transportation fuels gasoline, diesel
  - initial look at 1^{st} gen gasoline and diesel to set catalyst development targets
  - demonstrate product improvements via catalyst improvements
  - ASTM D4814 and D975
  - EN 228 and EN 590

- Examine aviation turbine fuel quality second as greater quantities of fuel become available from pilot plant

- Entered EPA registration process
- Began ASTM fuel qualification program
- Begin OEM interaction

Catalysts Are Key

- 1st generation hydrocarbon products had deficiencies
  - low conversion, residual N/S, low diesel cetane, etc
  - advanced catalysts developed to address many of these issues

- 2nd – 3rd generation catalyst packages
  - increased liquid yields (demonstrated)
  - shifted jet/diesel product into gasoline (demonstrated)
  - increased hydrogen / carbon ratio (demonstrated)
  - maximized fuel by converting heavy ends (demonstrated)
  - decreased aromatic content (demonstrated)
  - decreased product N and S (demonstrated)
  - improved product visual appearance/color (demonstrated)

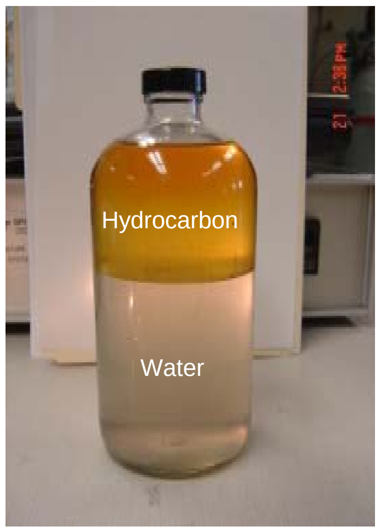
- 4th generation catalyst packages
  - increase diesel cetane (work in progress)
  - shift gasoline into jet/diesel (work in progress)

IH^2 Liquid Products (Wood)

Advanced catalysts improve product appearance and quality

Total Liquid Product
1st Gen Catalyst MBU

Total Liquid Product
2nd Gen Catalyst MBU



Gas/Jet/Diesel Product
3rd Gen Catalyst MBU

Gasoline Product
3rd Gen Catalyst ex
IH^2 50 Pilot Plant

Jet/Diesel Product
3rd Gen Catalyst ex
IH^2 50 Pilot Plant

Water Product
3rd Gen Catalyst ex
IH^2 50 Pilot Plant

"B5" Quality → "B25" Quality → "B60+" Quality →

"GOAL"
Drop In
Stand
Alone
"B100"

GRI

IH^2 50 kg/d Continuous Pilot Plant

Comparison of Lab and Pilot Units

	Pilot plant	Laboratory unit
Mode of operation	Continuous	Semi-continuous
Amount of biomass feed	2000 g/h	360 g/h
Automation/control system	Yes - Complete	Partial
Lock hopper – continuous feed	Yes	No (Batch)
Continuous char removal	Yes	No (Batch)
Compressor/recycle gas	Yes	No (Once-through)
Automated valves/interlocks	Yes	No
Primary reactor diameter	2.5x	1.0x
Cyclone separation	Yes	No
Gas velocity in primary Rx	2.0x	1.0x

Yield Comparison between Pilot Plant and Lab Unit

Yields in wt% of biomass feed (wood) on a moisture and ash free basis

	Pilot plant	Laboratory unit
Liquid hydrocarbon product	24-26	26
Char	11-14	13
Water	39-42	36
$CO + CO_2$	7-8	17
C1-C3 gases	12-15	13
Total*	105	105

*Total greater than 100% due to hydrogen uptake

Comparison of Liquid Quality from Woody Biomass

	Pilot plant	Laboratory unit
		
% Carbon	88.20	88.40
% Hydrogen	11.60	11.00
% Sulfur	0.02	0.02
% Nitrogen	<0.10	<0.10
% Oxygen	BDL	BDL
Total acid number, mg KOH/g	<0.05	<0.05

