CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Biomass-to-Electricity: Pilot Scale Testing of Baseload Compared With Flexible Power

Shockwave Gasification Enables Biomass Conversion Into Renewable Gases

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Taylor Energy evaluated three pathways to convert low-cost, woody biomass as a renewable energy feedstock into flexible electricity generation. The goals were to reduce greenhouse gas emissions and local criteria pollutants and to improve energy reliability by diverting significant volumes of waste biomass from landfill while lowering energy bills. The research team identified the potential for use of the existing natural gas pipeline distribution system as a near-term storage opportunity, and the conversion of woody biomass into hydrogen or methane as the best use of thermo-catalytic gasification technology for flexible electric power generation.

Taylor Energy achieved the project objectives of converting woody biomass into syngas products suitable for energy recovery, storage, and subsequent use for flexible electric power generation, employing high-purity renewable gases such as hydrogen and carbon monoxide intended for injection into a gas distribution system. Woody biomass was converted into product gases at a feed rate of 180 pounds per hour, typically sustaining operation for 6 to 10 hours during test campaigns and completing 300 hours of operation in an air-blown gasification mode. Air-blown biomass gasification resulted in a combined hydrogen and carbon monoxide content ranging from 18 to 36 percent by volume, with nitrogen content as the major diluent ranging from 40 to 45 percent by volume. The gasification process employed a jet-spouted bed for feed comminution, drying, and devolatilization, followed by an entrained-flow thermo-catalytic conversion section where pyrolysis tar-vapors were cracked into low-molecular weight gases, carbon-char, and mineral ash. A novel pulse-detonation power system generated supersonic shockwaves, used to intensify the gasification process by micronizing biomass solids and increasing gas/solids mixing, resulting in increased conversion efficiency of feedstock to renewable fuel.

Keywords: shockwave gasification, biomass-to-hydrogen, biomass gasification

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Introduction

Renewable energy resources can generate electricity with little or no pollution and minimal global warming emissions, therefore advancing California's environmental mandates to reduce the state's greenhouse gas emissions. However, a major barrier to achieving the state's mandated renewable electricity targets is the intermittent nature of fluctuating resources (like wind or solar), which can negatively affect the reliability and price of renewable power.

Using woody biomass to generate flexible (on-demand) renewable electric power is one approach to solving the problem of intermittent power generation. Forest residues are a large renewable fuel resource available in California that can be used for flexible power generation through thermo-catalytic gasification: the preeminent technology for efficient conversion of woody biomass into renewable gases. Environmentally friendly power generation that uses woody biomass as a renewable energy feedstock is needed to achieve California's legislative goals and clean energy objectives including Senate Bill 100, which requires the state to provide renewable and zero-carbon energy to utility customers by 2045.

The problem with current biomass gasification technology is that the installed capital cost is too high. One way to lower this cost is to increase the gasification process intensity and efficiency — which means converting more feedstock to energy without increasing equipment costs. However, most process intensification methods also increase parasitic electric power consumption. For example, the addition of high-temperature plasma with an electric arc increases biomass gasification process intensity (measured as biomass throughput capacity and system performance), which ultimately increases parasitic electric consumption.

This project advanced a thermo-catalytic conversion technology that employs pulse detonation power to intensify the reactions between gases and solids, potentially enabling cost-effective gasification of biomass residues that can produce storable energy products with minimal to no parasitic electricity consumption. Pulse detonation provided an intensification method that increased gas/solids mixing, thus enhancing multiple thermo-chemical conversion objectives including improved mass and heat transfer. These cumulative benefits enable cost reductions, including lower gasification hardware cost. Simplicity, durability, and affordability are the inherent advantages of the oxy-fuel pulse detonation power systems used to generate supersonic shockwaves, which are in turn used to intensify the gasification process.

Project Purpose, Goals, and Objectives

The overarching purpose of the project was to reduce the overall cost for flexible renewable electric power generation, leading to commercialization of biomass processing methods that benefit ratepayers by lowering energy bills and improving the environment.

