Biofuels and Bioproducts Process Pilot Verification Capabilities RFI Responses

Biochemical Facilities

Biochemical pathways for the conversion of biomass to fuels or products generally involve first-generation sugars (e.g., corn) or the hydrolysis of lignocellulosic biomass to intermediate cellulosic and hemicellulosic sugars. The production of these sugars is followed by a variety of upgrading methods to produce biofuels or bioproducts. The following ten responsive facilities fall into this category, each of which has provided a brief summary of its capabilities. (Facilities are listed in alphabetical order by **bolded** respondent.)

- **American Process, Inc.** reports a demonstration facility in Alpena, Michigan, which utilizes the hemicellulosic liquid waste stream (23 dry tons/day equivalent) from a neighboring hardboard mill to generate ethanol in a fully integrated process that can run 24/7.
- **American Process, Inc.** also has a demonstration facility in Thomaston, Georgia, which can continuously process 3.5 dry tons/day of a variety of lignocelluloses into nanocellulose fibers, separate C_5 or C_6 sugar streams, or ferment the sugars to hydrous ethanol.
- **Edeniq** has developed a Corn-to-Cellulosic Migration pilot plant in Visalia, California, with the capacity to process 1 ton/day of corn stover to ethanol. It has performed multiple 1,000-hour operation runs.
- The **Forest Bioproducts Research Institute (FBRI)** at the University of Maine has its primary pathway onsite to hydrolyze biomass to sugars, followed by upgrading to levulinic acid (at a rate of 160 kg/day) and formic acid. This facility can also generate cellulose nano fibers and solid pellet fuel.
- The **ICM** pilot plant located in St. Joseph, Missouri, is an integrated pilot biorefinery with the capacity to ferment sugars to ethanol, isobutanol, and various chemical intermediates from both starch and cellulosic feedstocks. The design feedstock capacities are 1,000 bushels of corn or 10 dry tons of cellulosic biomass per day.
- **Michigan Biotechnology Institute** uses ammonium fiber expansion (AFEX) to pretreat grasses and agricultural residue prior to enzymatic hydrolysis of sugars, which can then be fermented to ethanol. This pretreatment method requires no detoxification after the fact, meaning that hydrolysis can be performed in the same vessel after AFEX.
- The **National Corn-to-Ethanol Research Center** in Illinois is an integrated pilot facility that can process 400 bushels of corn per day to generate ethanol from first-generation sugar. The location has both a large-scale reactor (22,000 L) for ethanol production as

well as smaller options (30 L, 150 L, and 1,500 L) for cellulosic pretreatment, hydrolysis, and fermentation development.
- The **National Renewable Energy Laboratory's (NREL's) Integrated Biorefinery Research Facility** is the standard facility where BETO currently performs its large-scale research. This facility can accept milled cellulosic feedstock (<1 inch in size), which is then pretreated and subjected to enzymatic hydrolysis. The resulting sugar can be fermented onsite to alcohol or can undergo other aerobic/anaerobic treatments to produce a variety of fuels and chemicals with a throughput on the scale of approximately 1 ton/day.
- **Pinal Energy** of Maricopa, Arizona, also uses first-generation sugar (from corn, potatoes, sweet sorghum, and watermelons) to make ethanol.
- **ZeaChem, Inc.** has a facility in Oregon with a throughput of 10 dry tons/day of hardwoods, softwoods, agricultural residues, and energy crops. This site has capabilities to ferment cellulosic sugars to ethanol, amino acids, organic acids and other products.

Another biochemical pathway to biofuels and bioproducts is anaerobic digestion—a chain of biological steps in which microorganisms break down organic material in the absence of oxygen, producing biogas (a methane/carbon dioxide mixture) or a number of other chemicals if the process is properly controlled. Common feedstocks for these processes are food waste, agricultural residue, and municipal wastewater. The following three responding facilities that harness biochemical pathways utilize anaerobic digestion to valorize such waste streams, and they have provided the following information. (Facilities are listed in alphabetical order by **bolded** respondent.)

- **Argonne National Laboratory** in Illinois studies the prospect of transforming wet organic streams, such as wastewater sludge, to produce biogas and hydrocarbon precursor lipids. Separations are not currently integrated, but Argonne National Laboratory has resin-wafer electrodeionization units that can be used to purify organic acid products at a rate of 50 kg/day.
- **Earth Energy Renewables** of Bryan, Texas, uses its anaerobic digesters to convert food waste to short- and medium-chain fatty acids through the inhibition of methanogenesis.
- The **FBRI** in Maine has a mobile pilot system with a 1,500-gallon digester that can generate biogas at a rate of 10 m^3/day.

Thermochemical Facilities

Thermochemical conversion pathways involve thermal and chemical decomposition of biomass into a liquid or gaseous form, followed by upgrading and/or synthesis to finished biofuels or bioproducts. A total of 14 RFI responses fit into the thermochemical category. The responses are organized below by pyrolysis and gasification.

Pyrolysis is a form of direct liquefaction that produces a crude bio-oil product. Seven respondents provided descriptions of pilot or process development units (PDUs) based on the production of stable bio-oil. One of the seven respondents indicated that it has a fully integrated PDU or pilot facility. The other six pyrolysis facilities describe production of bio-oil that requires further upgrading via some form of hydroconversion (i.e., high-pressure addition of hydrogen) to produce biofuels or bioproducts. These six respondents with non-integrated pyrolysis facilities either have onsite, non-integrated capability to upgrade their bio-oil or expect to ship their bio-oil to a partner facility for upgrading to finished products or combustion in place of fuel oil. All seven pyrolysis facilities are listed below in alphabetical order by **bolded** respondent.

- **Amaron Energy** of Utah operates two mobile pyrolysis units for converting wood or other biomass materials into bio-oil, bio-char, and bio-gas. The externally-heated, rotary reactors are capable of 0.5 tons/day and up to 13 tons/day throughput, respectively.
- **Battelle Memorial Institute's** commercialization partner, Versa Renewables, LLC**,** has a 1 ton/day auger-type pyrolysis system in Albany, Georgia, that is capable of producing 150 gallons/day of stabilized bio-oil. The bio-oil produced in the Versa pilot can be upgraded to diesel-, jet-, and gasoline-range hydrocarbons by hydrotreating and hydrocracking at a rate of 50 gallons/day at the Sample Preparation Unit located at Battelle partner Assured Aerospace Fuels Research Facility on Wright-Patterson Air Force Base in Dayton, Ohio.
- **Iowa State University** (ISU) has a 0.7 ton/day fluidized bed fast pyrolysis unit with a novel fractionation condensation system at their BioCentury Research Farm. ISU has used their bio-oil fractionation technology to explore a range of alternative bioproduct and biofuel applications for bio-oil fractions. ISU also has a Biomass Preparation Facility at the BioCentury Research Farm capable of preparing a wide range of biomass feedstocks through various size reduction and drying methods.
- **KiOR** indicates that its fully integrated PDU in Pasadena, Texas, can process 10 tons/day of wood chips via *in-situ* catalytic fast pyrolysis followed by hydrotreating and distillation to naphtha and distillate-range fuel products.
- **NREL's** 0.5 ton/day Thermochemical Process Demonstration Unit (TCPDU) can be configured for either fast pyrolysis or *ex-situ* catalytic fast pyrolysis modes. NREL plans to ship their stabilized bio-oil to Pacific Northwest National Laboratory for upgrading. BETO is planning to conduct a process verification of the *ex-situ* fast pyrolysis pathway in NREL's TCPDU in 2017.
- **Research Triangle Institute (RTI)** has a 1 ton/day *in-situ* catalytic fast pyrolysis pilot plant capable of producing up to 80 gallons/day of stable, low-oxygen-content bio-oil from a variety of lignocellulosic feedstocks. RTI has a bench-scale hydrotreater that can be used to upgrade 12 L/day of the bio-oil produced in the pilot to gasoline- and distillate-range hydrocarbons.

- The **U.S. Department of Agriculture Eastern Regional Research Center** owns and operates a mobile pyrolysis unit. The Combustion Reduction Integrated Pyrolysis System (CRIPS) is a pyrolysis system that utilizes two circulating fluidized beds to achieve fast pyrolysis of biomass to produce bio-oils, biochar, and a low-Btu (British thermal unit) producer gas. CRIPS is self-sufficient; electric power is produced by a small biomass gasifier used to fuel an engine generator.

Biomass gasification is a higher-temperature form of thermal decomposition that produces a gaseous product comprised mainly of carbon monoxide, hydrogen, and carbon dioxide. In order to be suitable for synthesis into products, the synthesis gas (syngas) produced must be virtually free of contaminants and have suitable composition. Typically, syngas is produced in either an oxygen-blown gasifier or in a steam reformer where heat is provided by an external heat source (e.g., combustion of wood char from the gasifier stage). Eight respondents provided descriptions of facilities based on the production of syngas. Four of these are fully integrated, from biomass input to liquid product output. Three others are capable of producing clean syngas or converting syngas into liquids, and one is in the design phase.