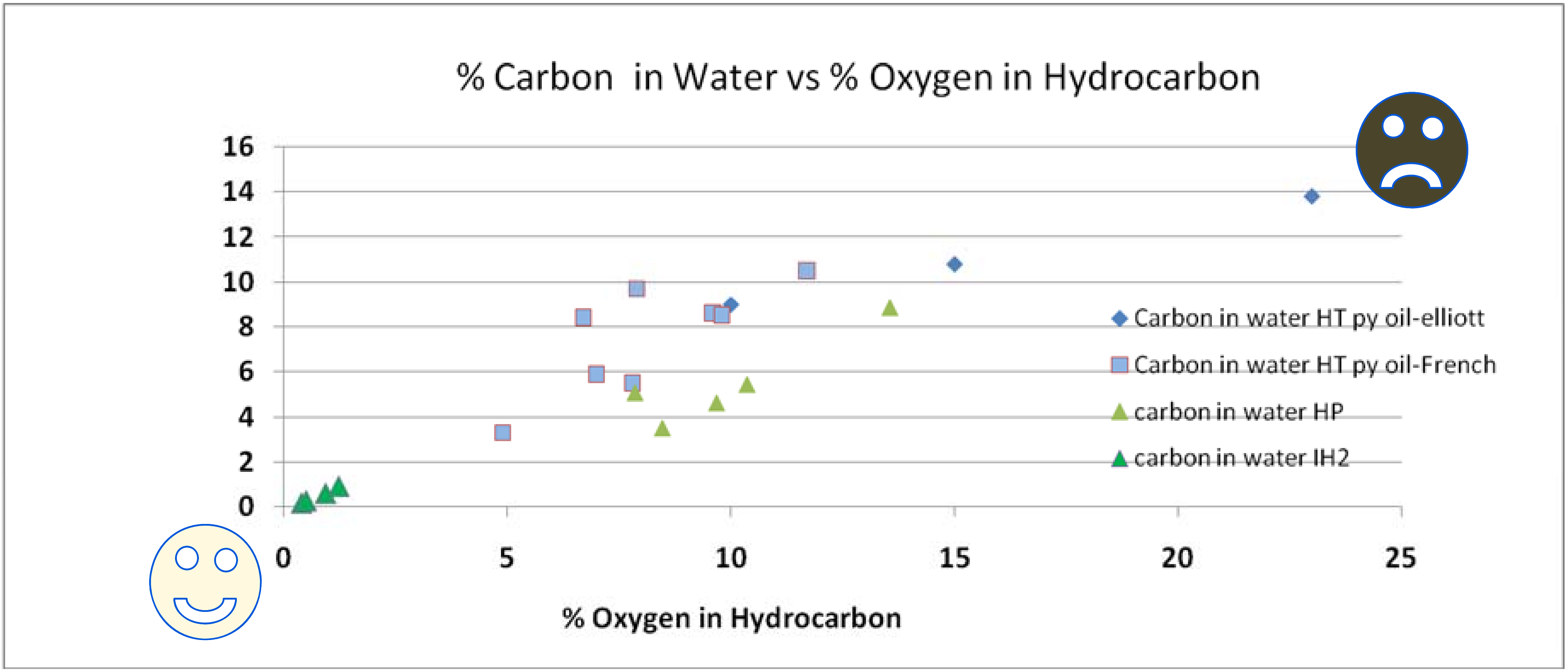
IH^2 Liquid Products (Wood)

- 3rd generation gasoline from IH^2-50 Pilot Plant
  - Distilled 5 gallons
  - Passed all D-4814-10b unleaded gasoline specifications as B100
  - Except Cu strip (2A vs 1) & Ag strip (4 vs 1)
  - Active S related, improved 2nd stage catalyst(s)

- 3rd generation jet from IH^2-50 Pilot Plant
  - Distilled 2 gallons
  - Extensive specifications

- 3rd generation diesel from IH^2-50 Pilot Plant
  - Distilled 2 gallons
  - Passed all D-975-11 as No 2, general purpose middle distillate fuel as B100
  - Except Cetane Index & Viscosity

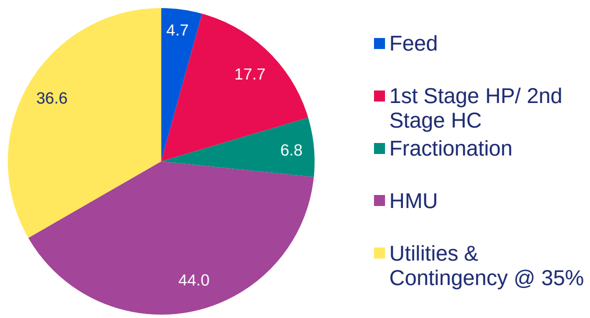
IH^2 Water is Clean!



