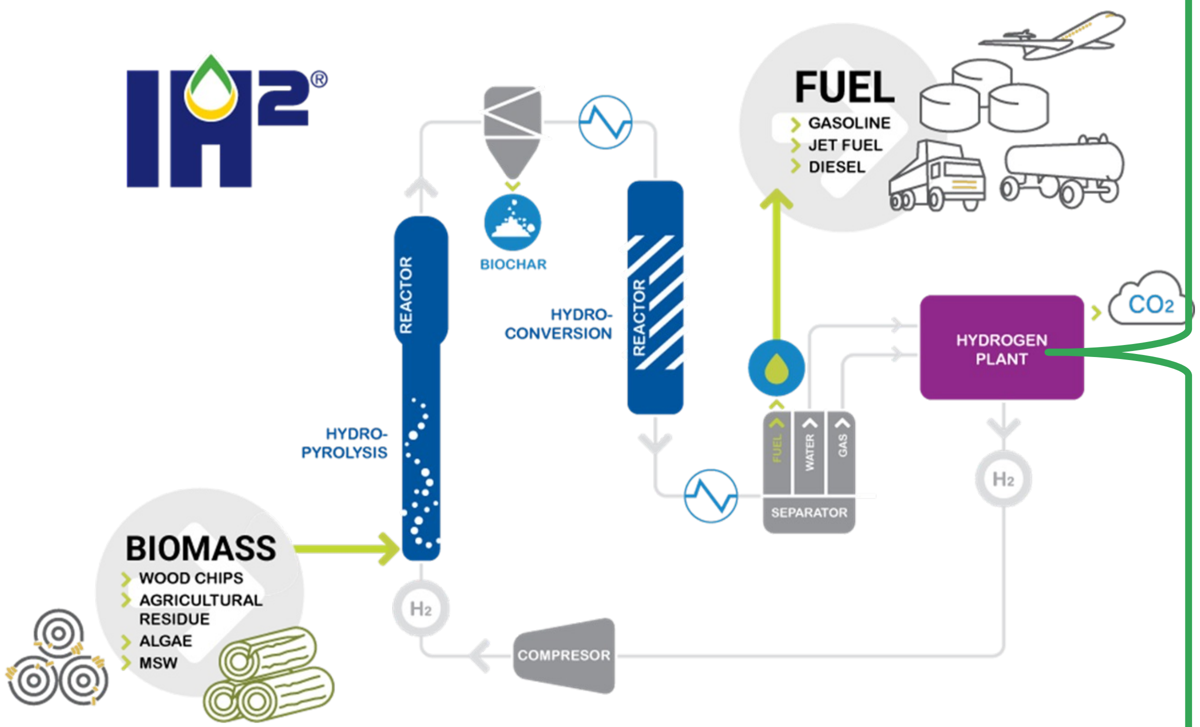
DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review



Integration of IH² with Cool Reformer for the Conversion of Cellulosic Biomass to Drop In Fuels DE-EE0008919 WBS 3.5.1.101

April 3, 2023
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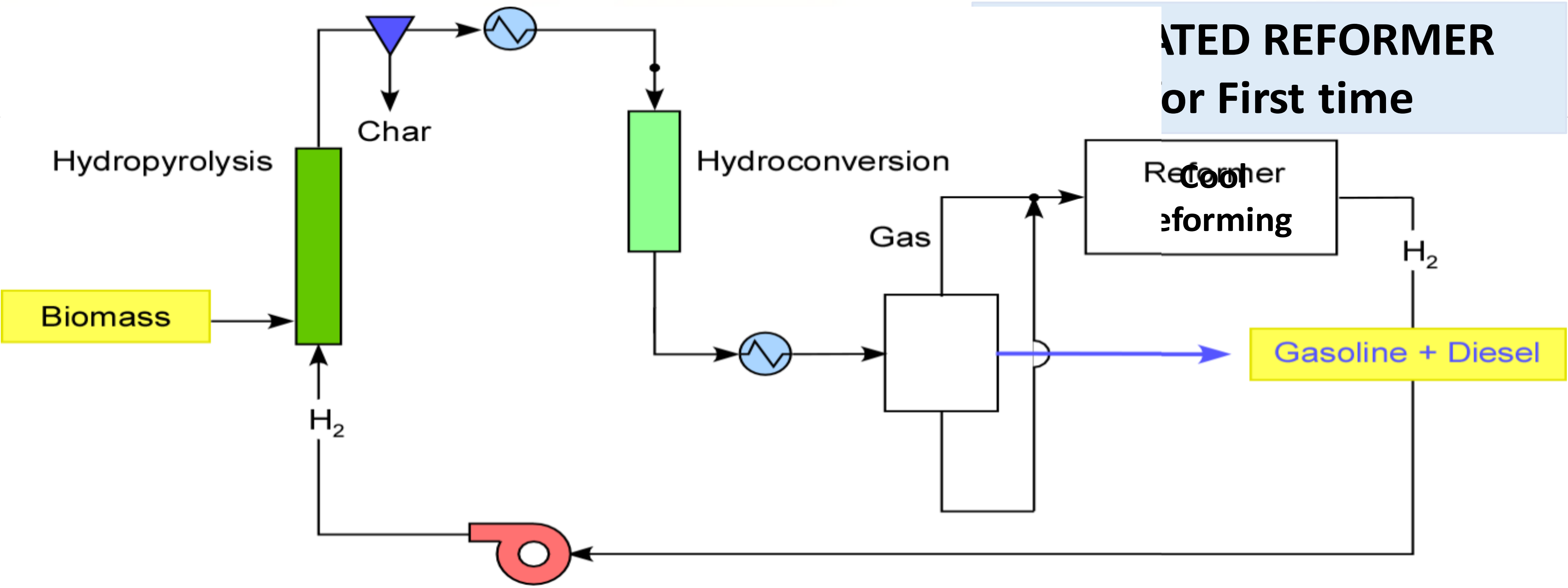
PROJECT OVERVIEW

