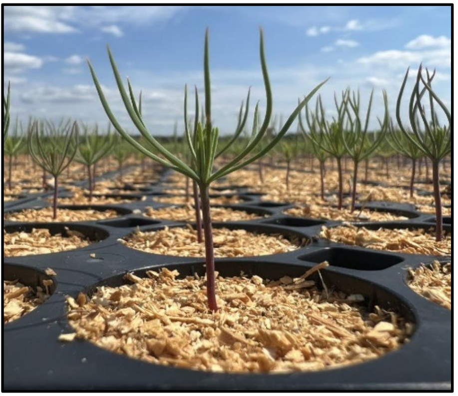
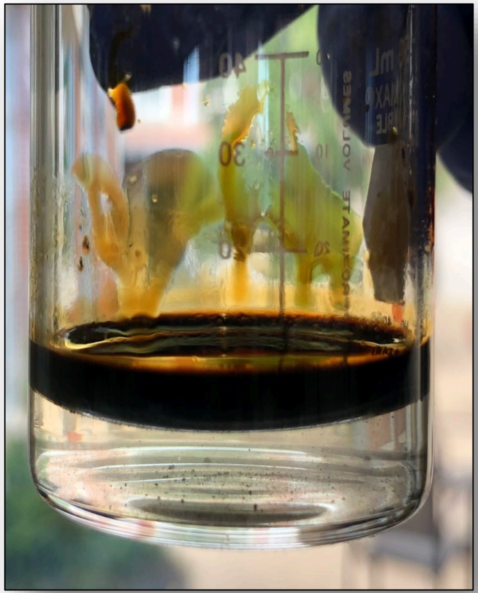


HYDROGEN PRODUCTION FROM MODULAR CO_2 ASSISTED OXY-BLOWN GASIFICATION OF WASTE BLENDS

AOI 2A: CLEAN HYDROGEN FROM HIGH-VOLUME WASTE MATERIALS AND BIOMASS

Award Number: DE-FE-0032214

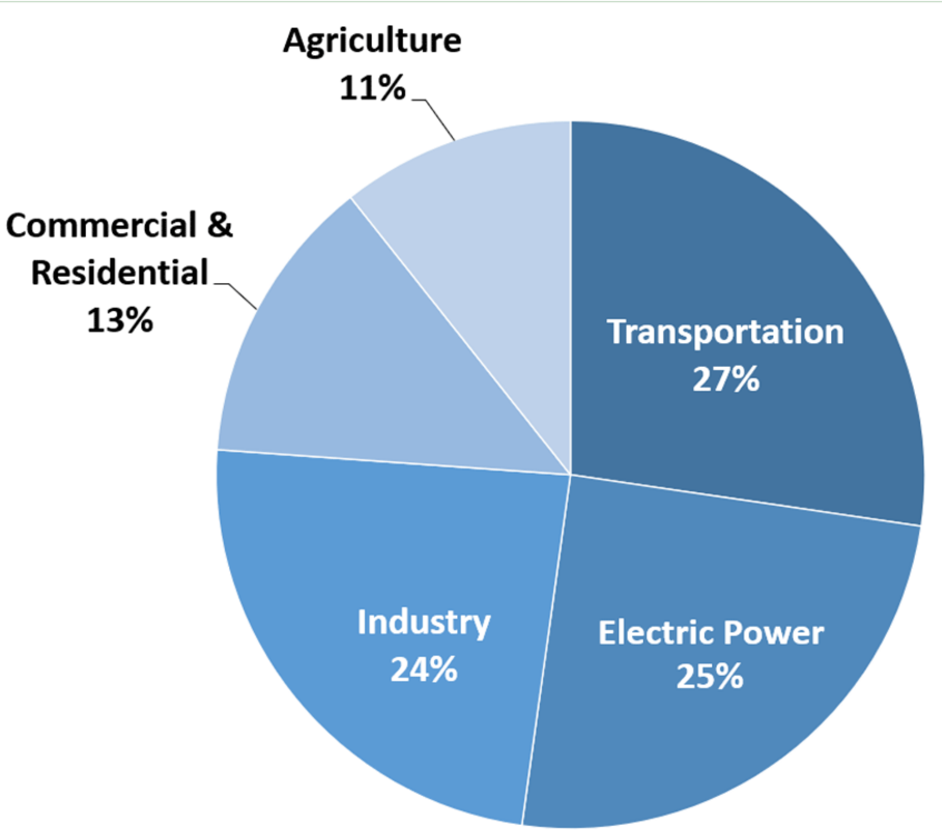
Sushil Adhikari, Oladiran Fasina, Sagar Kafle, Surendar Moogi, Ashish Bhattarai and Edith Ngoupeyou
Auburn University
Pradeep Sharma, David Dayton and Sameer Parvathikar
RTI International

Collaborators

Peter Chanin, Burcell Technologies Inc
Ray Robbins, Talladega, Alabama

Sources of Greenhouse Gas Emissions (2020)

2020: 5.98 Billion tons of CO_2

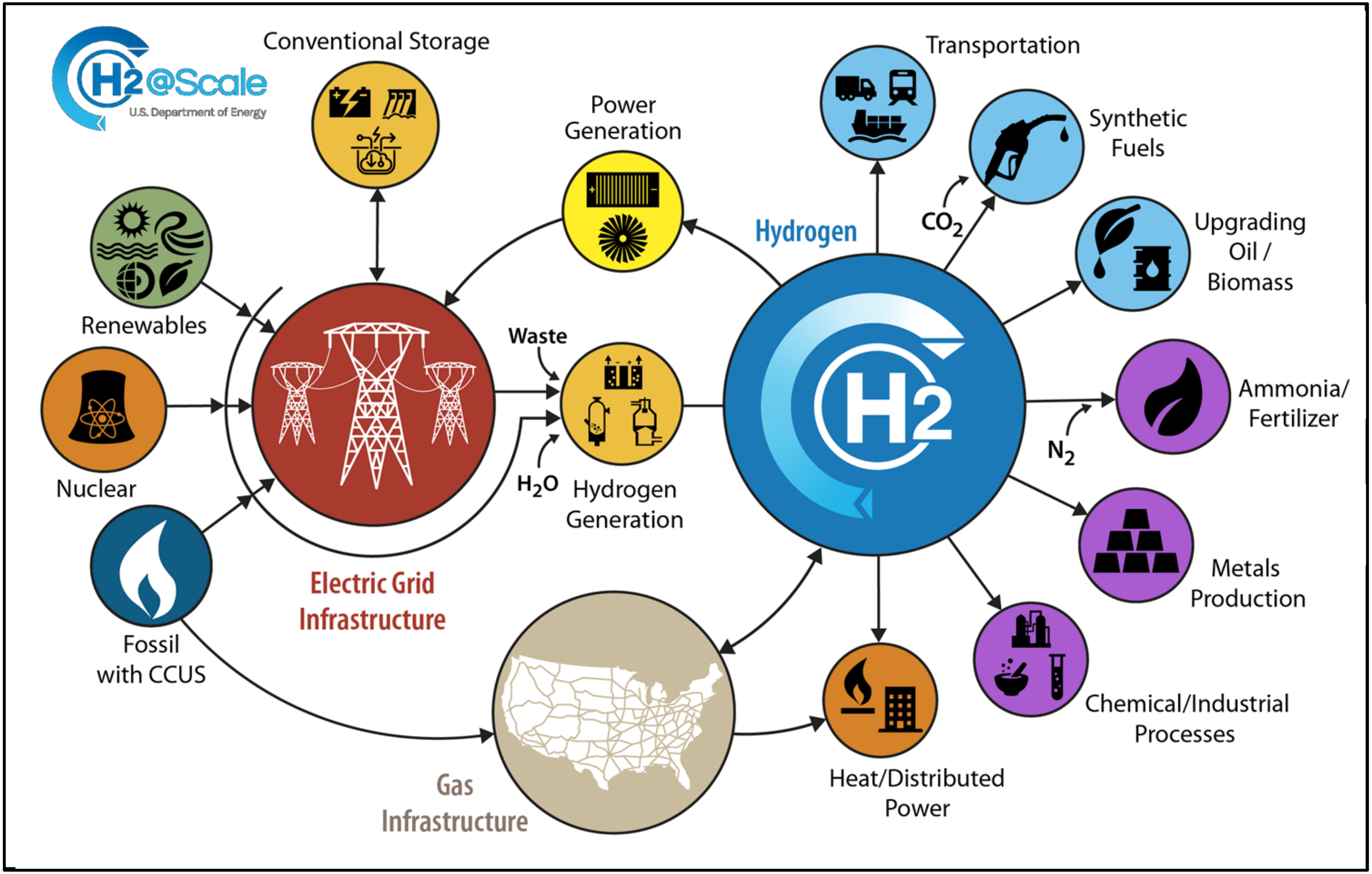


CO_2 Intensity (lbm/kWh)
- Coal-2.21
- Natural gas- 0.91
- Petroleum- 2.13

"The United States has set a goal to reach **100 percent carbon pollution-free electricity by 2035**,…." The White House Briefing Room, April 22, 2021.

Source: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

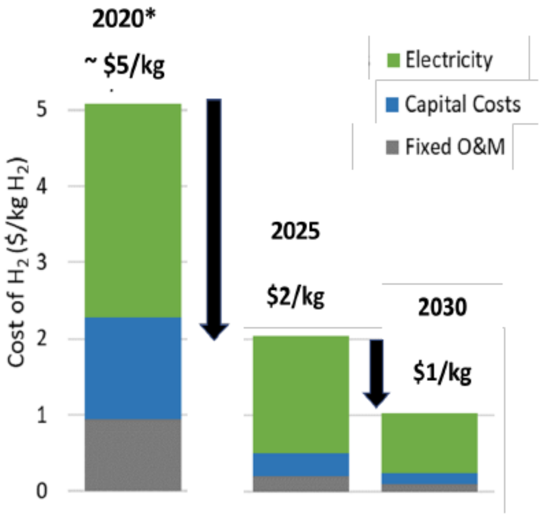
Hydrogen Potential in Decarbonization



Source: DOE National Clean Hydrogen Strategy and Roadmap (draft). Sept., 2022.

