WEST BIOFUELS

Modular Biomass Power Systems to Facilitate Forest Fuel Reduction Treatments

West Biofuels
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Project Team

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TSS Consultants

- Fred Tornatore
- Tad Mason

Project Summary Overview

- Develop a modular gasification system with a high-efficiency lean-burn engine
- Document characteristics of forest-source biomass and demonstrate performance in the gasification system
- Develop alternative viable approaches to gasification suitable to forest biomass in California

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Project Tasks

- Task 2: Feedstock Characterization & Processing
  - Lead: TSS Consultants
- Task 3: Configure and Test CircleDraft Gasifier System
  - Lead: West Biofuels
- Task 4: Configure and Test Engine-Generator System
  - Lead: West Biofuels
- Task 5: Modular Biopower System Feasibility Study
  - Lead: TSS Consultants

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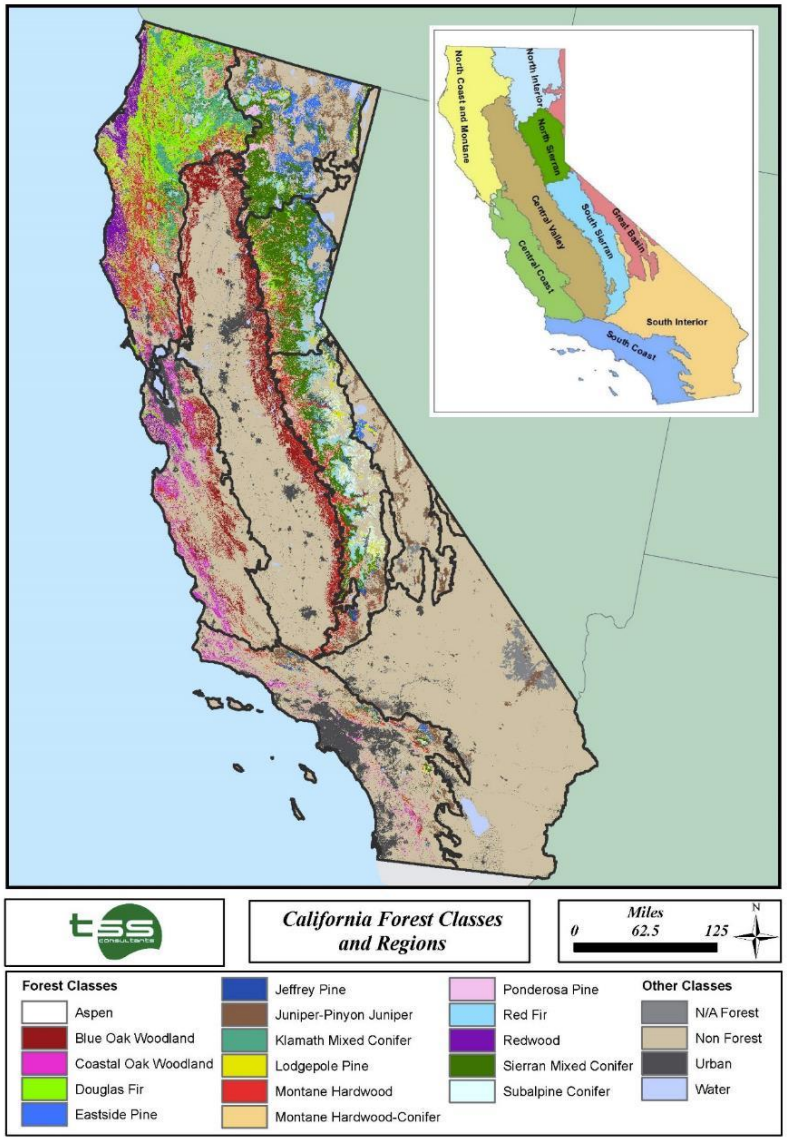
Task 2: Feedstock Characterization & Processing



- 9 Regions
  - Vegetation Classification and Mapping, US Forest Service (CalVeg)
- 17 Vegetation Types
  - California Wildlife Habitat Relationship
- 13 Land Ownership Classes
  - Fire and Resource Assessment Program (CalFire)

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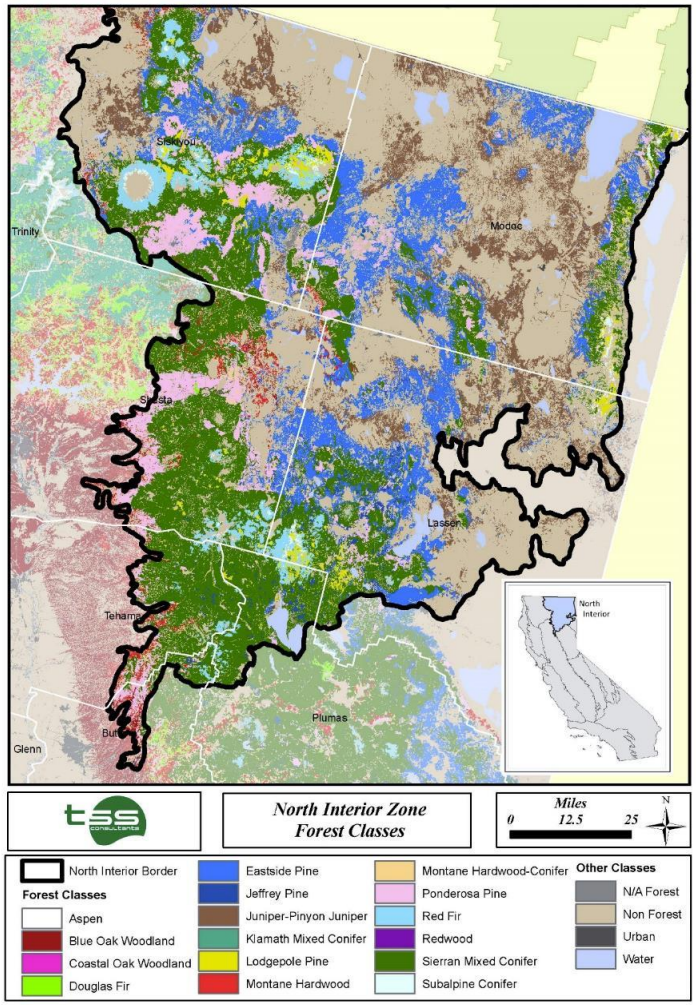
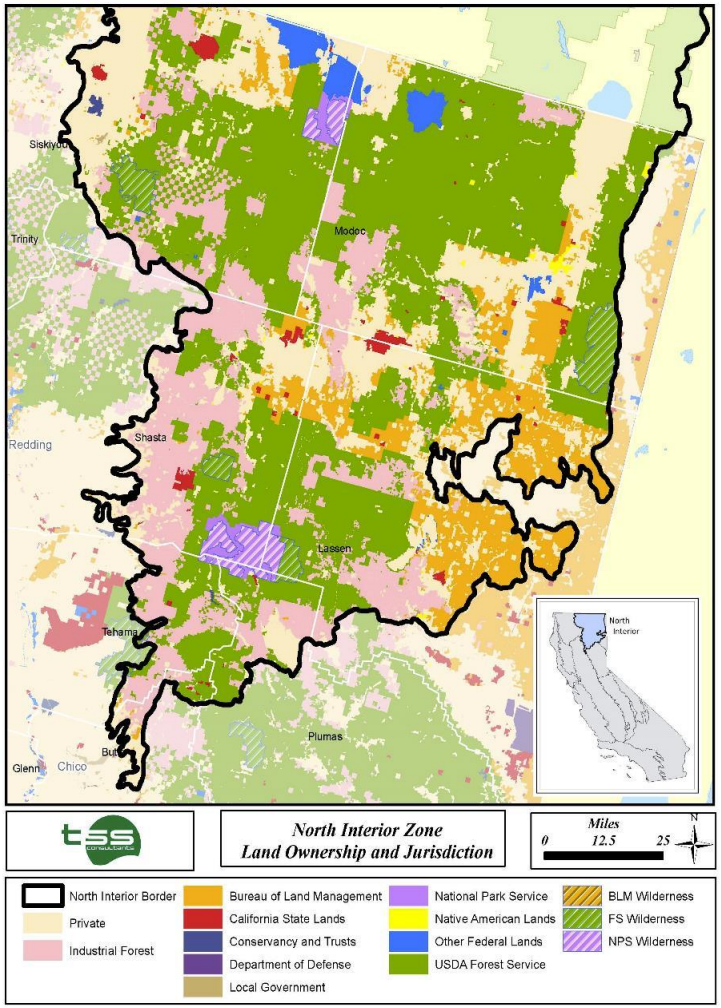
Task 2: Feedstock Characterization & Processing