The project goal was to compare three alternative biomass processing methods, then to select one optimum thermal processing method for extended testing. All three thermo-catalytic processing methods used pulse detonation power to intensify biomass conversion during pilot-scale testing. Each pathway produced intermediate byproducts (gases, liquids, and carbons) that can be stored and used for load-following, flexible, and on-demand power renewable energy generation.

The objective of this agreement was to evaluate the three following thermochemical biomass processing methods:

- Path-1: A clean fuel-gas production used for baseload power generation, using a solid oxide fuel cell or internal combustion engine.
- Path-2: Converting syngas into hydrogen intended for pipeline blending and storage for flexible power generation.
- Path-3: Direct production of crude bio-liquids for storage intended to fuel a slow-speed engine used for flexible power generation.

Lastly, the project had to identify an optimum processing methodology that provides the greatest value to investor-owned utility ratepayers and obtains 500 hours of pilot-scale operating data.

Project Approach

Taylor Energy is a California corporation developing gasification methods to convert biomass residues into pipeline-quality renewable gases. Donald G. Taylor of Taylor Energy and Dr. Arun Raju of the Center for Renewable Gas at the University of California, Riverside, served as co-principal investigators. Taylor Energy senior technicians and student operators performed operational testing of the gasification system, and Dr. Raju's group performed system analysis tasks using Aspen Plus models optimized for steam gasification. Taylor Energy performed the techno-economic analysis.

The project team convened a technical advisory committee comprised of five members with a diverse skill set of technical and business perspectives.

For this project, applied research and development at pilot-scale was employed to accomplish the technical objectives. Testing and verification of an optimum thermal processing path at pilot-scale will enable commercial-scale deployments in the future.

The research team increased process intensity without increasing electric consumption by applying pulse-detonation principles to three different thermo-catalytic processing paths used to convert biomass into renewable power. Pulse detonation is a "pressure-gain" exothermic process that converts 49 percent of fuel input into power in the form of supersonic shockwaves and gas compression waves (sound waves) according to the Humphrey cycle (Bellini, 2010). Shockwave power intensifies the gasification process by propelling superheated oxygen and steam into a dilute-phase conical jet-spouted bed that serves as the receiver for biomass feeds.

Taylor Energy also used a cost-effective inlet-manifold formed from high-density refractory, using a single central inlet (spout) for superheated oxygen and steam, which allowed the input of pulse detonation power in the form of supersonic shockwaves used for process intensification. The jet-spouted bed uses gas momentum to accomplish mixing and milling of the feed materials, which causes rapid ablation and size-reduction, providing the following benefits:

- Enables input of high-temperature gases with extremely high-momentum.
- Handles sticky-particles (ash eutectics) with no fluidization problems.
- Low-cost construction.
- Simple operation.

Project Results

The project team and the technical advisory committee defined Path 2 as "Converting syngas into hydrogen intended for pipeline blending and storage for flexible power generation" as the most optimal and advantageous path. This path has the technical potential to produce high-purity hydrogen from relatively low-quality syngas, including hydrogen recovery from low-pressure gas streams, and even potentially from gas mixtures with relatively low hydrogen partial-pressure.

The technical results demonstrated the successful gasification of biomass in a jet-spouted bed reactor and identified synergistic benefits using pulse-detonation methods that will likely enable the economical production of hydrogen-rich fuel gases. Path 2 applications should enable the low-cost conversion of biomass into hydrogen, using various advanced separation methods that enable blending bio-hydrogen into the utility pipeline, particularly including the emerging use of fuel cell technology in the proton pump configuration to recover high-purity hydrogen from low partial pressures hydrogen sources.

Biomass-to-hydrogen (Path 2) can achieve 65 percent net conversion efficiency and produce 99 percent hydrogen purity at 60 pounds per square inch gauge, resulting in a product that is ready for pipeline blending. Path 1, which is baseload power using optimum high-pressure biomass gasification, will achieve 40 percent net conversion efficiency. Biocrude liquids (Path 3) are thermally efficient, recovering 75 percent of the net energy content in biomass as a pumpable bio-crude liquid. However, a dedicated low-speed reciprocating engine or >20 megawatts electrical turbine engine designed to use bio-crude liquids would be required to achieve 36 percent net efficiency for biomass-to-electricity.