Cool Reforming Integrated with IH² (Integrated Hydropyrolysis and Hydroconversion)



- Directly make desired products
- Run all steps at moderate hydrogen pressure (100-500 psi)
- Utilize C_1-C_3 gas to make all hydrogen required
- Avoid making “bad stuff” made in pyrolysis – PNA, free radicals

Typical IH^2 Product Yields and Quality

	IH^2 Process Yields
Liquid yield, wt.%	26
Liquid Yield, GPT	86
Biogas yield, wt.%	24
Char yield, wt.%	18
Water yield %	36,5
Liquid quality, wt.% O	<0.4
Liquid quality, % gasoline	70
Liquid Quality, % diesel	30
Hydrogen requirements %	4.5
Hydrogen production % (from modeling)	4.5
Net hydrogen requirements % (calculated)	0

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Overall project objectives are to:

- Produce drop-in gasoline, jet and diesel for < \$2.5/GGE
- Show hydrogen (H_2) self-sufficiency of the integrated IH^2 and Cool Reformer system through tests at the pilot scale
- Show the integrated system is simple and low cost through testing, engineering and technoeconomic analysis

APPROACH

Approach - Integration of IH^2 with Cool Reformer for the Conversion of Cellulosic Biomass to Drop In Fuels

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- Demonstrate that all the H2 needed for IH^2 can be made by reforming IH^2 product biogas with a simplified integrated reformer for 250 hours
- Complete an engineering study showing the effect of simplified reformer and use of several other engineering improvements to reduce cost
- Overall goal- Reduce Capital and Operating Costs of IH^2 by 25% by using Cool reforming plus other engineering improvements

Terry's new Process Axium:- for best results don't pair a high tech conversion system with antiquated support systems.

Advantages of Cool Reformer

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- **Can handle CO, CO_2 and olefins in feed with no removal/pretreatment steps**
- **Improved active catalyst – very robust**
- **Simple low cost design**
- **Can use compact electric reformer**
  - **Small footprint/modular- <1/10 size of standard reformer**
  - **no CO_2 emissions**