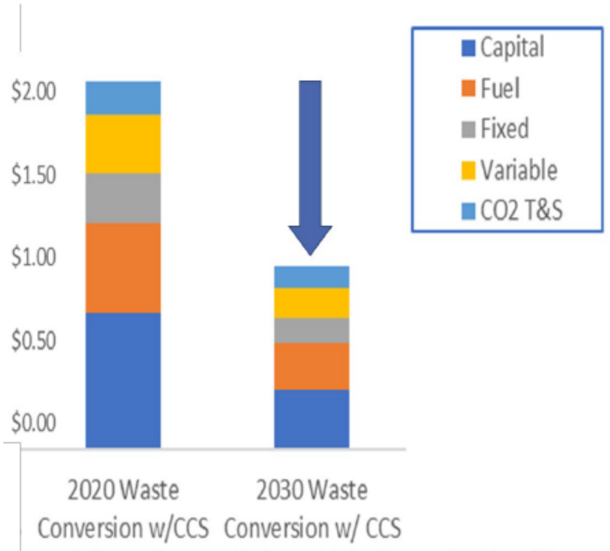
Hydrogen Production Cost

H_2 from Electrolysis



- Reduce electricity cost, improve efficiency and utilization
- Reduce capital cost >80%; operating & maintenance cost >90%

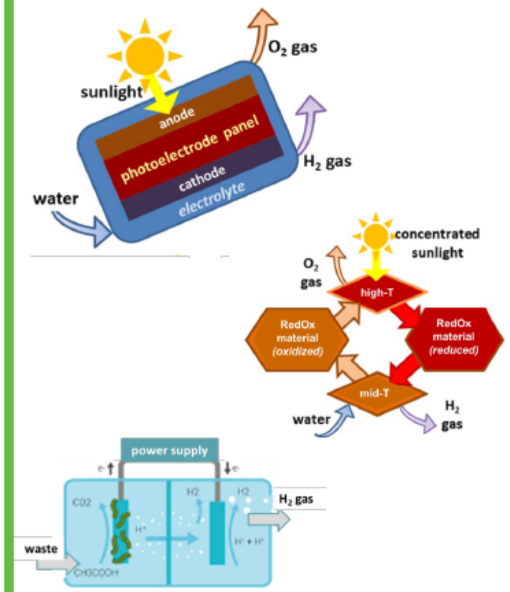
H_2 from Waste Conversion + CCS



* Waste coal, plastics, biomass residuals, municipal solid waste (MSW), and biogas

- Reforming, pyrolysis, air separation, catalysts, CCS, upstream emissions

Advanced Pathways



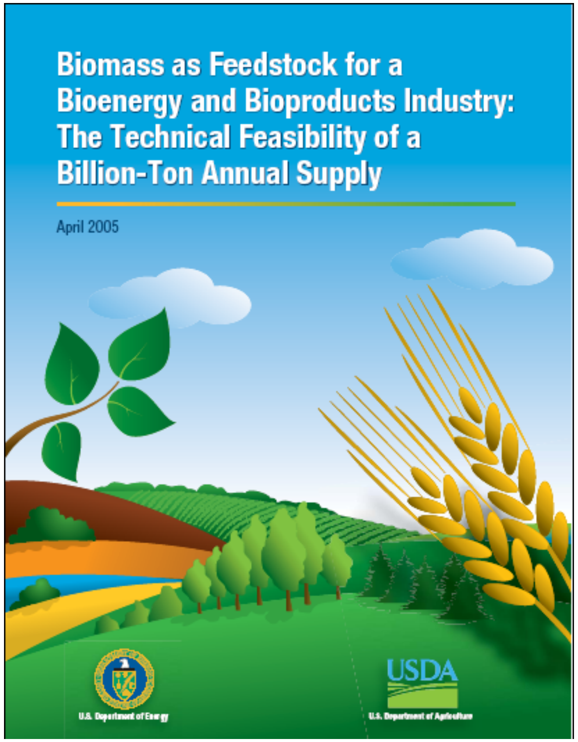
- Photelectrochemical (PEC), thermochemical, biological, etc.

"Hydrogen Energy Shot (1 1 1)": $1 for 1 kg of clean hydrogen in 1 decade. Secretary Jennifer Granholm. June 7, 2021

Source: DOE Update on Hydrogen Shot, RFI Results… in the Bipartisan Infrastructure Law. December 8, 2021.

Biomass Potential

1.3 billion dry tons/yr



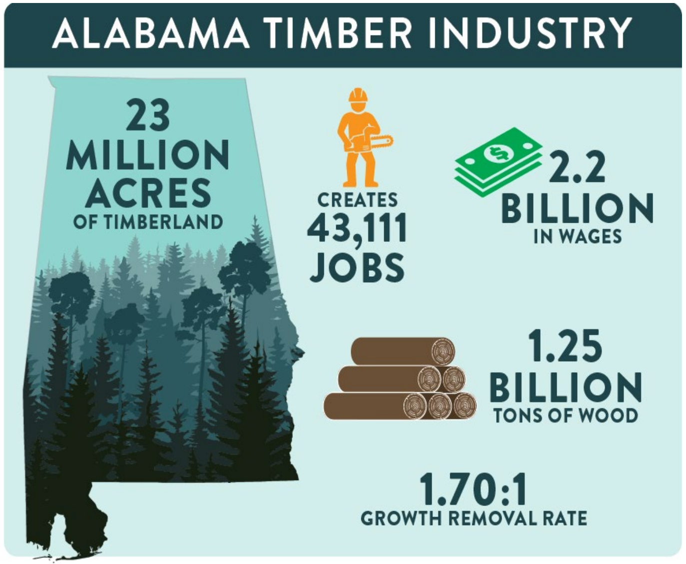
Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply

April 2005

U.S. Department of Energy

USDA

U.S. Department of Agriculture



Agricultural residues and forest residues contribute about 998 and 368 million dry tons per year, respectively. The U.S. has a potential to produce about 60 billion gallons of ethanol.

Source: USDA/DOE Billion Ton Study, 2005

Legacy Waste Coal

Property	Method	Sample 1	Sample 2	Sample 3
Ash, %	D3174	10.86	37.05	23.71
VM, %	D3175	32.11	19.90	25.27
FC, %	D3172	57.03	43.05	51.02
Sulfur, %	D4239	1.30	0.49	0.60
HHV, Btu/lb	D5865	13201	9229	11577

Source: Ray Robbins. Talladega Foundry & Machine Co Inc

Fig. A pile of coal waste in Alabama

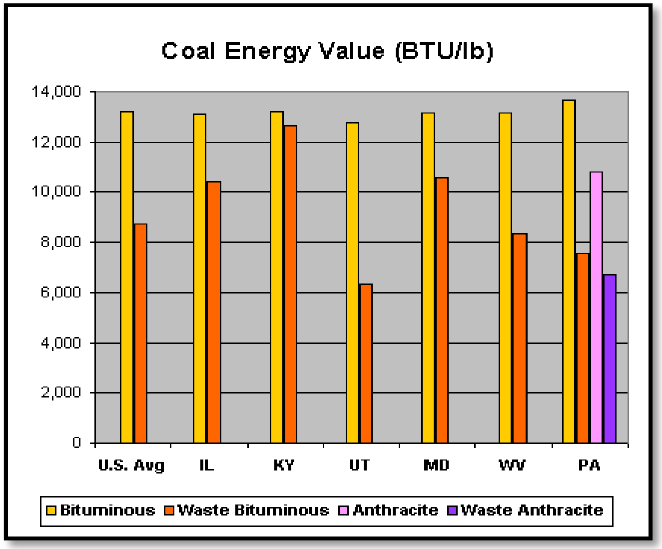
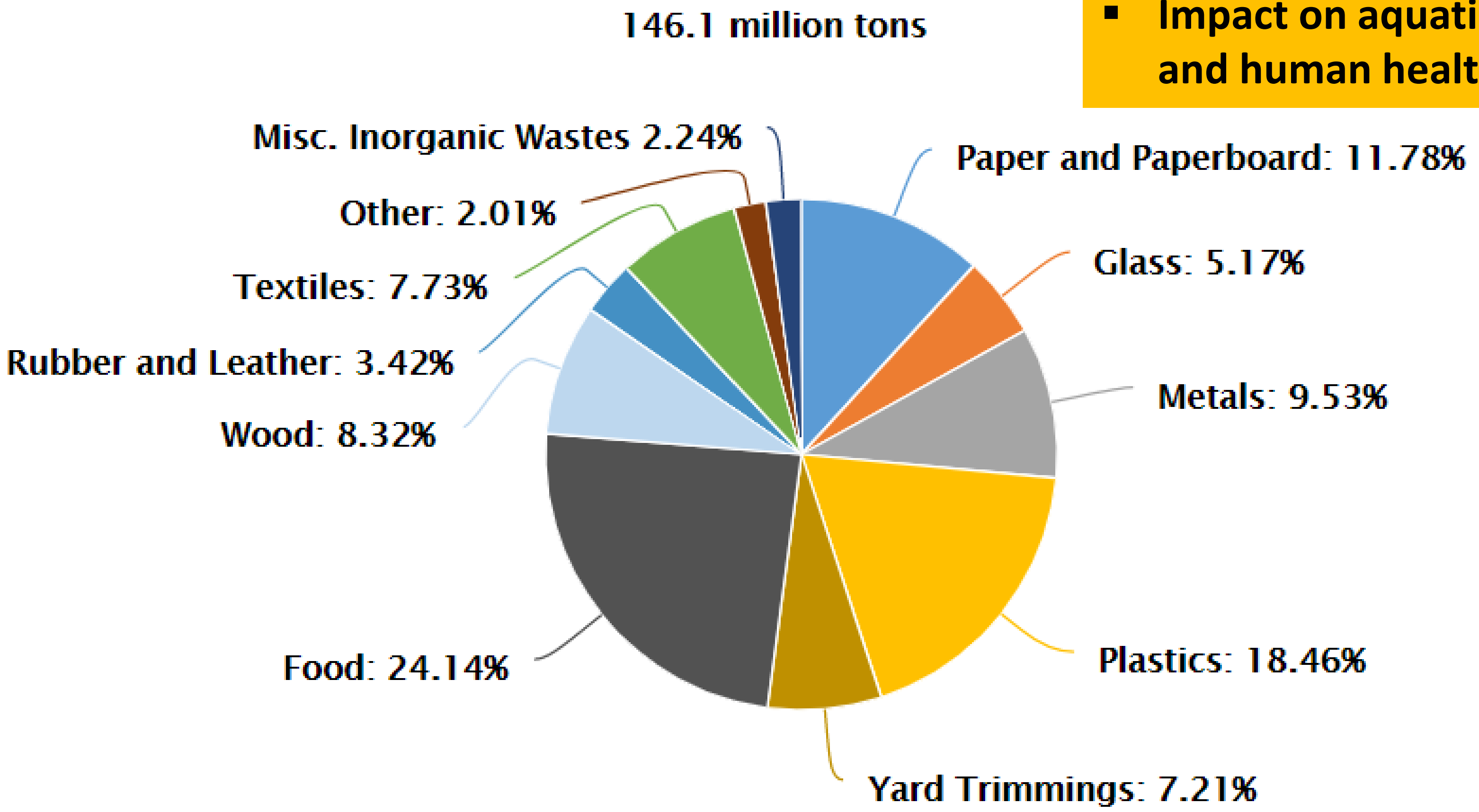