Advancing the Research to Market

Taylor Energy prepared a video presentation that summarized project objectives and reported on their progress. The project team also created a website (https://taylorenergy.org/) that provided information about the technology, the potential applications for biomass-to-hydrogen, and recent project advancements.

Taylor Energy's technical advisory committee concluded that the subject biomass-to-hydrogen technology must be successfully developed to demonstration scale before commercial relationships will advance the technology to full commercial deployment. This emerging biomass gasification technology will stimulate market adoption because the installed capital cost is about half the cost of existing gasification systems while still providing a simple gasification system with 90 percent online availability.

The research team has engaged in public meetings sponsored by stakeholders to describe the benefits of a biomass-to-hydrogen path and how it can produce cost effective bio-methanol. The team has engaged in ongoing efforts to provide support for the continuing development of the core gasification technology. Multiple proposals have been submitted in response to solicitations issues by the United States Department of Energy. There is a reasonable expectation that one or more fundamental research programs focusing on gasification process intensification.

Presently, the most interesting emerging market application for the technology seems to be for syngas production, directed to the catalytic synthesis of green methanol required by the shipping industry for the Los-Angeles-to-Shanghai green corridor. The research team has prepared technical and economic presentations for the Port of Los Angeles, the Port of Long Beach, and the Los Angeles County Public Works Department that focus on the use of "separated biomass" residues as a source of renewable feeds.

The City of Los Angeles adopted a 20-year (2005-2025) solid resources management blueprint called RENEW LA Plan (Recovering Energy, Natural Resources, and Economic Benefits from Waste for Los Angeles) to achieve zero waste within the city by 2025. RENEW LA relies on a key element: the establishment of seven conversion technology facilities, with one facility located in each of the city's six waste sheds and a seventh facility in Southern California, to process post-source separated municipal solid wastes disposed in landfills.

The Los Angeles County Department of Public Works has provided a project support letter. The county supports development of conversion facilities capable of managing the county's green waste by providing technical assistance with permitting, finance, outreach, market research, and feasibility studies to facilitate the development of conversion technology facilities.

Benefits to California Ratepayers

This project set the groundwork for future near-term demonstrations that will enable low-cost power generation using renewable energy feeds sourced in California from forest residues or separated biomass. Such generation offers multiple benefits to ratepayers, both environmentally and economically.

Environmental Benefits

- Energy savings by using separated biomass as a renewable feedstock.
- Diversion of significant volumes of waste biomass from landfills.
- Significant reductions of greenhouse gas emissions by using renewable resources.
- Improved energy reliability by using local energy feedstock sources and providing flexible power generation to back up intermittent wind and photovoltaic generation.
- Diminished risk of forest fires by using forest residues as feedstock.

- Reduced local criteria pollutants — carbon monoxide, nitrogen oxides, and particulate matter — when compared with air-curtain furnaces presently used to burn forest wastes.
- Ability to compress and store high-purity hydrogen in pipelines, salt caverns, and depleted gas wells for future use as needed.

Economic Benefits

- Lower cost, abundant forest residue, and separated biomass energy feeds compared with gaseous fossil fuels imported into the state through interstate pipelines.
- Expected savings of $998 million per year based on California's approximate 912,000 million British thermal units of available energy per day and a savings of $3 per million British thermal units using the biomass-to-hydrogen thermal conversion method, based on Taylor Energy's anticipated confirmation of ongoing findings.
- Potential to lower the cost of renewable power by $32 per megawatt by providing on-demand power generation that provides back-up for intermittent wind and photovoltaic.
- Potential to build an advanced recycling industry that employs thousands of people.

