Hydrogen Generation from Biomass-Derived Carbohydrates via Aqueous-Phase Reforming

October 23, 2006

Aqueous Phase Reforming (APR)

A Revolutionary Process Platform

- Glycerine
- Sorbitol
- Glucose
- Sucrose
- Starches
- Alcohols
- Ethylene Glycol
- Lignocellulosic Biomass

Temperatures < 260^{o}C
Pressures ~450 psi

Liquid Fuels

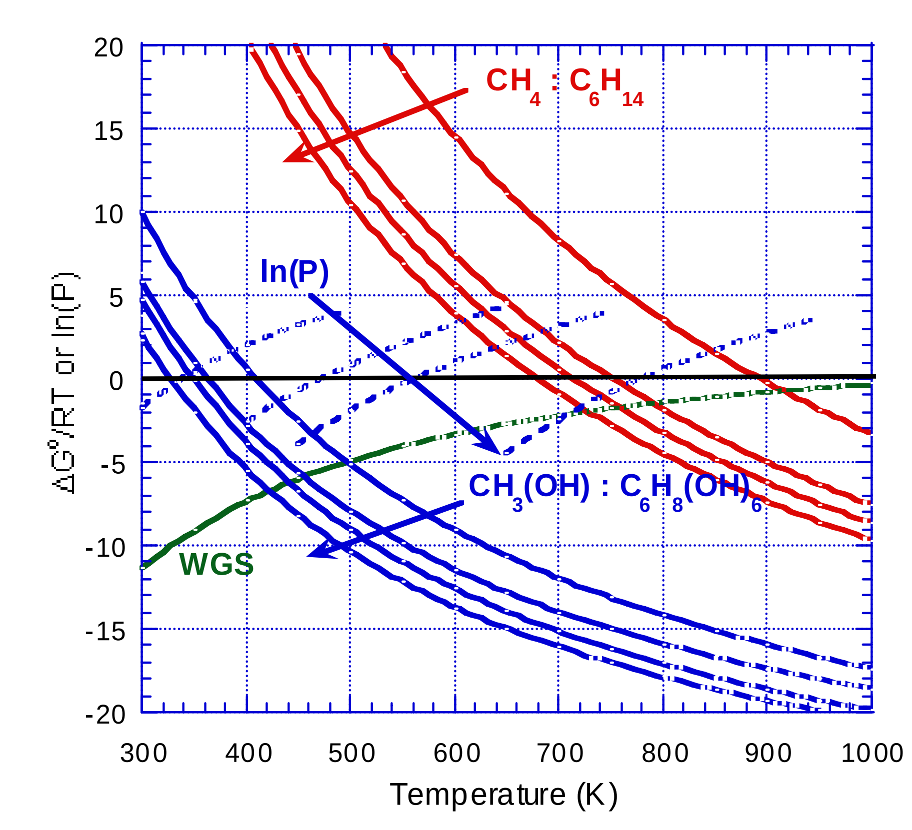
LPG

SuperNatural Gas™ (H_2/Alkane Mix)

Pure H_2

High Value Chemicals

Reforming Thermodynamics



Reforming of Hydrocarbons

$C_nH_{2n+2} + nH_2O \leftrightarrow nCO + (2n+1)H_2$

Reforming of Oxygenated Compounds

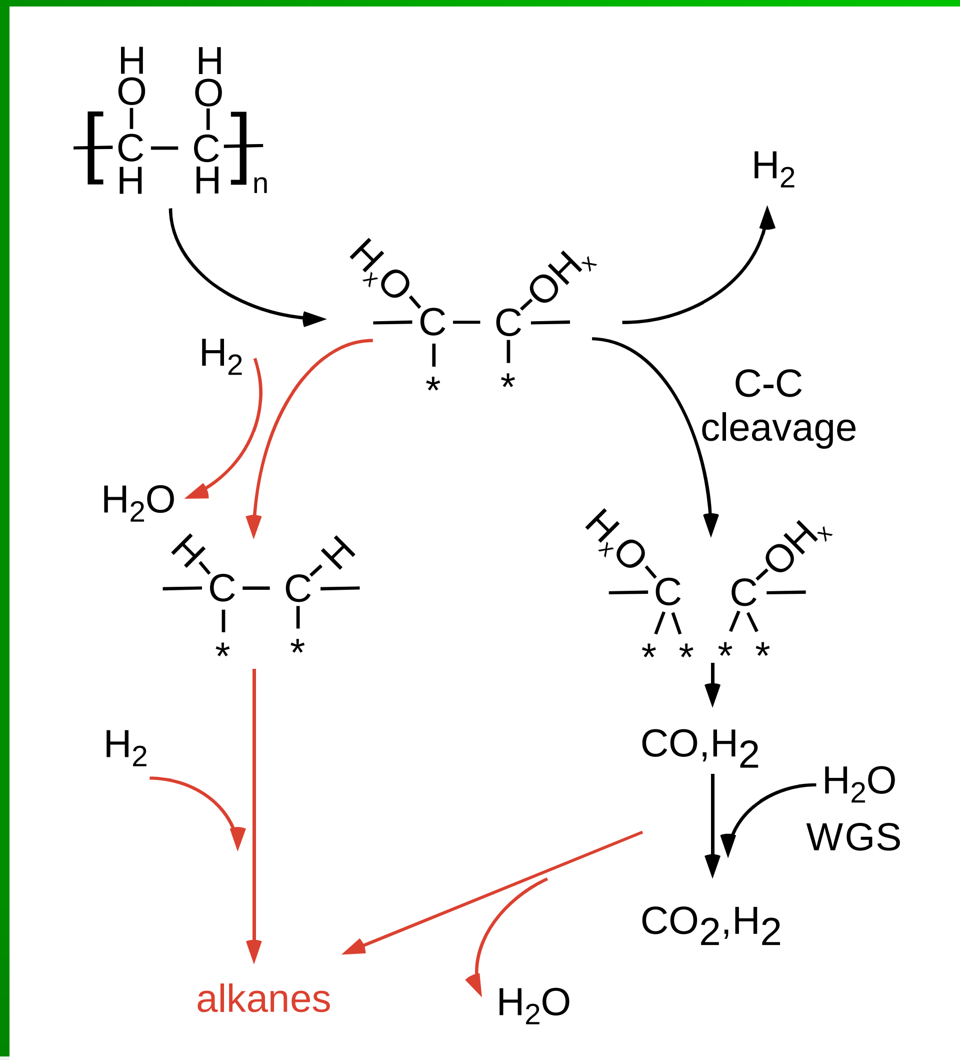
$C_nH_{2y}O_n \leftrightarrow nCO + yH_2$

Water-Gas Shift

$CO + H_2O \leftrightarrow CO_2 + H_2$

⇒ Equilibrium is favorable for reforming of oxygenated compounds at low temperatures.