Vegetation Type



Ownership Class



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Task 2: Feedstock Characterization & Processing

Region	Dominant Biomass Forest Classes used as Feedstock	Percent Public Forest	Percent Private Industrial Forest	Existing Forest Biomass Industry Characterization
North Interior	Sierran Mixed Conifer-White Fir Ponderosa Pine Red Fir	54%	46%	Robust
North Sierran	Sierran Mixed Conifer-White Fir Montane Hardwood Red Fir Ponderosa Pine	80%	20%	Robust
South Sierran	Sierran Mixed Conifer-White Fir Montane Hardwood Red Fir	94%	6%	Limited
Great Basin	Pinyon Juniper Eastside Pine	100%	0%	Very Limited

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Task 2: Feedstock Characterization & Processing

Region	Dominant Biomass Forest Classes used as Feedstock	Percent Public Forest	Percent Private Industrial Forest	Existing Forest Biomass Industry Characterization
North Coast East	Douglas Fir Klamath Mixed Conifer Montane Hardwood-Conifer Montane Hardwood Sierran Mixed Conifer-White Fir	82%	18%	Limited
North Coast Mid	Montane Hardwood Douglas Fir Montane Hardwood-Conifer Klamath Mixed Conifer	83%	17%	Limited
North Coast West	Redwood Montane Hardwood-Conifer Douglas Fir Montane Hardwood	13%	87%	Limited
Central Coast	Limited Biomass Utilization	>99%	<1%	Very Limited
South Coast	Limited Biomass Utilization	100%	0%	Very Limited

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Task 2: Feedstock Characterization & Processing

- Evaluated the lifecycle cost of the most common processing equipment
- Chipper was identified as the lowest-cost unit, but has the least feedstock flexibility

Make	Morbark	Morbark	Peterson	Bandit
Model	40/36 Chipper	4600 Grinder	4710 Grinder	3680 Grinder
Hourly Rate SMH	$231.00	$307.19	$240.36	$197.06
Hourly Rate PMH	$462.00	$614.38	$480.72	$394.12
Estimate Production (GT/PMH)	70 GT	72 GT	65 GT	53 GT
Cost/GT	$6.60/GT	$8.53/GT	$7.40/GT	$7.44/GT

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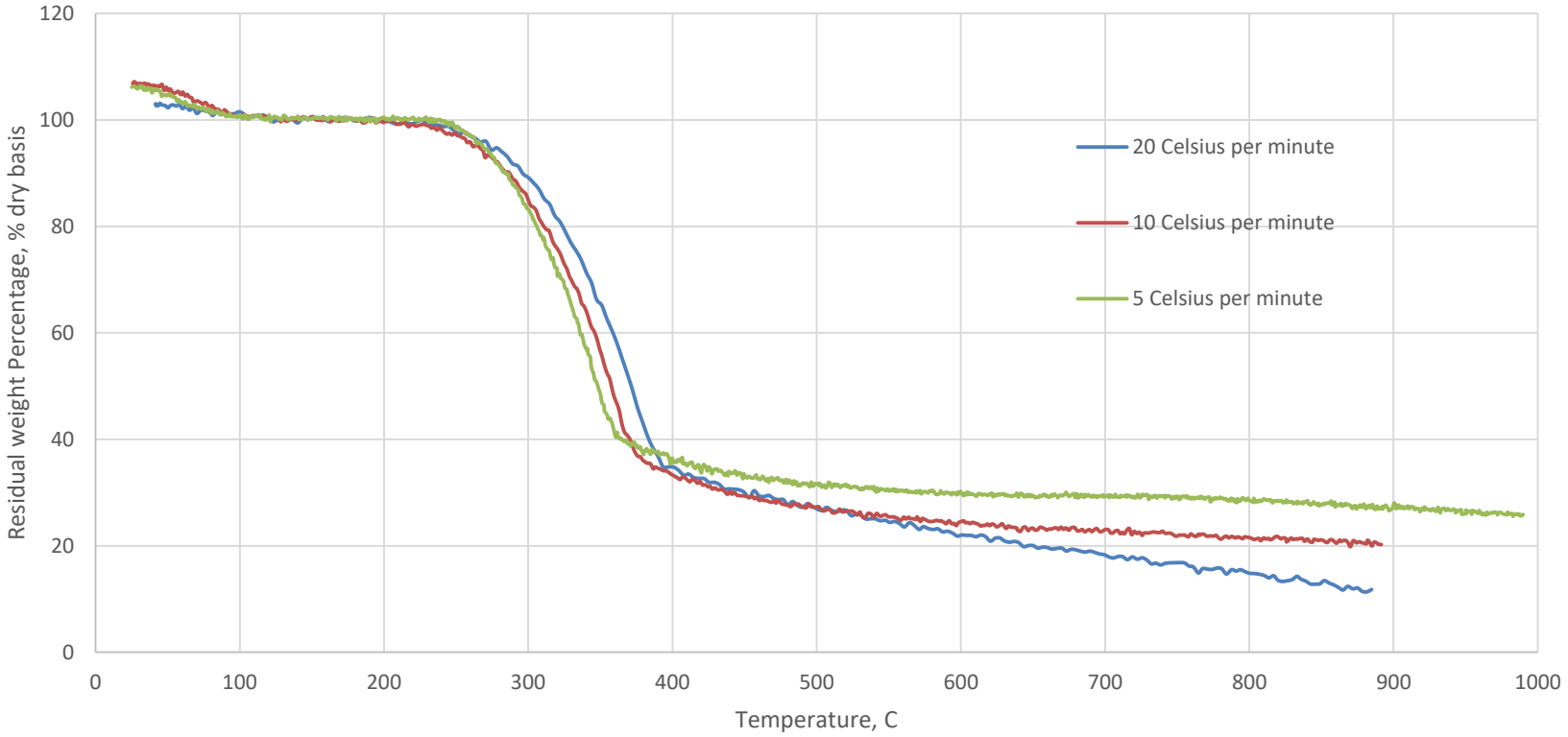
Task 2: Feedstock Characterization & Processing

- Thermogravimetric analysis was conducted to evaluate the characteristics of the volatiles



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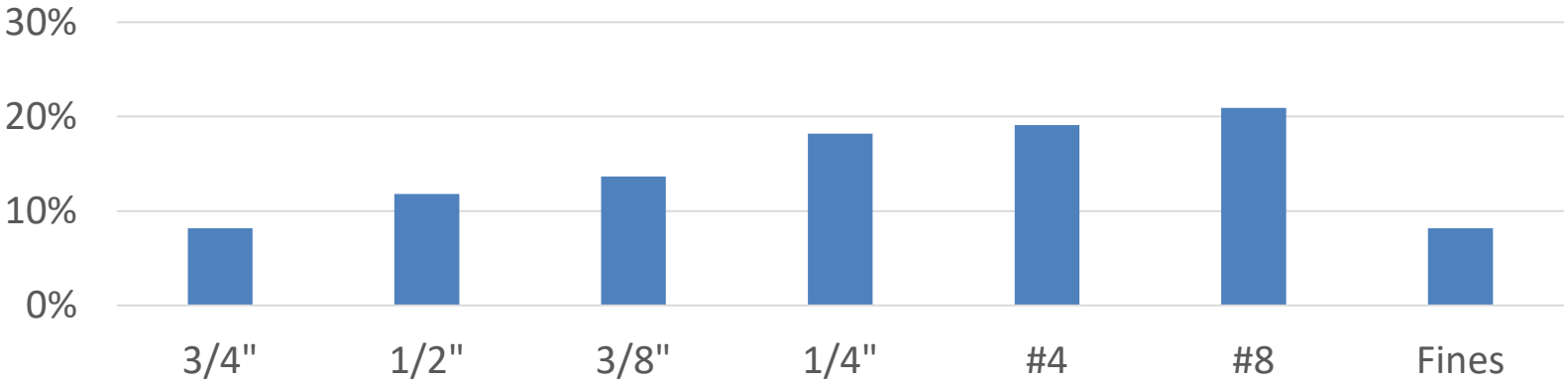
Task 2: Feedstock Characterization & Processing

- Classification was conducted to understand size parameters



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Task 3: Configure and Test Gasifier System

- Six runs conducted with exclusively forest wood
- First two runs were with mixed forest and agricultural wood for commissioning

Test Number	Test Descriptor	Gas Production Period (hr)	Biomass Input (kg)	Producer Gas Generated (kg)	Biochar Produced (kg)
3	June 2016 Run	37.5	4894	4446	718
4	October 2016 Run	23.5	5295	3984	799
5	December 2016 Run	26.0	4268	3980	610
6	February 2017 Run	5.2	1181	1142	140
7	June 2017 Run	6.5	2476	1498	224
8	September 2017 Run	4.3	*1249	984	113