CHAPTER 1: Introduction

Renewable energy resources generate electricity with little or no pollution and minimal global warming emissions. These resources contribute to California's goal of lowering greenhouse gas (GHG) emissions. A major barrier to achieving the state's mandated renewable electricity mandates, however, is the intermittent nature of fluctuating sources like wind and solar, negatively affecting both the reliability and price of electricity.

Recent efforts in California to integrate large amounts of intermittent power, primarily wind and photovoltaic-solar, have inadvertently served to periodically disrupt the grid. Some generators, such as nuclear, small hydroelectric, most geothermal, and combined heat and power plants, need to run continuously due to process requirements, require many hours for the startup and shutdown cycles, and have limited inherent turndown capability. For example, a certain amount of gas-fired power capacity must be operated at minimum levels (must run) to provide both ramping capability and ancillary services that include grid regulation and load-following power.

If the must-run generation exceeds demand, the California Independent System Operator (ISO) must act to balance supply and demand. Power prices may therefore become less economically favorable because electric power is valued by the type of generation and the time of day delivered. For example, baseload renewable power has less value when compared to flexible power, otherwise known as dynamic or load-following power.

Generating flexible (on demand) renewable electric power is one approach to solving this problem of intermittent power generation. Forest residue is a large source of renewable fuel in California. Thermo-catalytic gasification is the preeminent technology for the efficient conversion of woody biomass and separated biomass into hydrogen-rich synthesis gases, also known as syngas. The research team designed, constructed, and tested novel conversion processes that used a pulse-detonation burner to drive a jet spouted bed (Figure 1) gasification reactor that produced hydrogen-rich syngas.

Figure 1: Behavior of a Conical Dilute-Phase Jet Spouted Bed

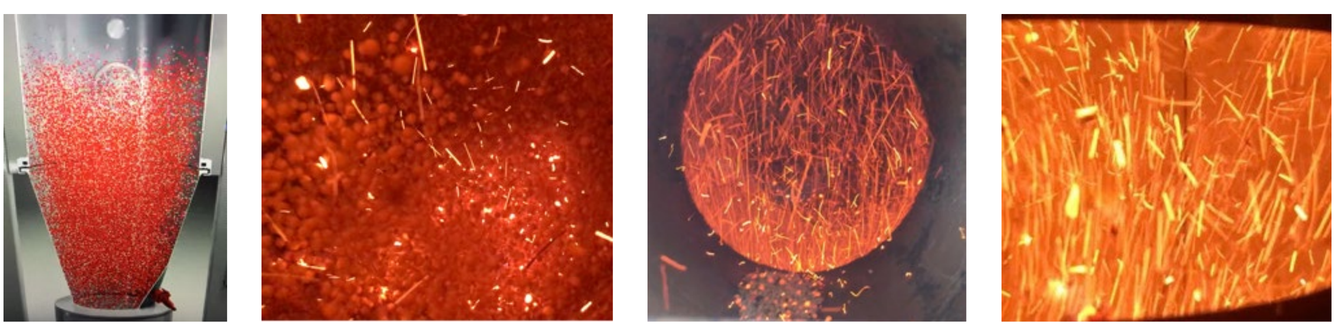


Photo Credit: Taylor Energy

The biomass gasification test facility that was modified for project testing is shown in Figure 2. The test facility, located at the University of California, Riverside (UCR), included use of an enclosed flare designed for the combustion of biomass gasification product gases (with ambient air) within a refractory lined structure.

When firing above the maximum design capacity of 2 million British thermal units (MMBtu) per hour, flames can be seen emerging at the top of the flare. Product gases from biomass gasification were delivered to the flare through an 8-inch pipe; a pilot flame easily ignited the various product streams resulting from thermo-catalytic conversion of biomass into fuel gas (Figure 2).

Figure 2: Gasification Test Facility During Operation: Flaring Renewable Gases

Photo Credit: Taylor Energy

The biomass gasification capacity required for commercial deployment in California, and additionally to achieve the state's renewable power mandates by 2045, is between 250 tons per day and 1,200 tons per day. The pilot plant has been tested using autothermal gasification, with air at 180 pounds per hour (2 tons per day capacity). The pilot plant design specification (using oxygen/water [O_2/H_2O]) is 7 pounds per minute, feeding 400 pounds per hour, processing 5 tons per day of biomass via gasification.