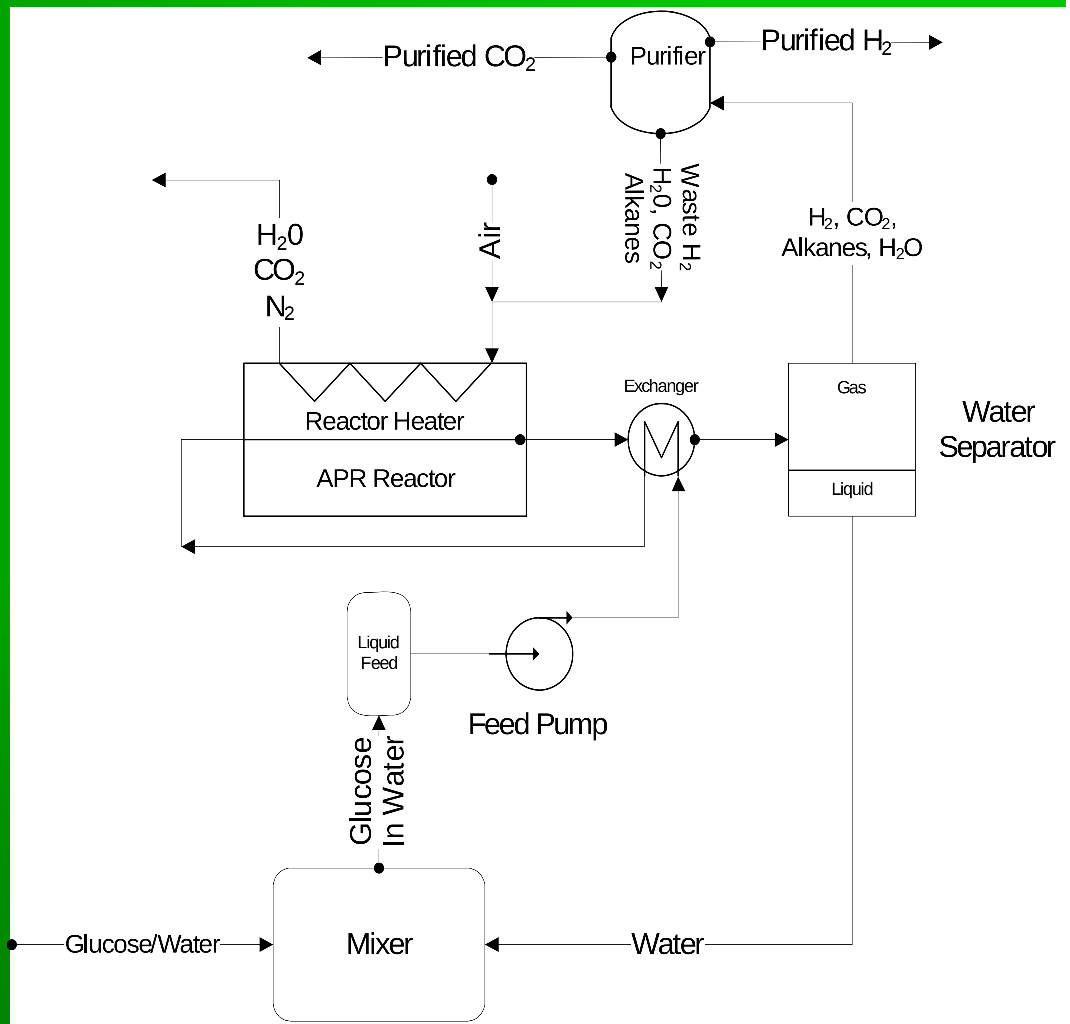
Reaction Pathways



Intellectual Property

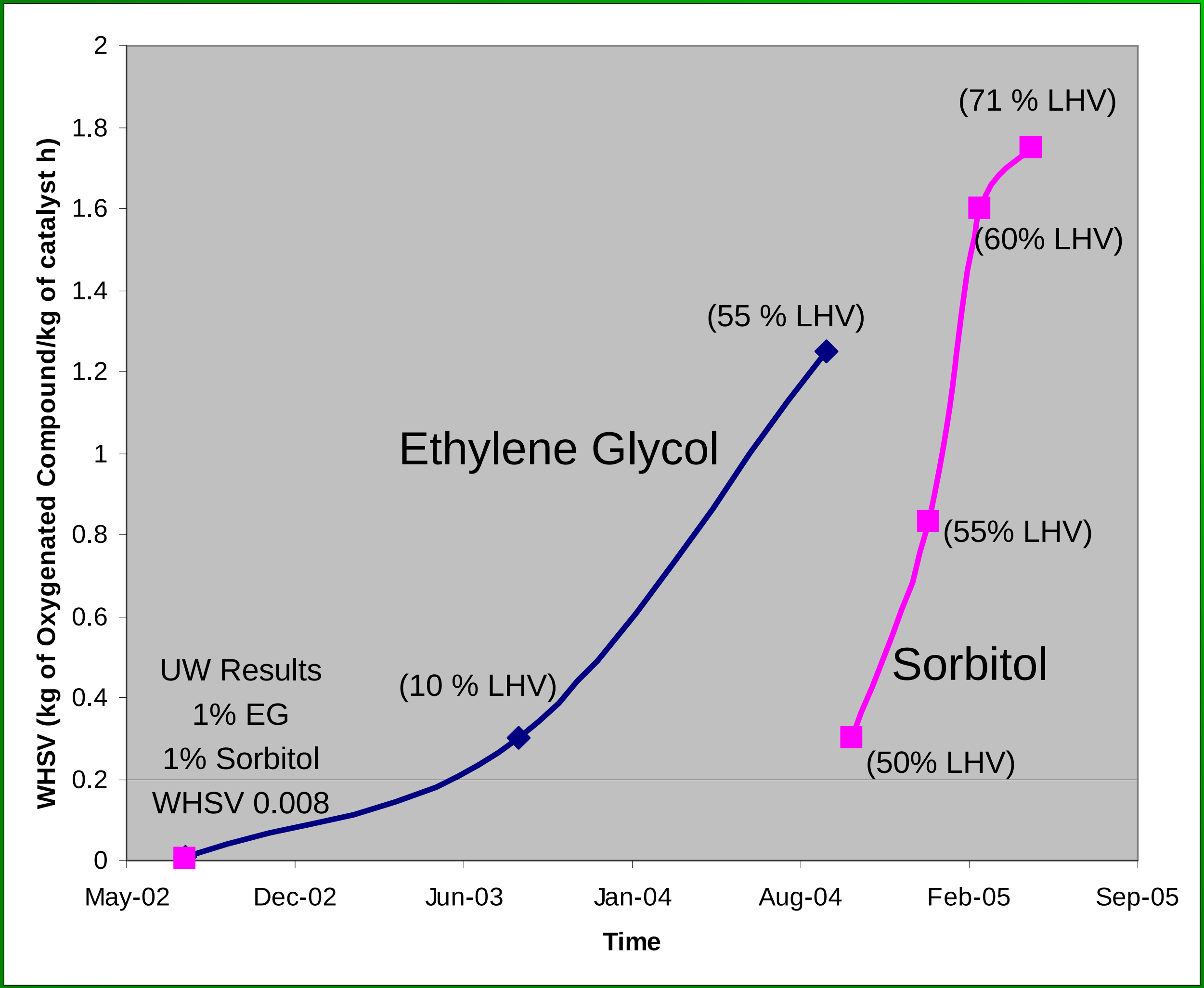
- Virent is the only company in the world that can commercialize the APR technology
- Four patents issued and licensed from the WARF:
  - One continuation pending
  - Covers all probable compositions and conditions needed for liquid phase reforming
- Virent: *Sole Technology Licensee*
  - Exclusive worldwide license
  - Right to sublicense
- Minimum of eight new patent applications to be filed this quarter by Virent