Fig. Waste coal energy values

Source: Energy Justice Network. Waste Coal. https://www.energyjustice.net/coal/wastecoal#:~:text=Waste%20coal%20is%20called%20%22culm%22%20in%20the%20eastern,or%20small%20mountains%20that%20are%20dark%20and%20barren.

Municipal Solid Waste

Issues with waste plastic
- **Environmental nuisance**
- **Micro plastics**
- **Impact on aquatic species and human health**



- ***Generation: ~ 292 million tons annually (4.5–5 pounds per person per day)***
- ***Land filled: ~146 million tons***
- ***Plastic recycling: ~ 10%***

Source https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#Generation

Research Objectives

- The **main objective** of this research is to produce hydrogen from blended feedstocks that include legacy waste coal, forest residues, and an organic-rich fraction of municipal solid waste (OFMSW) via carbon dioxide (CO2) assisted oxy-blown gasification.

- The specific objectives are to:

  (i) understand the flow properties and energy requirements for preprocessing for blended feedstocks;
  (ii) gasification behavior of the mixtures on syngas composition and contaminants;
  (iii) Evaluate syngas conditioning and clean-up catalysts/sorbents;
  (iv) process model(s) for hydrogen production cost; and
  (v) develop TMP to advance the technology beyond TRL-4

Project Schedule

Tasks/Milestones	3 month	6 month	9 month	12 month	15 month	18 month	21 month	24 month
	Year 1				Year 2			
Obj. 1: Feedstock Preparation and Charcaterization								
Subtask 2.1: Prepare 3 waste samples and theis blends for the study	SA, GRA1							
Subtask 2.2: Complete flow properties such as flow index, cohesive strength, Hausn	▨	OF, GRA2	▨	▨				
Subtask 2.2: Complete fluidization segregation and sifting segregation measuremen				▨	▨	▨	OF, GRA2	M 8 ●
Obj. 2: Gasification Characterization								
Subtask 3.1: Complete proximate, ultimate, heating value and ash analyses of 12 ble	▨	▨	SA, GRA1	▨	▨			
Subtask 3.2: Complete CO2 reactivity experiments for 12 blend samples and calcula			▨	SA, GRA1	▨	▨		
Subtask 3.3: Complete gasification of 12 blend samples		▨	▨	SA, GRA2	M 4 ●			
Obj. 3: Gas Cleanup and Upgrading Chracterization								
Subtask 4.1: Performance characterization of H2S and metal removal		▨	DD, RTI	M 2 ●				
Subtask 4.2: Performance characterization of syngas conditioning (WGS activity)		▨	▨	DD, RTI	M 5 ●			
Obj. 4: Integrated System Design and Performanace Testing								
Subtask 5.1: Design of syngas cleanup and upgrading					RTI			
Subtask 5.2: System Modification						AU		M 6 ●
Subtask 5.3: Operation of 1 kh/hr integrated system							AU	▨
Obj. 5: Process Modeling and TEA for hydrogen production from waste								
Subtask 6.1: A Preliminary ASPEN process model.		▨	SP & PS, RTI	●	M 3			M 7
Subtask 6.2: Updated ASPEN process model					▨	SP & PS, RTI	▨	●
Task 1: Project Management and Reporting								
Project SOPO, PMP Update, Preliminary TMP	▨ ●	M 1						
Project Kickoff Meeting	▨							
Quarterly Progress Report	▨	▨	▨	▨	▨	▨	▨	▨
Annual and Final Report, Updated TMP				▨				M 9 ●

Note: M = Milestone
SA: Sushil Adhikari
OF: Oladiran Fasina
DD: Dave Dayton, RTI
SP: Sameer Parvathikar, RTI
PS: Pradeep Sharma, RTI
GRA: Graduate Research Assistance

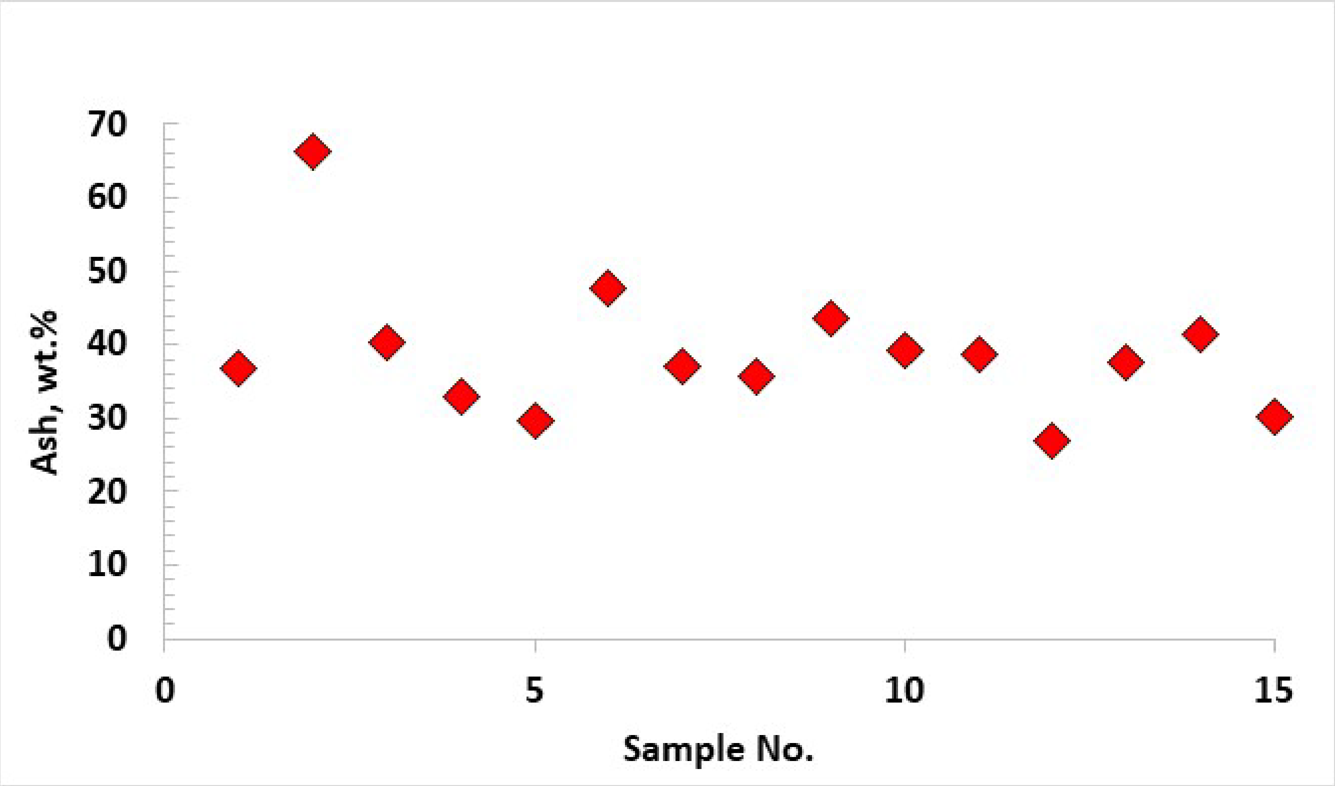
Proposed Development Efforts

Developmental Effort	Description
Feedstock characterization and gasification studies	▪ Feedstock blends will be characterized for flowability and segregation ▪ High moisture content and blend feedstocks will be tested to determine desirable gasification metrics.
Syngas cleanup and conditioning design, integration, and testing	▪ Tailor FB-WDP, TCRP, and AFWGS for syngas compositions derived from CO_2-assisted oxy-blown gasification of selected feedstocks ▪ Design, build, and operate a 1 kg/h gasifier integrated with syngas cleanup and conditioning for a cumulative 100 hours on-stream.
TEA and TMP	▪ Create detailed TEA comparing clean H_2 production from conventional processes with proposed processes using waste blends. ▪ Formulate plan to advance TRL for integration ▪ Assess market to identify next scales for demonstration as well as supply chain for supply of feedstocks, sorbents, and catalysts for larger scale demonstrations

Task 2: Feedstock Characterization

Legacy Waste Coal

Ash Analysis of Coal Samples



For a 2000 tpd plant, we will generate about 800 tons of ash (~40 truck loads) each day. This could potentially cost $<u>40,000</u> (@$50/ton disposal fee) each day for the plant.