- **Byproduct Cellulosic Liquid Fuel Corporation** is constructing a facility to convert 36 wet tons/day of woody biomass into 1,000 gallons/day of liquid fuels. The process is based on torrefaction of biomass followed by molten salt steam reforming of charcoal and Fischer-Tropsch synthesis to liquid fuels. The torrefaction plant is under construction, and Byproduct Cellulosic Liquid Fuel Corporation is seeking funding for the remainder of the plant.
- The **Gas Technology Institute** (GTI) in Des Plaines, Illinois, has an integrated, pressurized, oxygen-blown bubbling-bed gasifier and syngas conditioning system unit. This 19 ton/day GTI unit was integrated with Haldor Topsoe's TIGAS (Topsoe Improved Gasoline Synthesis) process in a successful BETO-funded demonstration project that produced >10,000 gallons of gasoline in 2012–2014. GTI also has a second 18 ton/day entrained-flow gasifier that can be integrated with the syngas conditioning train.
- **Iowa State University** has a 0.5 ton/day, oxygen-blown, bubbling fluidized-bed gasifier with integrated syngas conditioning train. Currently ISU does not have any integrated synthesis capability.
- **NREL**'s 0.5 ton/day TCPDU can be configured to operate in a gasification mode. BETO conducted its 2011 Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis verification at the TCDPU and is planning another syngas pathway verification at NREL in 2022.
- The **Southern Research** facility in Durham, North Carolina, has bio-syngas pathway capabilities, including the following:
    - Southern Research's waste-to-energy pilot plant
    - Southern Research's small pilot-scale gas-to-liquids facility located at the National Carbon Capture center in Wilsonville, Alabama.

- **ThermoChem Recovery International** has a fully integrated PDU. This PDU is located at Southern Research's facility in Durham, North Carolina. It has operated on a broad range of biomass feedstocks, including sorted municipal solid waste.
- The **University of North Dakota**'s Energy and Environmental Research Center (EERC) has multiple facilities with bio-syngas pathway capabilities.
    - EERC's 7 ton/day Transport Reactor Development Unit and 2.5 ton/day bubbling fluid-bed gasifier share common feed and syngas conditioning systems and can both be operated in pressurized oxygen-blown mode. These two reactor systems might be operated in an integrated manner to circulate solids between the circulating fluid-bed and bubbling fluid-bed reactors for either chemical-looping-type applications or for an integrated, indirectly heated gasification system. EERC has tested numerous skid-mounted client syngas systems, including Fischer-Tropsch reactors and hydrogen membranes.
    - EERC's advanced fixed-bed gasification system is available in a stationary, 1 ton/day scale, as well as a mobile, trailer-mounted, 4 ton/day scale. Both are suitable for integrated operation to demonstrate electricity, heat, and liquid fuel production. The mobile unit has a methanol synthesis reactor capable of up to 100 gallons/day production.
    - EERC's continuous tubular reactor is a fixed-catalyst-bed reactor suitable for testing thermocatalytic reactions at liquid flow rates up to nominally 1 gallon/hour, pressures up to 5,000 pounds per square inch (psi), and temperatures up to 900°F. The system has been used for upgrading bio-oils using hydrotreating or isomerization catalysts and for gas-to-liquid conversion with methanol synthesis catalysts. The system is suitable for many processes that utilize supported catalysts.
    - EERC's high-pressure liquid reformer was originally designed to convert first-generation renewable feedstocks (plant oils, plant-derived alcohols, etc.) to liquid fuels and/or hydrogen. It is capable of processing up to 100 lb/day of flowable liquid feedstocks at pressures up to 15,000 psi.
- The **University of Utah** has two pressurized oxygen-blown biomass gasifiers at its Industrial Combustion and Gasification Research Facility: a 0.5 ton/day bubbling fluidized bed and a 1 ton/day entrained-flow gasifier. The entrained-flow unit requires a flowable liquid feedstock (e.g., black liquor or bio-oil), and the bubbling bed can handle solid or liquid feedstocks. The gasifiers share a common filtration and thermal oxidizer, but they currently do not have syngas conditioning or synthesis capability.

There are other thermochemical approaches that are not based on pyrolysis or gasification. **Biofine** recently relocated their 1 ton/day pilot to the University of Maine's FBRI Technology Research Center. Biofine's process is based on two-stage, dilute-acid catalyzed hydrolysis of biomass under moderate pressure and temperatures. The primary product of Biofine's process

is the platform chemical levulinic acid. The University of Maine's FBRI Technology Research Center has other capabilities, including a 350 lb/hour pellet mill, a 1 ton/day nanocellulose pilot plant, and a mobile biogas production pilot. **Swift Fuels** has a facility for thermocatalytic conversion of acetone to aromatics. The Composite Materials and Engineering Center at **Washington State University** has facilities for primary-, secondary-, and tertiary-size feedstock reduction, feedstock conditioning, feedstock densification, feedstock blending, and feedstock classification, mostly at the scale of approximately 1 ton/day.

Summary

Overall, the responses to this RFI show that there are a wide variety of facilities across the country with capabilities to convert biomass into biofuels and bioproducts. These facilities span industry, government and academia and many have developed with assistance from BETO and other offices within DOE.

Tables

The tables in this PDF summarize the information reported by the respondents in Question 2 (Unit Operations), Table 1 (Unit Operations Summary Table) of the RFI. The tables below are organized by biochemical conversion facilities and then by thermochemical conversion facilities. Some spaces are blank where respondents left them blank or where they were marked confidential, proprietary, or privileged; all blank spaces are marked with dashes. Also, some respondents mentioned above in the report are not included in the tables below because they did not include the table in their reports.

Biochemical Conversion Facilities

Applicant (Site)	Unit Operation	Scale	Operating Conditions	Max Run Time	Acceptable Feedstock	Throughput per Day
American Process, Inc. (Alpena, Michigan)	Evaporation	152,000 lb H_2O/hour	Up to 15 pounds per square inch gauge (psig)	24/7	Liquid (pH 3–10)	0.5 million gallons/day
	Acid hydrolysis	8,000 gallons	Up to 75 psig	24/7	Slurry (pH 0–12)	52,000 gallons/day
	Clarification	-	Atmospheric	24/7	Slurry (pH 2–12)	53,000 gallons/day
	Solids filter	-	Vacuum	24/7	Slurry (pH 5–9)	54,000 gallons/day
	Propagation	2,750 gallons	30°–38°C, aerobic	24 hours/batch	Molasses, ammonia	2,500 gallons/day
	Fermentation beer well	4 x 64,000 gallons + 72,000 gallons	Atmospheric; anaerobic	72 hours/batch	Clarified hydrolysate	76,000 gallons/day
	Distillation dehydration	-	Up to 15 psig, Mole sieves	24/7	Fermented beer, 2%–6% ethanol	76,000 gallons/day, 2 million gallons/year of ethanol
	Evaporator condensate treatment	375 gallons of permeate/minute	Reverse osmosis	24/7	Acetic acid 0%–0.2%	400 gallons/ minute
	Wastewater treatment plant	-	Activated sludge	24/7/365	Max feed 100,000 lb/day biochemical oxygen demand	1.5 million gallons/day