The problem with current gasification methods is that increasing process intensity also increases parasitic power use. For example, input of high-temperature plasma increases gasification process intensity, but also increases the cost of parasitic power consumption. The innovative use of pulse-detonation power both increases process intensity while reducing the electricity required for converting biomass into syngas.

In the case of plasma (compared to pulse-detonation methods), the assertion is supported by the fundamental properties of the respective devices: a plasma torch consumes costly electric power to generate high-temperature process heat (plasma), achieving just 50 percent conversion efficiency of electric power into process heat, while 50 percent of the heat is drained to the environment through cooling water. The pulse-detonation methods convert 50 percent of a low-cost primary fuel (syngas) into high-temperature heat as a co-product of the detonation process; supersonic shocks and cyclic gas compressions also enable jet spouted bed operation as a primary product.

Taylor Energy's biomass gasification process (Figure 3 and Appendix A) is advantageous for producing hydrogen-rich synthesis gas. Modeling data projects 50 percent hydrogen (H_2) content at thermal chemical equilibrium conditions of 1652°F (900°C).

Figure 3: Thermo-Catalytic Gasification Test Facility: Test Site

Photo Credit: Taylor Energy

Currently, there is no commercial gasification equipment that can deliver suitable performance at low capital cost. For example, a market leader in waste biomass gasification based in Japan is commercial ready (Figure 4), but the installation cost is high.

Figure 4: Gasification Process Developed by Market Leader

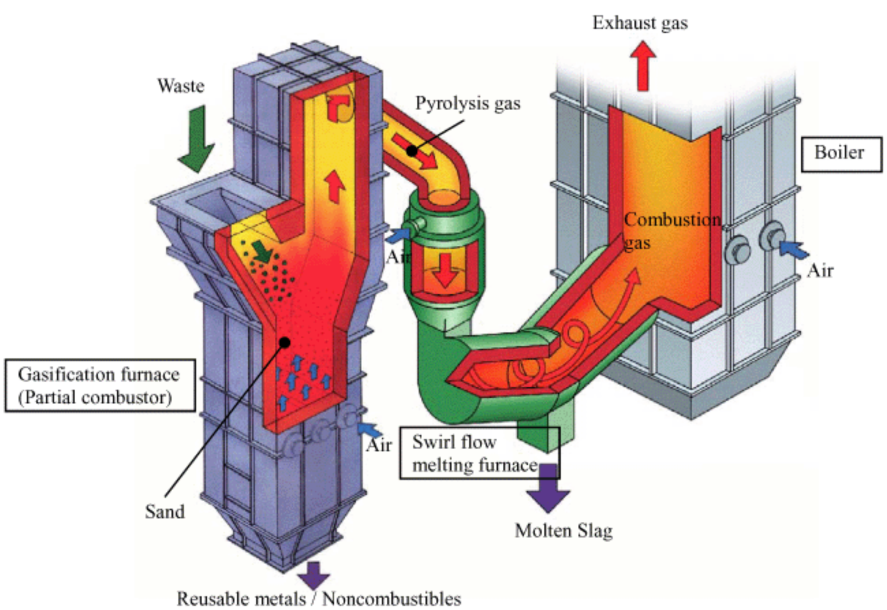


Photo Credit: Kawasaki

This project introduced the pulse-detonation power system that can provide supersonic waves with velocities of 2,000 meters per second and pressure gains of about 20 times the input pressure. Oxy-fuel pulse-detonation burners are highly efficient due to their constant-volume combustion process (Frolov, 2021). This method decreases the amount of energy required to gasify feedstocks when compared with a fluidized bed gasifier, which improves its economics. The project team was using the techniques reported by Wang et al., at the University of Science and Technology of China in Hefei, China, where studies have been performed on methane-oxygen (CH_4-O_2) detonation systems (Wang, 2017). Frolov, in studying gasification applications, has reported that "Cyclic detonations of ternary methane–oxygen–steam mixtures are proved to generate highly superheated steam (HSS) with temperatures exceeding 2250° Kelvin (K) when expanded to the atmospheric pressure." (Frolov, 2021).

