DOE Bioenergy Technology Office (BETO) 2023 Project Peer Review

Production of Liquid Hydrocarbons from Anaerobic Digester Gas

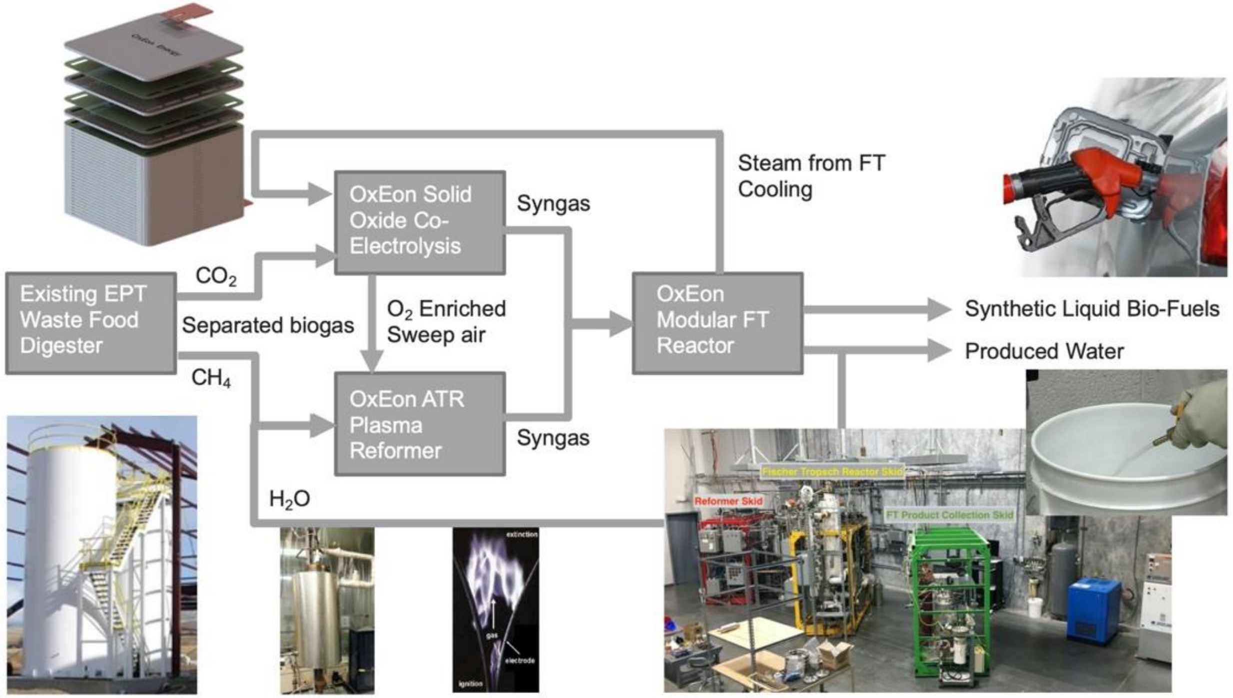
Technology Area Session: Systems Development and Integration – Scale Up Portfolio

PI: Joseph Hartvigsen
Deputy PI: Michele Hollist
PM: Jessica Elwell

Beyond Current Potential

Project Overview

- **Engineering-scale demonstration for production of liquid hydrocarbon fuels using both methane and carbon dioxide generated by a food waste digester**
- **Three key elements:**
  - **Solid Oxide Electrolysis Cell (SOEC) –** Converts steam and CO_2 to syngas
  - **Plasma Reformer –** Syngas production from bio-methane with oxygen, and water
  - **Fischer-Tropsch (FT) Reactor –** Liquid fuel production from syngas



Project Goals

BETO Goal of \$3.00/GGE (gasoline gallon equivalent): Data will feed a future technoeconomic analysis (TEA)

- Subsystem verification of SOEC, Plasma Reformer and FT to key targets set by BETO - Completed
- Full system fabrication and integration – Underway
- Full Integrated System Test – Next Budget Period

Go/No-Go Targets for SOEC Verification

- CO_2 conversion > 40% Single Pass
- Syngas H_2/CO ratio in range of 1.8 to 2.2
- Stack electrical η > 100%, i.e. Vop < 1.34 V/cell

Go/No-Go Targets for Plasma Verification

- Plasma Power < 350 W at 0.45 PF
- Cold Gas Efficiency (CGE) > 76% heat rate product/reactant
- CO selectivity > 80% (feed CH_n basis)
- Reformate residual CH_4 < 1 mol%
- Reformate C2 < 0.2 mol%

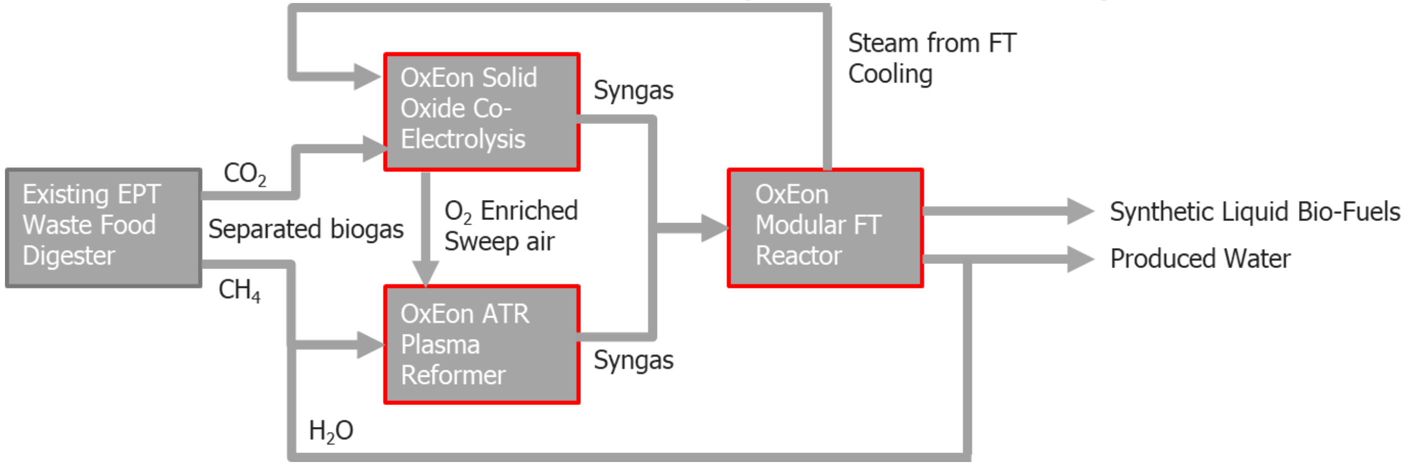
FT Fuel Production Verification Targets

Criteria	Target
CO Conversion	>80%
H_2 Conversion	>80%
CO Selectivity to C5+	>76%
Overall CO to C5+ (Conversion*Selectivity)	>67%
Mass balance closure	>92% on C
Product Distribution C_n peak	>C9