* Estimated based on equivalent raw wood input to a torrefier system prior to the gasifier

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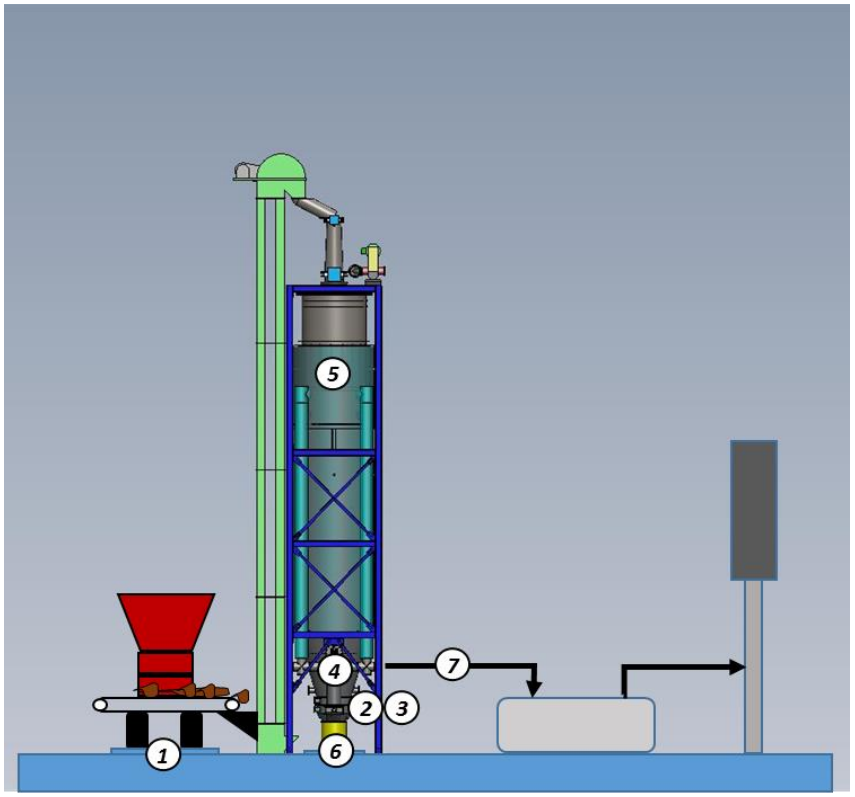
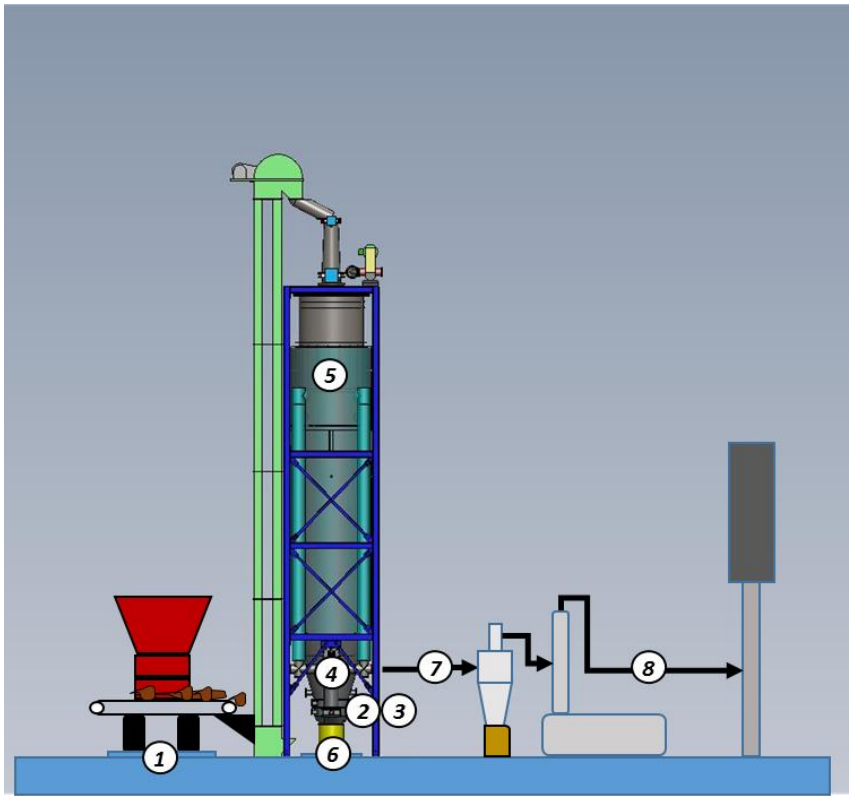
Task 3: Configure and Test Gasifier System



Sampling locations for the first phase raw gas testing.



Sampling locations for the second phase conditioned gas testing.

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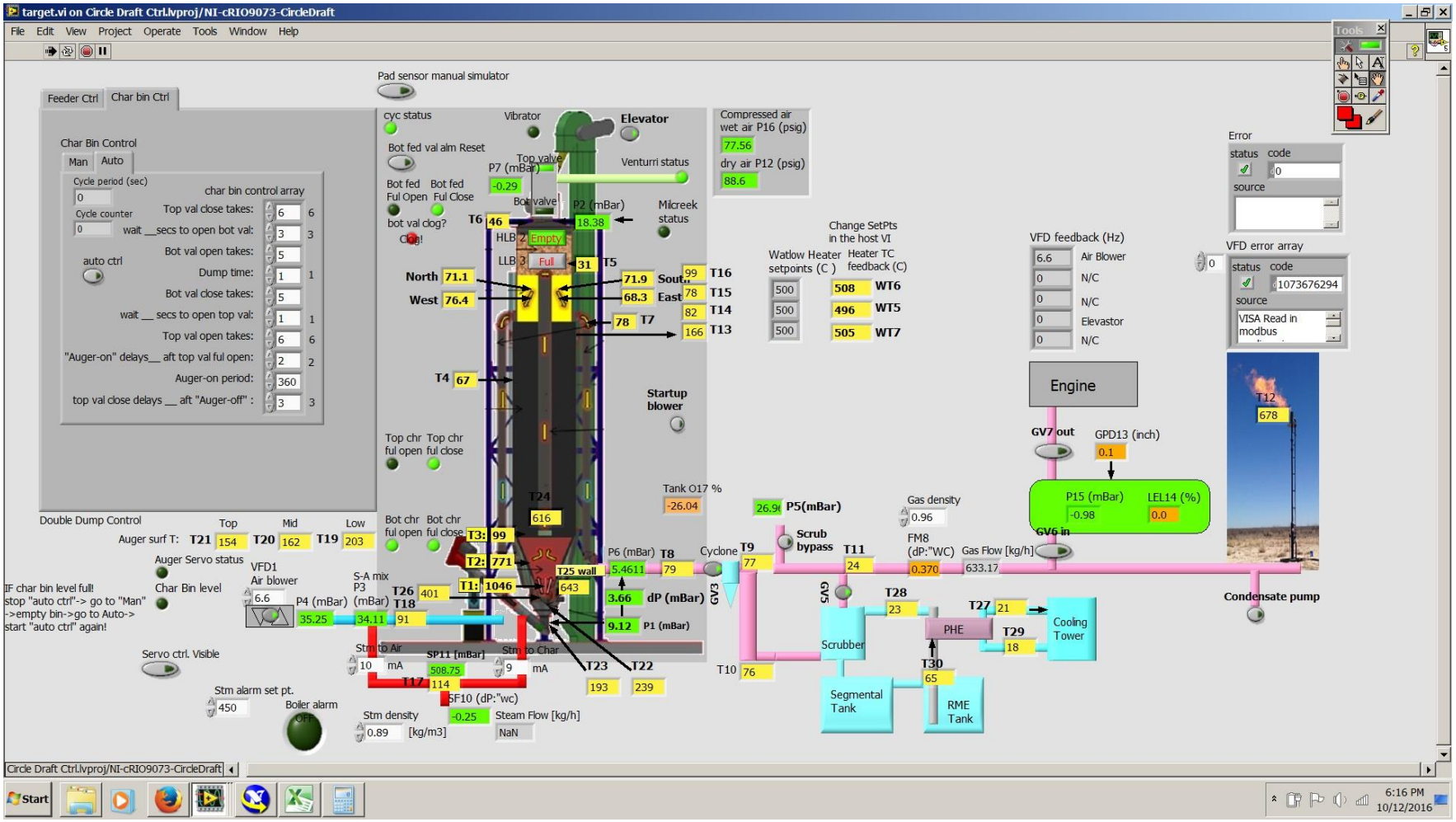
Task 3: Configure and Test Gasifier System