Pulse detonation provides an intensification method that increases gas/solids mixing, thereby enhancing multiple thermo-chemical conversion objectives including improved mass and heat transfer. The cumulative benefits enable cost reductions including lower gasification hardware costs (Bellini, 2010). Simplicity, durability, and low-cost are inherent advantages of the oxy-fuel pulse detonation power systems employed to generate the supersonic shockwaves used to intensify the gasification process (Figure 5 and Figure 6).

Figure 5: Pulse Detonation Cycle

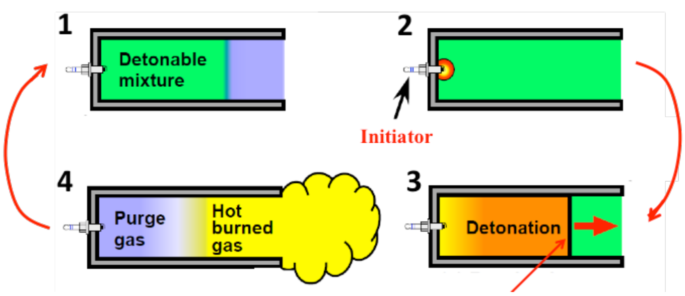


Figure 6: Pulse Detonations at 20-Hz

Photo Credit: Taylor Energy

The detonation power system was initially developed and tested outside of the biomass gasification reactor (Figure 7).

Figure 7: Pulse-Detonation Burner Drives Conical Dilute-Phase JSB

Photo Credit: Taylor Energy

During the gasification of organic feeds, the detonation system was operated with a controlled amount of superheated oxygen combined with superheated exhaust products, thereby controlling the operating temperature of the gasification reactor. The process heat was provided by partial oxidation reactions with oxygen, water, and carbon dioxide (Figure 8).