First of its kind testing of these technology components in an integrated system

Approach – Technical Approach

Initial Verification: Verification of individual components – Completed in BP1



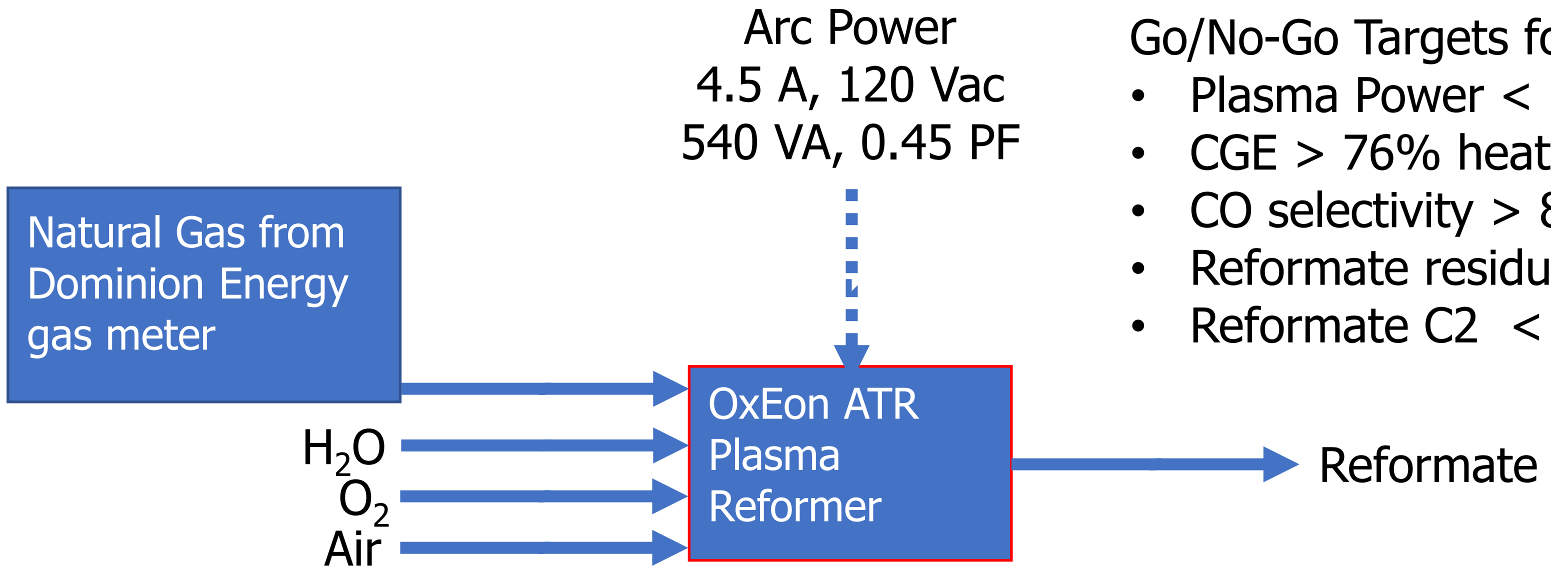
Demonstration Plant Design, Fabrication & Assembly – Underway in BP2

- Update from sub-level testing to overall integrated design
- Subsystem fabrication
- Full system integration

Demonstration Plant Commissioning & Operations – BP3

- SOEC Stack Fabrication and Test
- System commissioning at OxEon
- Digester Site Prep and interface work
- System install and test onsite

Approach – Sub System: Plasma Reformer Block Diagram



Go/No-Go Targets for Verification

- Plasma Power < 350 W at 0.45 PF
- CGE > 76% heat rate product/reactant
- CO selectivity > 80% (feed CH_n basis)
- Reformate residual CH_4 < 1 mol%
- Reformate C2 < 0.2 mol%

Nominal Reformer Feed & Performance

Stream	Rate	Units	Composition/Quality
Natural Gas	28	SLPM	92% CH4, 4 C2, 2.2 CO2, 1 N2, 0.5 C3, 0.3 C4+
Liquid water	2.7	g/min	room temperature liquid water
Primary Reformer Air	38	SLPM	Plant air compressor
Oxygen	12.15	SLPM	Room temperature oxygen from Lox dewar
Plasma power supply	540	VA	540VA transformer, 120Vac primary, 9kV, 60mA secondary
	243.0	Watt	Manufacturer reported power factor of 0.45
	1.35%		real power in W to natural gas higher heating value heat rate
Reformer Cold Gas Efficiency	82.6%	percent	heat rate of products to reactants
CO selectivity	81.8%	C atom%	Carbon as CO
CO2 selectivity	16.8%	C atom%	Carbon as CO2
CH4 selectivity	1.2%	C atom%	Carbon as CH4
C2H2 selectivity	0.1%	C atom%	Carbon as C2H4

Nominal Reformate Composition

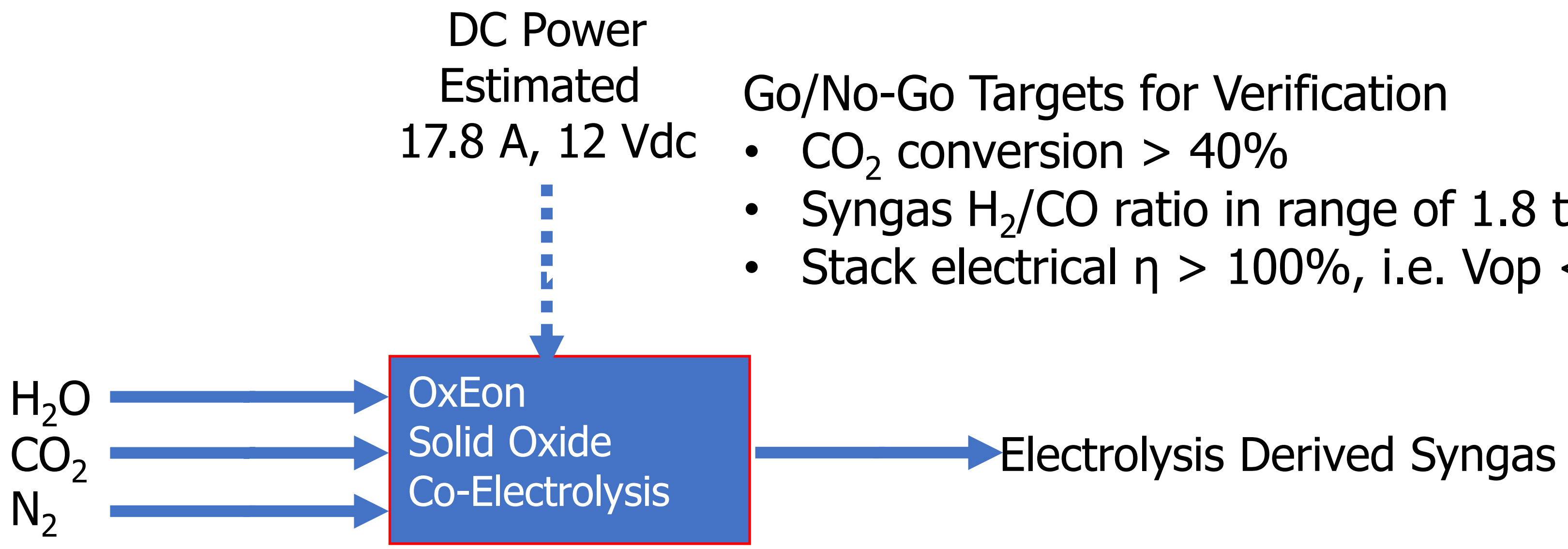
NITROGEN	27.6%	mole%	Internal reference for mass balance
ARGON	0.33%	mole%	Not detected in GC
HYDROGEN	44.6%	mole%	
WATER	0.0%	mole%	GC measurements dry basis
CARBON MONOXIDE	22.4%	mole%	
CARBON DIOXIDE	4.6%	mole%	
METHANE	0.3%	mole%	
ETHANE	0.00%	mole%	
ETHYLENE	0.02%	mole%	