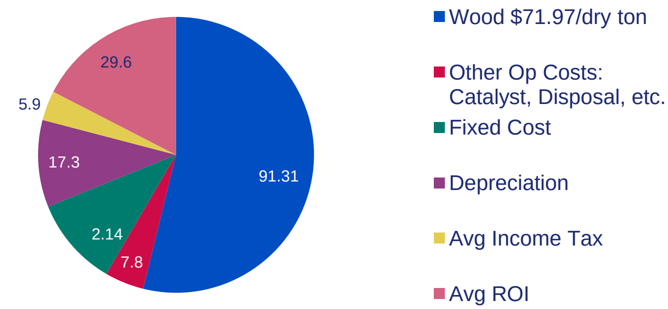
1 Elliott, Doug, Hart, Todd, Neuenschwander,Leslie, Zacher, Alan " Catalytic Hydropyrolysis Biomass Fast Pyrolysis Bio-Oil to Produce Hydrocarbon Products, Environmental Progress & Sustainable Energy",Aug 2009
2 French, Richard , Stunkel, Jim, Baldwin, Robert " Mild-Hydrotreating of Bio Oil: Effect of Reaction Severity and Fate of Oxygenated Species" , Energy and Fuels. Vol. 25(7) 21 July 2011

IH^2 Process Estimates

Installed Equipment Costs $112.6mln

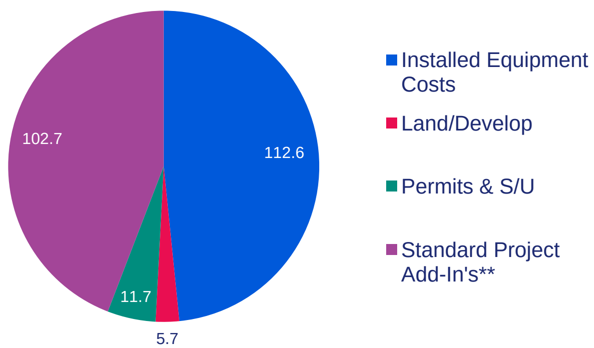


Operating Costs Total $1.60/gal*



*Includes $0.093/gal coproduct credit

Total Capital Investment $232.8mln



** Prorated Expense (10%), H O & Construction (20%), Field Expense (10%), Working Capital (10%) , Project Contingency (30%)

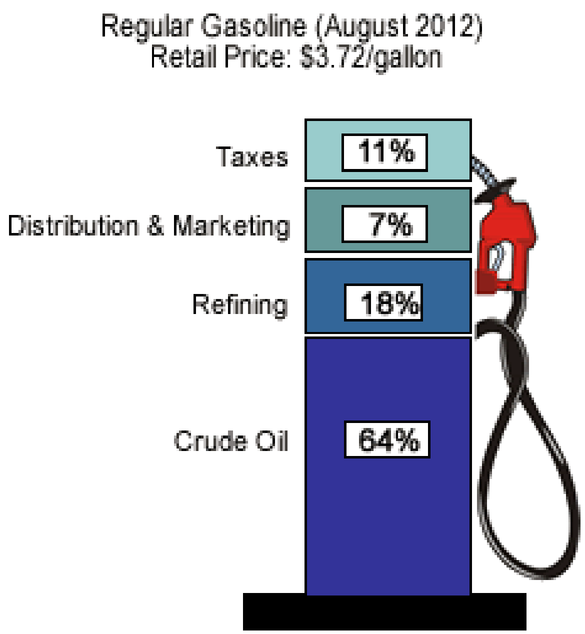
Title: Techno-economic Analysis of the Integrated Hydropyrolysis and Hydroconversion Process for the Production of Gasoline and Diesel Fuels from Biomass
Author: Eric C. D. Tan Platform: Analysis Report Date: May 23, 2011

- 2000mt/d wood (50% moisture fed, dried to 10% moisture at 1st stage)
- Land acquisition & development costs included
- Equipment cost - HMU is largest @ $44mln ~40% TIC
- Total Capital ~Double Installed Equipment
- Feed Stock ~55% of Operating Cost
- **Minimum Fuel Selling Price – $1.60/gal (2007) $1.76 (2012)**

- Refinery Synergy w/Refinery H_2 Supply
  - Reduces Capital Cost ~44.0MM$
  - **Estimated MSP $1.36/gal (2007) $1.49 (2012)**

- NREL capex validated by KBR
- NREL used early liquid yields (79 vs 92 gal/t)