Effects of Feed Concentration



- System Efficiency
  - Combustion of Hydrogen for Process Energy Required
  - Higher Feedstock Concentrations Reduce Heating Requirements

APR Improvements



(Thermal Efficiency)
Based on LHV

Theoretical
85 % LHV

Energy Densities of Oxygenated Fuels

Fuel	Energy Density (Wh/liter)
Ethylene Glycol (1:1 H_2O:C)	3700
Glycerol (1:1 H_2O:C)	3736
Sorbitol (1:1 H_2O:C)	3809
Glucose (1:1 H_2O:C)	3585
Methanol (1:1 H_2O:C)	3572
Li-Ion Battery	200 (Current)

Energy densities based on hydrogen produced via APR process

Ethylene Glycol, Glycerol, Sorbitol, and Glucose are non-flammable, non-toxic, and have higher energy densities than methanol

Viable fuels for combined APR process and fuel cell technologies for future replacement of batteries

Virent's 1st Generation Prototype

Integrated 300 cc/min system.

99.999% pure H_2 with palladium filter.

Hydrogen Generation for Lab Use.

Can be significantly reduced in size.

DOE H_2 from Glucose

Timeline

- Start – Sept 2005
- Finish – Aug 2008 (Tentative)
- 10 % complete

Budget

- Total project funding
  - DOE share -1,942 K
  - Contractor share - 679 K
- Funding received in FY05
  - 100 K
- Funding received for FY06
  - 200 K
- Funding Reduction in FY06 resulted in limiting work to catalyst development

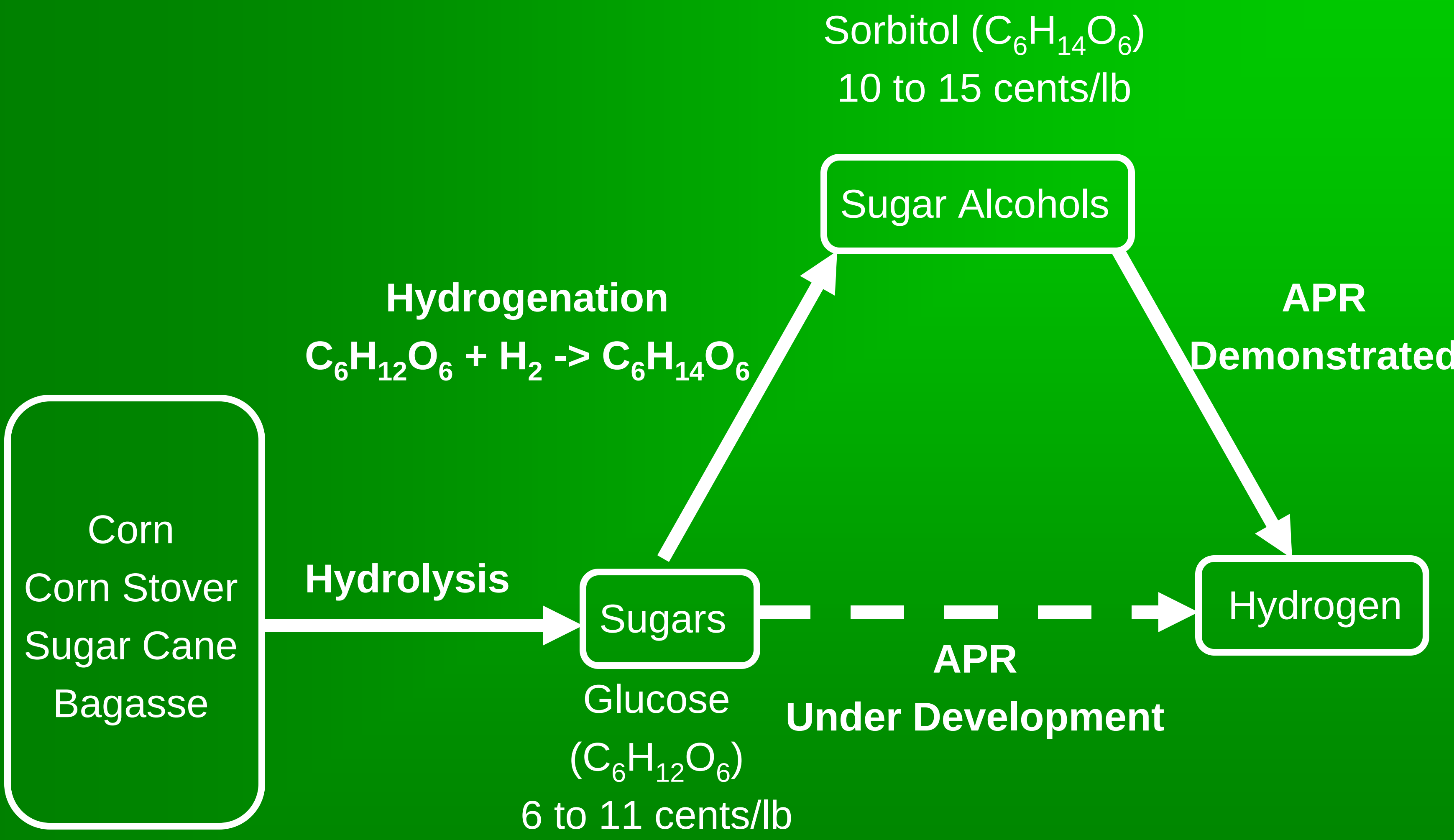
Barriers

- Feedstock Cost Reduction
  - 2005 Feedstock Cost Contribution $3.80/gge
  - 2010 Feedstock Cost Contribution $1.80/gge
- By 2010, reduce H_2 costs to $3.60/gge
  - Overall Efficiency 66%
- By 2015, reduce H_2 cost to $2.50/gge