Approach – Subsystem SOEC Block Diagram

Nominal Feed Rates
- 0.870 SLPM CO_2
- 0.108 SLPM N_2
- 0.108 SLPM H_2
- 1.29 g/min H_2O

Pressure < 1.5 bar_a

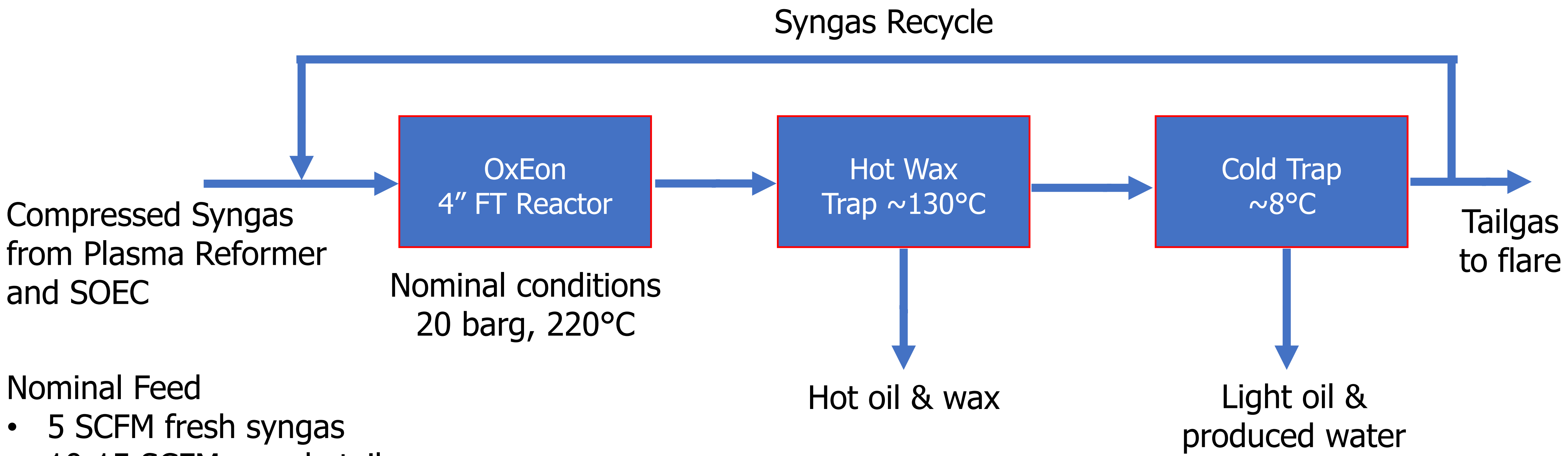
Go/No-Go Targets for Verification
- CO_2 conversion > 40%
- Syngas H_2/CO ratio in range of 1.8 to 2.2
- Stack electrical η > 100%, i.e. Vop < 1.34 V/cell



Nominal Stack Inlet/Exit Composition

	Simple Mole Fraction		Shift Equil Mole Fraction		
	Inlet	Outlet	Inlet	Outlet	Conversion
H2O	0.597	0.298	0.610	0.301	-0.496
CO2	0.323	0.162	0.311	0.160	-0.507
H2	0.040	0.338	0.027	0.336	0.496
CO	0.000	0.162	0.013	0.164	0.507
balance N2	0.040	0.040	0.040	0.040	0.000
	1.000	1.000	1.000	1.000	

Approach – Subsystem FT Block Diagram



Nominal Feed

- 5 SCFM fresh syngas
- 10-15 SCFM recycle tailgas (syngas with some methane)

- Targeting CH_4 selectivity < 12%
- Water separated from light oil
- Oil & wax products blended for product analysis/mass balance

Go/No-Go Targets for Verification

- CO & H_2 conversion > 80%
- Selectivity of CO reacted to C5+ > 76%
- Overall CO to C5+ > 67%
- Mass balance closure > 92% for C
- SimDist Peak C_n > C_9
    - Oil & Wax product > 9 liters/day

Approach – Challenges

- **Realized (and retired):**
  - FT performance with existing catalyst to program targets
    - Worked with catalyst supplier to manufacture targeted performance catalyst
    - Currently running catalyst characterization tests parallel to fabrication effort to develop operating strategy and test plan for integrated system

- **Existing:**
  - Timeline for fabrication driven by workforce and supply chain
  - Commissioning of full integrated system: first of a kind demonstration. Sub level verification test planning throughout fabrication schedule will reduce the challenge of final assembly level commissioning

Approach – Risk and Mitigation for Current Budget Period

OxEon energy

Design Based Risk and Mitigation Strategy

Risk/Issue Description	Probability of Occurrence	Impact	Risk Rank	Mitigation Strategy (Yellow/Red)
Supply Chain Issues (Lead times, costs, availability	Moderate	High	High	Longest lead items will be ordered as soon as possible after Preliminary Design Review (PDR).
Fin and Catalyst loading issues	Moderate	Critical	High	Pipe boring if fins won't load; Catalyst loading test
Control panel lead times	Moderate	Moderate	Moderate	Total I/O count will be used to order a main PLC panel immediately. I/O cards and junction boxes will be ordered upon completion of 3D layout.
Welding of design is intractable	Low	High	Moderate	Confirmed approach with design/fabrication shop; they deemed the design doable.
Finding correct catalyst	Low	High	Moderate	The catalyst obtained will be tested in a smaller reactor for verification.
Reactor fitting in existing skid	Extremely Low	Moderate	Moderate	The diameter is fine for the new skid. The existing skid has a removable top in case the height required is too tall. This removable top can be extended.
Reaching process design requirements	Low	High	Moderate	FT reactor is oversized to minimize chance of the reactor being unable to reach process requirements
Length of reactor required is too long for erection	Extremely Low	Low	Low	Rigging company will mount FT reactor in structure
Fin Joining Issues	Low	Low	Low	Fin joining will be tested on smaller lengths as part of other projects to verify joining technique.