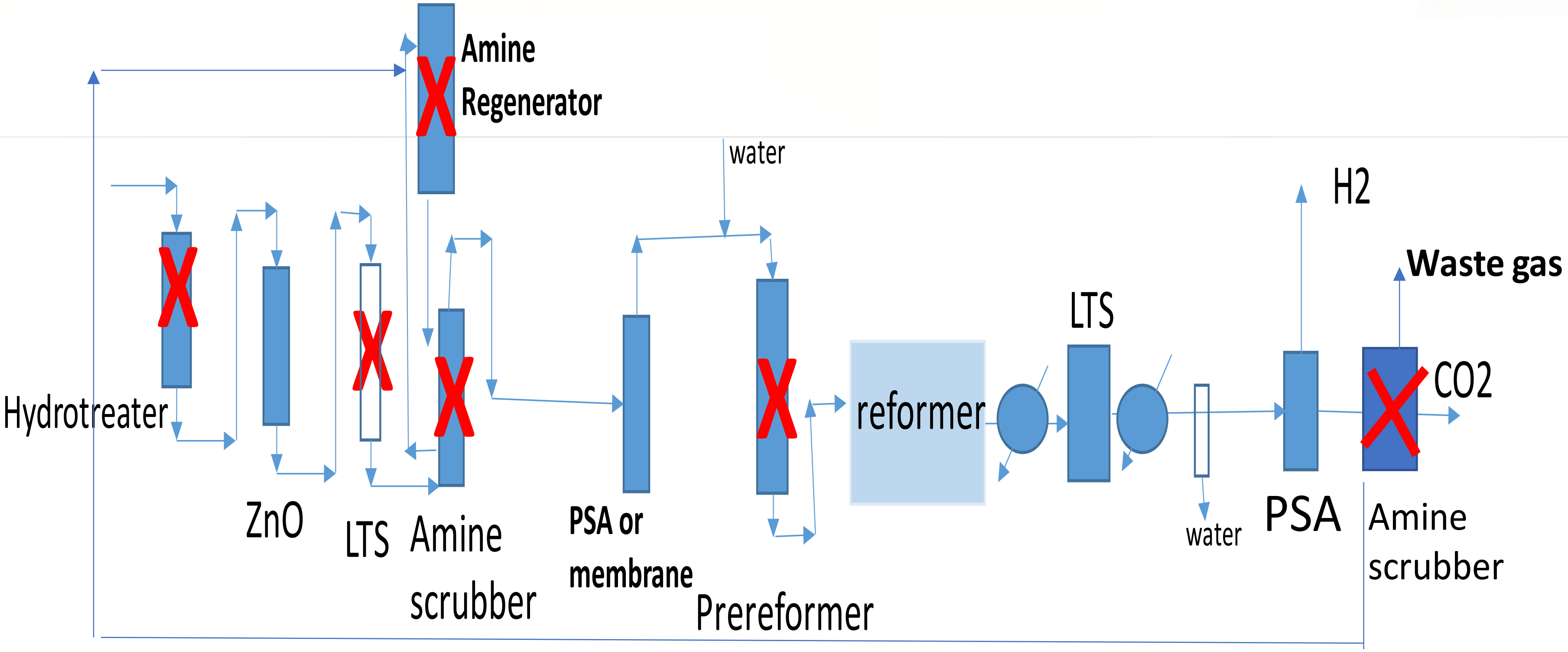
Cool Reformer Reactions

(I) $H_2O + CH_4 \rightarrow CO + 3H_2$	CO and H_2 formation (800^{o}C)	Reactor 1
(II) $CO_2 + CH_4 \rightarrow 2CO + 2H_2$	CO and H_2 formation (800^{o}C)	Reactor 1
(III) $CO_2 + H_2 \rightarrow H_2O + CO$	Water-gas shift to equilibrium	Reactor 2

Cool reformer = Reactor 1
Low temperature Shift in reactor 2

What is special about the Cool Reformer :
Super active stable catalyst which can do steam methane reforming plus dry reforming
Can handle CO, CO2,olefins in feed
Can be electric reformer – with small footprint

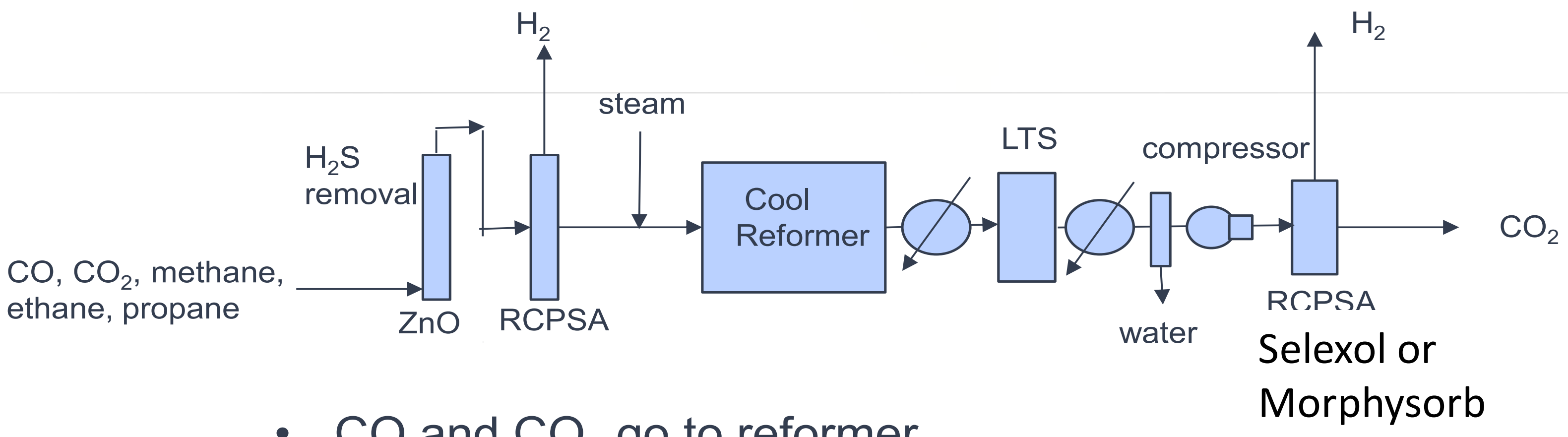
Process Steps Removed from Current Hydrogen Plant design by use of Cool Reformer System