Control System - 10/12/2016 Run



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2nd generation Clean-up system
Canola biodiesel Sulzer scrubber system

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Flare System

1st generation system:
Open flare with
underground gas piping

Task 3: Configure and Test Gasifier System

- Tar measurements and removal efficiency

	Pre-Scrubber			Post-Scrubber			Average Reduction
(mg/Nm^3)	Min	Max	Average	Min	Max	Average	
Tar Species							
Benzene	723	1943	1266	423	600	499	61%
Toluene	394	1533	964	164	437	237	75%
Ethylbenzene	0	586	338	0	55	4	99%
Xylene	131	514	323	0	117	23	93%
Styrene	42	431	257	0	66	14	95%
Naphthalene	27	239	144	0	22	4	97%
***Unidentified**	1237	13984	8320	194	1176	507	94%
Total Tar	2554	19231	11613	781	2455	1287	89%
Total Particulate				536	829	683	

Task 3: Configure and Test Gasifier System

Objective	Original Target	Current Testing Results	Expected Performance	
Thermal Efficiency:	≥70%	63-77%	65%	*NO*
Throughput Rate:	≥ 900 dry lb/hr	140-620 dry lb/hr	450 dry lbs/hr	*NO*
Syngas Energy Content:	≥ 150 Btu per ft^3	168-210 Btu per ft^3	190 Btu per ft^3	*YES*
Tar Content:	< 20 mg per Nm^3	20 to 500 mg per Nm3	1000 mg/Nm^3	*NO*
Tar Dew Point:	< 15°C	Method Implementation	> 40° C;	*NO*
Particulates:	< 5 mg per Nm^3 and less than 1 micron	< 5 mg per Nm3	600 mg/Nm^3	*NO*
Hydrogen Sulfide:	< 50 ppm	13-40 ppm	25 ppm	*YES*
Biochar Production:	≥ 72 dry lb/hr	20-75 dry lb/hr	75 dry lbs/hr	*YES*
Biochar Quality:	(IBI) Biochar Standards	76.8-81.5% Fixed carbon	>60% fixed carbon	*YES*

Task 4: Engine Testing

- Installed a Caterpillar G3406 TA engine

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Task 4: Engine Testing

- Final exhaust emissions (after catalyst)
- Too high for targets in CA, additional controls would be needed in commercial operation

	Raw Exhaust (pre-cat)			Final Exhaust (post-cat)		
Component	Min	Max	Average	Min	Max	Average
NO_x (ppm)	>2500	>2500	>2500	82	209	104
SO_2 (ppm)	60	61	61	45	56	52
CO (ppm)	3552	3760	3655	62	204	106
NO_x Control (%)				96.7%	91.6%	95.8%
SO_2 Control (%)				26.2%	8.1%	15.3%
CO Control (%)				98.3%	94.4%	97.1%

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Task 4: Engine Testing

- Tars in producer gas were too high to sustain long-term operation

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Task 4: Engine Testing

- CircleDraft gasification system could not meet manufacturer requirements
- Used lessons learned from the testing to evaluate alternatives for modular systems
  - Tar variability in producer gas can be significant and poses high levels of financial risk
  - Feedstock variability and size configuration (ground) are not conducive to a fixed bed gasification system

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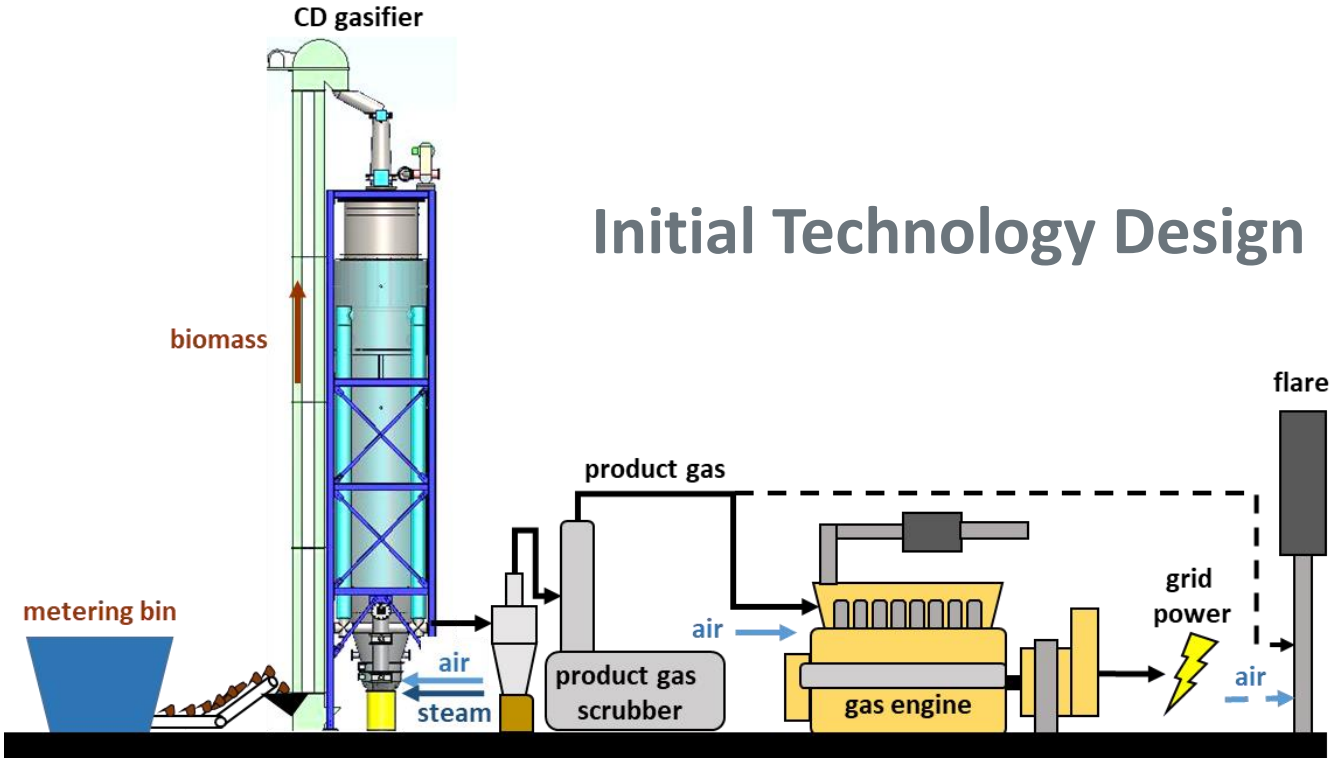
Task 3-4: Alternative Design



Initial Technology Design

- Evaluated other alternatives to gas engine
- Organic Rankine Cycle turbine

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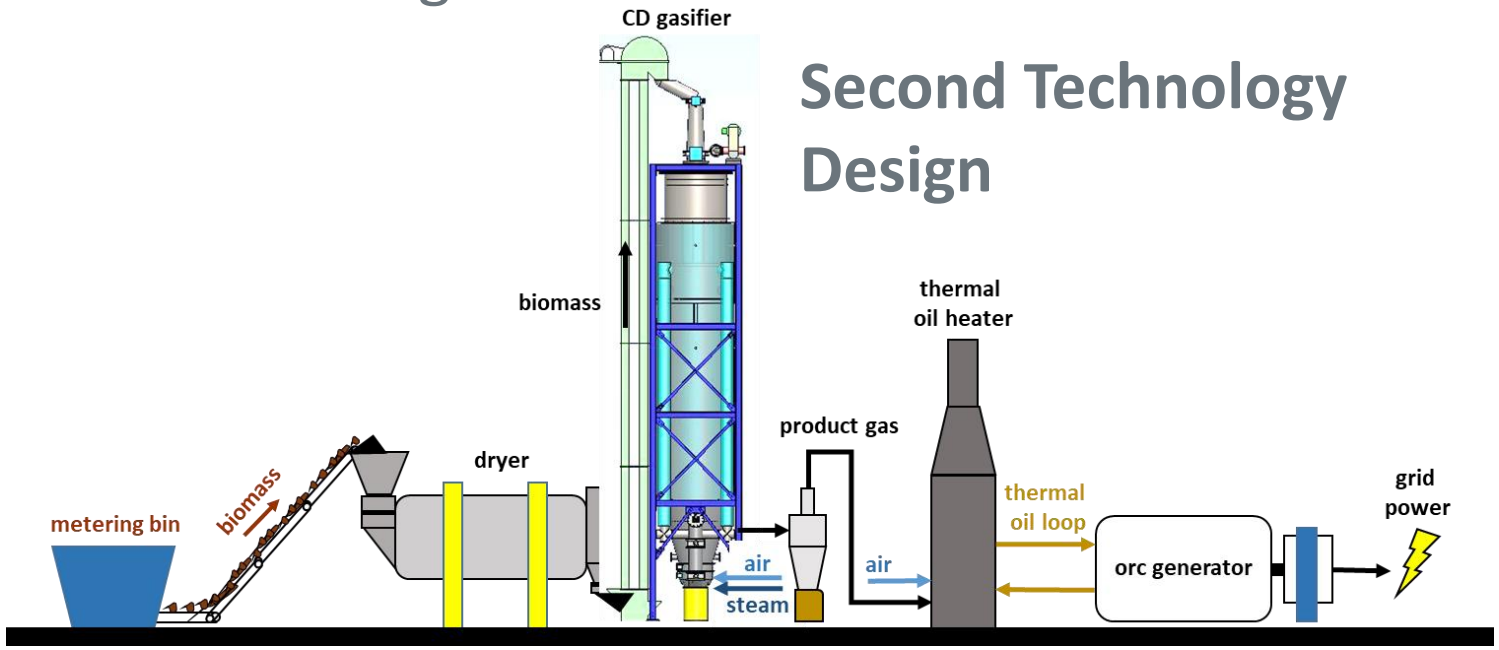
Task 3-4: Alternative Design