Approach – Communication and Stakeholder Review

- *Verification Test:*
  - May 2020: Verification completed for SOEC and Plasma
  - October 2021: Verification completed for FT

- *System Design PDR:* May 2022
  - Program review and preliminary design review for full integrated system
  - Attendees: BETO Office and ICF Consultants

Progress and Outcomes – Progress update

- **BP1**: All tasks in BP1 Completed
- **BP2**: In process, approved 9 month no cost extension to accommodate workforce and supply chain impacts
  - PDR Completed
  - Internal Design finalization underway with fabrication starting
- **BP3**: Expected to complete with extended schedule

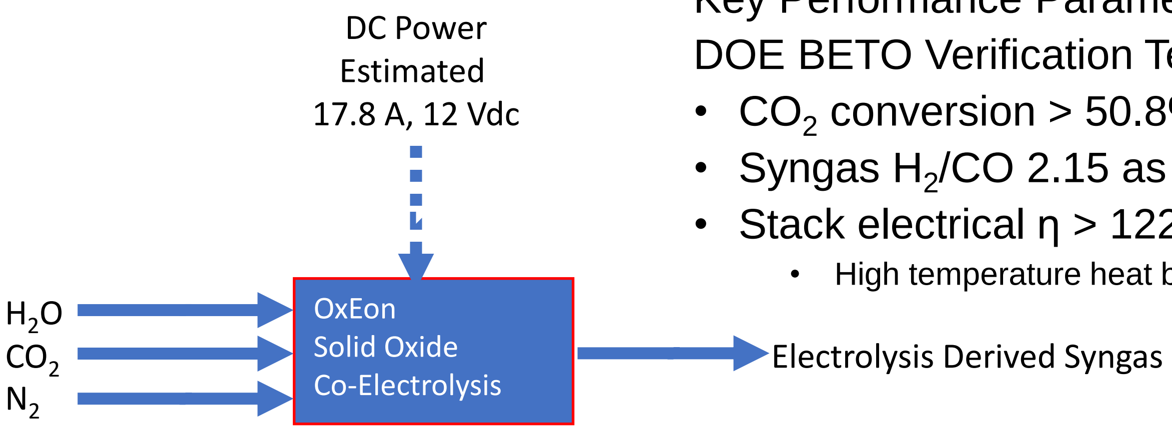
SOEC Verification Results

Nominal Feed Rates
(model gas stream)

- 0.74 SLPM CO_2
- 0.135 SLPM H_2
- 1.1 g/min H_2O
- N_2 optional

Will work with test site to identify impurities in digestor gas and pretreat as necessary

- OxEon's proprietary SOEC electrode has demonstrated extreme sulfur tolerance as a fuel cell



Key Performance Parameters Results of DOE BETO Verification Testing

- CO_2 conversion > 50.8%
- Syngas H_2/CO 2.15 as predicted from feed.
- Stack electrical η > 122%, (V_{tn}/V_{op}=1.34/1.099)
  - High temperature heat brings overall stack to η = 100%

Expected Stack Inlet/Exit Composition

	Simple Mole Fraction Inlet	Simple Mole Fraction Outlet	Shift Equil Mole Fraction Inlet	Shift Equil Mole Fraction Outlet	Conversion
H2O	0.615	0.308	0.633	0.312	-0.492
CO2	0.326	0.163	0.308	0.158	-0.515
H2	0.059	0.366	0.040	0.361	0.492
CO	0.000	0.163	0.018	0.168	0.515
balance N2	0.000	0.000	0.000	0.000	0.000
	1.000	1.000	1.000	1.000	

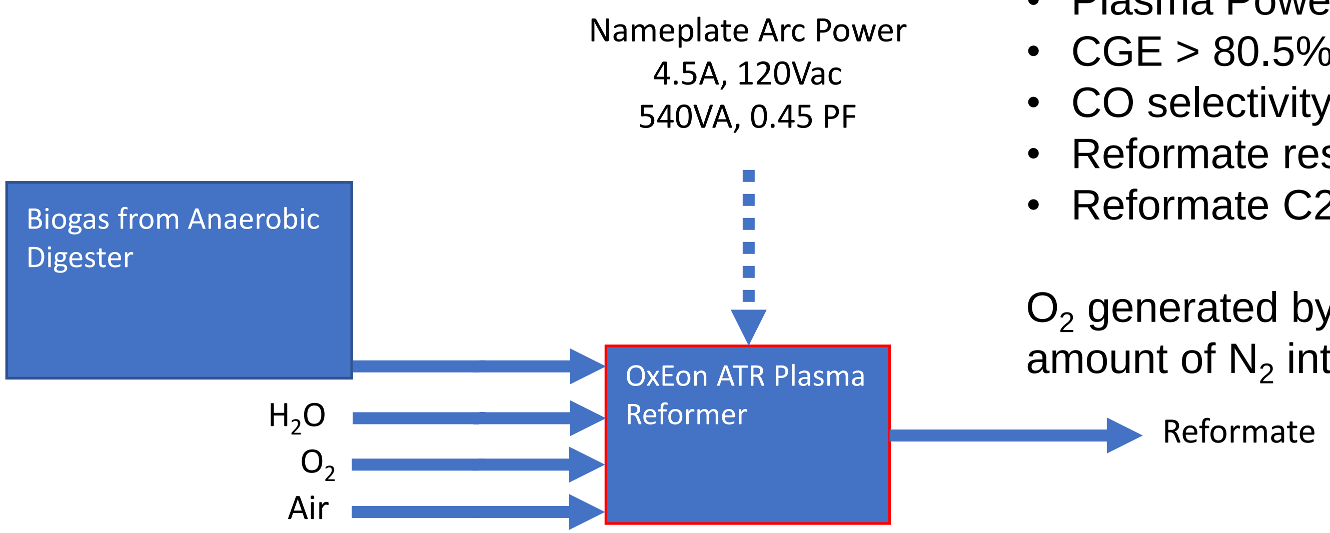
Progress and Outcomes – Key Technical Accomplishments

Plasma Reformer Verification Results

Key Performance Parameters Results of DOE BETO Verification Testing

- Plasma Power 295W at 0.45 PF
- CGE > 80.5% heat rate product/reactant
- CO selectivity > 81.1% (feed CH_n basis)
- Reformate residual CH_4 0.15 mol%
- Reformate C2 not detected

O_2 generated by SOEC used to reduce amount of N_2 introduced by air



Expected Reformer Feed & Performance

Stream	Rate	Units	Composition/Quality
Natural Gas	28	SLPM	92% CH4, 4 C2, 2.2 CO2, 1 N2, 0.5 C3, 0.3 C4+
Liquid water	2.7	g/min	room temperature liquid water
Primary Reformer Air	38	SLPM	Plant air compressor
Oxygen	12.15	SLPM	Room temperature oxygen from Lox dewar
Plasma power supply	540	VA	540VA transformer, 120Vac primary, 9kV, 60mA secondary
	243.0	Watt	Manufacturer reported power factor of 0.45
	1.35%		real power in W to natural gas higher heating value heat rate
Reformer Cold Gas Efficiency	82.6%	percent	heat rate of products to reactants
CO selectivity	81.8%	C atom%	Carbon as CO
CO2 selectivity	16.8%	C atom%	Carbon as CO2
CH4 selectivity	1.2%	C atom%	Carbon as CH4
C2H2 selectivity	0.1%	C atom%	Carbon as C2H4

Expected Reformate Composition

NITROGEN	27.6%	mole%	Internal reference for mass balance
ARGON	0.33%	mole%	Not detected in GC
HYDROGEN	44.6%	mole%	
WATER	0.0%	mole%	GC measurements dry basis
CARBON MONOXIDE	22.4%	mole%	
CARBON DIOXIDE	4.6%	mole%	
METHANE	0.3%	mole%	
ETHANE	0.00%	mole%	
ETHYLENE	0.02%	mole%	