Figure 8: 2-Inch Pulse Detonation Generates Superheated Products

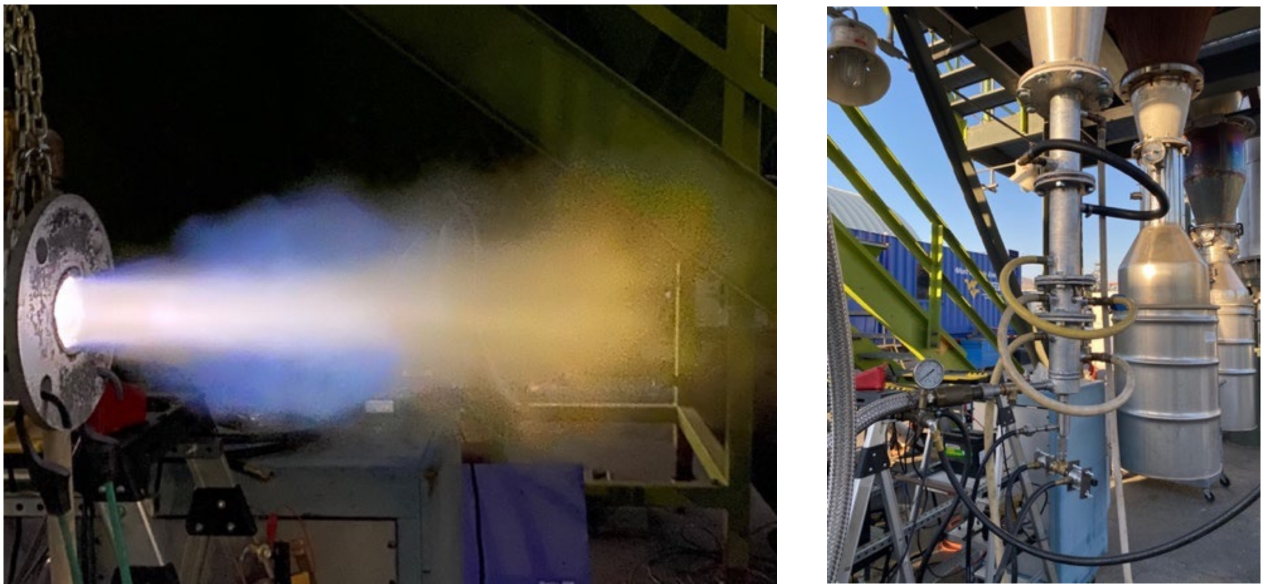


Photo Credit: Taylor Energy

California has a need for community-scale biomass-to-power generation. Inefficient Rankine steam-cycle systems, or small-scale biomass gasification equipment integrated with engine-generators, are the only offerings for thermochemical biomass-to-energy conversions. There are no cost-effective, high-efficiency commercial offerings for the size range of 3 megawatts electrical (MWe) to 30 MWe for biomass-sourced community-scale power generation.

With California Energy Commission (CEC) funding, Taylor Energy advanced state-of-the-art biomass gasification by applying a process intensification method that uses pulse-detonation power to increase heat and mass transfer between gases and solids.

The jet spouted bed reactor configuration demonstrated the ability to input high-power shock-waves, expressed as cyclic compression waves (sounds), improving the mixing of gas and solids. Successful results could lead to technological breakthroughs that overcome barriers to achieving California's statutory energy goals by advancing a low-cost means to convert woody biomass into electricity, both efficiently and with a wider operating range, to achieve 100 percent dynamic power generation.

CHAPTER 2:
Project Objectives and Approach

Objectives

The objective of this project was to perform pilot-scale testing of biomass gasification methods, comparing a baseload power generation method that relies on continuous production of syngas with two other flexible power generation methods that rely on production of intermediate liquids stored and used for flexible power generation. To achieve the project goals, the team evaluated three methods for electric power generation:

- **Path-1:** Clean fuel-gas production used for baseload power generation, using a solid oxide fuel cell or internal combustion (IC) engine.
- **Path-2:** Converting syngas into hydrogen intended for pipeline blending and storage for flexible power generation.
- **Path-3:** Direct production of crude bio-liquids for storage intended to fuel a slow-speed engine used for flexible power generation.

After selecting the optimum method for further development of the three paths, the project team obtained 300 hours of pilot-scale operating data. The full 500-hour objective was not met due to the Covid-19 pandemic and closure of the site facility by the University of California, Riverside (UCR) for six months.

Approach

Taylor Energy's existing gasification test facility at UCR was modified to perform the pilot-scale testing. The existing gasification equipment is called a process development unit, which uses a modular design easy to modify and use to test different operating methods. The biomass gasification process development unit was designed and constructed to test advanced thermal gasification methods.

Unique to Taylor Energy's gasification equipment is the use of pulse detonation power (in place of a traditional fluidized bed gas distributor) to generate spouted bed gas momentum in the form of sub-sonic compression waves. These waves flow through the gasification process, moving faster than the gases and solids, intensifying the chemical reactions.

Tests were performed to evaluate Path 1, Path 2, and Path 3. All employed pulse detonation power. Some information on this method is therefore included in the approach (see Appendix A for more detail).

Path 1: Clean Fuel-Gas Production Used for Baseload Power Generation, Using a Solid Oxide Fuel Cell or Internal Combustion (IC) Engine

In this path, the research team focused on biomass-to-syngas, optimizing the system to produce fuel-gases for baseload electric power generation path using either a fuel cell or dual-fuel engine/generator. The concept was based on the quick-start capability of a biomass gasifier when intensified with pulse-detonation power; the gasification system can begin producing fuel gases within about 10 minutes from initial startup.

The potential for 15-minute startup times for an integrated gasifier/dual-fuel engine led the research team to evaluate this simple-cycle approach, which can qualify as a flexible electric power source if the gasifier is able to deliver fuel gases when the engine is warmed and ready for full power output (which requires about 15 minutes). The gasification reactor would not reach its equilibrium operating temperature for several hours, and consequently the initial thermal conversion efficiency would be relatively low but would gradually increase. The quality of fuel gases produced during initial start-up is therefore suitable for successful dual-fuel engine operation, with certain limitations discussed in this report.

