DOE Working Group Meeting

11/06/2007

Renewable Hydrogen Production Using Sugars and Sugar Alcohols

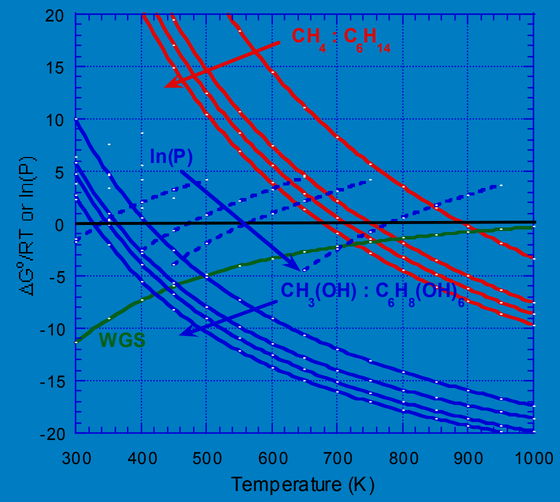
- **Problem:** Need to develop renewable hydrogen production technologies using diverse feedstocks

- **Description:** The BioForming™ process uses aqueous phase reforming to cost effectively produce hydrogen from a range of feedstocks, including glycerol and sugars. The key breakthrough is a proprietary catalyst that operates in the aqueous phase and has high hydrogen selectivity at low temperature.

- **Impact:** Sugars and sugar alcohols are capable of producing hydrogen for \$2 to \$4/gge.

- **IP Position:** Exclusive worldwide licenses have been granted, multiple new patent applications placed, and solid trade secret position established.

- **Status:** A pilot plant for hydrogen production from glycerol is in operation and one using sugar is being developed as part of a DOE funded program.