Processes MSW after Burcell Unit

Right. Overs from 1” from Trommel after

Left. 1” unders from Trommel after Burcell

Task 2: Feedstock Characterization

- **Proximate and Ultimate Analyses**

			wt.% (a.r.)		
Sample	Moisture	Ash	Volatile Matter	Fixed Carbon	HHV, MJ/kg
Coal	1.59	36.80	22.70	38.91	19.65
OFMSW	5.86	20.67	72.28	1.19	15.22
Pine Residue	10.20	1.15	83.62	5.03	18.54

			wt.%		
Sample	C (%)	H (%)	N (%)	S (%)	O (%)
Coal	49.33	3.14	0.85	0.4	9.48
OFMSW	42.13	5.87	0.77	0.17	30.39
Pine Residue	48.69	6.82	0.11	0.04	43.19

Task 2: Feedstock Characterization

	Sample Type		
	Coal	**OFMSW**	**Pine**
Bulk density (kg/m³)	768.55 ±3.9	136.63 ±0.5	250.85 ±0.8
Particle density (kg/m³)	1655.48 ±18.4	1664.26 ±1.7	1444.71 ±3.9
Tap density (kg/m³)	1049.68 ±11.9	194.43 ±2.3	313.81 ±3.7
Hausner Ratio	1.36	1.42	1.25
Flow Index	7.7	3.2	3.0

Flow Index (FI)	Flowability
FI < 2	Very Cohesive
2 < FI < 4	Cohesive
4 < FI < 10	Easy Flowing
FI > 10	Free Flowing

Jenike, 1964

Task 3: Gasification Experiments

- Laboratory-scale fluidized bed CO2-assisted gasification to determine the syngas composition and contaminants under steam and oxygen gasification conditions.

Table: Composition of mixtures analyzed within the design space (mass percentage).

Sample No.	Waste Coal	Biomass	OFMSW
1	100%	0%	0%
2	50%	50%	0%
3	50%	0%	50%
4	0%	100%	0%
5	0%	50%	50%
6	0%	0%	100%
7	33%	33%	34%
8	66.6%	16.7%	16.7%
9	16.7%	66.6%	16.7%
10	16.7%	16.7%	66.6%

Lab-Scale Gasification Unit

Bed Temperature T1 (°C)	Free-Board Temperature T2 (°C)	Free-Board Temperature T3 (°C)	S/C	ER
875-947	967-1019	978-1035	4	0.2

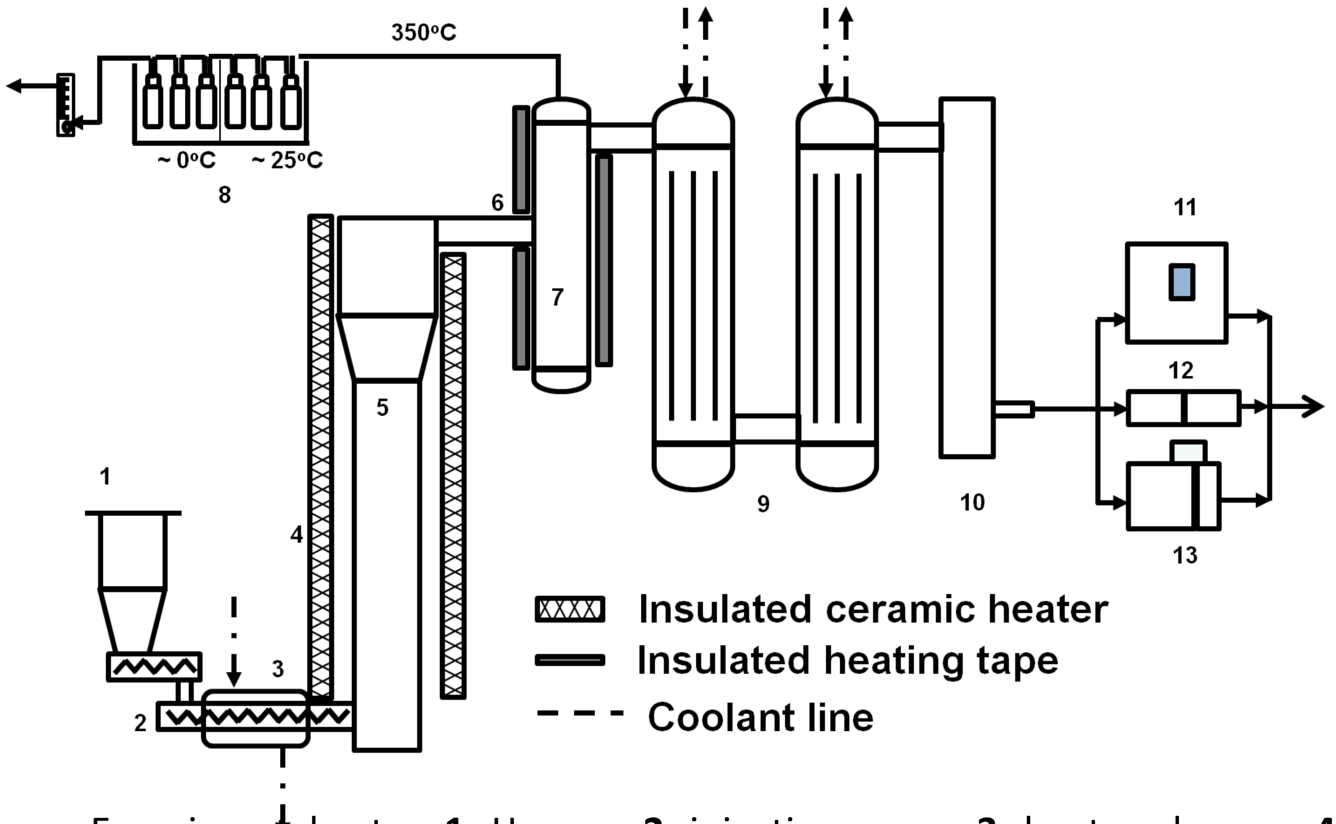
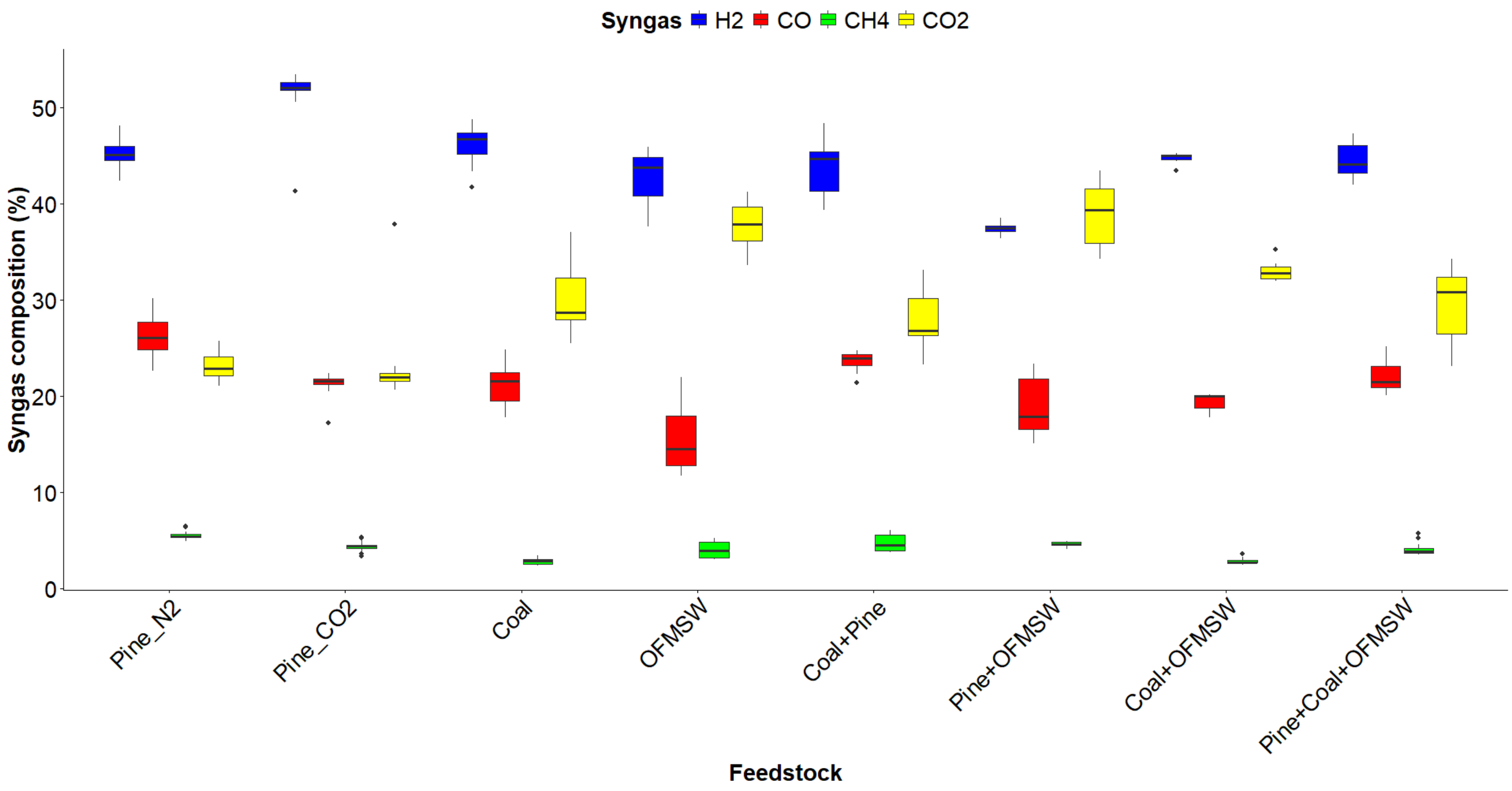
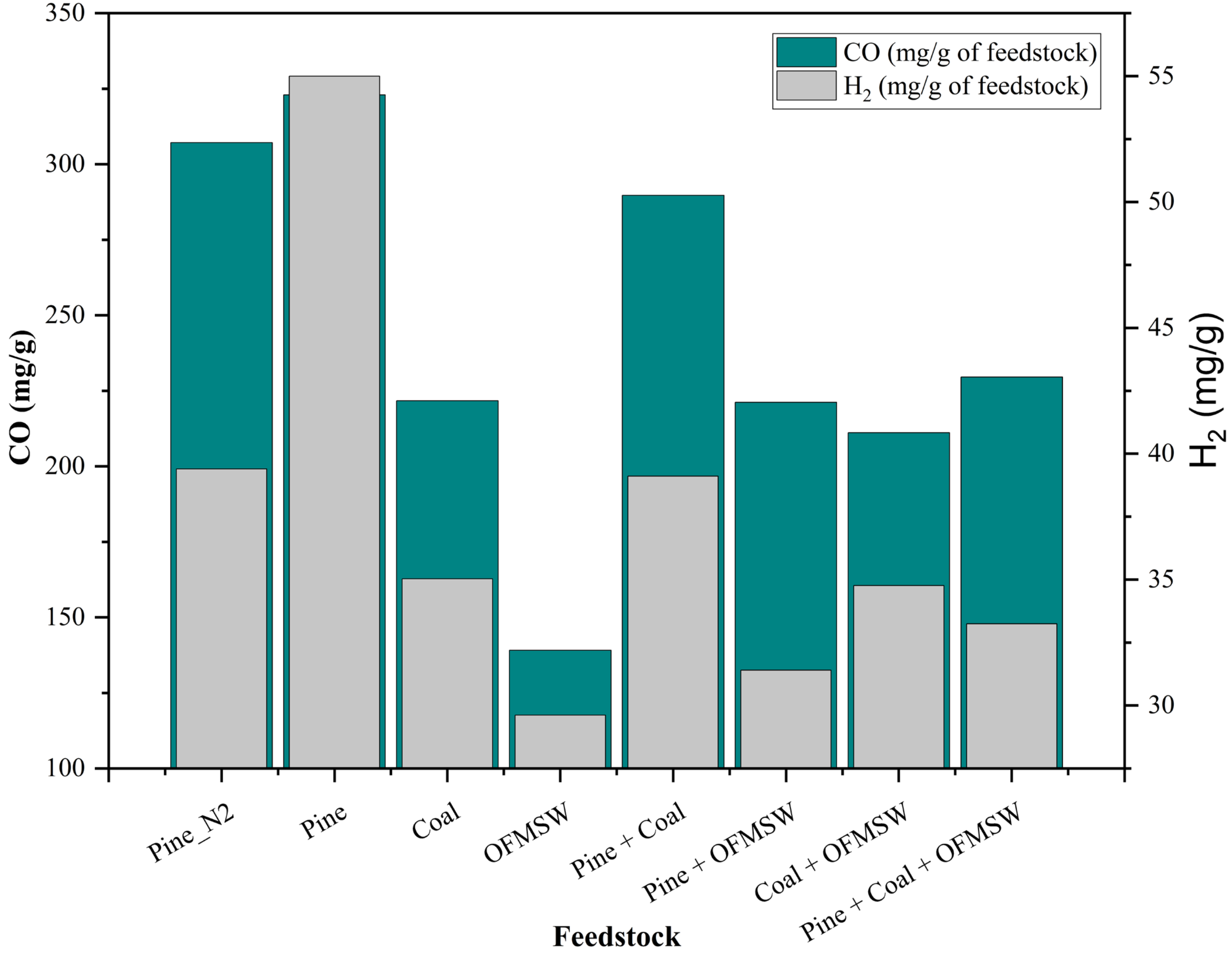