American Process, Inc. (Thomaston, Georgia)	Continuous digester	7 ft, 3 in.	265 psig, 400°F (pH 0.5–14)	Continuous 24/5	Wood chips, ag residue (<2 in.)	3.5 dry tons/day
	Washing	400 gallons/minute feed centrifuge	Gas tight	Semi-continuous, 5 stages	Suspended solids (<5%)	1,000 gallons/batch
	Washing	10 gallons/minute feed Screw Press	Sealed	Continuous, 2 stages	Fibers (<10%)	10 bone dry tons/day
	Chemical recovery	18 trays (theoretical) stripper	Vacuum/100 psig	5 days	Liquid/solvent max 0.5% total suspended solids	7 gallons/ minute
	Evaporation	2,500 lb H_2O/hour	Up to 15 psig	Continuous 24/5	Liquid (pH 1–12)	0.5 million gallons/day
	Acid hydrolysis	300 gallons	Up to 150 psig	Semi-batch	Slurry (pH 0–14)	2 gallons/ minute
	Enzymatic hydrolysis	2 x 1,000 gallons + 2,000 gallons	Up to 150 psig	Semi-continuous	Slurry total suspended solids (<20%)	-
	Enzymatic hydrolysis	8,000 gallons	Up to 150 psig	Batch	Slurry total suspended solids (<8%)	2 gallons/ minute
	Clarification	5 gallons/minute feed centrifuge	Atmospheric pressure	Semi-batch	Slurry (pH 1–12)	5 gallons/ minute
	Crystallization	50 lb/hour evaporation	Vacuum	Batch	Slurry (pH 5–9)	30 gallons/ batch
	Propagation	2–7 gallons (lab)	30°–30°C, aerobic	24 hours per batch	Molasses, ammonia	5 gallons
	Fermentation	4 x 6,000 gallons + 1,000	Jacketed anaerobic	72 hours per batch	Clarified hydrolyzate	2 gallons/ minute

		gallons				
	Distillation dehydration	24 trays (theoretical) stripper	Up to 50 psig	Continuous 24/5	Fermented beer 1%–6% ethanol	76,000 gallons/day, 2 million gallons/year of ethanol
	Cooling water and cond. treatment	4,000 gallons storage	Municipal wastewater treatment plant	Batch	Neutralized to pH 6–9	250 gallons/ minute maximum
	Exhaust gas treatment	500 lb SO_2 absorption	NaOH scrubber	Continuous	-	-
	Wastewater treatment	3 x 8,000 gallons storage	Designated landfill	Truck loadout	-	-
Argonne National Laboratory (Argonne, Illinois)	Fermentors	2–14 L	0°–70°C, up to 20 pounds per square inch (psi)	24 hours	Solids, liquids, and gas	Depends on hydraulic retention time
	Resin-wafer electrodeionization units	5–40 kg/hour of processing fermentation broth, 10–60 kg/hour for aqueous desalination	20°–60°C, <30 psi, 1–13 pH	>1,600 hours continuous operation	Charged species separation from hydrolysate liquid, wastewater, and fermentation broth	20–50 kg/day of organic acids capture, 300–600 kg/day of hydrolysate liquid
Biofine Technology, LLC (Old Town, Maine)	Feedstock handling (bag and hoist conveyor/weighted feeder)	1 dry metric ton/day	Atmospheric pressure	300 hours	Paper sludge, municipal solid waste (MSW) (paper), saw dust, stover, wood chips	1 dry metric ton/day
	Feedstock	500 L	Atmospheric	300 hours	Paper sludge, MSW	6 dry metric

	acidification mixing tank		pressure		(paper), saw dust, stover, wood chips, dilute sulfuric acid	tons/day
	Feed slurry pumping—progressing cavity pump	250 L/hour	200 psig, 85°C	300 hours	Paper sludge, MSW (paper), saw dust, stover, wood chips, dilute sulfuric acid	6 dry metric tons/day
	First-stage reactor	4 cm diameter, 300 cm long, Zirconium, seconds residency time	14 bar (gauge), 200°C, steam injected	300 hours	Paper sludge, MSW (paper), saw dust, stover, wood chips, dilute sulfuric acid (partially hydrolysated)	6 dry metric tons/day
	Second-stage reactor	76 cm diameter, 190 cm long, zirconium agitator	200°C, 200 psig, 3% sulfuric acid, continuous operation	300 hours	Paper sludge, MSW (paper), saw dust, stover, wood chips, dilute sulfuric acid	8 dry metric tons/day
	Gravity settler	3,600 L + 316 L, stainless steel	Atmospheric pressure	300 hours	Acid hydrolysate	6 dry metric tons/day
	Partial neutralization	3,000 L + 316 L, stainless steel, agitator	Atmospheric Pressure	300 hours	Acid hydrolysate	6 metrics tons/day
	Evaporation tank	1,400 L + 316 L, stainless steel	50 millimeters of mercury (mmHg) vacuum, agitator	300 hours	Partially neutralized hydrolysate	6 metrics tons/day
	Crystallization tank	1,700 L + 316 L stainless steel	Atmospheric pressure, agitator	300 hours	Levulinic acid concentrate	1 metric ton/day
	Crystal filtration	1 m^2 plate and	50°C,	300 hours	Levulinic acid	0.25 metric

		frame, polypropylene	atmospheric pressure		concentrate	ton/day
	Lignin/char centrifugation	6 kW horizontal bowl (scroll disch.), 316 L stainless steel	Atmospheric pressure	300 hours	Lignin char slurry	6 metrics tons/day
Earth Energy Renewables (Bryan, Texas)	Anaerobic digester	-	-	-	-	-
	Liquid/solid separation	-	-	-	-	-
	Membrane filtration	-	-	-	-	-
	Reverse osmosis membrane system	-	-	-	-	-
	Distillation system	-	-	-	-	-
	Liquid/liquid extraction	-	-	-	-	-
Edeniq, Inc. (Visalia, California)	Pretreatment vessel (2x)	430 gallons	-	-	-	-
	Flash tank	430 gallons	-	-	-	-
	Hydrolysis and fermentor tanks (12x)	1,630 gallons	-	-	-	-
	Yeast propagation tanks (4x)	75 gallons	-	-	-	-
	Beer wells (2x)	2,500 gallons	-	-	-	-
	Distillation	-	-	-	-	-

	column					
	Stillage tank	1,900 gallons	-	-	-	-
	Product hold tank	587 gallons	-	-	-	-
ICM, Inc. (St. Joseph, Missouri)	Feedstock handling	75 tons onsite storage, 10 tons/day processing	Ambient	1,200 hours	Pass 2-in. screen as received, pass #10 screen into process	10 dry tons biomass, 1,000 bushels of grain
	Pretreatment	18-in. diameter x 20-foot agitated column	2%–4% acid, pH <2, 150°–200°C, 5–15 minutes	1,200 hours	Pass #10 screen into process	10 dry tons biomass, 1,000 bushels of grain
	Hydrolysis	4 x 35,000 gallons	20°–60°C	1,200 hours	10%–15% solids slurry from pretreatment	10 dry tons biomass, 1,000 bushels grain
	Solid/liquid separation	Rotary vacuum drum filter equal to 15 gallons/minute, press equal to 20 gallons/minute, centrifuge equal to 120 gallons/minute	Rotary vacuum drum filter equals 0–15 gallons/minute, press equals 0–20 gallons/minute, centrifuge equals 0–120 gallons/minute	1,200 hours	Liquid slurry from hydrolysis or broth from fermentation	-
	Anaerobic fermentation	4 x 15,000 gallons, 4 x 35,000 gallons	20°–60°C	1,200 hours	Corn mash or 10%–15% solids from pretreatment or hydrolysis	-
	Aerobic	3 x 30 L, 1 x 500	20°–60°C	1,000 hours	Sugar syrups from	-

	fermentation	L, 3 x 7,000 gallons	aeration to 0.5 vvm (volume per volume per minute)		hydrolysis or evaporator concentrate	
	Product recovery	Distillation: to 20 gallons/minute, centrifuge: to 120 gallons/minute	Distillation: 5–20 gallons/minute, centrifuge: 0–120 gallons/minute	1,200 hours	Beer from anaerobic fermentors, broth from aerobic fermentors	-
	Product drying		1,200 hours	-	Solids from hydrolysis or fermentors	
Michigan Biotechnology Institute (Lansing, Michigan)	AFEX pretreatment reactor	18-in. diameter, 9 ft high	Up to 300 psi, 50°–150°C, pH - ~12 (highly concentrated ammonia)	Unknown	Grasses and agricultural residues, roughly 1-in. particle size at 18%–25% moisture, compressed to a density of 80–120 kg/m^3 dry weight	0.5 tons/day
	150-L fermentor	100 L	Temperature range: 15°–125°C, pH range: 3–14	Project specific	Must be mixable with Rushton impeller (2 horsepower [hp])	Variable
	200-L fermentor	150 L	Temperature range: 15°–125°C, pH range: 3–14	Project specific	Must be mixable with Rushton impeller (3 hp)	Variable
	3,800-L reactor	3,000 L	Temperature range: 15°–	Project specific	Must be mixable with Rushton and axial flow	Variable