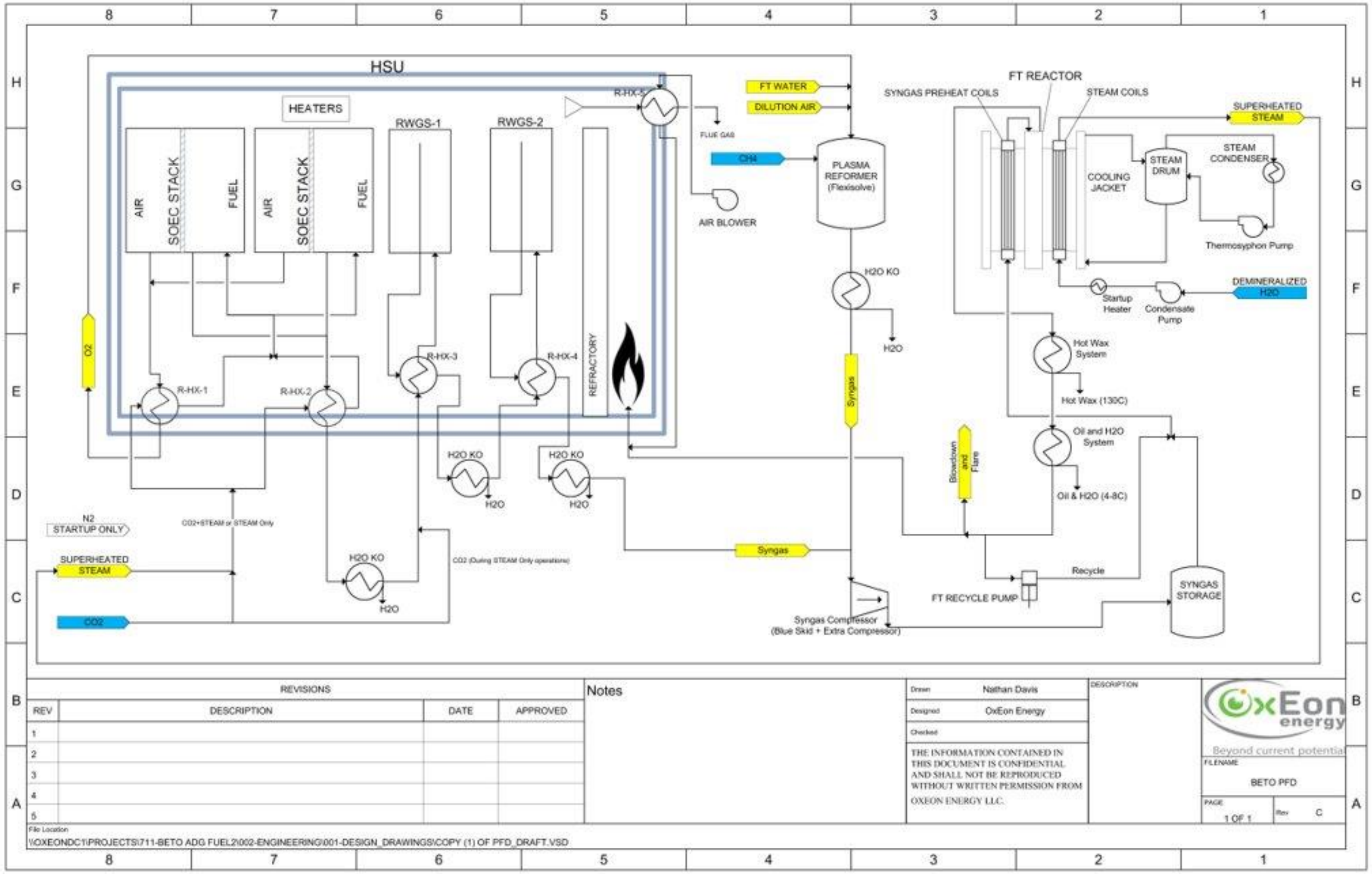
Progress and Outcomes – Key Technical Accomplishments

FT Verification Results

Criteria	Target	Overall Averages 10/21-10/29 and 10/30-11/3		Overall Averages 10/21-11/3	2020 Results
CO Conversion	>80%	84.2%	86.1%	84.9%	92%
H_2 Conversion	>80%	93.4%	93.8%	93.6%	92%
CO Selectivity to C5+	>76%	80.2%	75.9%	78.6%	73.2%
Overall CO to C5+ (Conversion*Selectivity)	>67%	67.4%	65.4%	66.7%	67.2%
Mass balance closure	>92% on C	95.8%			98.80%
Product Distribution C_n peak	>C9	SimDis product peak at C9-C10		C9-C10	C8-C9

Progress and Outcomes – Key Technical Accomplishments

Integrated System Design – Nearing completion, sublevel fabrication underway



Milestone 1.0: Completion of initial verification process with the DOE BETO Verification Team

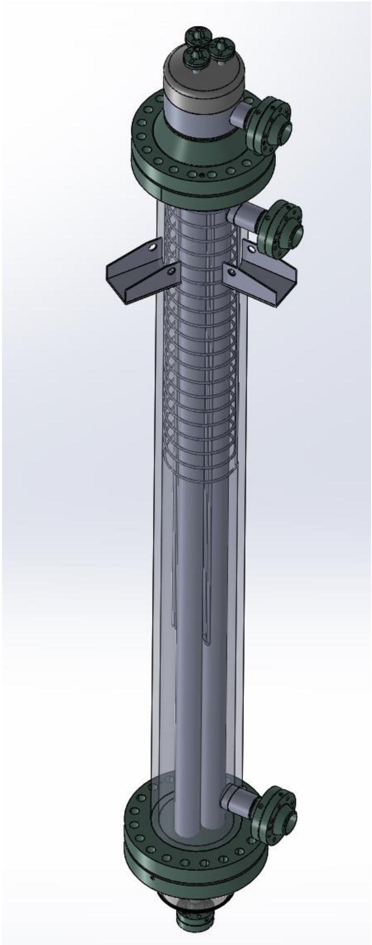
- Verification testing included BETO verification team (virtual)
- All Key Performance Parameters were met or exceeded
- Go/No-Go for BP1 passed with Milestone 1.0 completion

BP1 verification test system (left) and produced liquid fuel product (above)