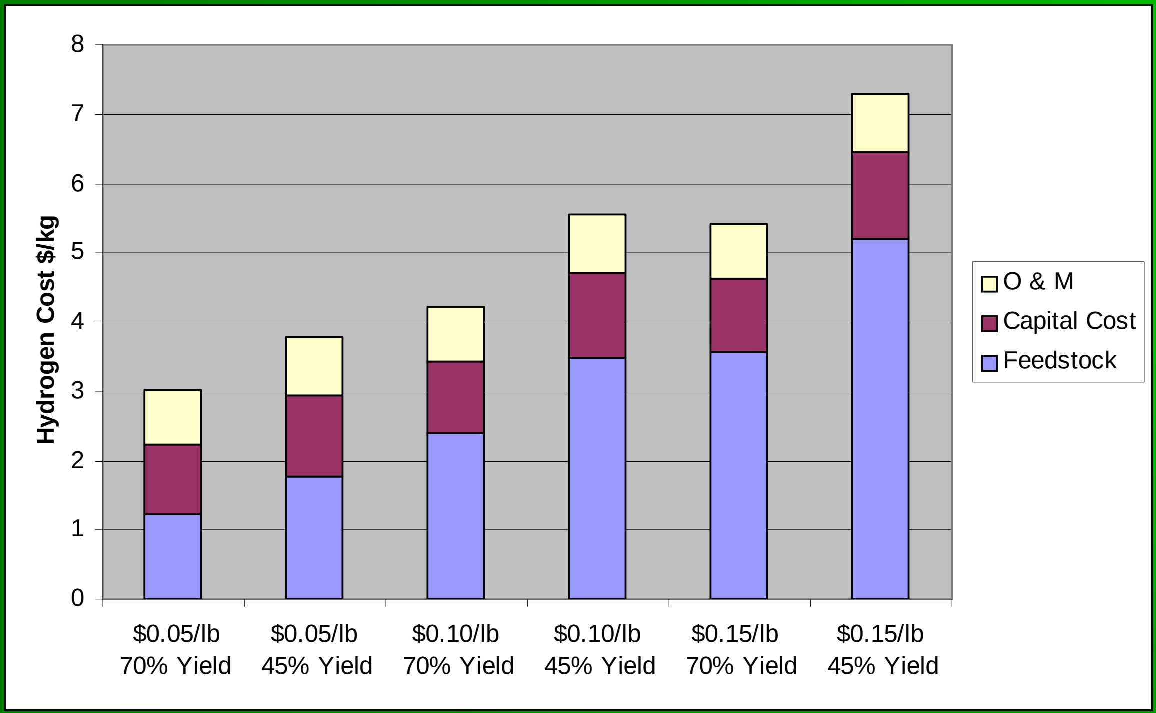
Partners

- ADM
- University of Wisconsin

Hydrogen Generation from Sugars



Projected Cost of Hydrogen Generation using the APR Process



USDOE Model
H2A

Capital Cost
Includes
APR
PSA
Compression
Storage
Dispensing

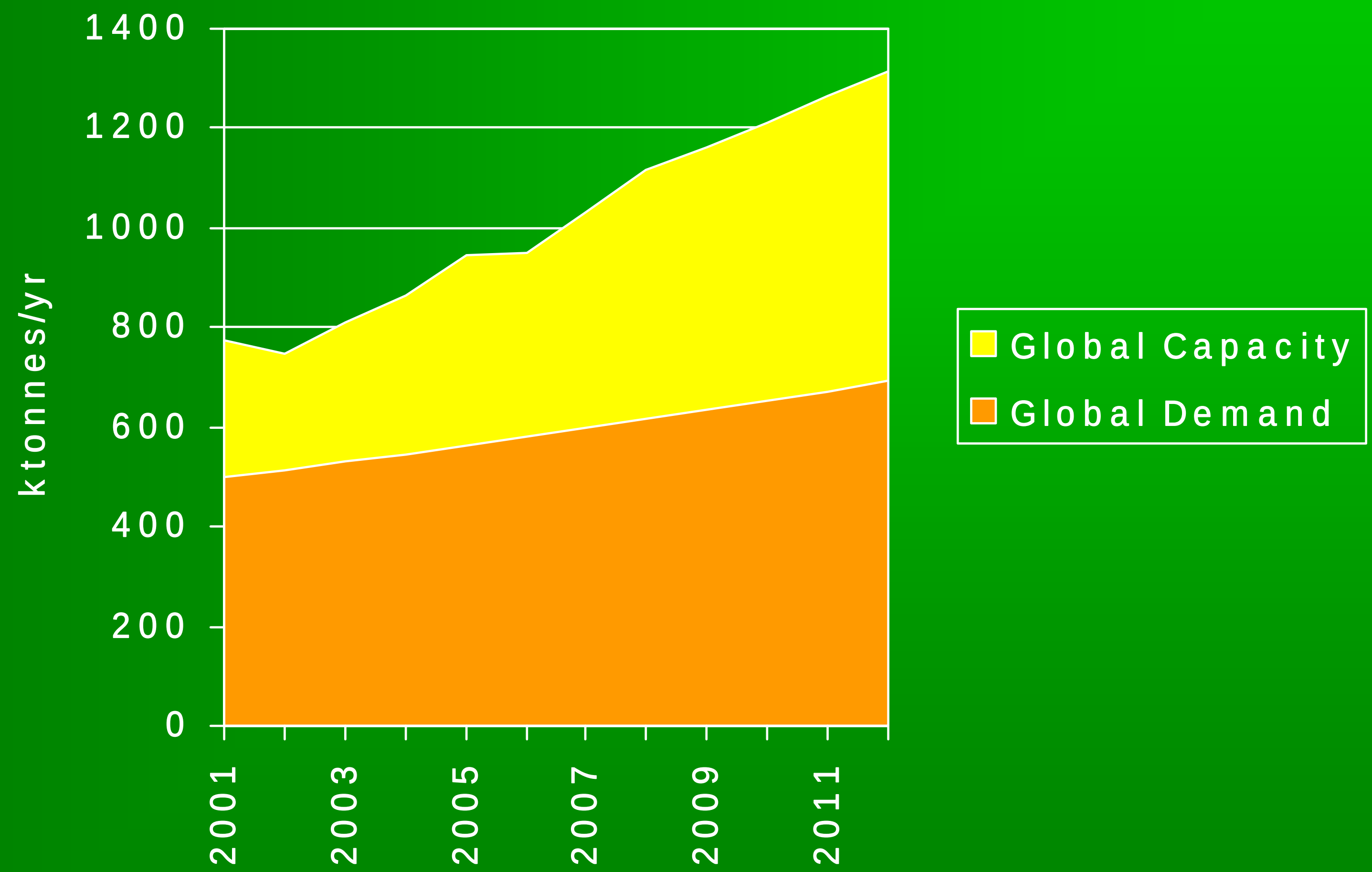
Current
Performance
Sorbitol
45% Yield

Projected
Performance
70% Yield

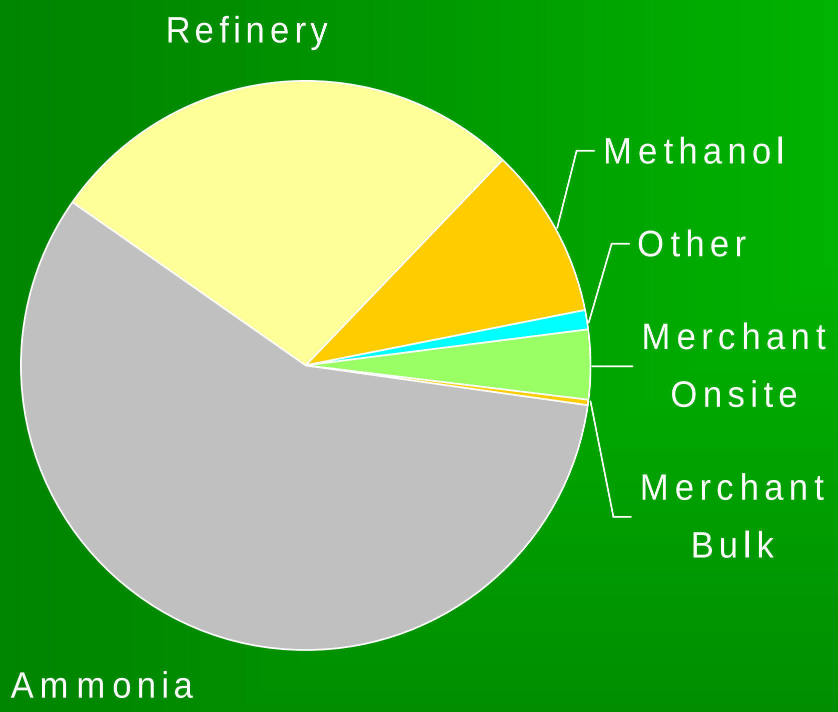