			125°C, pH range: 3–14		impeller (25 hp)	
	3,800-L fermentor	3,000 L	Temperature range: 15°–125°C, pH range: 3–14	Project specific	Must be mixable with Rushton impeller (25 hp)	Variable
	3,800-L processing tank	3,000 L	Temperature range: 15°–80°C, pH range: 3–14	Project specific	Must be mixable with 1-hp motor	Variable
	3,800-L fermentor	6,000 L	Temperature range: 15°–80°C, pH range: 2–14	Project Specific	Must be mixable with 1.5-hp motor	Variable
	1,700 SIP tank	1,500 L	Temperature range: 15°–125°C, pH range: 2–14	Project Specific	Must be mixable with 1-hp motor	Variable
National Corn-to-Ethanol Research Center (Edwardsville, Illinois)	Bliss hammer mill	Up to 2,000 lb/hour	-	24/7	-	-
	Buffalo hammer mill	Up to ~100 lb/hour	-	24/7	-	-
	Corn cleaning	Up to 2,000 lb/hour	-	24/7	-	-
	Dry fractionation	Up to 50 bushels/hour	-	-	-	-
	Bioreactors	30 L, 150 L, 1,500 L, 22,000 L	pH, oxygen delivery, temperature control, agitation,	-	-	-

			aeration			
	Decanter centrifuge	2–35 gallons/minute	-	24/7	-	-
	Distillation	2–5 gallons/minute	-	24/7	-	-
	Evaporator	300- or 700-gallon evaporator, 0–1,500 lb/hour evaporation rate	-	24/7	-	-
	Drying: Rotary drum dryer	Feed rate 200 lb/hour material at 65% moisture	-	24/7	-	-
	Drying: Ring dryer	Feed rate ~100 lb/hour material at 65% moisture	-	24/7	-	-
	Boiler	Up to 3,800 lb/hour steam production	-	24/7	-	-
	Reverse osmosis system	0–9 gallons/minute	-	24/7	-	-
National Renewable Energy Laboratory (Golden, Colorado)	Feedstock milling (two continuous knife mills with dust handling and direct transfer to pretreatment or bagging)	20 to 80 kg/hour biomass	Atmospheric temperature and pressure, moisture content of <20%	Unlimited	Herbaceous or agricultural residues of up to 12-in. particle size, wood chips of up to 1.5-in. maximum dimension	Up to 2 tons dry feedstock/day (milling systems have higher throughput

						rating than rest of pilot plant)
	Feedstock preprocessing and chemical impregnation	50 L to 2,000 L (batch paddle reactors) with associated continuous dewatering screw presses	Up to 120°C (up to 3 bar), stainless steel (316) allows for alkaline and acidic conditions (temperature <100°C)	Batch systems, can run several consecutive batches per day	Milled biomass (< 2 in. nominal feedstock size)	Up to 0.5 tons dry feedstock per day
	Continuous horizontal pretreatment system (large)	Up to 40 dry kg feedstock/hour through reconfigurable multi-tube reactor	Up to 210°C (up to 15 bar) via steam injection, Hastelloy construction allows pH 1–13	96 hours, residence time range 2–120 min	Woody and herbaceous feedstocks (including blends), 10%–40% solids in pretreat slurry	-
	Continuous horizontal pretreatment system (small)	5–10 dry kg feedstock/hour	Up to 210°C (up to 15 bar) via steam injection, Hastelloy construction allows pH 1-13	96 hours, residence time range: 3–30 minutes	Woody and herbaceous feedstocks (including blends), 10%–40% solids in pretreated slurry	Up to 0.2 tons dry feedstock/day
	Continuous horizontal pretreatment system (large—	Up to 45 dry kg feedstock/hour	Up to 210°C (up to 15 bar) via steam injection,	96 hours, residence time range: 1–45 minutes	Woody and herbaceous feedstocks (including blends), 10%–40% solids in	Up to 1.0 tons dry feedstock/day

	north)		Zirconium construction allows pH 1–13		pretreat slurry	
	Continuous horizontal pretreatment system (large—south)	Up to 45 dry kg feedstock/hour, optional second stage for lower-temp. operation	Up to 210°C (up to 15 bar) via steam injection, Hastelloy construction allows pH 1–13	96 hours, residence time range: 10–100 minutes	Woody and herbaceous feedstocks (including blends), 10%–40% solids in pretreat slurry	Up to 1.0 tons dry feedstock/day
	High-solids enzymatic hydrolysis paddle reactors	4,000 L (4), 1,900 L (1), 170 L (1), 10 L (several—roller bottles)	20°–75°C, pH 2–10, stainless steel (304) with mixing paddles, up to 30% solids	~168 hours	All forms of pretreated biomass	Staged operation allows nominal throughput of 1 dry ton/day
	Bioreactor/ fermentation vessels	9,000 L (4), 1,500 L (2), 160 L (2), 30 L (1)	25°–50 °C	~168 hours (considerably longer in continuous mode)	Partially/fully hydrolyzed biomass from all feedstock types	Staged operation allows nominal throughput of 1 dry ton/day
	Dewatering screw presses (2)	100 kg/hour (1), 10 kg/hour (1)	Atmospheric temperature and pressure	~8 hours	Milled native biomass, preprocessed/pretreated biomass	Up to 1 ton/day (dry feedstock basis)
	Perforated bowl filtering centrifuges (3)	2.9 m^2 (1), 1.1 m^2 (1), 0.2 m^2 (1)	Atmospheric temperature and pressure	~24 hours	Pretreated or hydrolyzed slurry	Up to 0.5 ton/day (dry feedstock

						basis)
	Solid bowl decanter centrifuges (2)	1,200 L/hour (1), 100 L/hour (1)	Atmospheric temperature and pressure	~8 hours	Pretreated or hydrolyzed slurry, fermentation broth, stillage	Up to 1 ton/day (dry feedstock basis)
	Tangential flow (cross-flow) filtration system	Up to 200 kg hydrolysate slurry/hour	Up to 60°C	~24 hours	Hydrolyzed biomass slurry	Up to 0.8 ton/day (dry feedstock basis)
	Evaporation systems (2)	Batch vacuum and continuous forced recirculation	23 inches of mercury (batch), 0 psig (continuous)	~24 hours	Clarified hydrolysates: fermentation broth	Up to 0.5 ton/day (dry feedstock basis)
	Distillation (stripping) column	19 plate, 10 m tall, 0.5 m diameter	-	~48 hours	Fermentation brother (designed for ethanol/butanol)	Up to 1 ton/day (dry feedstock basis)
Pinal Energy, LLC (Maricopa, Arizona)	Feedstock grinder	0.5 tons/hour	Variable, 33°–200°F	Manual operation only limited by staffing capability	Unclear	Depending on needed storage tank time
	Containment tank	9,675 gallons	Atmospheric temperature	Not limited manual loading	Unclear	Depending on needed storage tank time
	East holding tank	6,451 gallons	Low 80°–212°F	Not limited	Unclear	Depending on needed storage tank time
	West holding tank	6,451 gallons	Low 80°–212°F	Not limited	Unclear	Depending on needed storage tank time

University of Maine (Old Town, Maine)	Feed hopper	2 tons/day at 50% solids	Room temperature	Continuous	Sawdust, small particle size	1 dry ton/day
	Chain drag conveyor	2 tons/day at 50% solids	Room temperature	Continuous	Sawdust, small particle size	1 dry ton/day
	Feed tank	550 L	-	Continuous	-	-
	Reactor feed pump	10 L/minute	30 bar	Continuous	-	-
	First hydrolysis reactor	3.5 L	Low pH	Continuous	-	-
	Second hydrolysis reactor	757 L	Low pH	Continuous	-	-
	Flash drum	87 L	Atmospheric	Continuous	-	-
	Hydrolysate settler	3,600 L	-	Continuous	-	-
	Evaporator	1,363 L	-	Batch	-	118 kg water/hour removal
	Char centrifuge	900 kg liquid/hour	pH 3	Continuous	-	900 kg liquid/hour
	Oven	216 ft^3	200°–500°F	-	-	-
	TDO reactor	50 L	up to 450°C	Batch	TDO salts	24 L/day oil
	ASTM fuel distillation	1.5 L	-	Batch	-	-
	ASTM fuel distillation	10 L/minute	-	Batch	-	Soon to be installed
	Trickle bed reactor	2-in. diameter	Max temperature 600°C, max 6,000 psi	Continuous	Fuels or chemicals	0.5 L/day for TDO oil
	Grinder	-	-	Continuous	-	-