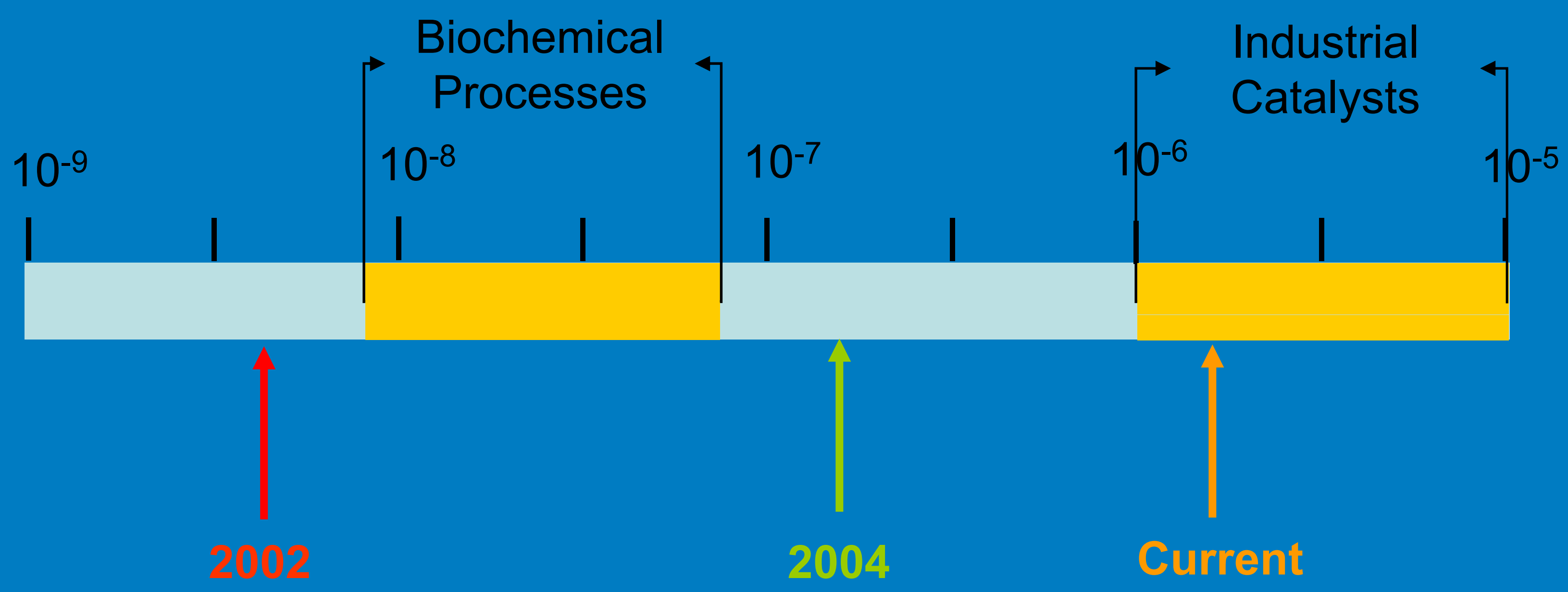


10 kg/day Hydrogen Pilot Plant

BioForming Catalyst Development

Measure of Productivity: Space Time Yield

(*moles reactant per second per cc of reaction volume)*

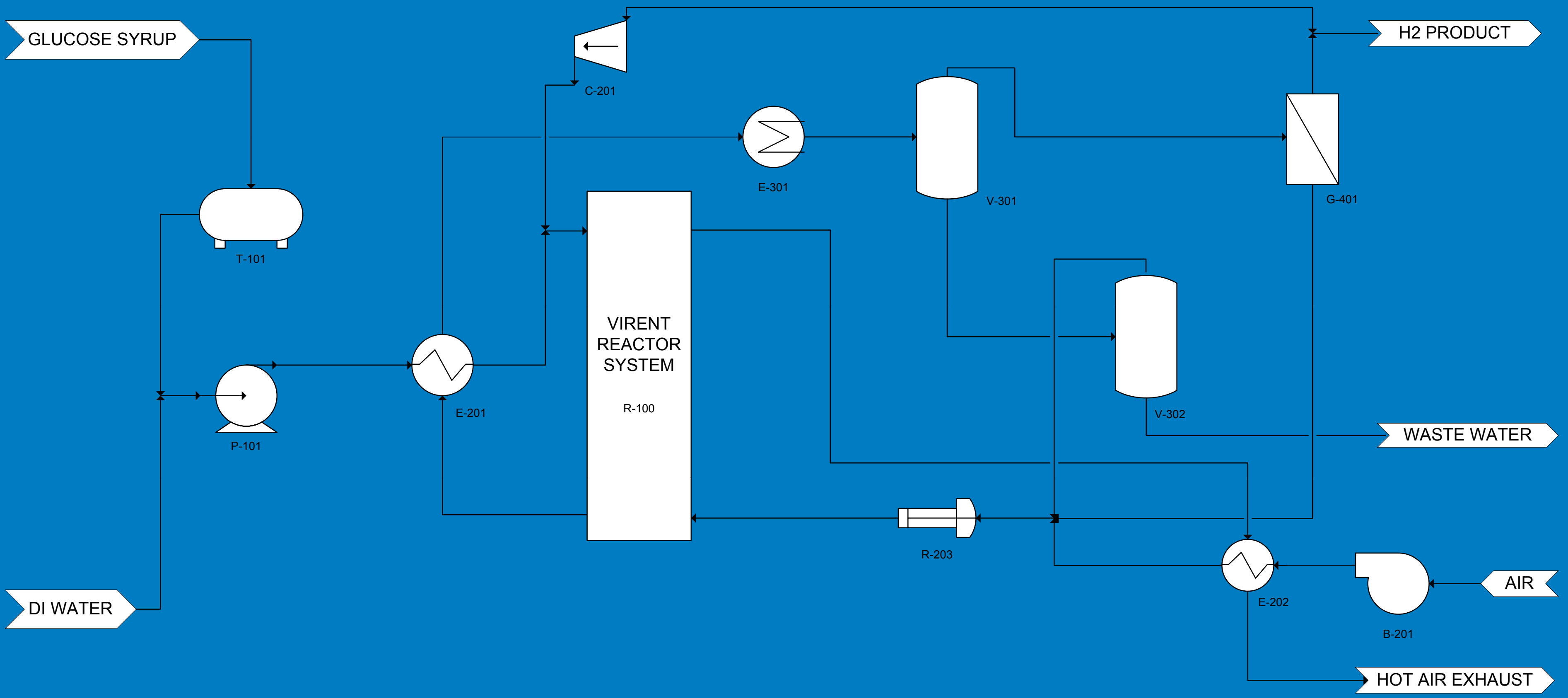


BILIWG Metrics

	Current Status	2017 Metrics
WHSV	1 - 2	5 - 10
Feed Concentration	30%	50%
Feed Conversion	100%	100%
Hydrogen Yield	> 50%	> 80%

- 2017 Metrics represents one set of catalyst characteristics that enables the Virent APR process to meet the DOE Hydrogen Cost Target

Sugar to Hydrogen PFD



T-101
GLUCOSE SYRUP
STORAGE TANK

E-201
FEED/EFFLUENT
EXCHANGER

C-201
H2 RECYCLE
COMPRESSOR

E-301
PRODUCT
COOLER

V-301
SEPARATOR

V-302
DISENGAGER

G-401
PRESSURE
SWING
ABSORBER

P-101
FEED PUMP

R-100
APR REACTOR
SYSTEM

R-203
COMBUSTOR

E-202
AIR TO AIR
EXCHANGER

B-201
COMBUSTION
AIR
BLOWER

Equipment Costing (PFD Level)