- An ORC solutions solved for variation in syngas output due to material flow challenges
- Significantly reduced technical risk by de-coupling the gasifier and the generator



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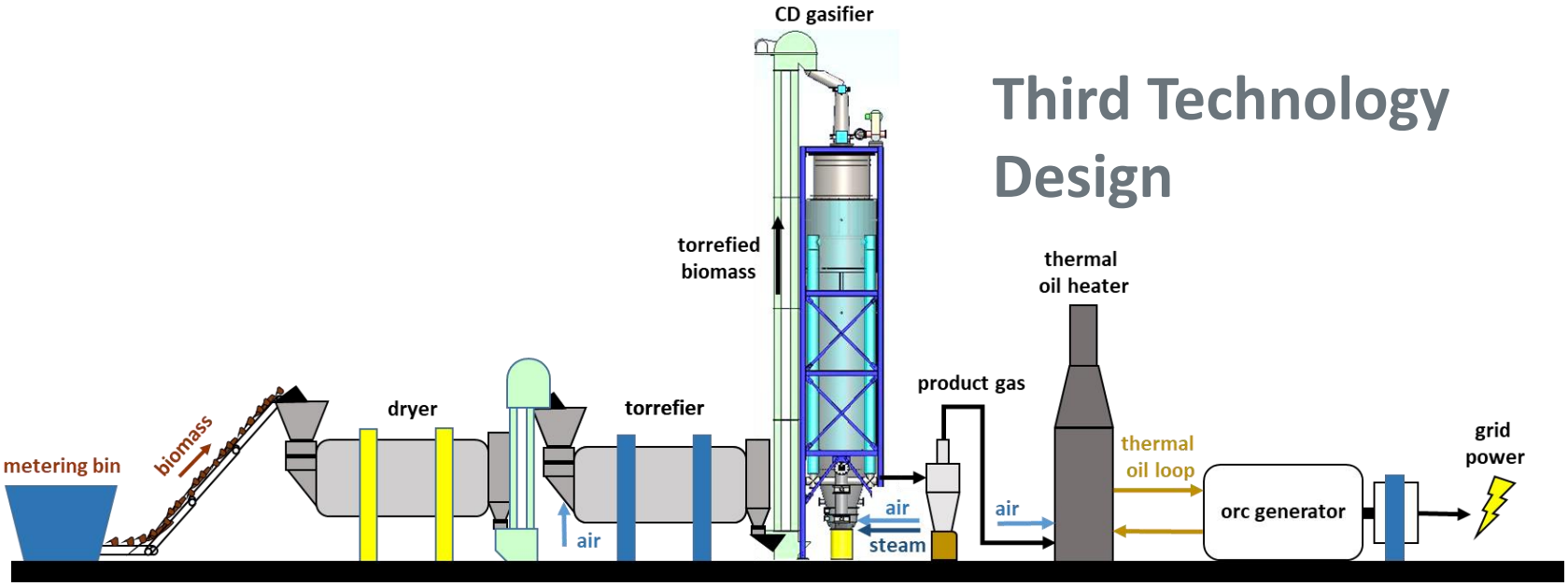
Task 3-4: Alternative Design

- Still needed to solve material flow challenges
- Evaluated torrefaction as a pre-processing step
  - Reduces binding characteristics of the feedstock



Third Technology Design

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Task 3-4: Alternative Design

- Partnered with TSI to evaluate torrefaction opportunities using TSI's test facility

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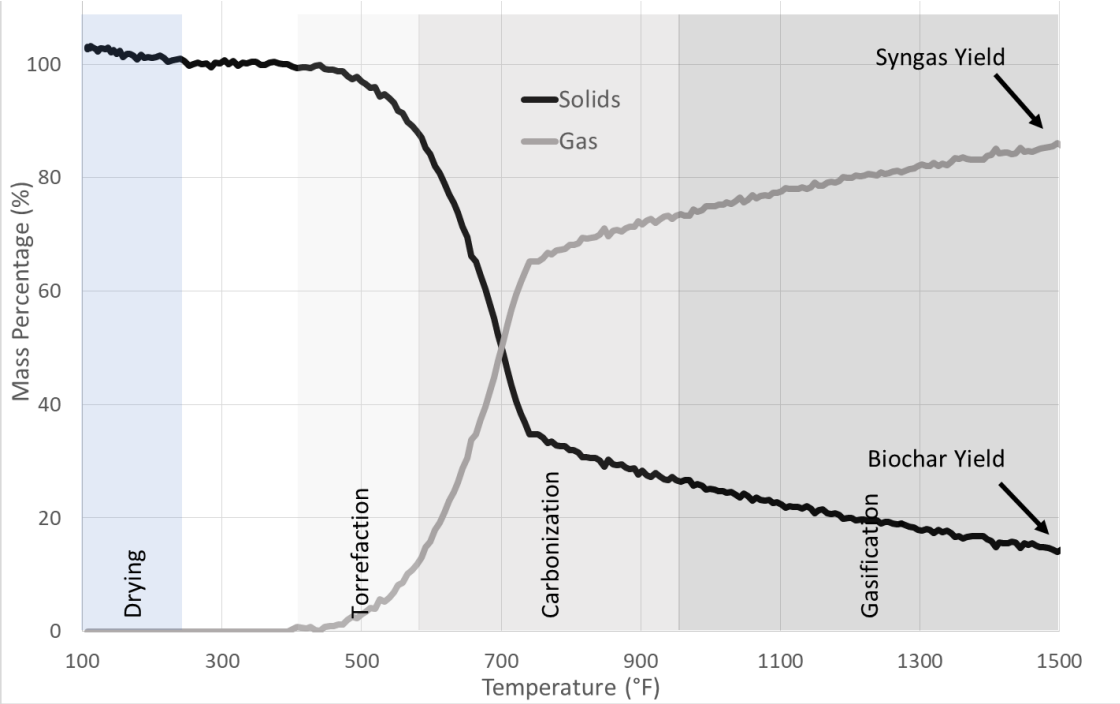
Task 3-4: Alternative Design

- Successful torrefaction testing
- Evaluated higher temp. gasification with a rotary system
- Successful high temperature gasification/carbonization



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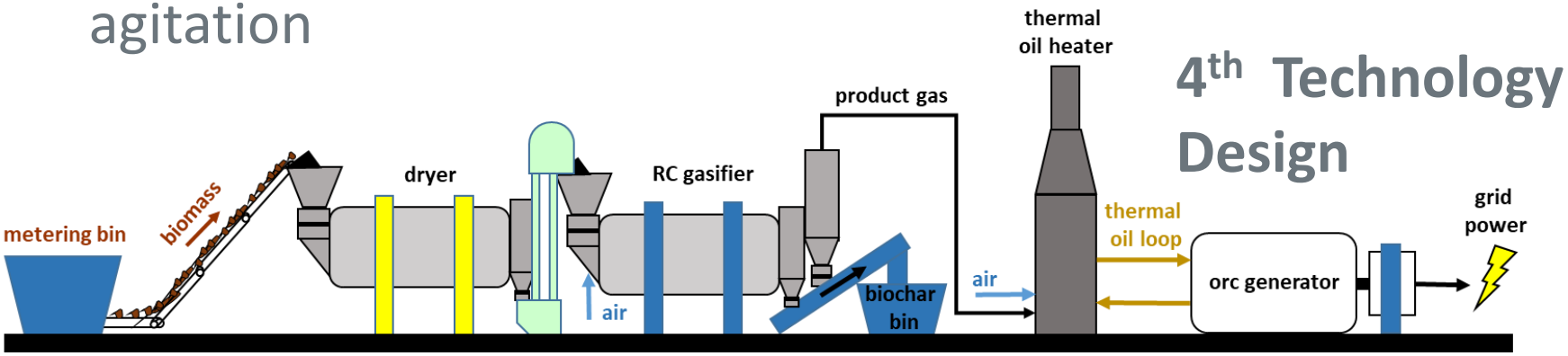
Task 3-4: Alternative Design