Figure . Experimental setup **1.** Hopper, **2.** injection screw, **3.** heat exchanger, **4.** heaters, **5.** fluidized bed gasifier, **6.** filter heaters, **7.** high temperature filter, **8.** impingers for tar sampling, **9.** condensers, **10.** ESP, **11.** primary gas analyzer, **12.** FTIR gas analyzer and **13.** FPD GC

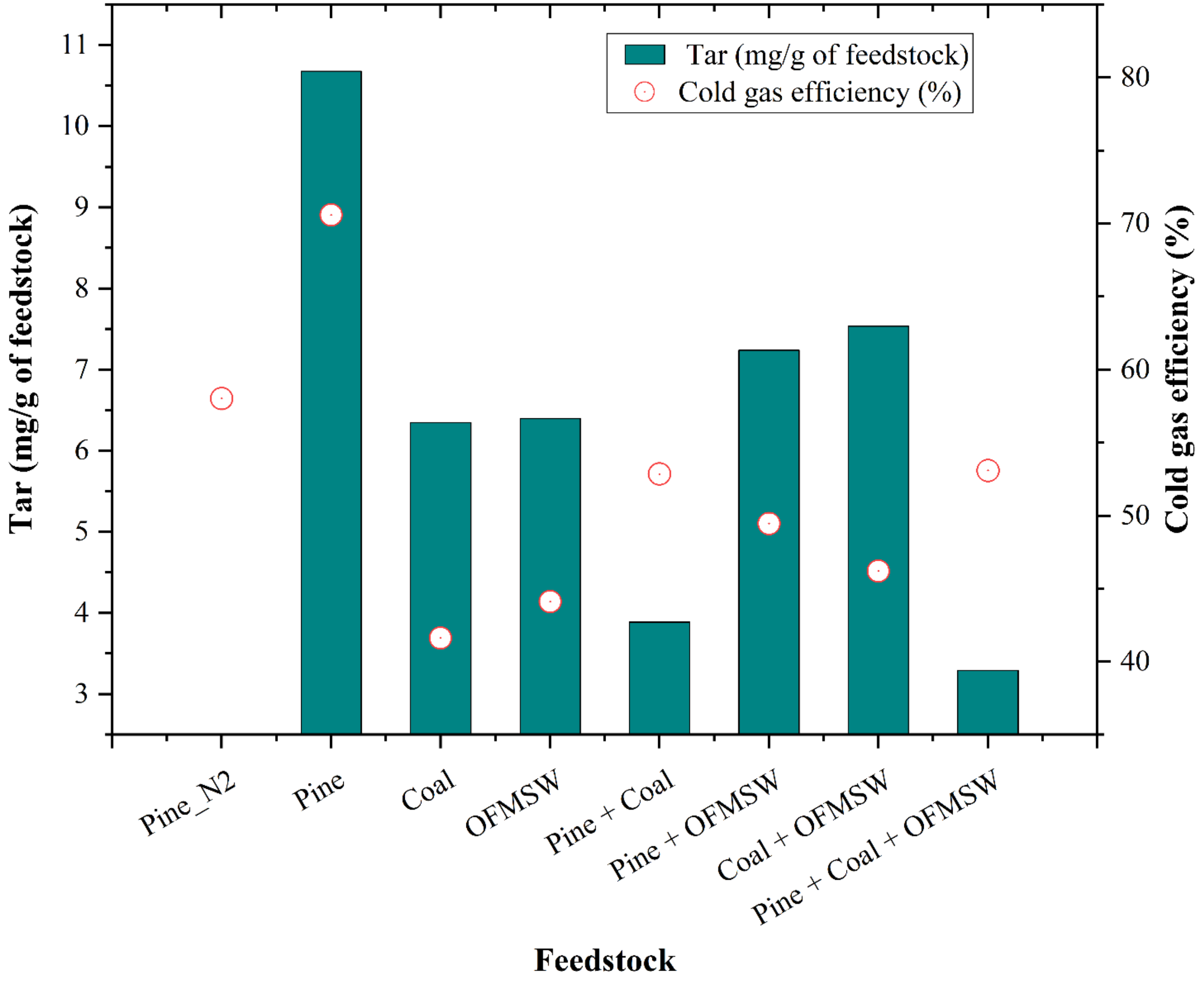
Syngas Composition Data



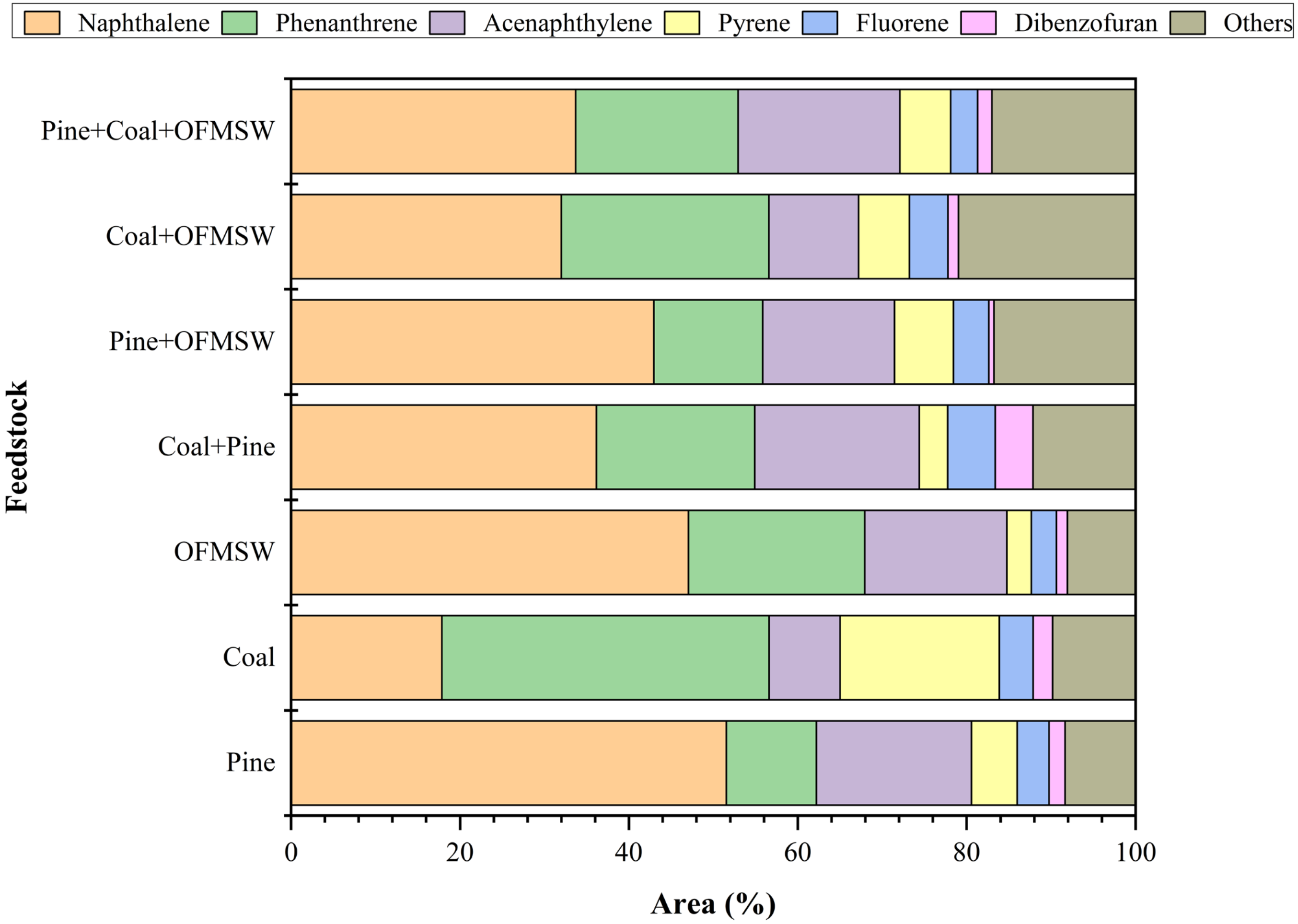
Syngas Composition: CO and H_2

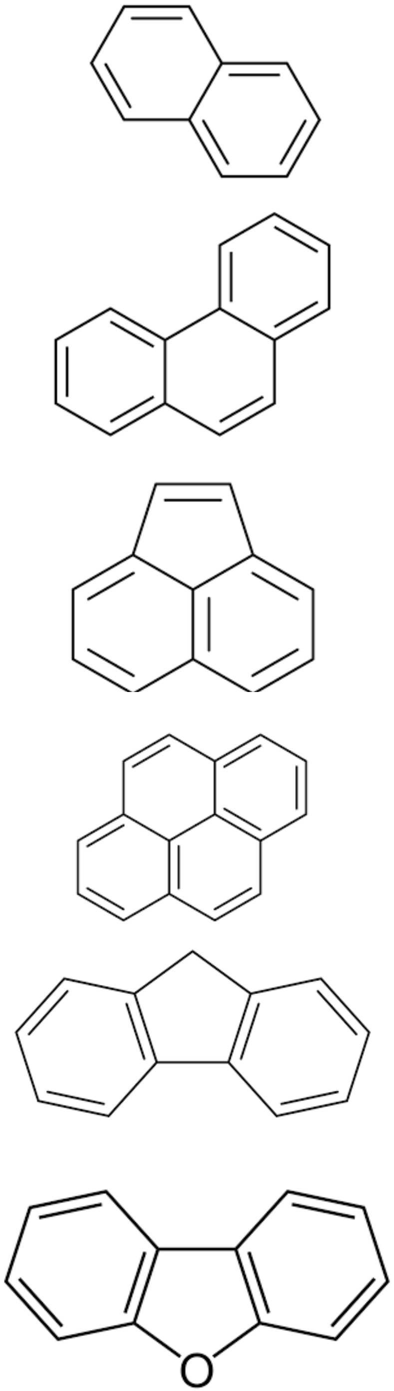


Syngas Contaminants and Efficiency



Major Tar Compounds





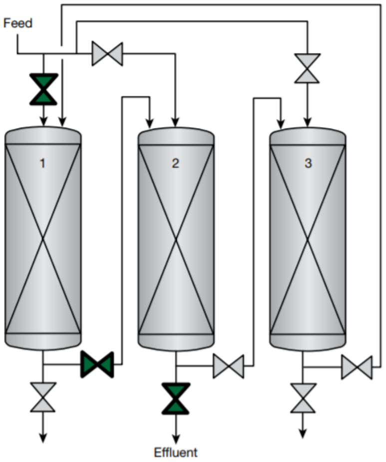
Task 4.0: Syngas Cleanup and Upgrading Characterization

Subtask 4.1 – Performance characterization of syngas cleanup

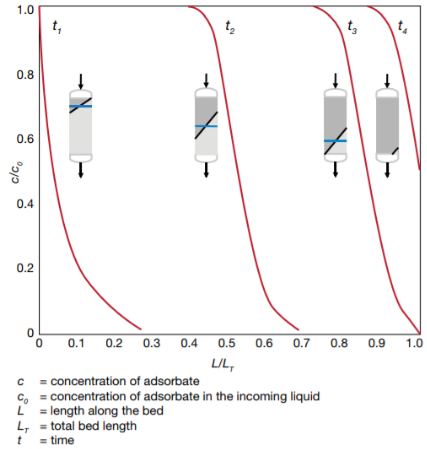
Objective: Understand and optimize the performance of syngas cleanup technologies and derive design parameters for integration with waste blend gasification.

- ☐ Synthesis, characterization, optimization, and scale-up of regenerable fixed Bed Warm Desulfurization Process (FB-WDP) sorbent extrudates.
- ☐ Optimize FB-WDP process parameters for process design.

FBWDP Development Parameters