10% ROI,
7 Year Depreciation,
Reformer Replacement after 11 years
Costs do reflect $0.43/kg byproduct credit for 45% Yield case

Cost Model
6/6/2006
RDC/Virent

Glycerol Supply / Demand



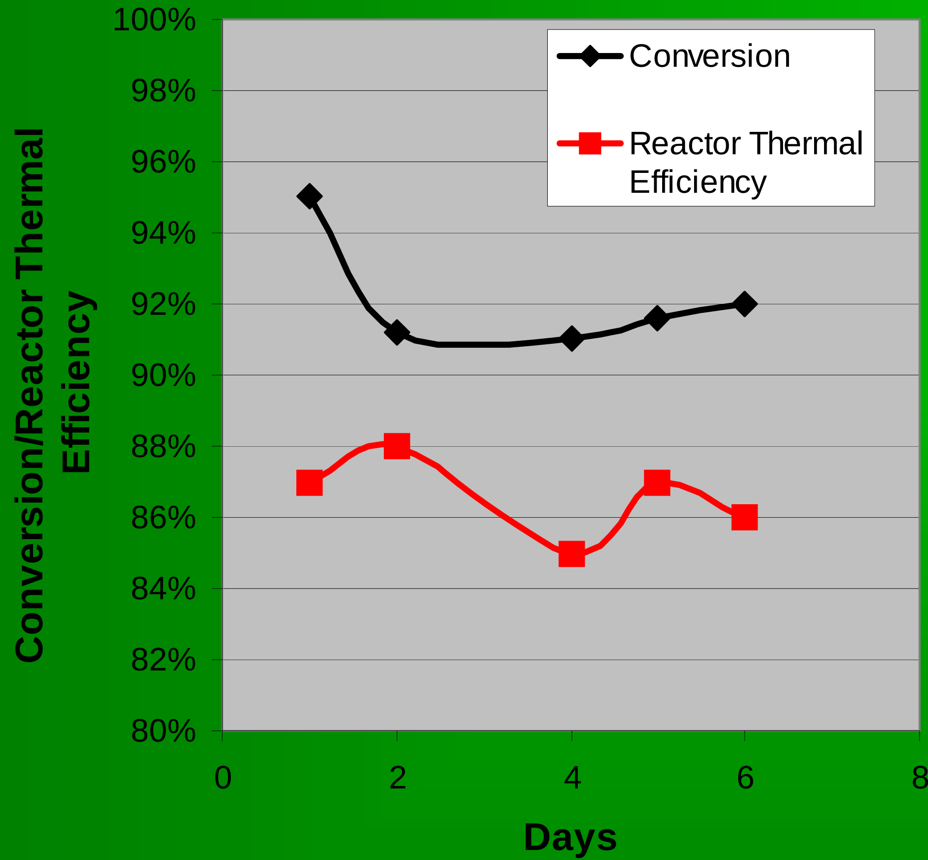
Global Hydrogen Market



40205 ktonnes of Hydrogen

Total Glycerol Projected to be available in 2012 is equivalent to 40 – 100 ktonnes of Hydrogen