- Using the ORC generation configuration, can combine the torrefaction reactor with the gasifier to reduce equipment costs
- Maximizes the advantages of syngas flexibility with an ORC system
- Rotary gasification provides continual mechanical agitation



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Task 3-4: Alternative Design

- Performance analysis was conducted for each of the four configurations evaluated

Objective	Units	System 1	System 2	System 3	System 4
Gasifier Objectives					
Thermal Efficiency:	(%)	65%	56%	56%	64%
Throughput Rate:	(dry kg/hr)	3000	3490	4970	4350
LBG Energy Content:	(MJ/kg)	6.1	6.1	6.1	10.7
Tar Content:	(mg/Nm^3)	1,000	1,000	14,700	>15,000
Tar Dew Point:	(°C)	> 40	> 40	> 100	> 300
Particulates:	(mg/Nm^3)	600	600	600	ND
Hydrogen Sulfide:	(ppm)	25	25	25	44
Biochar Production:	(% dry mass)	16%	16%	16%	17%
	(dry kg/hr)	481	558	795	739
Biochar Quality:	(% fixed carbon)	83%	83%	83%	78%

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Task 5: Feasibility Study

- Detailed economic analysis was conducted for each of the four scenarios

Technical Entries	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Project Capacity (MW)	3	3	3	3
Capital Cost ($/kW)	5,750	6,650	7,625	5,625
Fixed O&M ($/kW)	945	990	889	684
Fixed O&M Escalation	2%	2%	2%	2%
Variable O&M ($/MWh)	0	0	0	0
Variable O&M Escalation	0%	0%	0%	0%
Fuel Cost ($/MBtu)	1.67	1.67	1.67	1.67
Fuel Cost Escalation	2%	2%	2%	2%
Heat Rate (Btu/kWh)	15,232	15,232	28,672	26,656
Capacity Factor	50.9%	73.6%	78.0%	81.1%
LCOE ($/MWh)	$403	$310	$317	$242

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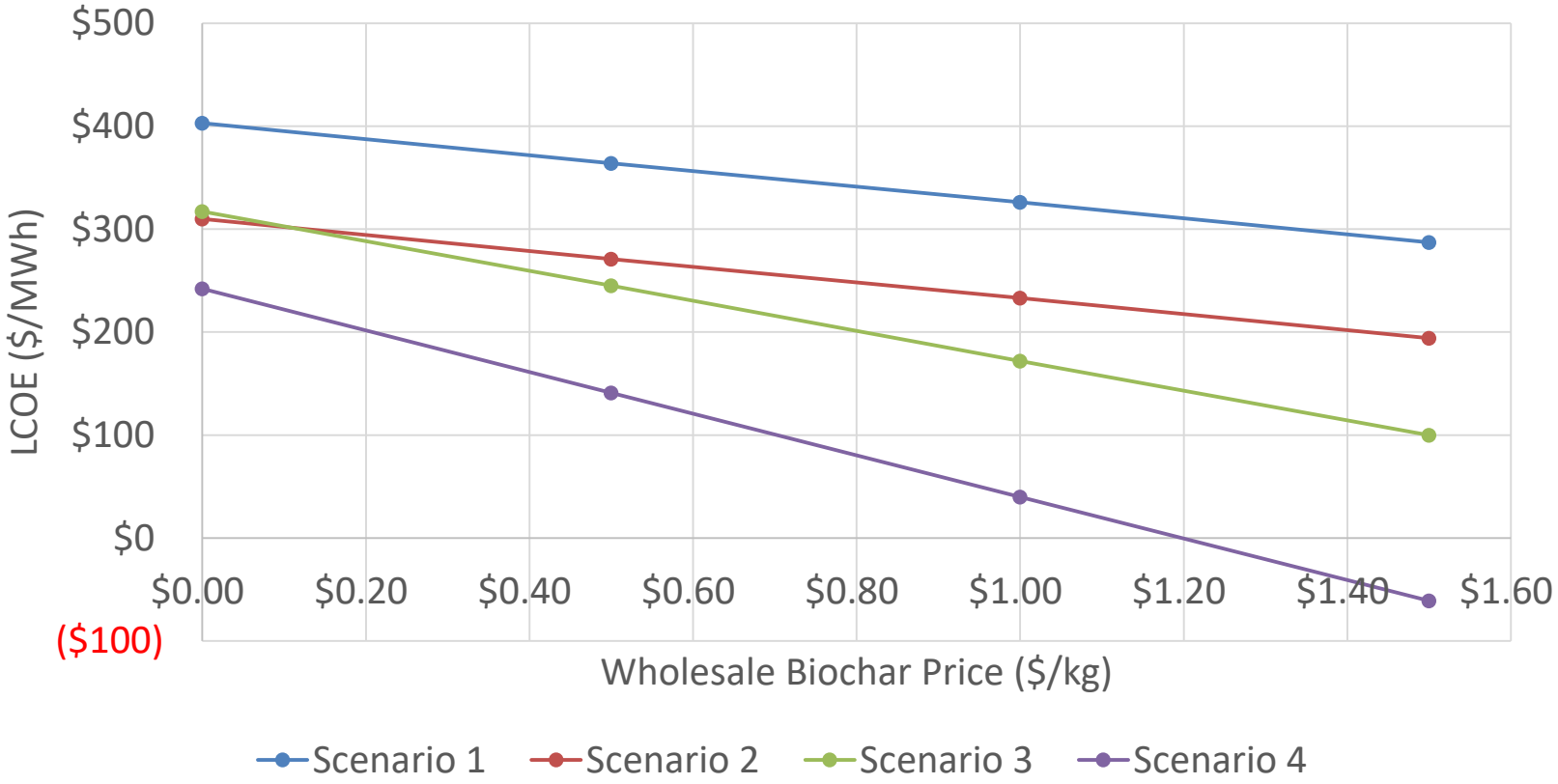
Task 5: Feasibility Study

- Baseline modeling did not include biochar value as a co-product



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Task 5: Feasibility Study

- Detailed Rule 21 interconnection process
- Detailed BioMAT program participation requirements
- Identified 10 potential sites for deployment (that are not already under development)
- Detailed the relevant environmental permits

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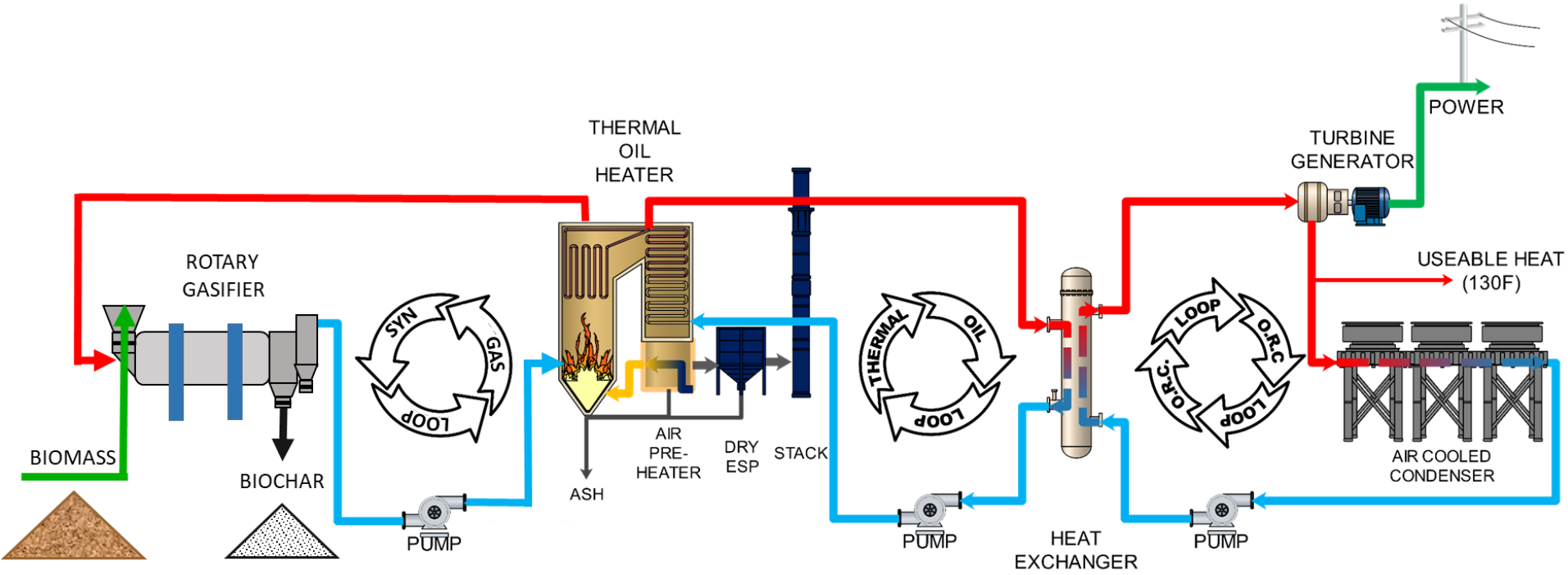
WHERE ARE WE NOW?
BIOCHAR AND POWER PRODUCTION