- Aspen Simulations
  - Current Data
  - Sensitivity Analysis on Process Efficiency
- Initial Sizing Estimates
  - ~3 Line specs
    - Equipment Sizing
    - Utility Utilization
- Costing based on standard graphs/charts with appropriate materials of construction and pressure considerations
- Equipment costing cross-checked utilizing price quotes for current equipment and vendor quotes
- Multiple Third Party Verification

H2A Inputs-Capital Equipment

- Uninstalled APR Reforming Equipment (Capital Investment)
  - Purchased Equipment
  - Skid Fabrication
    - Equipment Delivery and Skid Mounting
    - Instruments and Controls
    - Piping
  - Learning Curve factor (@ 5000 Units)
    - Forecourt Specific Assumptions 2005 (DTI Study)
- Installation Factor = 1.1 (H2A)

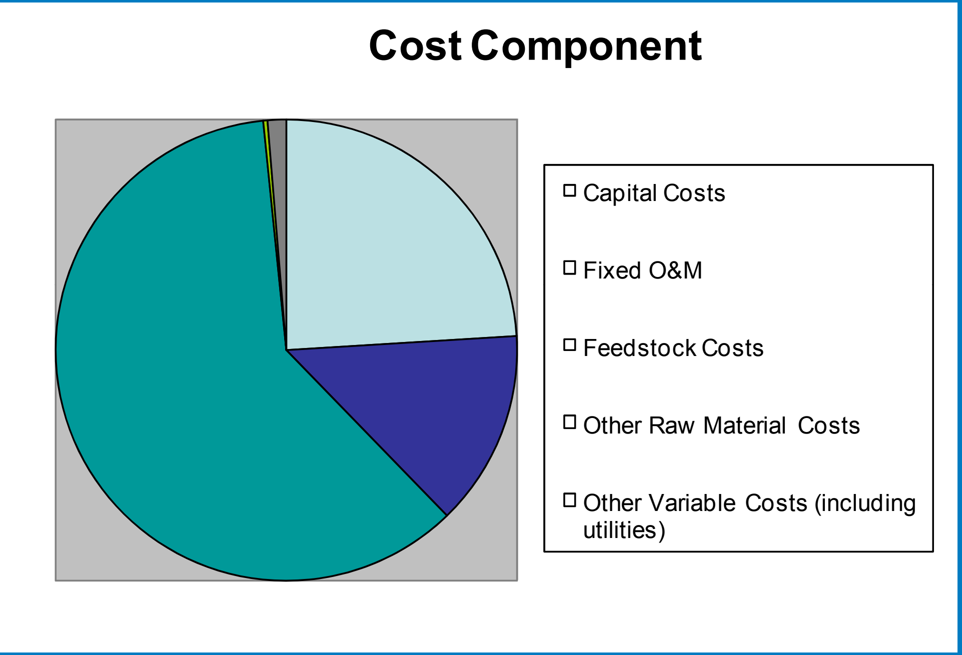
Virent APR 2017– H2A

Production Unit H2 Efficiency	70.4%	Aspen Model
Virent Package	\$ 791,000	Installed Cost
Product Handling Package	\$ 833,000	H2A
Indirect Depreciable	\$ 297,000	H2A
Feedstock *(LHV 14.1 MJ/Kg)*	12.2 kg / kg H2	Aspen Model
Other Raw Materials	~ \$0.011 / kg H2	Aspen Model / H2A
Utilities	\$13,400 / yr	Aspen Model / H2A