Reactor Performance



Single Pass Conversion

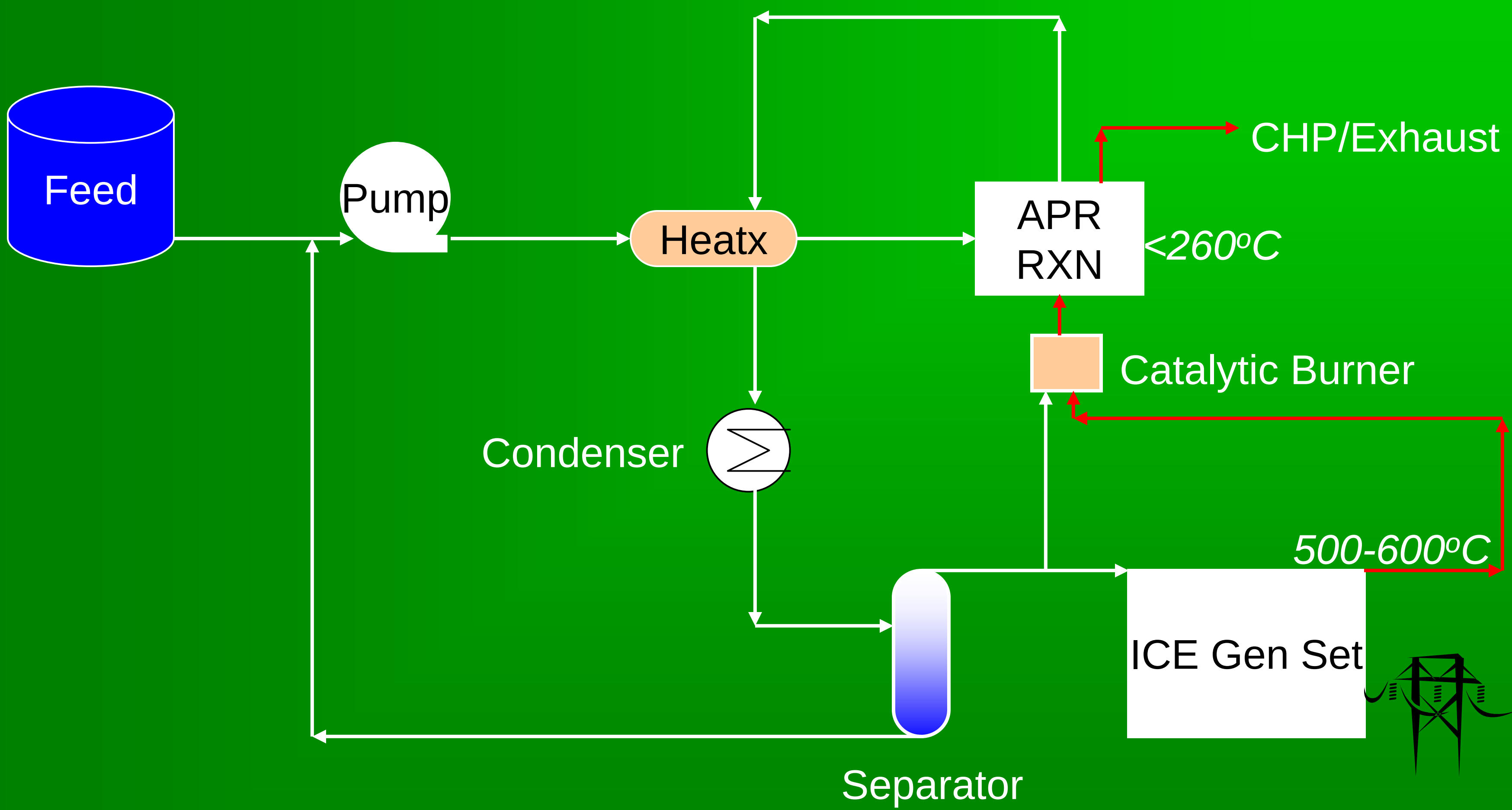
50 wt% Glycerol

Reactor Thermal Efficiency

$$100 \times \left(1.0 - \frac{\text{Process Energy}}{\text{LHV of Product Gas}}\right)$$

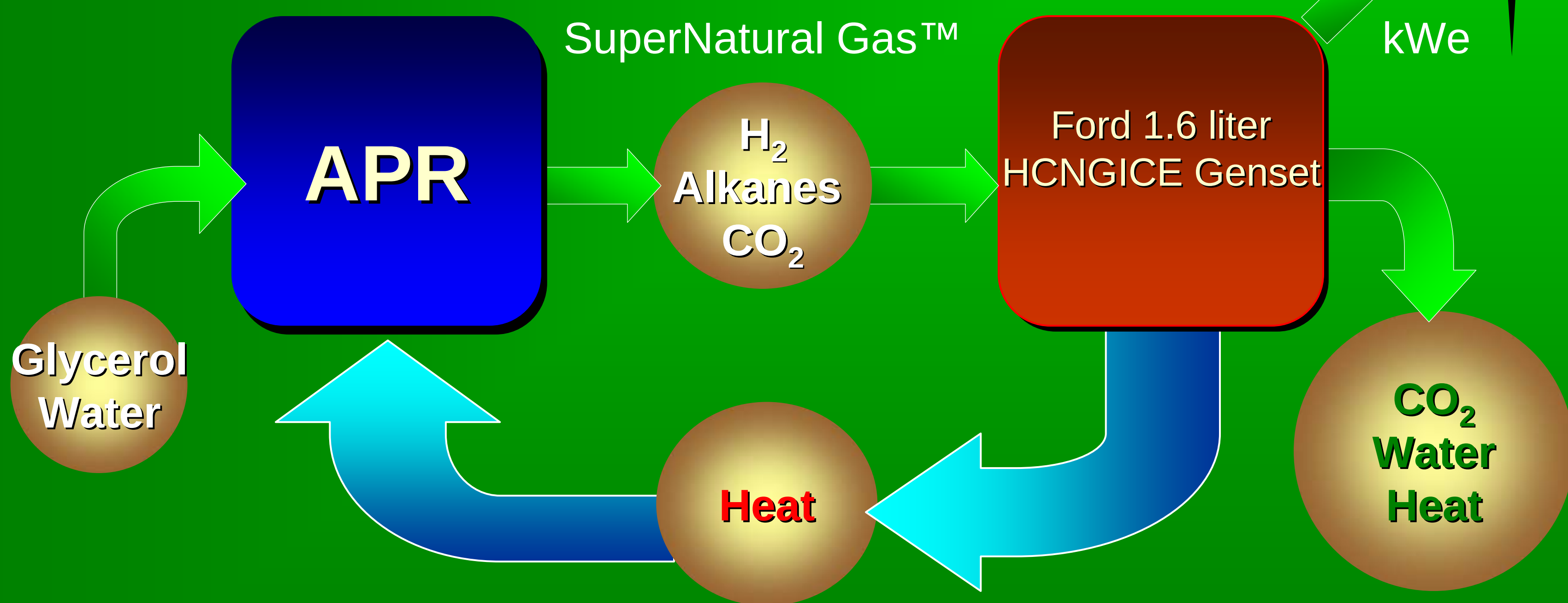
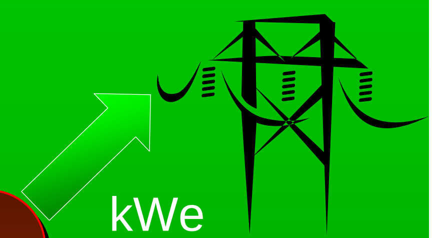
Process Thermal Efficiency
78.5 % of LHV of Feed