CONCEPTUAL LAYOUT

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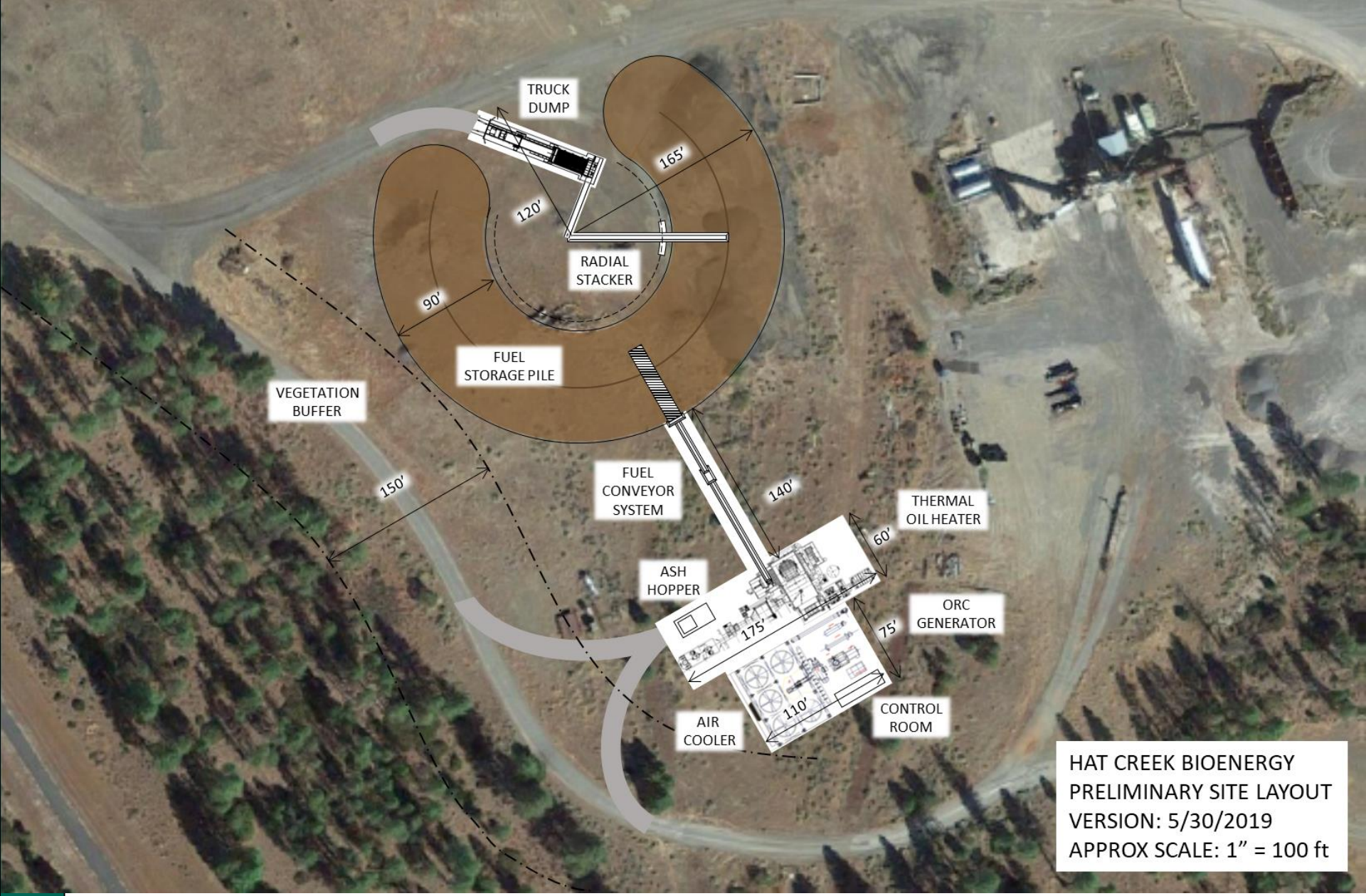

Hat Creek Bioenergy Project

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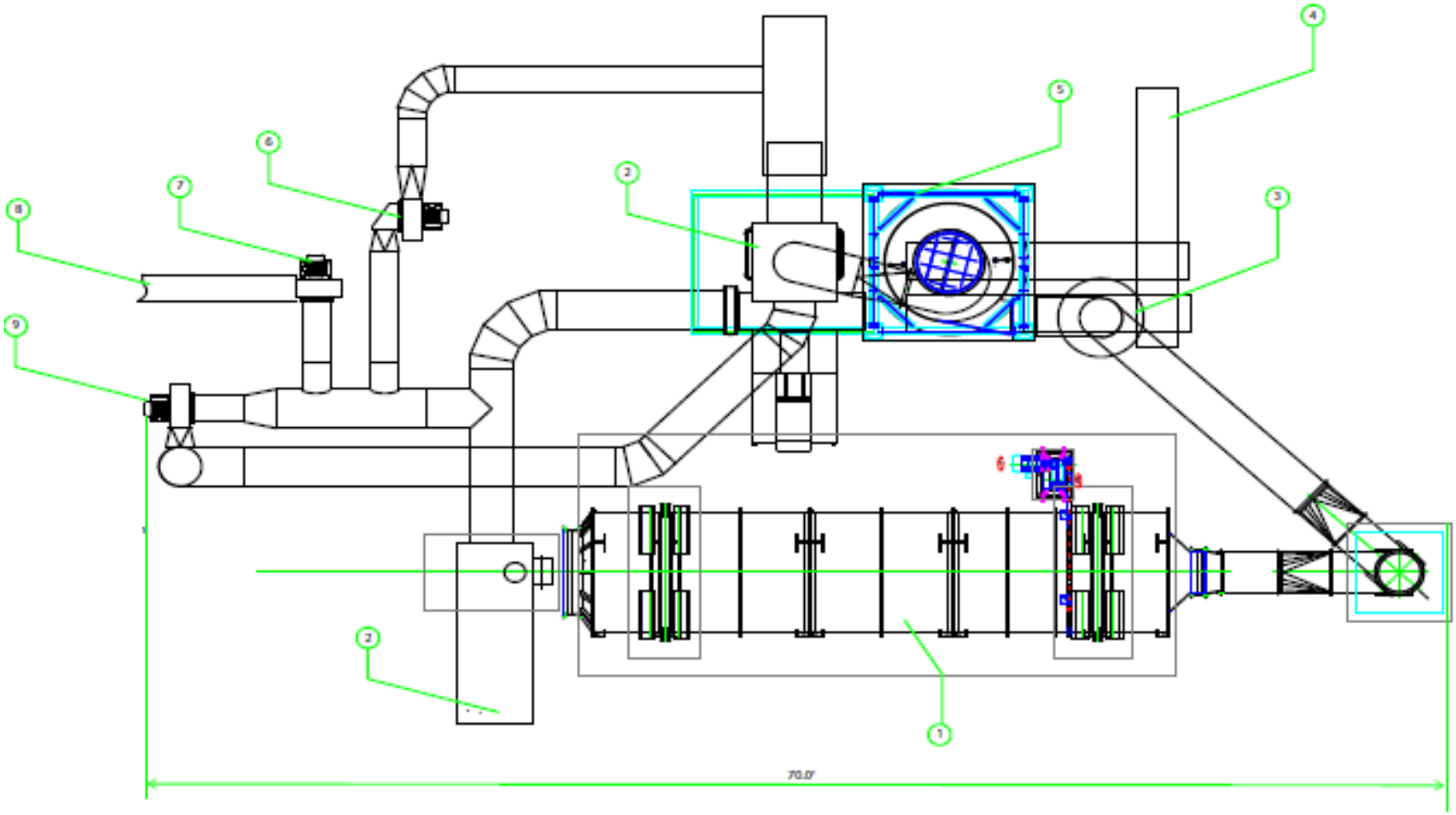
Rotary Gasifier System