Cool reformer system requires less equipment

Simpler = better for small skid mounted designs

Simplified Gas Feed and Post Treatment for Cool Reforming

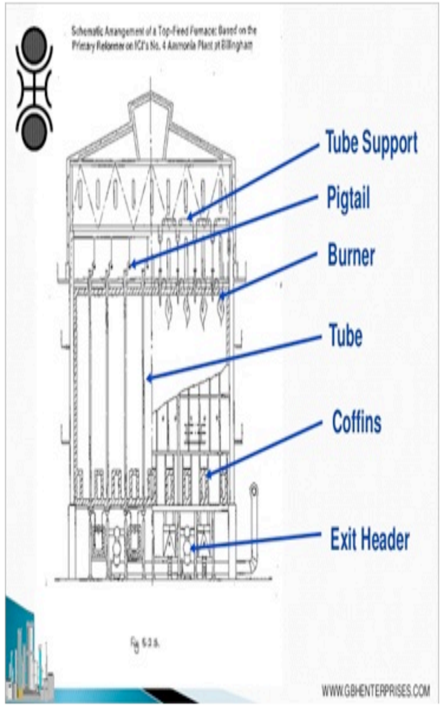


- CO and CO_2 go to reformer
- No need for gas pretreatments
  - No gas hydrotreating to remove organic sulfur
  - No low-temperature shift (LTS)
  - No amine scrubbing to remove CO_2
- Simple reformer with new catalyst
  - No prereformer
  - Lower temperature operation
- Estimated cost* for 500t/d wood feed is <$23 million
- Significant Energy reduction over amine scrubbing

* Estimated from component literature database

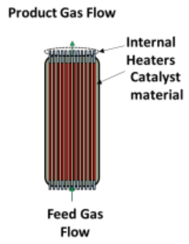
Technical Concept: Electric Reformer How does it work?

Typical Commercial Scale Stream Methane Reformer



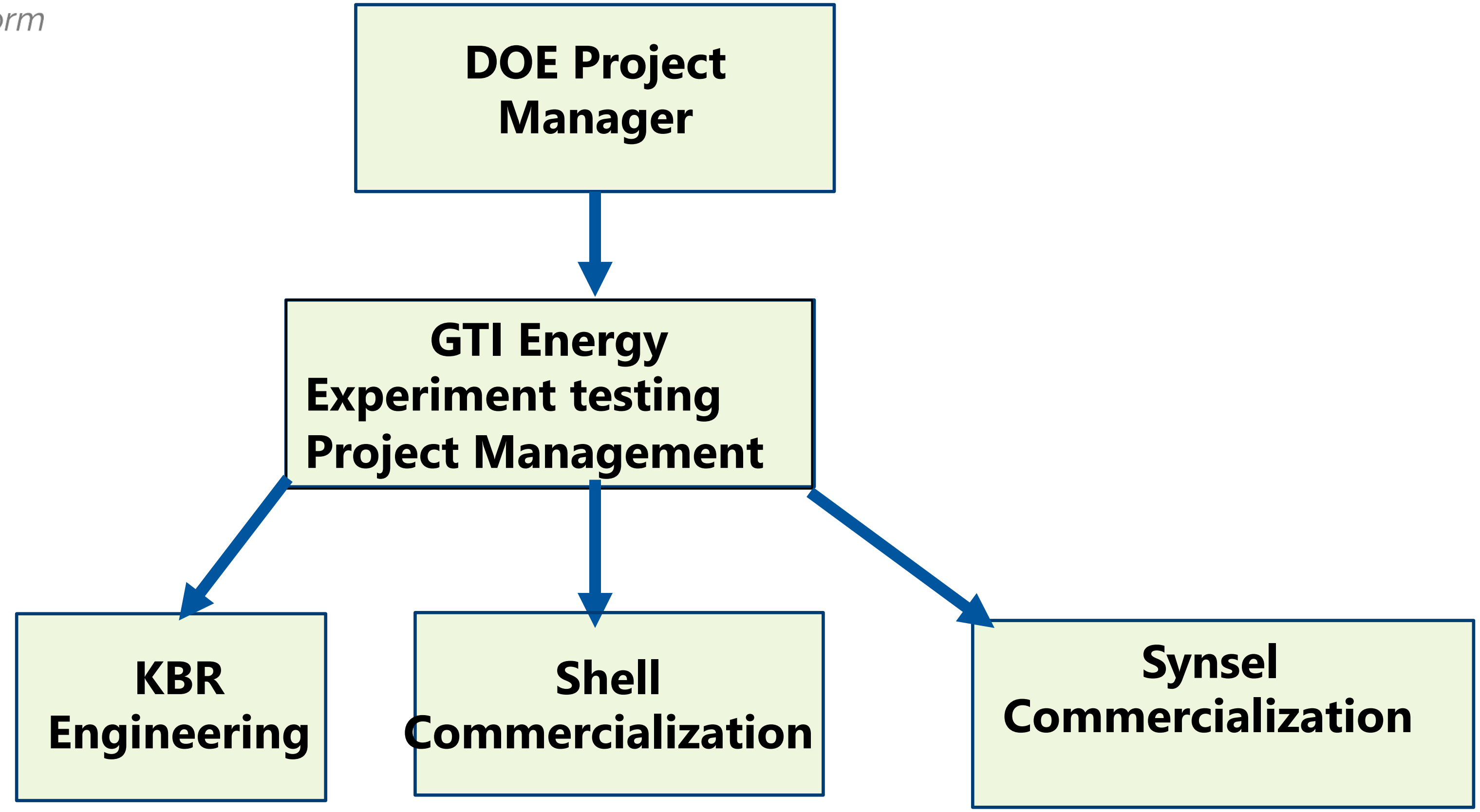
Moving from Gas fired reformer to electric reformer