	Pellet mill	Up to 350 pellets/hour	-	Continuous	Wood, grasses, biomass	4,800 pellets/day
	Pulper	2,000 gallons	-	Batch	-	4–6 tons/day
	Stock chest	3,000 gallons (2x)	-	Batch	-	-
	Refiner loop	12-in. or 20-in. double disk	3% solids	Batch	-	1 dry ton/day cellulose nano fibers
	Masuko supermass colloider	-	3% solids	Batch	-	100 lb/day
	Spray dryer	5–24 lb/day	200°C	Continuous	Cellulose nano fibers or crystals	5 lb cellulose nano fibers or 24 lb cellulose nano crystals per day
	Biogas plant feed mix tank	200 gallons	Ambient	-	Slurried solids	-
	Digester	1,500 gallons	Ambient	Fed batch	Slurried solids	3–10 m^3/day methane
Washington State University, Composite Materials and Engineering Center (Pullman, Washington)	Tub grinder	Approximately 30 ft^3	Dry furnish, baled material preferable	20 hours	Baled materials preferable, medium to low density feedstock	~25 tons/day
	Sumner chipper	30-in. diameter head with two 6-in. knives, knife gap is adjustable	Ambient	20 hours	Green logs (1-in. to 8-in. diameter)	3–10 tons/day depending on feedstock
	Mobile yard waste chipper	Up to 4-in. diameter log	Ambient	20 hours	Green logs (1-in. to 4-in. diameter)	3–10 tons/day depending on

		and tree trimmings				feedstock
	Hombak drum flaker	8-in. diameter infeed	Ambient	20 hours	Green logs (1-in. to 8-in. diameter)	1.5–4 tons/day
	CAE disc flaker	5-in. diameter infeed	Ambient	20 hours	Green logs (1-in. to 5-in. diameter)	1.5–4 tons/day
	Pallmann strander: Model PZU-L4-150	7-in. diameter infeed	Ambient	20 hours	Green logs (1-in. to 7-in. diameter)	1.5–4 tons/day
	Genox shredder	Two shaft shredder model M400	Ambient	20 hours	2 in. thick and 14-in. width minimum	0.5 tons/day
	Pratter hammermill	1,800 revolutions per minute (rpm) drive, 40-in. grinding chamber, throughput of approximately 400 lb/hour at 0.25-in. screen opening	Dry furnish provides more uniform final product	20 hours	Chips, small hole pieces, some initial breakdown is very helpful	4 tons/day
	Bliss EMF hammermill	3,650 rpm drive, 24-in. grinding chamber, throughput of approximately 300 lb/hour at 0.0217-in.	Dry furnish provides more uniform final product	20 hours	Chips, small hole pieces, some initial breakdown is very helpful	3 tons/day

		screen opening				
	Pallmann ringmill	27-in. diameter	Green chips	20 hours	Chips, small hole pieces, some initial breakdown is very helpful	~3 tons/day
	Bauer dual-disc attrition mill	24-in. diameter	Green chips	20 hours	Chips, small hole pieces, some initial breakdown is very helpful	~3 tons/day
	Single-disc attrition mill	12-in. diameter	Green chips	20 hours	Chips, small hole pieces, some initial breakdown is very helpful	~3 tons/day
	Across International Model PQ-N20 planetary ball mill	56 cubic in. vessels (4 each)	Dry furnish, batch runs only	20 hours	Small grind material only	~500 lb/day
Washington State University, Feedstock Conditioning (Pullman, Washington)	Steam digester	12 x 60-in. diameter steam chamber, pressurizable to 100 psig steam pressure	100 psig steam, ~150°C temperature	Batch runs based on needs	Length up to 5 ft, diameter up to 12 in.	Depends on needs
	Rotary dryer	4 ft in diameter by 5 ft long, electric element tumble dryer	~125°C ambient dryer	20 hours	1-in. chips down to 250 mesh ground material	~5 tons/day, depends on feedstock
	Atmospheric dryer	4 ft x 4 ft x 1.5 ft (L x W x H)	Ambient with air drawn through	20 hours	1-in. chips down to 100 mesh ground material	~2 tons/day, depends on feedstock

			furnish			
	Atmospheric dryer with heat	4 ft x 4 ft x 1.5 ft (L x W x H)	Ambient with heated air drawn through furnish	20 hours	1-in. chips down to 100 mesh ground material	~2 tons/day, depends on feedstock
	Louisville rotary steam tube dryer	2 ft diameter x 30 ft long, 300 lb/hour	Up to 125 psig	20 hours	200 or small mesh particles	3 tons/day
	Conditioning chamber (5 each)	20 x 16 x 12 ft (L x W x H)	Adjustable based on needs	24 hours	Any feedstock	Depends on desired equilibrium conditions and starting point
	Conditioning chamber	4 x 4 x 4 ft (L x W x H)	Adjustable based on needs	24 hours	Any feedstock	Depends on desired equilibrium conditions and starting point
	Conditioning chamber	20 x 8 x 12 ft (L x W x H)	Adjustable based on needs	24 hours	Any feedstock	Depends on desired equilibrium conditions and starting point
Washington State University, Feedstock Densification (Pullman, Washington)	CPM 3016-4 pellet mill	16-in. diameter die	Ambient	20 hours	Ground feedstock	12 tons/day
	CPM lab-scale pelletizer	12-in. diameter die	Ambient	20 hours	Ground feedstock	1.5 tons/day
	Williams & White 1,000-ton hydraulic press	54 x 104-in. platens	Room temperature up to 400°F	20 hours	Chips, particles, loose fibers, etc.	Depends on processing conditions

	Coe Manufacturing 300-ton hydraulic press	30 x 38-in. platens	Room temperature up to 400°F	20 hours	Chips, particles, loose fibers, etc.	Depends on processing conditions
	Cincinnati Milacron extrusion—86 mm	86-mm conical screw diameter, 1,200 lb/hour	Room temperature up to 400°F	20 hours	20 or smaller mesh particles	12 tons/day
	Cincinnati Milacron extrusion—55 mm	55-mm conical screw diameter, 500 lb/hour	Room temperature up to 400°F	20 hours	20 or smaller mesh particles	5 tons/day
	Cincinnati Milacron extrusion—35 mm	35-mm conical screw diameter, 50 lb/hour	Room temperature up to 400°F	20 hours	20 or smaller mesh particles	0.5 UST/day
Washington State University, Feedstock Blending (Pullman, Washington)	Scott ribbon blender	30 x 48-in. mixing chamber	Batch processing	20 hours	Chips, particles, loose fibers, etc.	12 UST/day
	Rotary blender	4 ft diameter x 2 ft deep	Batch processing	20 hours	Chips, particles, loose fibers, etc.	6 UST/day
	Rotary blender	6 ft diameter x 3 ft deep	Batch processing	20 hours	Chips, particles, loose fibers, etc.	Depends on mixing cycle length
	Paddle blender	12-in. diameter, 30-in. retention chamber	Continuous processing	20 hours	Chips, particles, loose fibers, etc.	~3 UST/day
Washington State University, Feedstock Classification (Pullman,	Black & Clawson screening table	2 x 8 ft table	Ambient, continuous	20 hours	Chips, particles, loose fibers, etc.	5 UST/day
	Sutton, Steele, & Steele, Inc. air classifier	44 x 63-in. table	Ambient, continuous	20 hours	Chips, particles, loose fibers, etc.	5 UST/day

Washington)						
Washington State University, Bioproducts Conversion and Thermal Processing (Pullman, Washington)	Auger reactor	25 kg/hour	Room temperature	20 hours	Biomass, 2 in. or less	0.5 UST/Day
	Cincinnati Milacron extrusion—86 mm	86-mm conical screw diameter	Room temperature up to 400°F	20 hours	10 or smaller mesh particles	6.5 UST/day
	Cincinnati Milacron extrusion—55 mm	55-mm conical screw diameter	Room temperature up to 400°F	20 hours	10 or smaller mesh particles	5 UST/day
	Cincinnati Milacron extrusion—35 mm	35-mm conical screw diameter	Room temperature up to 400°F	20 hours	10 or smaller mesh particles	0.5 UST/day
ZeaChem, Inc. (Boardman, Oregon)	Pretreatment	10 tons (dry)/day	Depends on pretreatment mode	4,500+ hours	Nearly all lignocellulosic feedstocks	10 tons (dry)/day*
	Enzymatic hydrolysis	4–40,000 gallons	Depends on feedstock and enzyme	120-hour batches	Pretreatment substrates	Depends on feedstock and enzyme
	Fermentation	4–40,000 gallons	Anaerobic, aerobic	120-hour batches	All sugars and pretreatment hydrolysates and enzymatic saccharification hydrolysates	Depends on microorganism
	Recovery	4–40,000 gallons	Depends on system and recovery requirements	Depends on system and recovery requirements	All broths	Depends on system and recovery requirements