An example three column arrangement where column 1 serves as the lead and column 3 serves as the guard with column 2 in regeneration mode

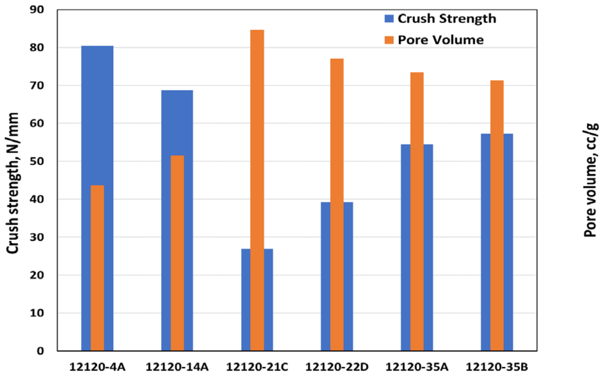


The mass transfer zone, indicated by the black diagonal line on each column, moves along the length of a fixed bed of adsorbent

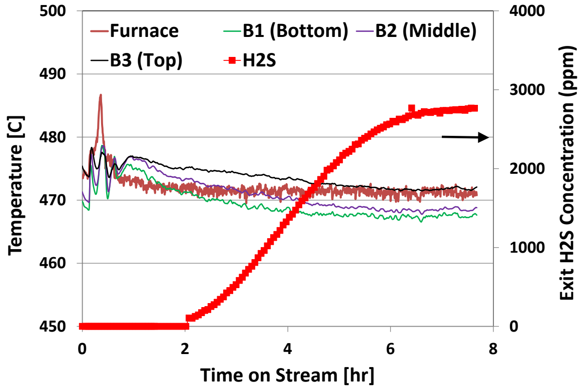
FBWDP Cycle Optimization

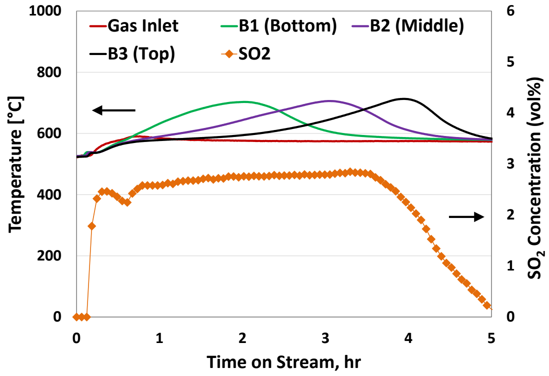
- ☐ Adsorbent Development
  - – Desired chemistry for the process
  - – Balance crush strength and porosity
- ☐ Adsorbent Particle Size
  - – Smaller particle size lower mass transfer limitation but increase pressure drop, Common particle size range: 2-4 mm
- ☐ Superficial Gas Velocity
  - – Length of MTZ increases with increasing gas velocity with a corresponding decrease in bed utilization, Typical velocity range: 0.15-0.45 m/s
- ☐ Bed Length
  - – Longer bed allows for longer time-on-stream and higher bed utilization
  - – However, it is more expensive and leads to higher pressure drop
- ☐ Process Conditions
  - – Process temperature and pressure will help determine the energy requirement of the process and optimize PTSA cycle
  - – Understanding the regeneration exotherm will help design the heat management system