Basic System Flow Schematic

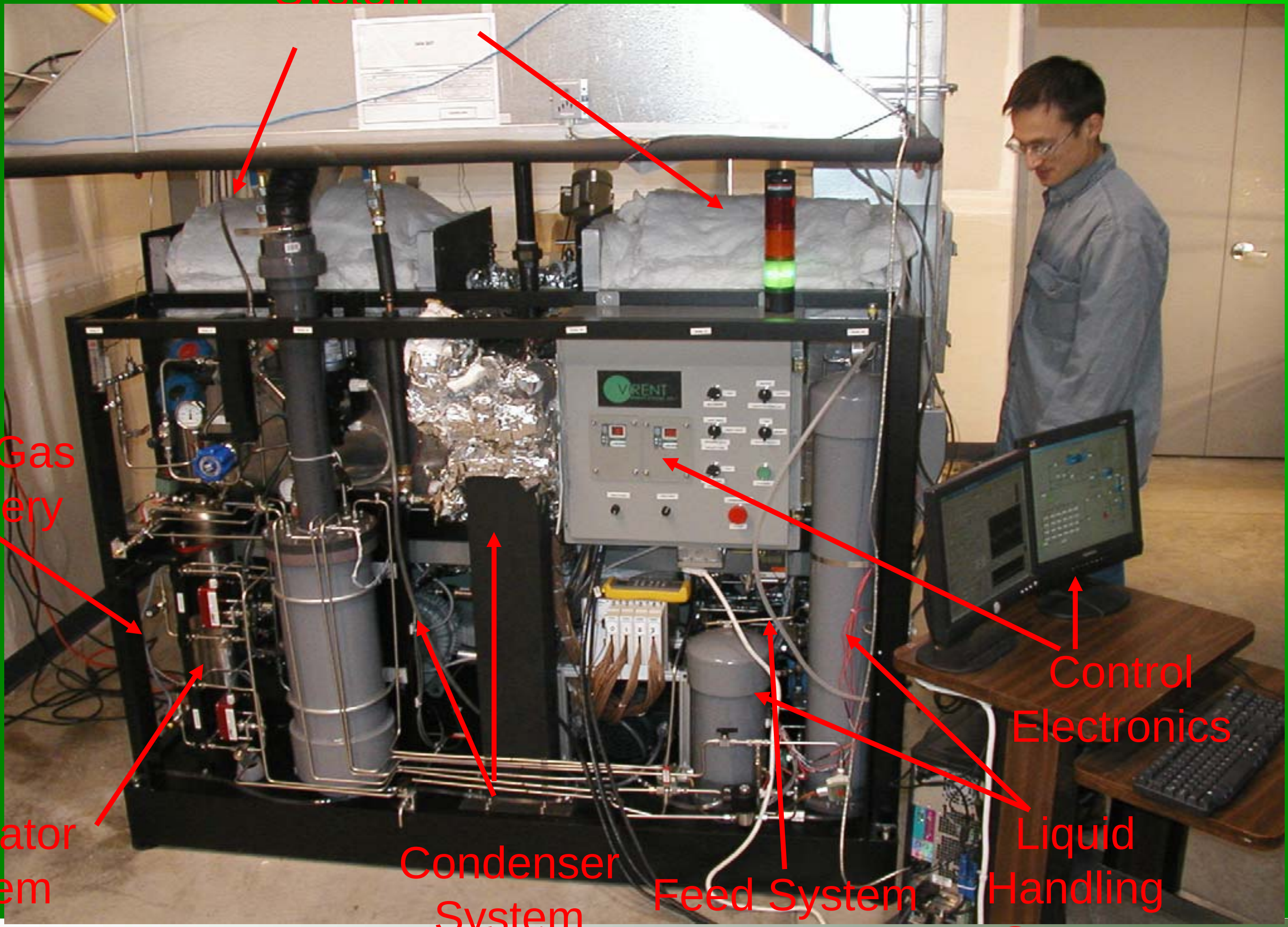


APR: ICE Integration
Madison Gas & Electric Project

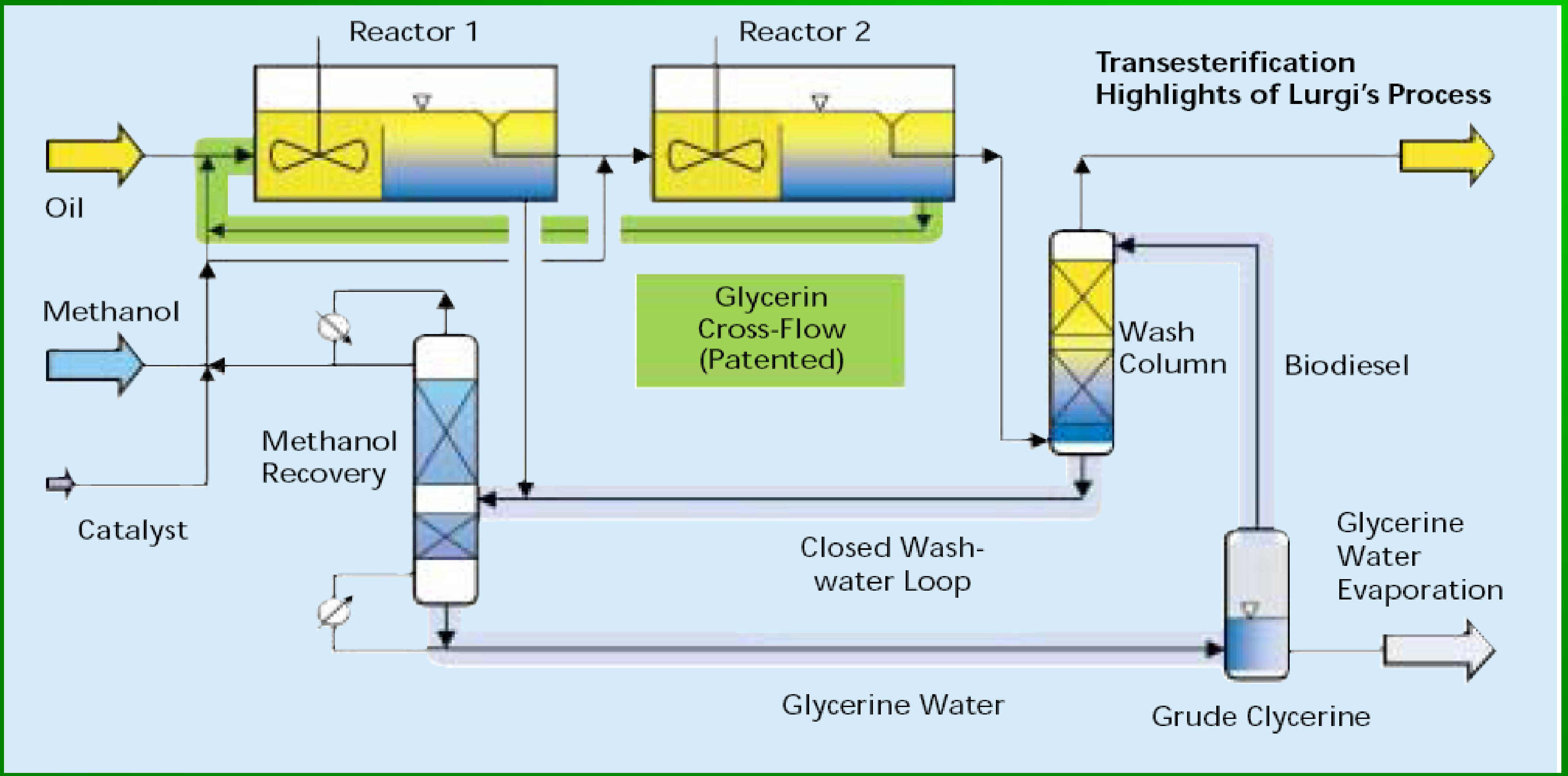
- Can operate in "unteathered" mode
- Can be run in Combined Heat and Power mode
- Can meet cost & reliability targets with near zero emissions

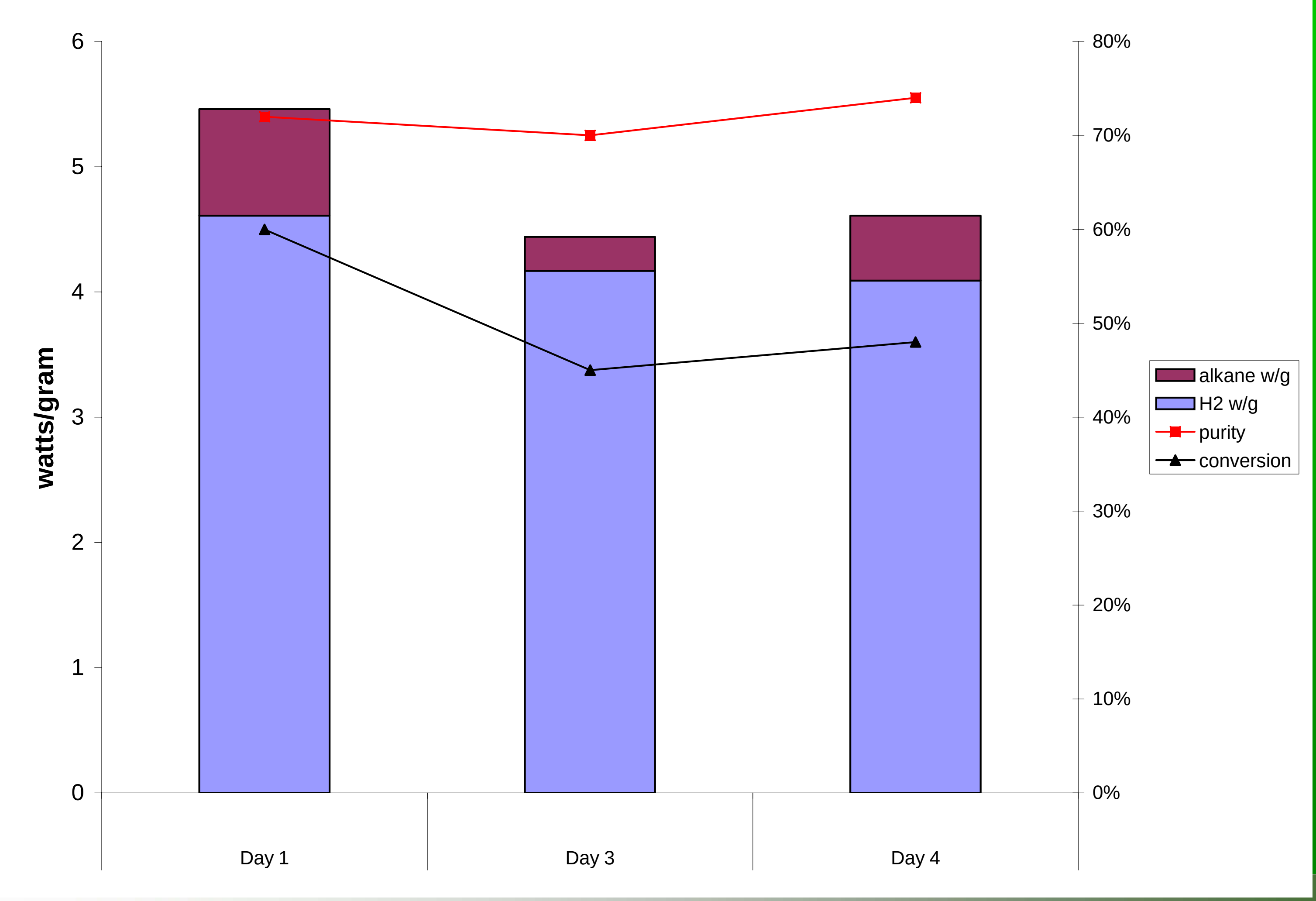
Green Energy Machine (GEM) Alpha Unit



Lurgi's Biodiesel Production from Seed Oils



Conversion of Crude Glycerol



Biodiesel Glycerol Composition

- Observed Contamination Effects
  - Methanol Increases Hydrogen Yield
  - Can Process Stream with Free Fatty Acid/Soap Content up to 3 %
  - Can Process Streams with Trace Amounts of Biodiesel
  - High Concentrations of Salts (greater than 1 %) cause plugging problems in APR reactor
  - Chloride Salts cause corrosion problems
- Evaporation Treatment
  - Reduces salt content
  - Low levels of sulfates (50 – 100 ppm)

Utilization of Glycerol