GTI's Electric Reformer Design with Internal Heating Elements



Low Cost
Small Footprint
No CO2

Cool Reformer PROJECT TEAM



Shell owns all the rights to IH2

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TIMELINE

Nov 2019 | Nov 2022 | Sept 2023

BP1

- Project kickoff
- Initial verification

BP2

- **Integration of reformer and IH2**
- **Shakedown of reformer +IH2**
- **Short test/verification of Integrated system**

BP3

- **Long test/verification integrated system**
- **Engineering study**
- **Final Report**

Potential Risks for the Project

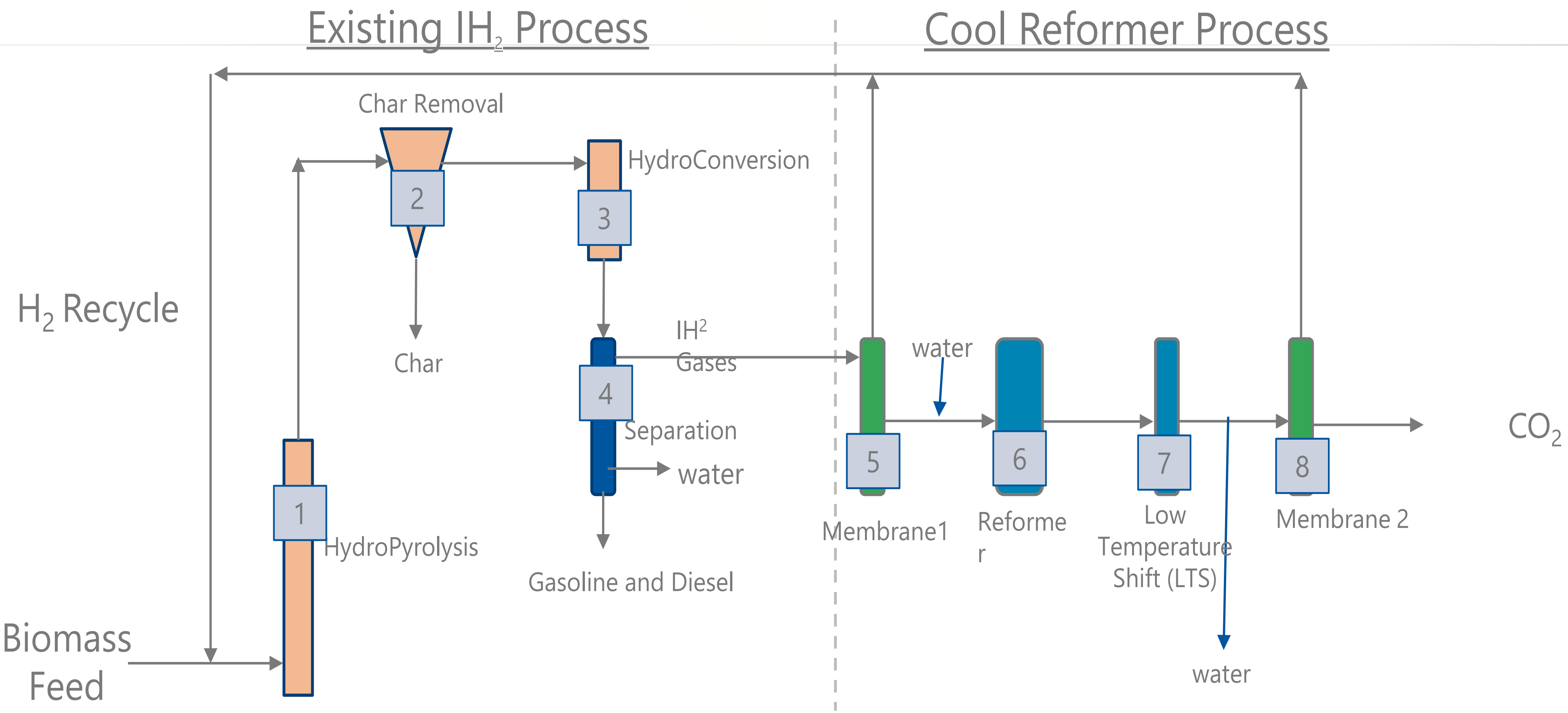
- **Risk of IH^2 unit upsets causing reformer issues**
- **Risk that we would be unable to show Hydrogen self sufficiency**
- **Risk of coking or catalyst deactivation with reformer feed containing CO, CO2 methane ethane and propane.**
- **Risk of Heater burn outs on electric reformer**
- **Risk that Cool Reformer plus other improvements can’t reduce capital and operating costs by 25% as planned**