IH² Process Economics: US Retail Price Build Up



<u>Fossil</u>

$0.41/gal $0.48/gal

$0.26/gal $0.56/gal

$0.67/gal $0.56/gal

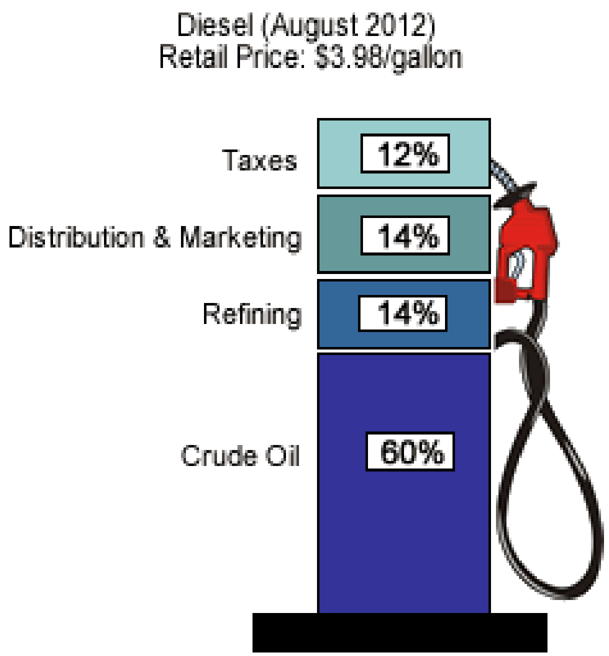
<u>$2.38/gal</u> <u>$2.39/gal</u>

$3.72/gal $3.98/gal

$100.14/bbl

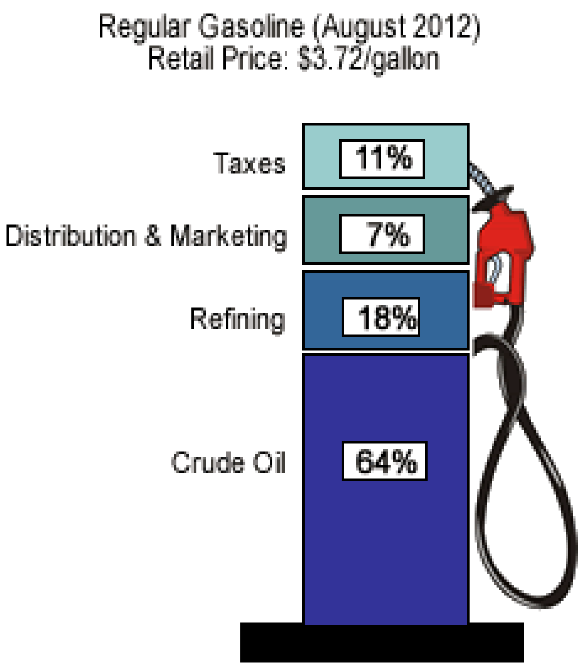
$3.05/gal $2.95/gal

(crude + refining only)