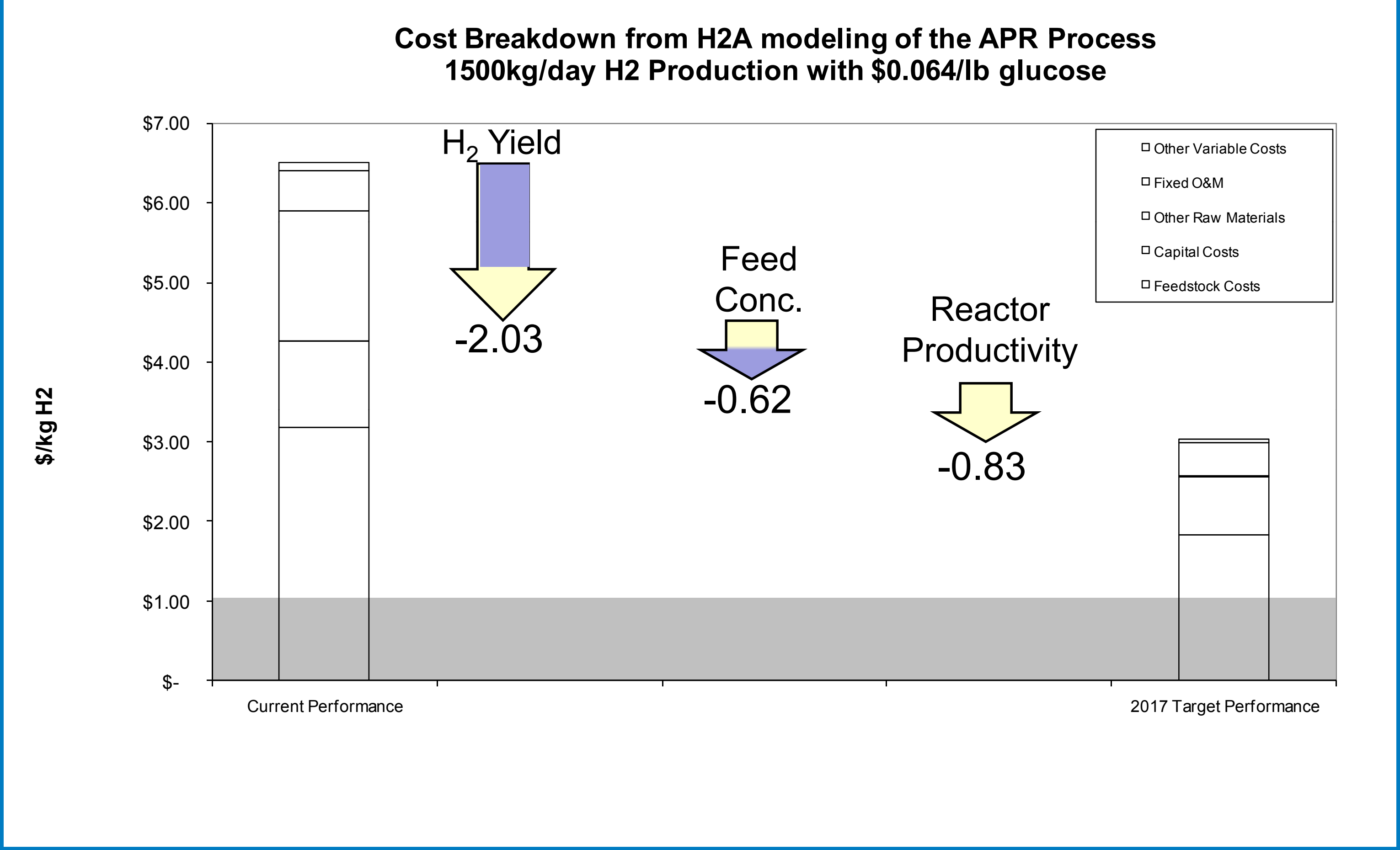
2017 Cost Breakdown

Specific Item Cost Calculation

Cost Component	Cost Contribution ($/kg)	Percentage of H2 Cost
Capital Costs	$0.727	24.0%
Decommissioning Costs	$0.000	0.0%
Fixed O&M	$0.415	13.7%
Feedstock Costs	$1.834	60.6%
Other Raw Material Costs	$0.011	0.3%
Byproduct Credits	$0.000	0.0%
Other Variable Costs (including utilities)	$0.040	1.3%



Cost Breakdown



Uncertainties

- Cost of Feedstock (> 60% of Total Cost Stack)
  - Developing a feedstock flexible process
  - Process design maximizes feedstock utilization
- Catalyst Performance Metrics
  - Hydrogen Yield
  - Feed Concentration
  - Reactor and Catalyst Productivity
- Impact of Mass Production
  - Utilize learning curve methodology
  - Continue to investigate other approaches
- Capital Cost Estimation
  - Incorporate Industry Best Practices
  - Independent 3rd Party Review
  - Utilize Vendor Cost Estimates where Possible

Response to Reviewer Comments

- Not much has been accomplished.
  - Periods of limited funding have resulted in delays to the original project plan
  - Technology Progress
    - 10 X reduction in hydrogen cost
    - 700 X scale-up reactor demonstrated

- Performance is behind conventional reforming technology
  - Reforming of oxygenated hydrocarbons like glycerol and glucose using conventional technology is not favorable.
  - Conventional reforming has been in existence since the early 1900's- APR was discovered in 2002.

Response to Reviewer Comments

VIRENT

- ADM is the only company interested, potentially to use a thermochemical route for corn sugar.
  - Virent has several strategic investors , industrial collaborators, and other government agencies interested in using sugar as a feedstock for hydrogen production.
- No information on the commercial availability of catalyst.
  - Virent is developing the catalysts for the aqueous phase reforming of carbohydrates. Catalysts will be scaled and manufactured by supplier/partners using Virent’s recipe.