So far everything worked well with no issues of any kind

PROGRESS AND OUTCOMES

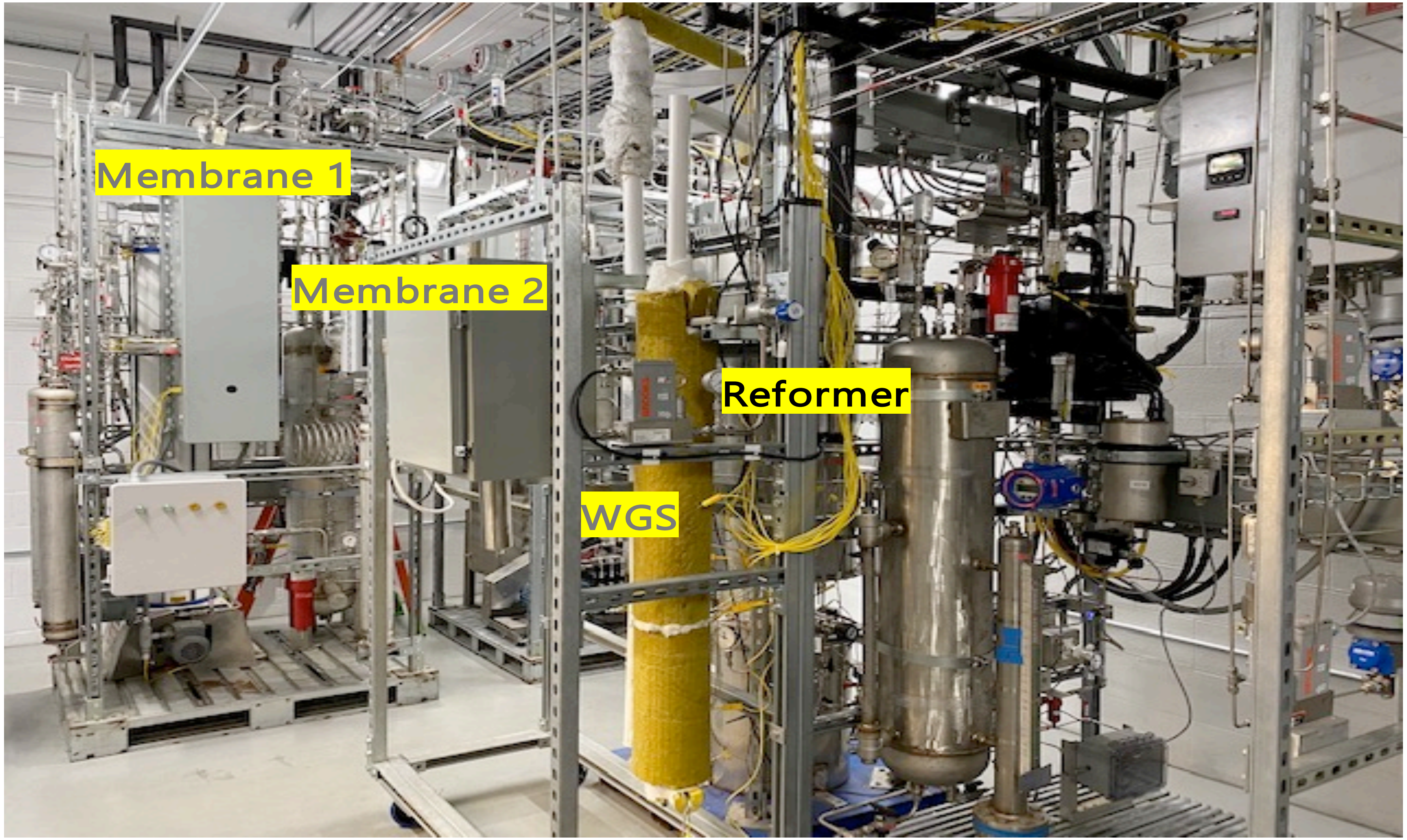
Integrated Testing Diagram

Block Flow Diagram for the IH² and Cool Reformer



IH^2 Pilot Plant

Cool Reformer Pilot Plant



Key Milestones

Completed Milestones

1. Initial verification on lab scale unit
2. Integration and shakedown of the Cool Reformer and IH² unit
3. Short term testing (50 hours)of the Integrated Cool Reformer and IH² Unit
4. BP2 Verification

Remaining Milestones

1. 250 hour integrated testing
2. Engineering/Technoeconomic Study
3. Final report /Verification

Goals of BP 2 Verification test

- Run Integrated IH^2 + reformer system for 50 hours
- Show Hydrogen self sufficiency for 50 hours – that all the hydrogen used in the IH^2 process can be made from reforming the product gases
- Produce more than 4 gallons of IH2 liquid with <0.4%oxygen