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Rotary Gasifier System

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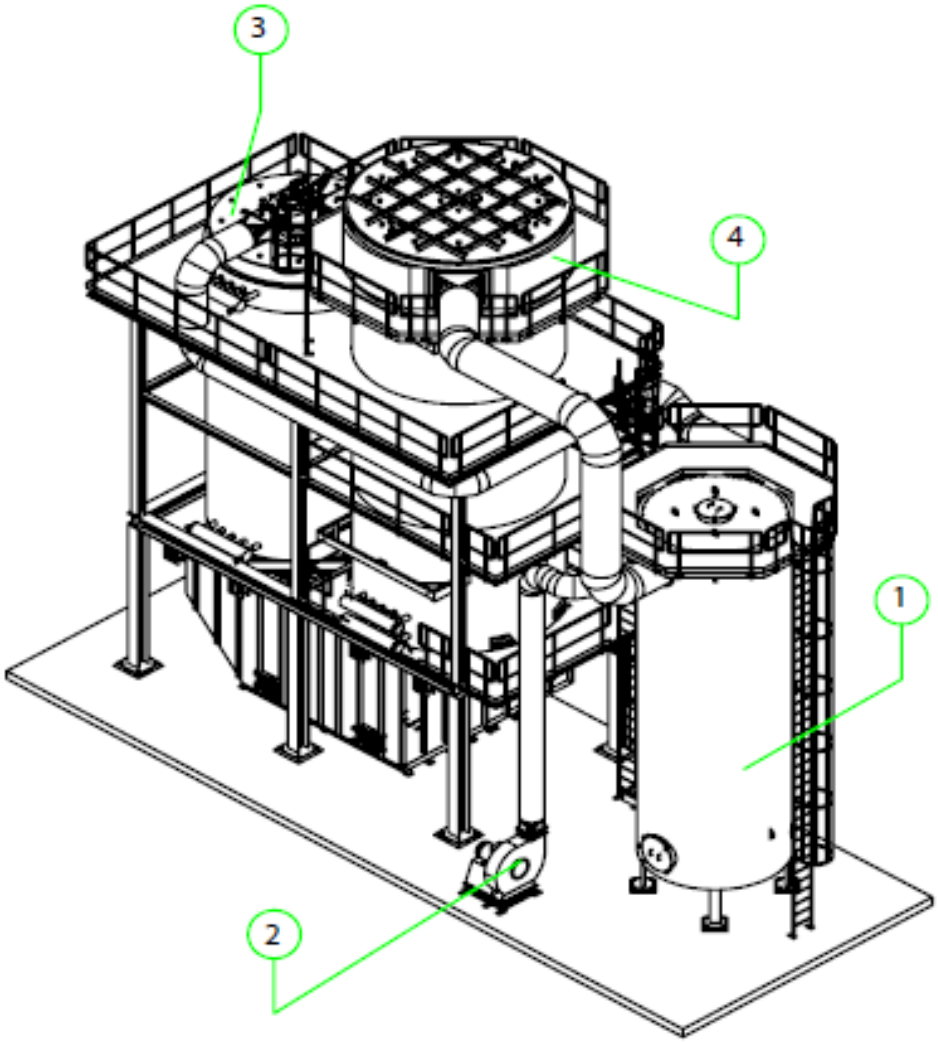
Thermal Oil Heater System



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Thermal Oil Heater System

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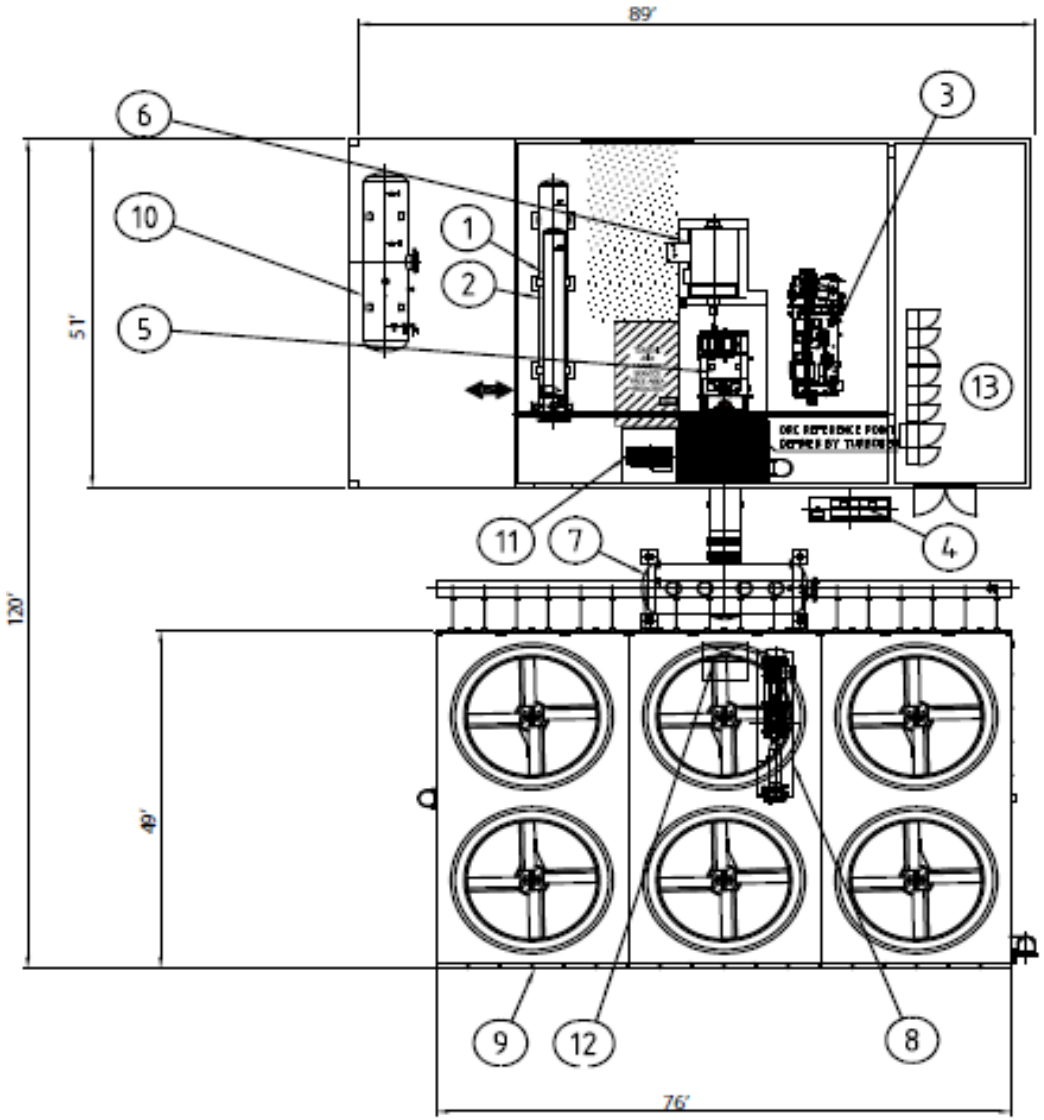
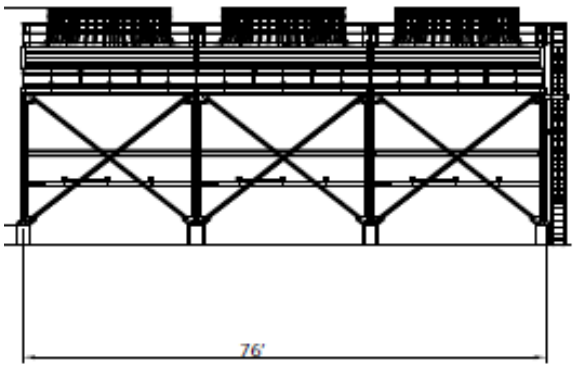
ORC Turbine Generator System and Switchgear





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ORC Turbine Generator System

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Thank You

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