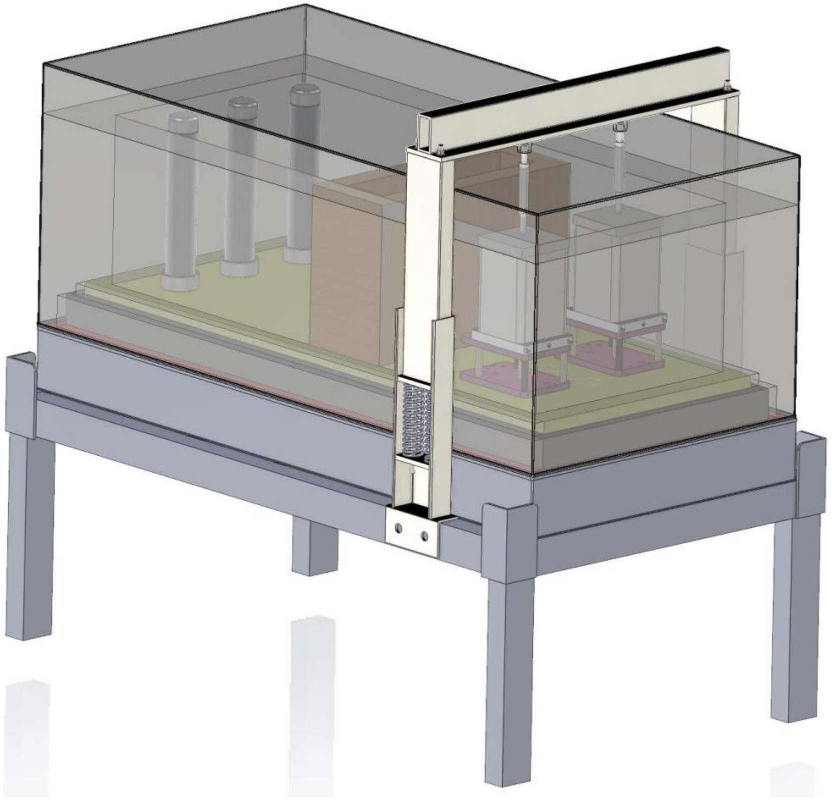
Progress and Outcomes – Key Milestones

Milestone 1.1: Completion of Preliminary Design Review (PDR) with project team

- Preliminary integrated system design reviewed with project team and PDR passed



FT reactor



SOEC Hot Section Unit

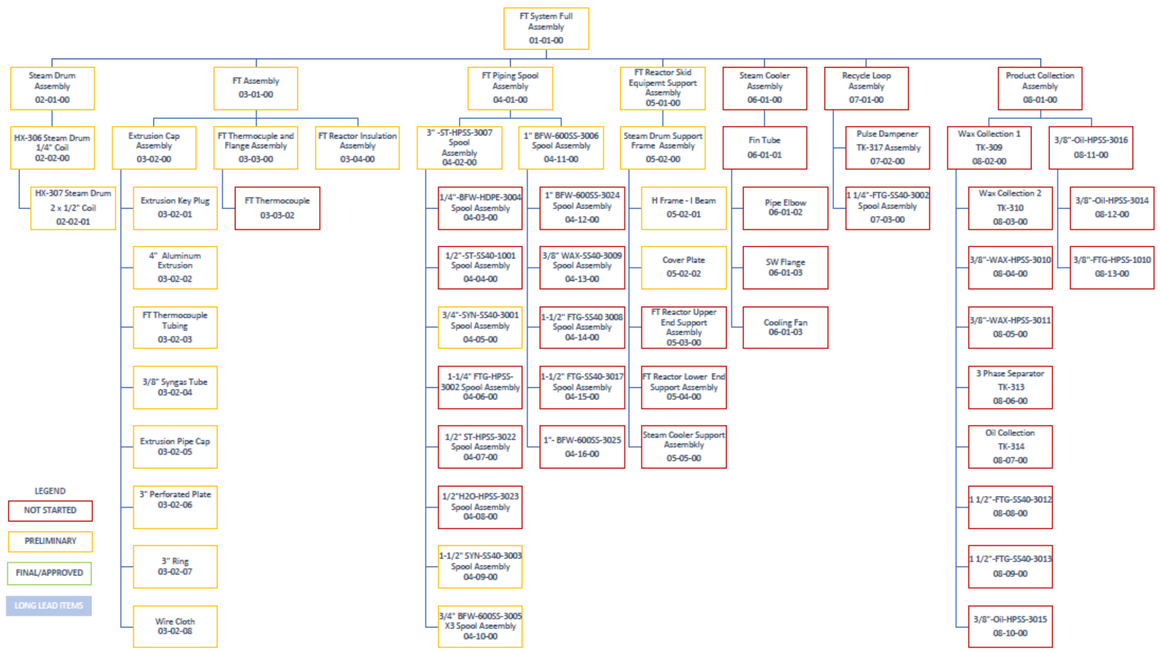
Plasma Reformer

Progress and Outcomes – Key Milestones

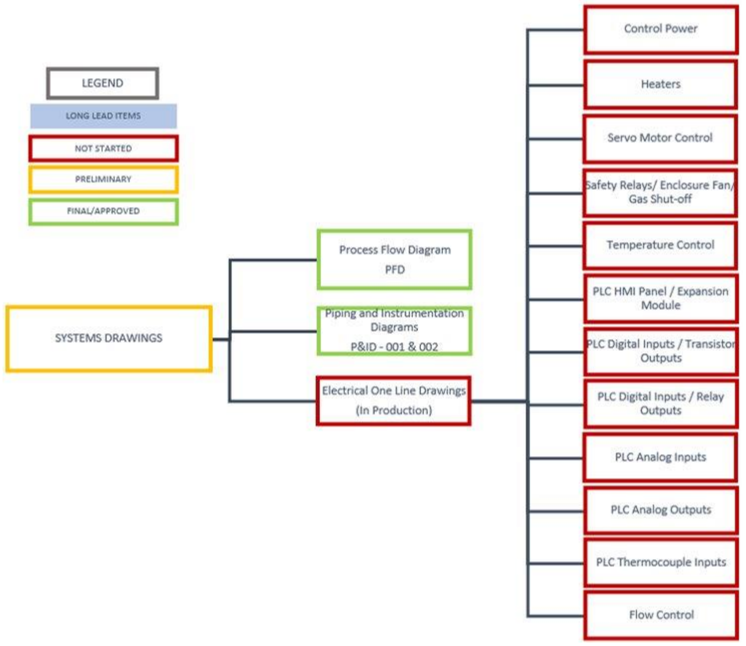
Milestone 1.2: Completion of Fabrication Drawings and COTS table with vendor quotes

- Subsystem drawings are in release process along with BOM approval
- Long Lead items for all systems approved and purchasing underway