BP2 Verification - IH^2 Test Section Resultss

	11/29-11/30	11/30-12/1
Material balance closure, wt%		
Feed rate g/hr. (MAF)		
Gallons of liquid product		
%O in liquid product		
Wt. % liquid (MAF)		
Wt.% water (MAF)		
Wt.% char (MAF)		
Wt.% gas ((MAF)		
Wt.% H2 added (MAF)		
g/hr. H2 added or required		

Budget Period 2 Verification test- IH^2 liquids

	11/29-11/30	11/30-12/1
Material balance closure	**103**	**103**
% Hydrocarbon conversion	**85**	**97**
% Volume expansion	**150**	**180**
g/hr of hydrogen produced	**73**	**67**

[illegible] Hydrogen Balance - Verification Test period

	11/29-11/30	11/30-12/1
Hydrogen required for IH2 g/hr	62.5	64
Hydrogen produced from reformer	73	67
% of hydrogen produced which is needed	117	105

Future Work- Phase 3

- Longer test with Integrated IH2 + reformer system
  - Show Hydrogen self sufficiency – that all the hydrogen used in the IH2 process can be made from reforming the product gases
  - Produce additional IH2 liquid with <0.4%oxygen
- Engineering and Technoeconomic analysis with KBR
  - Advantages of Cool Reformer system with IH2
  - Advantages of other improvements
    - Smaller lock hoppers with rapid cycling valves
    - RCPSA instead of PSA,
    - Crumbles instead of hammermills
    - Closely integrated char boiler
    - Fully modularized system

IMPACT

- Reducing cost of IH² will lead **to faster commercialization of IH²**
- **GTI invented IH² Technology but Shell has purchased all rights to commercialize IH²**
- **Shell and KBR are project partner and well positioned to implement these improvements**
- **GTI Energy trying for fast IH² commercialization**

Shell IH² Demonstration unit in Bangalore India

SUMMARY

Integration of IH^2 with Cool Reformer for the Conversion of Cellulosic Biomass to Drop In Fuels DE-EE0008919 R

- Cool Reformer worked well integrated with IH^2 process
- Hydrogen self sufficiency for IH^2 shown
- Longer testing planned
- Engineering study planned for 2023
- Project very successful so far
  - All milestones met as planned

Quad Chart Overview

Integration of IH2 with Cool Reformer for the Conversion of Cellulosic Biomass to Drop In Fuels DE-EE0008919

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Timeline

- *Oct 2019*
- *Dec 2023*

	FY22 Costed	Total Award
DOE Funding	$119,000	1.32 Million
Project Cost Share *		

TRL at Project Start: 4
TRL at Project End: 6

Project Goal

Reduce cost of IH2 process 25% through use of integrated Cool Reformer to make all H2 from IH2 gas plus addition of other engineering improvements

End of Project Milestone

- **Show H2 self sufficiency with integrated Cool Reformer**
- **Show 25 % Capital and Operating cost reduction in Engineering study**

Funding Mechanism

DE-EE0008919.

Project Partners*

- **Shell**
- **KBR**

*Only fill out if applicable.

Cool Reformer Related Patents/presentations

Patent #	Date granted	Title	Covers
10,738,247	8/11/2020	Processes and systems for reforming of methane and light hydrocarbons to liquid hydrocarbon fuels	Cool GTL which includes Cool reformer
10,906,808	2/2/2021	Noble metal catalysts and processes for reforming of methane and other hydrocarbons	Cool reforming catalyst
11.111.142	9/7/2021	Processes and catalysts for reforming of impure methane-containing feeds	Ccol reforming process and catalyst

No patents have come from this project, but several are prior art to this project and related