Thermochemical Conversion Facilities

Applicant (Site)	Unit Operation	Scale	Operating Conditions	Max Run Time	Acceptable Feedstock	Throughput per Day
Amaron Energy (Salt Lake City, Utah)	Torrefaction	0.5-ft diameter	280°–325°C	8 hours	Juniper wood	0.2 tons
	Pyrolysis	0.5-ft diameter	450°–600°C	24 hours	Wood, pellets, municipal solid waste (MSW), grease, etc.	0.5 tons
	Pyrolysis	2.0-ft diameter	450°–600°C	9 hours	Juniper wood, chicken manure	13 tons
Byproduct Cellulosic Liquid Fuel Corporation (Callaway, Virginia)	Dryer	7 ft x 7 ft x 9 ft	up to 200°C	2 hours	<40% moisture	36 tons
	Converters (2x)	7 ft x 7 ft x 9 ft	up to 450°C	4 hours	6% moisture	9 tons
	Torches for wood gas (2x)	1.5 ft x 1.5 ft x 2 ft	Variable feed rate	24 hours split between both	up to 450°C gas	-
	Dip tanks for cooling	8-ft diameter, 1-ft high	Continuous water flow	4 hours per load	Charcoal below 100°C	4.5 tons
	Tank dump to supersacks	Sacks 4 ft x 4 ft x 4 ft	12-ft x 12-ft x 12-ft storage	Under crane	Charcoal below 100°C	9 tons as needed
	Knuckle boom	18-ft boom	Truck unload	As needed on two shifts	Mostly 170-ft pulpwood	36 tons
	Sawmill	42	Reduced logs	Two shifts	Length >4 ft,	Up to 36 tons

		horsepower (hp) diesel 18 ft x 36 in. capacity	to 4 in. x 4 in.		diameter <36 in.	
	Edger	4-ft x 10-ft electric	Boards to 4 in. x 4 in.	Two shifts	Wide boards	Up to 18 tons
	Chipper	4ft x 4 ft x 18 ft, 100 hp	Boards to 4 in. x 4 in. or slabs	Two shifts	Any wood form	Up to 36 tons
	Diesel generator	250 kilowatts (kW) three phase	Continuous water flow	Two shifts	No public three phase	-
	Dump truck	16-ft x 8-ft x 4-ft bed	¼-mile run and return	Two shifts	Chips and blocks	Up to 36 tons
	Front end loader	54 hp diesel	Load tanks	Three shifts	Chips, blocks, or granular	36 tons
	Crane	5-ton, 22-ft hook height	Coverage 24 ft x 100 ft	Three shifts	All transport under roof	Up to 72 tons
Gas Technology Institute (Des Plaines, IL)	Gasifier	11.5-in. diameter x 30-ft height	2,000°F, 500 pounds per square inch gauge (psig)	7,500 hours	Densified or pelletized biomass or 1-in. wood chips	19 tons/day as-received biomass
	Gasifier	6-in. diameter, 3 ft or 6 ft long	2,500°–5,000°F, 385 psig	7,500 hours	Pulverized, torrefied wood or liquid pyrolysis oils, glycerin	18 tons/day pulverized feed, 1.2 tons/day liquid feed
	Hot gas filter	24-in.	Up to	7,500 hours	Any biomass	96 tons/day raw

		outer diameter, 13-ft height	1,000°F at 500 psig			synthesis gas (syngas) w/ 100 lb/hour solids
	Ultra-hot gas filter	12-in. diameter, 12.25-ft height	Up to 1,440°F at 135 psig	3 days, fines storage	Any biomass	4.8 tons/day raw syngas w/ 20 lb/hour solids
	Tar reformer	3-ft 8-in. diameter, 22-ft height	Up to 1,725°F at 500 psig	30 days catalyst life	Any biomass	60 tons/day solids-free syngas
	Direct gas cooler	2-ft diameter, 21-ft height	510°F at 500 psig	7,500 hours	Any biomass	24 million British thermal units (Btu)/hour (6.5 million Btu/hour for 3 heat exchangers), 165 gallons/minute circulation
	Syngas compressor	250 hour hp at 900 rpm	Up to 120°F at 120 psig (inlet), 1,100 psig (outlet)	7,500 hours	Any syngas with tars below 10 parts per million by weight	59,542 standard cubic feet per hour (scfh) (approx. 40 tons/day)
	Acid gas plant: countercurrent solvent scrubber with integrated chiller and	16-in. outer diameter x 50-ft height (absorber), 12-in. outer	Up to 350°F at 1,200 psig	7,500 hours	Any tar-free syngas	320 million Btu/hour (approx. 3000 lb/hour syngas)

	reboiler	diameter x 25-ft height (stripper)				
	Sulfur guard: sorbent tower for H_2S removal (if needed)	6-ft inner diameter x 25-ft height	Up to 600°F at 300 psig	7,500 hours	Any syngas	645 ft^3 ZnO sorbent
	Thermal oxidizer: natural gas–fired syngas combustor with stack	6-ft inner diameter x 45-ft height	1400°–1800°F, atmospheric pressure	7,500 hours	Any syngas	-
Iowa State University—Pyrolysis (Ames, Iowa)	Biomass feed system (Pyrolysis)	-	Ambient temperature and pressure	120 hours	1/8”-minus herbaceous or woody feedstock at <15 wt% (weight percent) moisture	0.7 dry tons
	Pyrolysis reactor (Pyrolysis)	6-in. diameter	350°–600°C	120 hours	1/8”-minus lignocellulosic biomass <15 wt% moisture	0.7 dry tons
	Cyclone filters (Pyrolysis)	-	350°–600°C	120 hours	Pyrolysis vapors, aerosols, and char	0.7 dry tons
	Fractional condensation system (Pyrolysis)	-	10°–150°C	120 hours	Pyrolysis vapors and aerosols	0.7 dry tons

Iowa State University—Gasification (Ames, Iowa)	Biomass feed system (Gasification)	-	Ambient temperature, 0–20 psig	16 hours	1/8"-minus herbaceous or woody feedstock at <15 wt% moisture	-
	Gasification reactor	-	700°–850°C, 0–20 psig	16 hours	Syngas and char	0.5 dry tons/day
	Cyclone filters (Gasification)	-	700°–850°C, 0–20 psig	16 hours	Syngas	0.5 dry tons/day
	Tar scrubber (Gasification)	-	90°–850°C, 0–20 psig	16 hours	Syngas	0.5 dry tons/day
	Sulfur scrubber (Gasification)	-	425°C, 0–20 psig	16 hours	Syngas	0.5 dry tons/day
	Oil scrubber (Gasification)	-	65°–425°C, 0–20 psig	16 hours	Syngas	0.5 dry tons/day
	Light tar scrubber (Gasification)	-	80°–105°C, 0–20 psig	16 hours	Syngas	12 standard liters per minute slip stream
KiOR, LLC (Pasadena, Texas)	Wood yard	-	Wood flour with average particle size ~1 mm and moisture content <10 wt%	Continuous	Softwoods and hardwoods, various energy crops	10 bone dry tons/day
	Biomass fluid catalytic converter	-	<40 psig, max. regenerator temperature of 1,400°F	Continuous	Typical catalyst average bed density of 0.75; average particle size of 70µ	10 bone dry tons/day

	Hydrotreater	-	Max. operating pressure of 2,000 psig	Continuous	Partially de-oxygenated, thermally stable biocrude	5 bone dry tons/day
	Fractionation	-	<25 psig, three cut fractionator, up to 800°F normal boiling point	Continuous	Naphtha, kerosene/jet, distillate, and fuel oil cuts	10 bone dry tons/day
National Renewable Energy Laboratory—Gasification (Golden, Colorado)	Feed system (loss-in-weight feeder, rotary valves, feed transfer screw)	10 to 20 kg/hour biomass	Atmospheric temperature and pressure	Unlimited	Pellets <10% moisture: woody and herbaceous feedstocks acceptable	Up to 0.5 metric tons/day feedstock
	Gas feed system	15 to 30 kg/hour super-heated steam and/or nitrogen	650°C, ~600 kilopascals (kPa)	Unlimited	Steam and/or nitrogen gas	0.5 metric tons/day feedstock
	Two-stage gasification reactor (fluidized-bed reactor), coupled to	Fluidized-bed reactor: 8-in. diameter bed, entrained-	Fluidized-bed reactor: 650°C at 5-15 sec residence time, entrained-	~72 hours	Crushed pellets entrained in steam/nitrogen; olivine or other fluidizable bed material	0.5 metric tons/day feedstock

	entrained-flow reactor	flow reactor: 1-1/2-in. diameter, 29 m length	flow reactor: up to 900°C at 2–4 sec residence time			
	Dual-cyclone char and ash removal system	Full-stream, 1-1/2-in. inlet/outlet, 4-in. diameter barrel	400°–500°C	~72 hours	Steam, syngas, nitrogen, char and ash, tars	0.5 metric tons/day feedstock
	Fluidized-bed reformer	Full-stream, 14-in. diameter bed	500°–900°C, residence time: 5–15 seconds	~72 hours	Steam, syngas, nitrogen, tars; fluidizable catalyst bed material	0.5 metric tons/day feedstock
	Polishing packed bed reformer	Full-stream, 3 packed-bed vessels, 6-in. diameter	500°–900 °C, residence time 0.5–1.5 seconds	~72 hours	Steam, syngas, nitrogen, tars; packed bed catalyst	0.5 metric tons/day feedstock
	Circulating riser reactor system	Partial-stream 4-in. diameter riser with 6-in.	500°–900°C, residence time 1–2 seconds, catalyst-to-biomass	~72 hours	Steam, syngas, nitrogen, tars; Geldart Group A or B catalysts; steam and/or air regeneration; steam	Up to ½ full stream; with minor modifications, system can be operated at full stream capacity.