FT SYSTEM 711- Design Tree



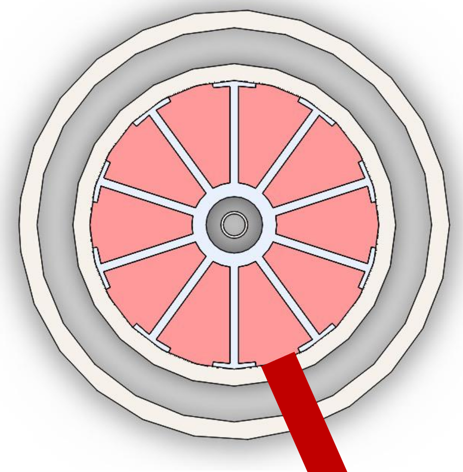
Drawing Tree for FT System Portion

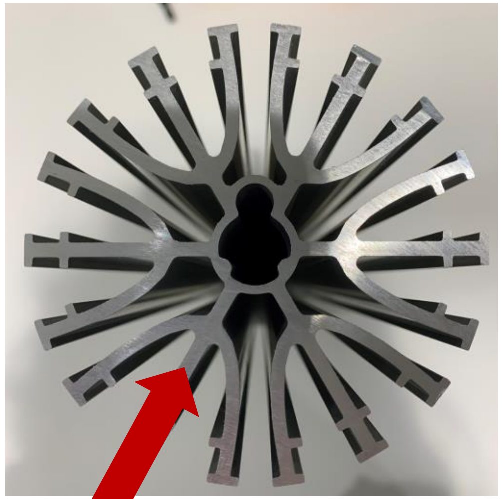


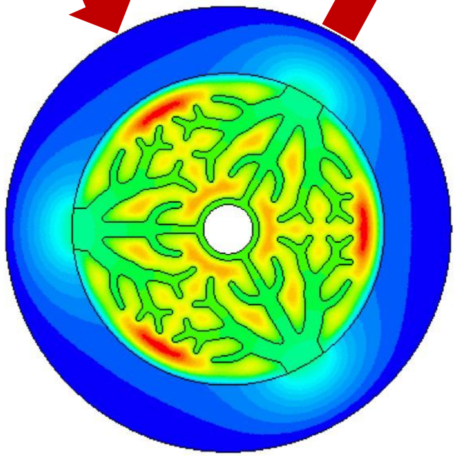
Drawing Tree for Balance of Plant

Milestone 1.4-1.6: Subassembly system fabrication – In Progress

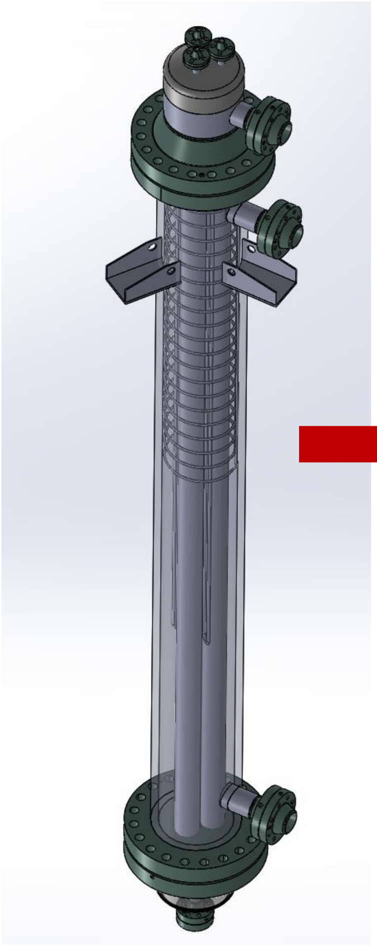
- Fabrication underway for approved components of the FT system and skid
- Control panel fabrication underway







HPC4EI partnership with LLNL to generate optimized FT fin



Impact

Prior funding in the proposed technology areas focused primarily on the development of individual devices.

- Electrolysis stacks were tested using steam or steam and bottled CO_2 as feed gas. The reformer was primarily tested using pipeline natural gas or bottled biogas in laboratory setting.
- OxEon FT technology has been tested using natural gas derived syngas and syngas from a coal-biomass gasifier. These tests have been done in an industrial laboratory environment.

The unit operations will be integrated, and the integrated system will be sited and run on biogas at an operational commercial anaerobic digester plant. This will be the first of a kind test to combine the technologies to use methane and CO_2 from a biodigester to produce liquid fuel.

Without DOE-EERE funding to provide the opportunity for an onsite engineering demonstration to de-risk the technology components, it would be difficult to attract funding for demonstration at commercial scale. Successful demonstration will allow the anaerobic digester partner to attract developers for a full-scale plant.

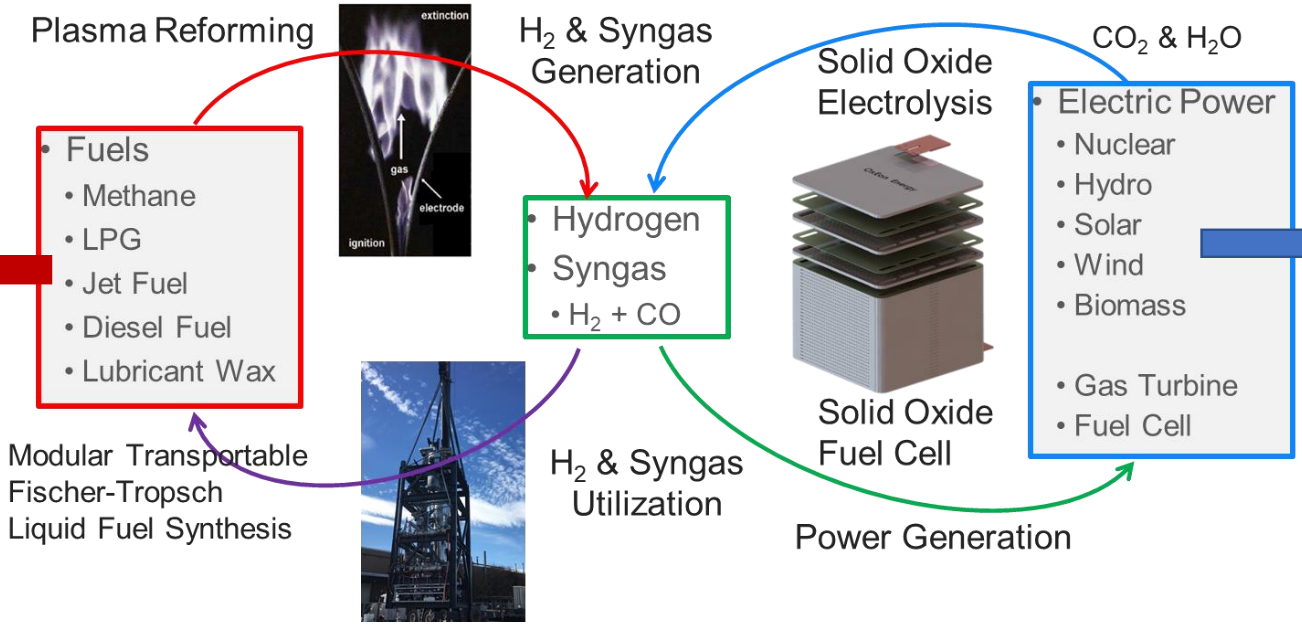
Impact – Dissemination of Results

Presentations in aerospace and defense on technology development for sustainable aviation fuel production

Multiple bids outstanding or in process for replicate demonstration systems for various industries

Two FT demonstrations underway

- Use CO_2 extracted from seawater for fuel production
- Use direct air capture CO_2 for fuel production



Reversible SOC systems currently produce and consume H_2

- Success of BETO integration will bolster case for integrating with FT and Plasma technologies for additional end products