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BACKUP INFORMATION

Shell Bangalore India Demonstration scale IH^2 Plant

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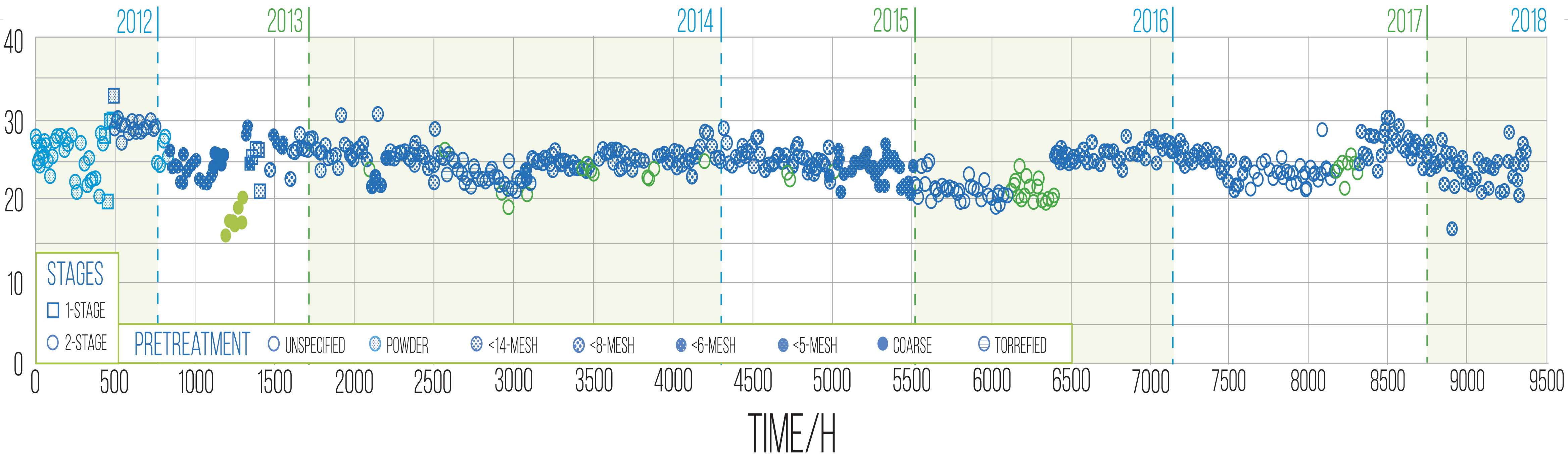
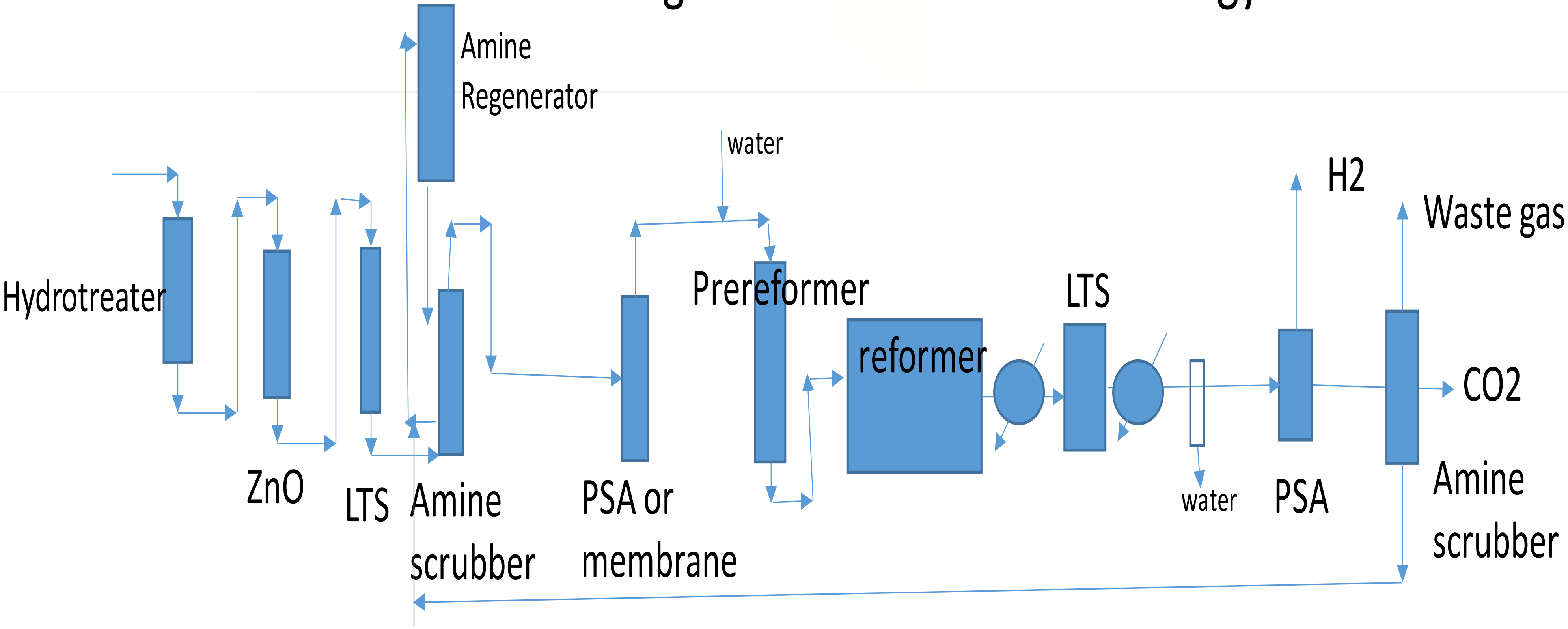
- **Smooth operation**
- **Expected yields**
- **Signed off on engineering design package for commercial scale**

IH^2 Liquid Yields in IH^2 -50 Continuous Testing- Many Hours of Testing Completed



Current Reformer Section Design for IH^2 – Extreme Complexity

Gas Feed Preparation and Hydrogen Plant Design for Biogas C1- C3 feeds containing CO+CO2 Using Standard H2 Plant Technology



- Extensive pretreatment required
- More complex H2 plant