		diameter regeneration vessels	ratio range 8:1 or higher		and/or nitrogen stripping	
	Scrubber system: steam condensation and collection	Full-stream, 1-1/2-in. piping	40°–50°C	~72 hours	Steam, syngas, nitrogen, tars	0.5 metric tons/day feedstock
	Online analytical (GC, NDIR, TCD)	Sample stream, 1 L/minute gas	Atmospheric temperature and pressure	Unlimited, but taken offline to calibrate daily	Light and permanent gases, sulfur species	N/A
	Online MBMS	Sample stream, 1–3 L/minute hot gas	350°–400°C	~72 hours	Gasification vapors including tars	N/A
National Renewable Energy Laboratory—Fast Pyrolysis (Golden, Colorado)	Feed system (loss-in-weight feeder, rotary valves, eductor)	10–30 kg/hour biomass	Atmospheric temperature and pressure	Unlimited	Pellets < 10% moisture: woody and herbaceous feedstocks acceptable	Up to 0.5 metric tons/day feedstock
	Gas feed system	15–20 kg/hour preheated nitrogen gas	650°C, ~600 kPa	Unlimited	Nitrogen gas	0.5 metric tons/day feedstock

	Pyrolysis reactor (entrained-flow reactor)	Full-stream, 1-1/2-in. diameter, 29 m length	480°–550°C, 60 kPa, residence time: 3–5 seconds	8–20 hours, depending on feedstock	Crushed pellets entrained in nitrogen	0.5 metric tons/day feedstock
	Dual-cyclone char and ash removal system	Full-stream, 1-1/2-in. inlet/outlet; 4-in. diameter barrels	400°–500°C	8–20 hours, depending on feedstock	Nitrogen gas, char and ash, pyrolysis vapors	0.5 metric tons/day feedstock
	Scrubber system: bio-oil condensation and collection	Full-stream, 1-1/2-in. piping; holds inventory of ~3 gallons of pyrolysis oil	40°–50°C	8–20 hours, depending on feedstock	Product gases and pyrolysis vapors	0.5 metric tons/day feedstock
	Online analytical (gas chromatograph, nondispersive infrared sensor,	Sample stream, 1 L/minute gas	Atmospheric temperature and pressure	Unlimited, but taken offline to calibrate daily	Light and permanent gases	N/A

	thermal conductivity detector)					
	Online MBMS	Sample stream, 1–3 L/minute hot gas	350°–400°C, full vacuum	2–4 hours	Pyrolysis vapors	N/A
National Renewable Energy Laboratory—*Ex-Situ* Catalytic Fast Pyrolysis (Golden, Colorado)	Feed system (loss-in-weight feeder, rotary valves, eductor)	10–30 kg/hour biomass	Atmospheric temperature and pressure	Unlimited	Pellets <10% moisture: woody and herbaceous feedstocks acceptable	Up to 0.5 metric tons/day feedstock
	Gas feed system	15–20 kg/hour preheated nitrogen gas	650°C, ~600 kPa	Unlimited	Nitrogen gas	0.5 metric tons/day feedstock
	Pyrolysis reactor (entrained-flow reactor)	Full-stream, 1-1/2-in. diameter, 29 m length	480°–550°C, 60 kPa, residence time: 3–5 seconds	8–20 hours, depending on feedstock	Crushed pellets entrained in nitrogen	0.5 metric tons/day feedstock
	Dual-cyclone char and ash removal system	Full-stream, 1-1/2-in. inlet/outlet; 4-in. diameter	400°–500°C	8–20 hours, depending on feedstock	Nitrogen gas, char and ash, pyrolysis vapors	0.5 metric tons/day feedstock

		barrels				
	Circulating riser reactor system	Full-stream, 4-in. diameter riser with 6-in. diameter regeneration vessels	400°–600°C, residence time: 1–2 seconds, catalyst-to-biomass ratio range: 8:1 or higher	8–20 hours, depending on feedstock	Nitrogen gas and pyrolysis vapors; Geldart Group A or B catalysts; steam and/or air regeneration; steam and/or nitrogen stripping	0.5 metric tons/day feedstock
	Scrubber system: pyrolysis oil condensation and collection	Full-stream, 1-1/2-in. piping; holds inventory of ~3 gallons of pyrolysis oil	40°–50°C	8–20 hours, depending on feedstock	Product gases and upgraded pyrolysis vapors	0.5 metric tons/day feedstock
	Online analytical (gas chromatograph, nondispersive infrared sensor, thermal conductivity detector)	Sample stream, 1 L/minute gas	Atmospheric temperature and pressure	Unlimited, but taken offline to calibrate daily	Light and permanent gases	N/A

	Online MBMS	Sample stream, 1–3 L/minute hot gas	350°–400°C, full vacuum	2–4 hours	Pyrolysis vapors	N/A
RTI International—Pilot (Research Triangle Park, North Carolina)	*In-situ* catalytic fast pyrolysis unit	6-in. diameter mixing (pyrolysis) zone, 2-in. diameter riser, total residence time: ~1-2 seconds, 18-in. diameter bubbling bed regenerator with a 24-in. disengagement zone	Temperatures: Pyrolysis: 350°–650°C; Regenerator: 700°C max.; process piping: 300°–500°C; quench system: 5°–120°C; pressure: 10–35 pounds per square inch absolute (psia); catalyst-to-biomass ratio: 10:1 to 20:1; catalyst circulation rate: 1,000–2,000	35 hours in one continuous run that was stopped after bio-crude production target was achieved; over 500 hours total run time	Loblolly pine; hardwood pellets; hybrid poplar; corn stover sawdust with 0.25-in. top size—no apparent limit on fines content, desired moisture content ~10%–15%, apparent minimum bulk density ~8–10 lb/ft^3	Nominal 1 dry ton of biomass per day; produces 50–80 gallons/ton of bio-crude; total initial catalyst inventory is 125–200 kg, depending on density; catalyst addition is possible

			lb/hour			
RTI International—Bench (Research Triangle Park, North Carolina)	*In-situ* catalytic fast pyrolysis unit	Total reactor volume: 350 ml; catalyst volume: 20–350 ml of catalyst	Liquid hourly space velocity: 0.5–1.0; flow rates: 10–250 ml/hour; design temperature: 450°C; max. operating temperature: 430°C; design pressure: 3,000 psig; max. operating pressure: 2,500 psig	300 hours continuous; over 1,000 total hours since April 2015	Vacuum gas oil, light cycle oil, diesel, bio-crude, blends	Up to 12 L/day
Southern Research and ThermoChem	ThermoChem Recovery	-	-	-	-	-

Recovery International (Durham, North Carolina)	International process development unit					
	Feed system	-	-	-	-	-
	Gasification system	-	-	-	-	-
	Gas cleanup, gas to liquids	-	-	-	-	-
Southern Research (Durham, North Carolina)	Waste-to-energy system	-	-	-	-	-
	Coal-biomass to liquids pilot unit	-	-	-	-	-
Swift Fuels, LLC (Lafayette, Indiana)	Feed tank and heat exchanger	600-gallon tank, 1 gallon/minute feed	Up to 400°C, up to 150 psi, 304 stainless steel	500,000 gallons/year	Bio-acetone or equivalent	500,000 gallons/year
	Gas-phase catalytic reactor	57 separate 3-in. catalyst tube reactors, each 30 in. tall	Up to 400°C, up to 150 psi, 316 L stainless steel	500,000 gallons/year	Bio-acetone or equivalent	Bio-mesitylene: 250,000 gallons/year + byproducts
	Skid-mounted Dowtherm	Up to 225 psig	Up to 400°C	N/A	Heating oil	N/A

	unit					
ThermoChem Recovery International (Durham, North Carolina)	Feeder system	-	-	-	-	-
	Steam reformer	-	-	-	-	-
	Carbon trim cell	-	-	-	-	-
	Primary gas cleanup	-	-	-	-	-
	Syngas compressor	-	-	-	-	-
	Secondary gas cleanup	-	-	-	-	-
	Syngas synthesis Reactor	-	-	-	-	-
University of North Dakota—Advanced Fixed-Bed Gasifier (Grand Forks, North Dakota)	Advanced fixed-bed gasifier	20–120 lb/hour	500°–1000°C, atmospheric pressure	5–100 hours	Chipped wood including fines, pellets, or particles; size: 1–2 in.; <40% moisture	0.24–1.44 tons/day
	Feed system	20–150 lb/hour	20–40°C, Atmospheric pressure	Controlled, intermittent or continuous	Chipped wood including fines, pellets, or particles; size: 1–2 in.; <40% moisture	-
	Residue extraction system	10–50 lb/hour	500°–700°C, atmospheric pressure	Intermittent	Residue particle size up to 2.5 in.	-
	Oxidizer injection	Air: 100 standard	Preheated, 200°C	Continuous as per the gasifier	-	-