FBWDP Sorbent Development and Process Design



Steam reforming catalysts crush strengths in the range of 25 to 50 N/mm



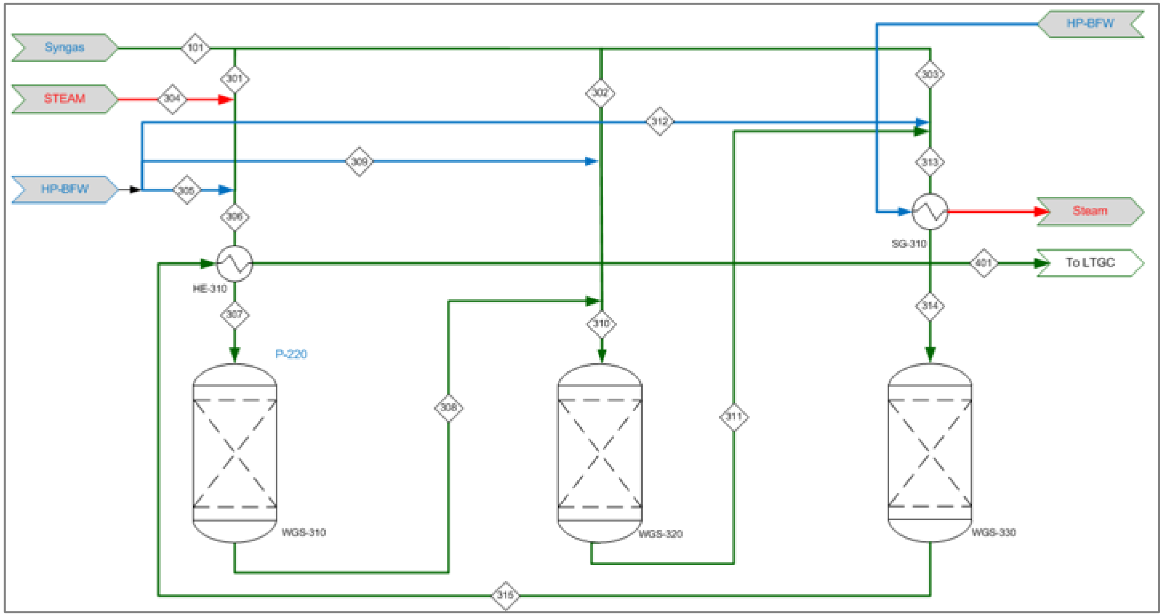


Sorbent synthesis is optimized, and sorbent performance is reproduced (at high H_2S concentrations)

Task 4.0: Gas Cleanup and Upgrading Characterization

Subtask 4.2 – Performance characterization of syngas conditioning

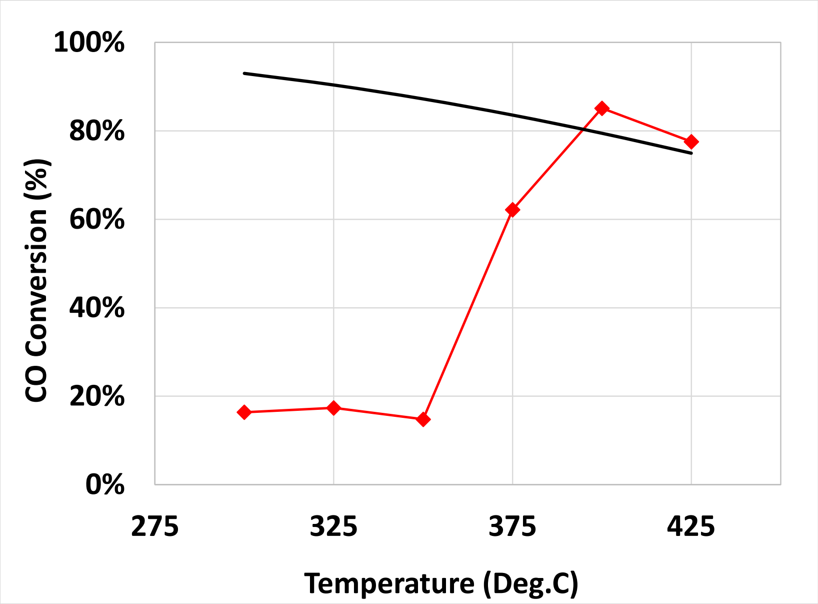
- ☐ Procure and benchmark the activity of commercially available water gas shift (WGS) catalysts in novel AFWGS process.
- ☐ Optimize the process conditions for the AFWGS for cost-effective syngas conditioning and collect design data for integration with gasifiers for waste blends.



AFWGS Process Performance and Design

- Study performance (activity and long-term stability) of high-temperature shift (HTS), medium-temperature shift (MTS) and low-temperature shift (LTS) catalysts.
- HTS Performance Testing

Parameter	Value
Catalyst	Shiftmax 120
Operating Temperature (°C)	300-425
Operating Pressure (psig)	100
Syngas Composition	mol %
H_2	37.2
CO	23.0
CO_2	31.6
CH_4	3.8
N_2	4.3



Task 5.0: Integrated System Design and Performance Testing

Subtask 5.1 – Design of syngas cleanup and upgrading

- Leverage the results from subtasks 4.1 and 4.2 and develop process design
- Develop a basic engineering design package consisting of a process flow diagram (PFD), heat and mass balance (HMB) and a process and instrumentation diagram (P & ID)
- Complete a safety hazard and operability (HAZOP) analysis an integrated operations

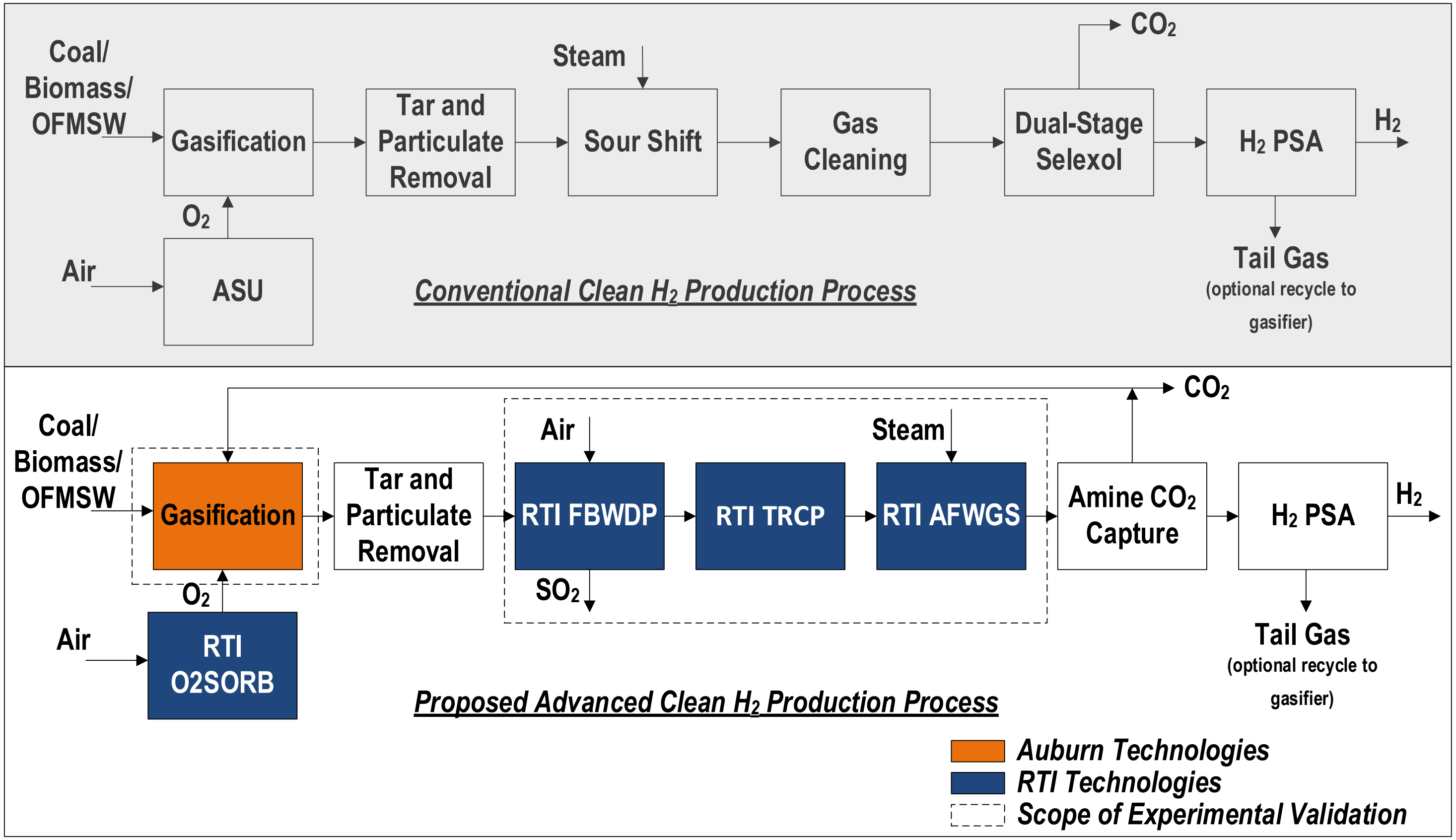
Subtask 5.2 – System modification

Subtask 5.3 – Operation of 1 kg/h integrated system

Task 6.0: Process Modeling and TEA

- ☐ Develop process models for the proposed process incorporating experimental performance data from individual process units resulting from Tasks 2, 3, 4 and 5.
- ☐ Complete TEA to produce clean H_2 from oxy-blown waste blend gasification in a conventional process that uses commercially available technology.