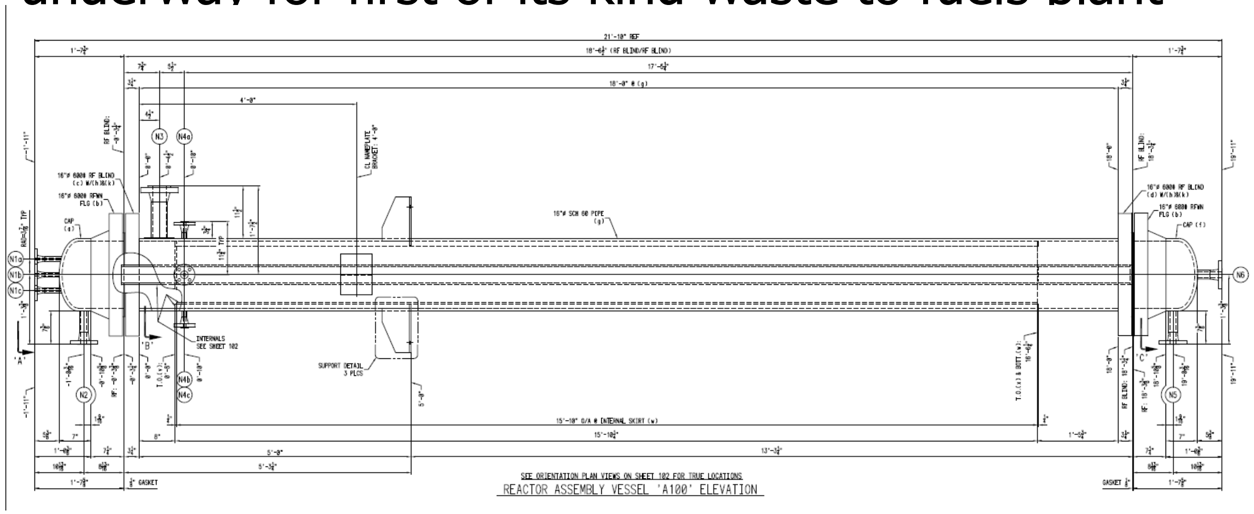
OxEon's Technology Space allows for flexibility of system inputs and products, as well as partnerships with other successful technologies for new and renewable energy systems.

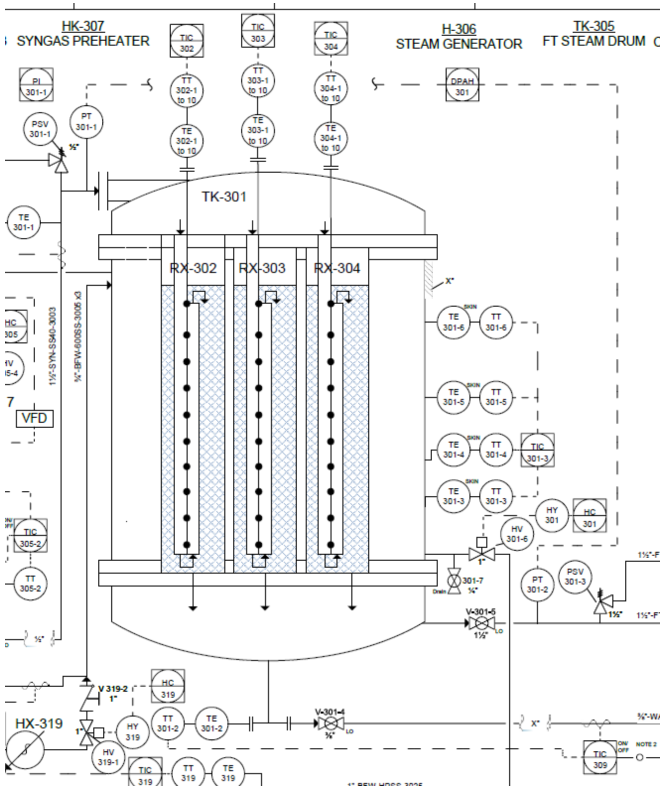
Summary

Subsystem verification showed each technology is capable of meeting the program requirements for an integrated system

Preliminary design review passed with BETO Review Team

Fabrication underway for first of its kind waste to fuels plant





Quad Chart Overview

Timeline

- *October 1, 2019*
- *September 30, 2024*

	FY22 Costed	Total Award
DOE Funding	*$294,130*	*$1,995,388*
Project Cost Share*	$73,530	$498,848

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

Project Goal

Construction of a biogas to synthetic fuels facility having a nominal capacity of 8 gallons of liquid hydrocarbon fuel per day utilizing OxEon's co-electrolysis, plasma reformation, and Fischer-Tropsch technologies

End of Project Milestone

Successful demonstration of >50% biogenic carbon to fuel with a minimum 500 hours operation and 100 gallons of biofuel product from combined methane and CO_2 digester inputs.

Funding Mechanism

DE-EE-0008917.0001

Project Partners*

- Wasatch Resource Recovery (Digester Site)
- Naval Research Laboratory/ONR
- LLNL HPC4e CRADA

Responses to Previous Reviewers Comments

OxEon energy

- If your project has been peer reviewed previously, address 1-3 significant questions/criticisms from the previous reviewers' comments which you have since addressed

This project has not been previously peer reviewed

- Also provide highlights from any Go/No-Go Reviews

Go/No-Go Review results shown in tables

Plasma Reformer

Criteria	Target	2020 Test Results
Plasma Power	< 350 W	295 W
CGE	> 76%	80.5%
CO Selectivity	> 80%	81.1%
Reformate residual CH_4	< 1 mol%	0.15%
Reformate C_2	< 0.2 mol%	Not detected

Stack

Criteria	Target	2020 Test Results
CO_2 Conversion	> 40%	50.8%
Syngas H_2/CO ratio	In rage of 1.8 to 2.2	2.15
Stack electrical eff > 100%	> 80%	122% (Vtn/Vop = 1.34/1.099)

Fischer Tropsch

Criteria	Target	2021 Test Results
CO Conversion	>80%	84.1%
H_2 Conversion	>80%	93.5%
CO Selectivity to C5+	>76%	79.8%
Overall CO to C5+	>67%	69.0%
Mass balance closure	>92% on C	95.1%
Product Distribution C_n peak	>C9	SimDis product peak at C10

Publications, Patents, Presentations, Awards and Commercialization

- **Presentations**

1. J. L. Barrera, J. J. Hartvigsen, M. Hollist, J. Pike, A. Yarosh, N. P. Fullilove, V. A. Beck, Design optimization of integrated cooling inserts in modular Fischer-Tropsch reactors, Chemical Engineering Science 268 (2023) 118423
2. J. J. Hartvigsen, J. Elwell, N. Davis, M. Hollist, J. Pike, and S. Elangovan, Serendipitous Process Integration of Solid Oxide Electrolysis Coupled Electro-Fuel Synthesis Biomass, 3rd Bioenergy Sustainability Conference, AIChE Institute for Sustainability, VIRTUAL, December 9-10, 2021
3. J. J. Hartvigsen, Considerations for Small Modular Gas to Liquids Plants, University of Utah, Undergraduate Process Design II Seminar, April 2021.
4. J. J. Hartvigsen, S. Elangovan, and L. J. Frost, 02-2543: (Invited) Increasing Biogas to Liquid Fuel Yield By Solid Oxide Co-Electrolysis of Biogas CO_2 Fraction, PRIME Pacific Rim Meeting on Electrochemical and Solid-State Science, Virtual, October 2020

- **Patent**
  - Application "Reactor Fin Insert Design", joint invention with LLNL on a HPC4e CRADA

- **Licensing**
  - OxEon has licensed some of these technologies to a large US EPC for certain regions of the world.
  - A flare gas abatement project in an OPEC country is in the works.