	system	cubic feet per minute (scfm); O_2: 1–15 scfm; steam: 100 lb/hour				
	Feed hopper system	Solid feedstock; 300–400 lb	40°C maximum, atmospheric pressure	Filling intermittent	Chipped wood including fines, pellets, or particles; size: 1–2 in.; <40% moisture	-
	Particulate and tar removal system	Syngas flow rate, 15–90 scfm	40°C maximum, atmospheric pressure	Continuous as per the gasifier	-	-
	Syngas flow control and measurement system	10–150 scfm	40°C maximum, up to 5 psig	Continuous as per the gasifier	-	-
	Syngas Thermal Oxidizer	Syngas throughput, 100 scfm maximum	500°–900°C, atmospheric pressure	Continuous as per the gasifier	Clean syngas	-
	Engine generator	Syngas: 50 kW, dual-fuel – diesel/syn	Outdoor operations	Continuous as per the gasifier	-	-

		gas: 30 kW				
University of North Dakota—Continuous Tubular Reactor Catalytic Fixed-Bed System (Grand Forks, North Dakota)	Liquid pump, Haskel pneumatic piston pump	100 gallons/day	5,000 psi	1,000+	Liquid feedstocks, bio-oil, alcohol, other	100 gallons
	Gas mass flow controllers	100 scfh/day (4x)	5,000 psi	1,000+	Gas reactants, syngas, hydrogen, nitrogen, etc.	Greater than 400 scfh with additional mass flow controllers
	Catalytic Reactors	Two at 1.5-in. inside diameter × 60-in. long; two at ¾-in. inside diameter × 63-in. long	5,000 psi, 900°F	1,000+	Liquid or gaseous feedstocks	100 gallons
	Condenser	100 gallons/day water or glycol cooling coil	5,000 psi, 900°F	1,000+	Condensable gases and liquids	100 gallons
	Automated liquid letdown	100 gallons/day	5,000 psi, 900°F	1,000+	Condensable gases and liquids	100 gallons
University of North	Feedstock	¼-in. inlet,	<50°C	Indefinitely	Liquid feedstocks	0–100 lb feed

Dakota—High-Pressure Water Reformer (Grand Forks, North Dakota)	and water pumps	0–100 lb/day, 15,000 psi			(alcohols, oils, other hydrocarbons)	
	Preheater	¼-in. dia., 0–100 lb/day, 15,000 psi	<500°C	Indefinitely	Liquid feedstocks (alcohols, oils, other hydrocarbons)	0–100 lb feed
	High-pressure water reformer	¼-in. diameter, 0–100 lb/day, 15,000 psi	<600°C	Indefinitely (if no sulfur present)	Liquid feedstocks (alcohols, oils, other hydrocarbons)	0–100 lb feed
	Water condenser	0–100 lb/day, 15,000 psi	<100°C	Indefinitely	Wet gas	0–100 lb feed
	CO_2 scrubber	3-in. diameter × 10 ft, 0–100 lb/day, 15,000 psi	<100°C	Indefinitely	Dry gas	0–100 lb feed
	Methanator	0.438-in. diameter × 10 in., 0–50 lb/day, 15,000 psi	<500°C	Indefinitely	Dry gas	0–50 lb through
	Gas purification	3-in. diameter × 3 in., 15,000 psi	<100°C	Tandem pressure swing adsorption trains operate continuously with	Dry gas	0–200 scfh product H_2

				alternating desorption cycling after approximately 1 hour of operation		
University of North Dakota—Transport Reactor Circulating Fluid-Bed and Bubbling Fluid-Bed Reactors (Grand Forks, North Dakota)	Feed hopper super sacks	2,500 lb capacity, 1,000 lb capacity	Atmospheric pressure	-	Hammer-milled pine or pellets, switchgrass, stover, <35 wt% moisture	-
	Pressurized feed system	1700 lb cap., 12-in. diameter top with 16-in. diameter bottom, diverging hoppers	Up to 500 psig	Continuously with alternating lock hoppers	Hammer-milled pine or pellets, switchgrass, stover, dried algae, lignin	-
	Transport reactor circulating fluid bed	1-megawatt thermal, 300 scfm, O_2 blown; 400 scfm, air blown	150 psi, 2,000°F, air blown, oxygen blown, or steam blown	Continuously up to 12 days	Hammer-milled pine or pellets, switchgrass, corn stover	Feed basis: 300–600 lb/hour
	Bubbling fluid bed	10-in. bed with 16-in. freeboard	1,800°F, 150 psig air blown, oxygen blown, or	Continuously	Hammer-milled pine or pellets, switchgrass, corn stover	150–200 lb/hour

			steam blown			
	Hot gas filter vessel	48-in. diameter, 85-in. long, 1.5 m candles (up to 19x)	1,000°F, 150 psig	Filter blowback with automated lock hopper ash letdown	Filter face velocity: 2.5 ft/minute, particulate loading: <20,000 ppm	up to 400 scfm
	Gas quench sieve tower scrubbers	400 scfm	150 psig, 125°–225°F, 200 psig	Direct water quench with blowdown	Syngas with tar/oil/water	-
	Warm syngas compressor	150 psig inlet	500°–600°F, 150 psig inlet, 500 psig outlet	Continuous three-stage	Warm or cold syngas	250 scfm
	Fixed-bed regenerable sulfur sorbent	<5 parts per million by volume H_2S	500°–900°F, 500 psig	Continuous with alternating beds for regeneration	-	250 scfm
	Fischer-Tropsch reactor slipstream skid	5 scfm; easily expandable to four-tube reactor	400°–700°F, 1,000 psig max.	Continuous two-tube fixed-bed reactor	Syngas	1 L/hour liquid products
	H_2 membrane slipstream skid	100 scfm	1,000°F, 500 psig	-	-	100 lb/hour H_2

University of Utah (Salt Lake City, Utah)	Pressurized fluidized bed gasifier	0.5 tons of dry biomass per day. Bed diameter 10 in. (25 cm).	Maximum 900°C; system rated to 20 atmospheres (atm), but boiler pressure limits practical operation to 6 atmospheres (90 psi). Indirectly heated by 80 in-bed heaters able to provide 32 kW of heat. Heating can also be augmented by co-feeding oxygen	Only limited by shift workers. Longest run (with black liquor) was 252 hours.	Solid feedstocks: chipped wood or agricultural waste (approx. 1/8 to 1/2 in.). Anything pelletized feeds well. Liquid feedstocks: bio-oil, concentrated black liquor, glycerine, etc. Liquid feed system can be heated to 120°C so high viscosity feedstocks can be fed.	0.5 ton/day feed on dry basis, 0.75 ton/day for 33% moisture material
	Pressurized entrained-flow gasifier	Nominal 1 ton/day feed. Can push to 1.5	Max 1,600°C (2,900°F) and 28 atm (400 psi), although O_2	Can operate at least 4–6 hours continuously, or more for low-ash feedstocks	Liquid feedstocks only. Does not currently have dry feed capabilities. Bio-oil, black liquor,	Nominal 1 ton/day feed. Can push to 1.5 ton/day at maximum pressure.

		ton/day at the highest pressures. Reactor is 8 in. diameter by 60 in. long.	supply pressure limits practical operation to 18 atm.	provided there are sufficient operators available.	glycerine, off-spec biofuels, etc. are all fine. Can also prepare slurry with bio-char (straight biomass does not work well), provided viscosity of slurry does not become excessive.	
U.S. Department of Agriculture, Agricultural Research Station—Eastern Regional Research Center (Wyndmoor, Pennsylvania)	Combustion Reduction Integrated Pyrolysis System (CRIPS)	Reduction bed: 6 in. x 8 in., oxidation bed: 8 in. x 24 in.	500°–550°C	~1 to 2 hours before refill feed system can be modified for continuous operation and indefinite run duration	Lignocellulosic biomass <12% moisture ground to 3 mm, including switchgrass, forest thinnings, equine waste, crop residues, etc.	1–2 metric tons dried and sized biomass per day, depending on feedstock
	Gasifier/generator	15–17 kW, depending on feedstock	750°–850°C	~4 to 6 hours before refill depending on load and feedstock feed system can be modified for continuous operation and indefinite run duration	Nut shells (e.g., walnut, hazelnut), softwood chips (e.g., fir, pine), hardwood chips (e.g., oak, ash), corn cobs, coconut shells, palm kernel shells, <20% moisture, sized 0.5 in. to 1.5 in.	Approx. 300 kWh