Process Modeling for Hydrogen Production



Coal/ Biomass/ OFMSW
Gasification
Tar and Particulate Removal
Steam
Sour Shift
Gas Cleaning
Dual-Stage Selexol
CO_2
H_2 PSA
H_2
O_2
Air
ASU
Tail Gas
(optional recycle to gasifier)

Conventional Clean H_2 Production Process

CO_2
Coal/ Biomass/ OFMSW
Gasification
Tar and Particulate Removal
Air
RTI FBWDP
SO_2
RTI TRCP
Steam
RTI AFWGS
Amine CO_2 Capture
H_2 PSA
H_2
O_2
Air
RTI O2SORB
Tail Gas
(optional recycle to gasifier)

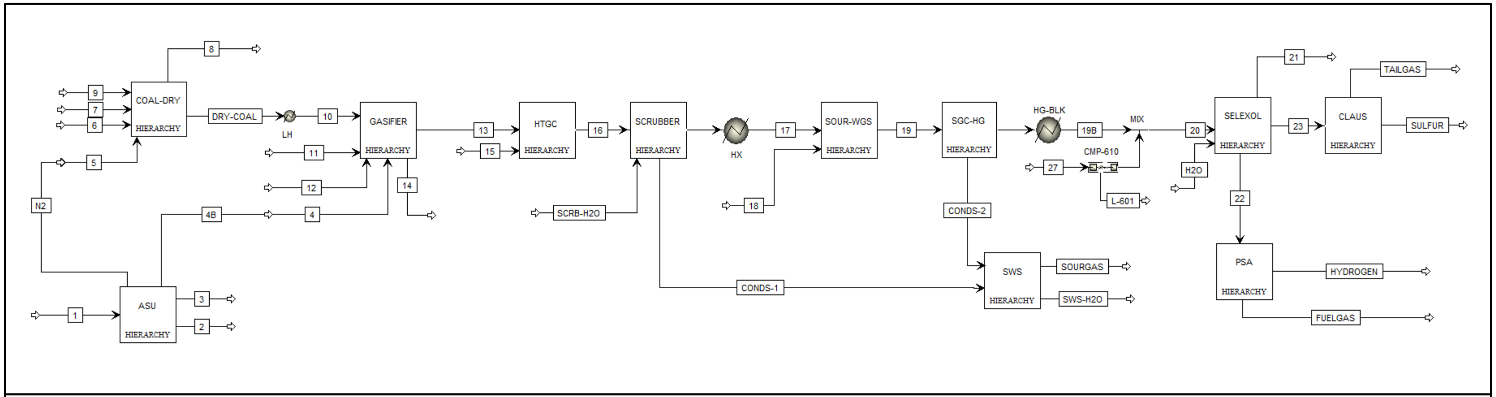
Proposed Advanced Clean H_2 Production Process

🟧 *Auburn Technologies*
🟦 *RTI Technologies*
⬚ *Scope of Experimental Validation*

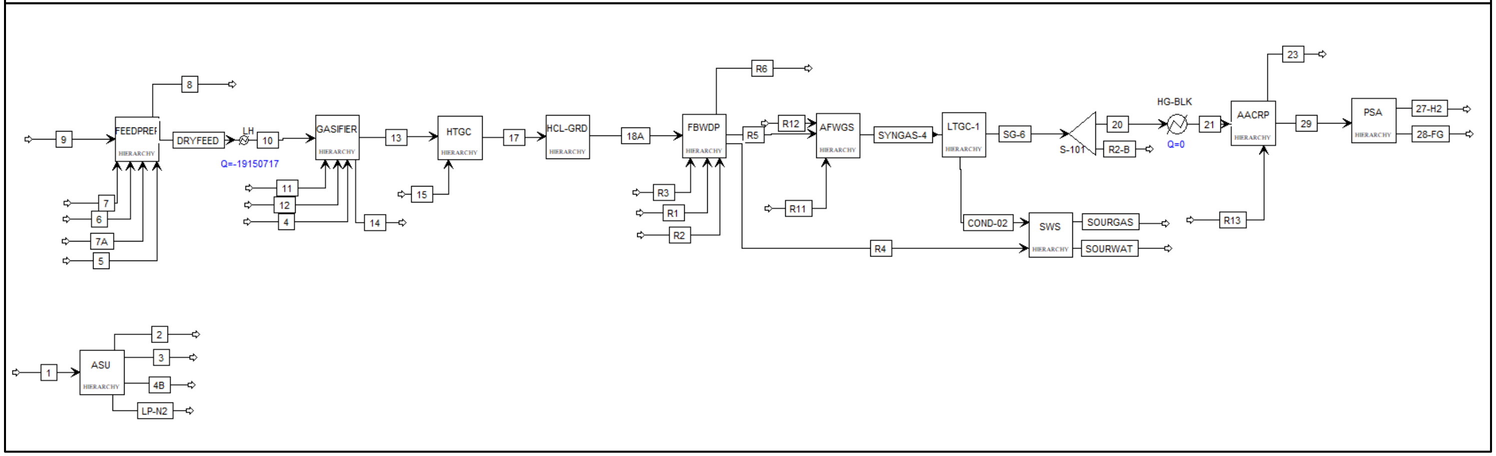
H_2 Production Scheme

Process Models

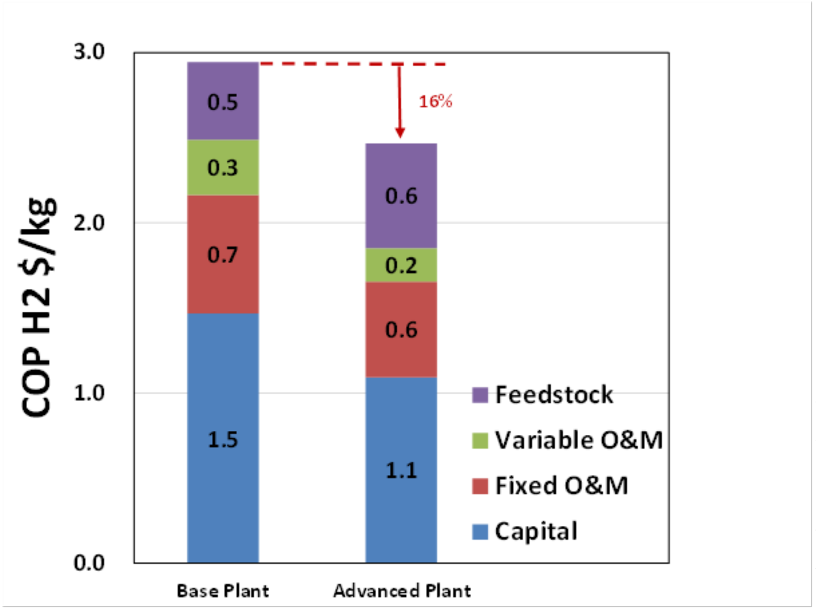
Conventional Technologies



Advanced Emerging Technologies

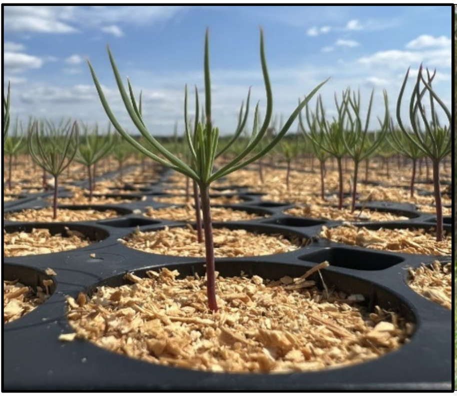


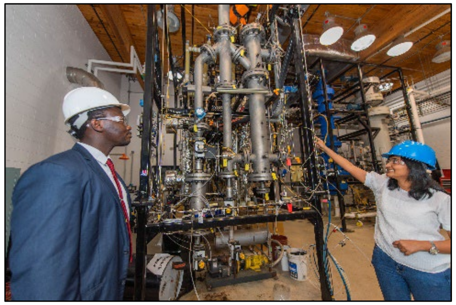
Technoeconomic Analysis Results



Feedstock Cost: Biomass- $40/ton, Plastics- $100/ton, Coal- $36/ton

- Emerging technologies can achieve about 16% reduction in hydrogen production cost (2.94$/kg to 2.47$/kg)
  - ~22% reduction in Capex
  - ~23% reduction in operating costs (fixed and variable)
- Feedstock cost can significantly impact the hydrogen production cost
- Sensitivity analysis will be completed to capture the impact of various cost components on the cost of hydrogen production (COP)



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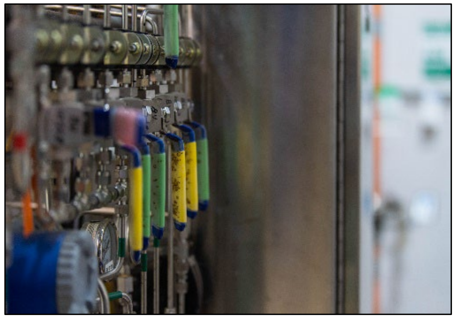
- Biosystems Engineering Department Staff
  - James Johnson
  - Caroline Whiting
  - Bobby Bradford




Thank You!

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