source: http://www.eia.gov/petroleum/gasdiesel/ 10/3/2102

Breakeven Crude Price Simplified Estimate



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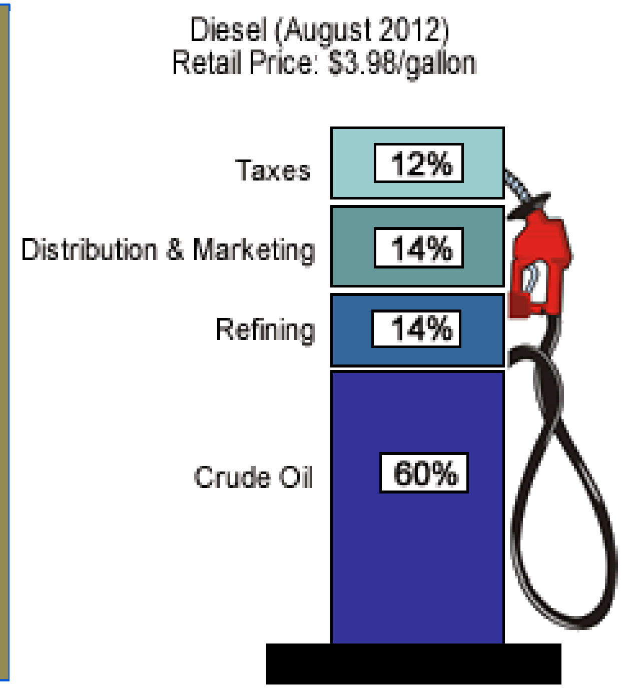
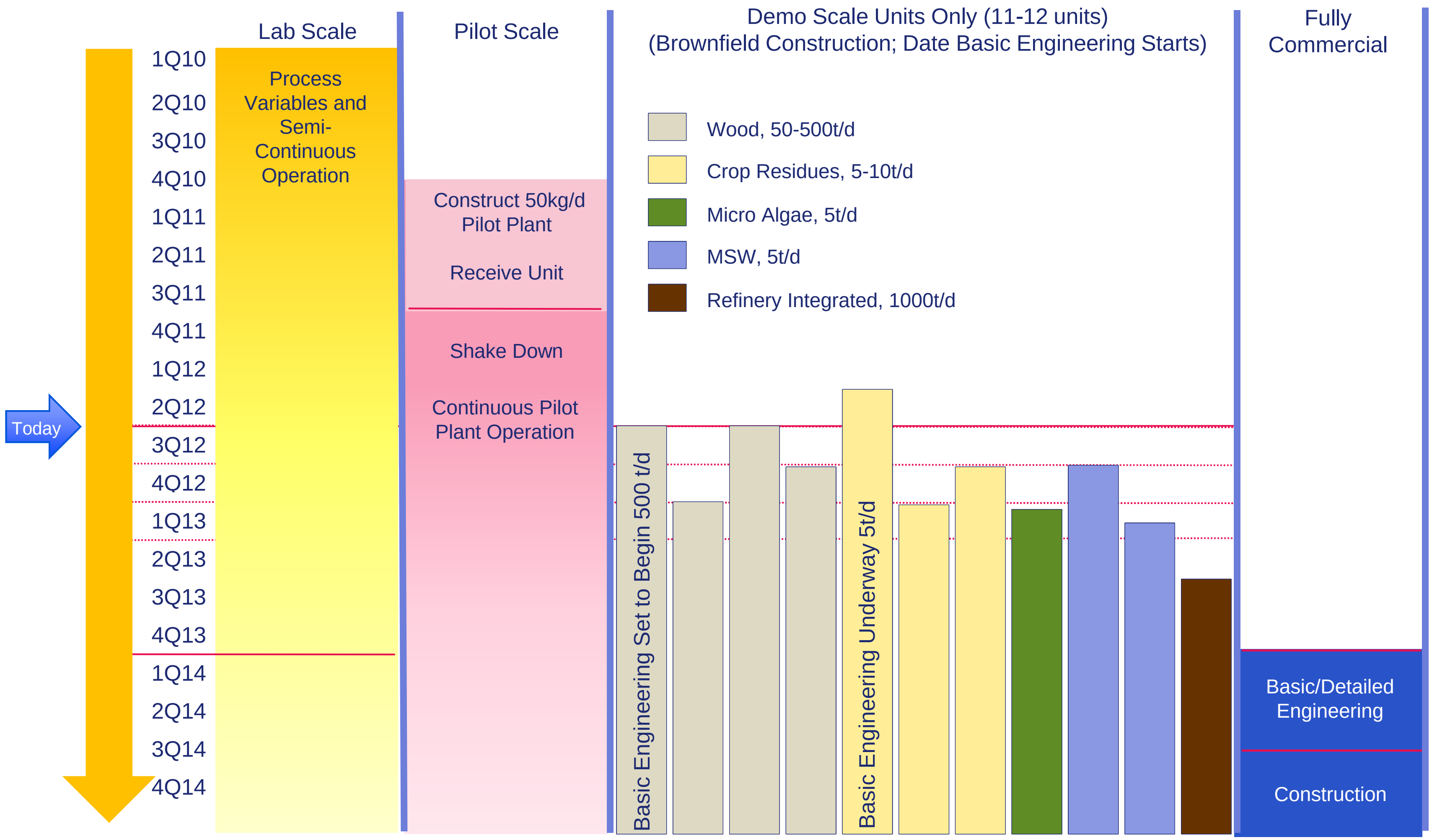


$1.76/gal	$1.76/gal	wood + refining
$1.25/gal	$1.25/gal	no "refining"

source: http://www.eia.gov/petroleum/gasdiesel/ 10/3/2102

$60/bbl estimated breakeven (wood)

Commercial Timeline, Current Status



Conclusions

- The IH^2 technology is
  - a cost-effective catalytic thermochemical process that converts biomass directly to hydrocarbon fuels / blend stocks
  - self-sufficient and self-sustaining with little impact on the surrounding environment needing only transport in/out of the site
  - feedstock agnostic, able to consume broad range of biomass straight, mixed and varied feeds including MSW and algae
  - <u>not</u> gasification/FT based
  - scalable from 40 to ≥3000mt/d feed
  - nearly carbon-neutral (LCA ≥94% GHG* reduction)
  - currently in basic engineering for multiple feed demonstrations
  - available exclusively from CRI

Thank You

Learn more at
www.cricatalyst.com/renewables