The research team selected and tested a 3406-CAT engine/generator with 14:1 compression ratio, trimmed for dual-fuel operation (Figure 9).

Figure 9: 3406-CAT Engine Generator Operating in Dual-Fuel Mode

Photo Credit: Taylor Energy

The specific approaches used to evaluate base-load power production follow.

- Evaluate Path 1 by operating the biomass pilot plant continuously for six hours with woody biomass input of 3 pounds per minute (1.3 MMBtu per hour with energy content of 7,000 Btu per pound), with energy output of 0.780 MMBtu per hour, demonstrating a 60 percent net conversion efficiency of feed into fuel gases as the energy output.
- Evaluate Path 1 by operating the pilot plant continuously for six hours with woody biomass input of 3 pounds per minute (1.3 MMBtu per hour with energy content of 7,000 Btu per pound), using oxygen-enriched air to 33 percent O_2, with energy output of 0.780 MMBtu per hour, demonstrating a 60 percent net conversion efficiency of feed into syngas as the energy output.

Path 2: Converting Syngas Into Hydrogen Intended for Pipeline Blending and Storage for Flexible Power Generation

The second method tested was a biomass-to-syngas approach intended for production of a compressed gas used for energy storage. The initial objective for this task was to test a Fischer-Tropsch catalytic synthesis skid designed to produce hydrocarbon liquids and methane gas. However, the Fischer-Tropsch skid offered by Ceramatec, Inc., was not available for testing within the time frame required to perform the project tasks. In consultation with the Energy Commission agreement manager, the project's Path 2 approach was modified from using syngas (to make Fischer-Tropsch) to using syngas to make hydrogen intended for pipeline blending and storage in existing utility pipelines, salt caverns, or depleted gas wells selected for pressurized hydrogen gas storage. Both the United States Department of Energy and the state of California have identified hydrogen as a clean fuel.

The specific approach used to evaluate a biomass-to-syngas path is summarized:

- Evaluate Path 2 by operating the pilot plant continuously for six hours with woody biomass input of 3 pounds per minute (1.3 MMBtu per hour with energy content of 7,000 BTU per pound), using oxygen-enriched air to 33 percent O_2, with energy output of 0.780 MMBtu per hour, demonstrating a 60 percent net conversion efficiency of feed into syngas as the energy output.

Path 3: Direct Production of Crude Bio-Liquids for Storage Intended to Fuel a Slow-Speed Engine Used for Flexible Power Generation

Taylor Energy's gasification test facility at UCR was modified to perform the pilot-scale testing for bio-liquids production and biocrude by employing fuel-gas recycle, which was used to supply hydrogen-rich fuel gases to the pyrolysis zone, thereby increasing the bio-liquid's quality (Figure 10).

Figure 10: Fuel-Gas Recycle Duct/Blower Used to Increase Bio-Liquids

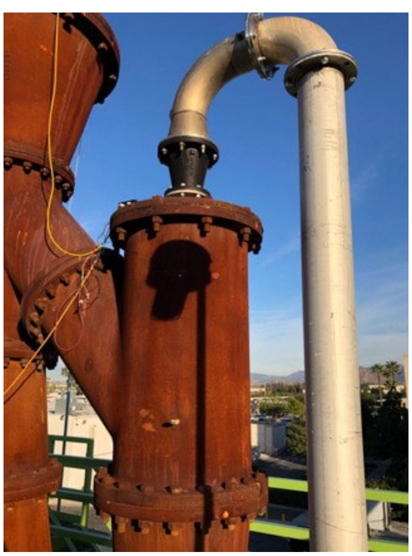


Photo Credit: Taylor Energy

As part of this path, the project team designed, constructed, and tested a moving-bed granular filter, which is a state-of-the-art moving-bed device that produces hot-filtered bio-liquids largely free from both particulate minerals and fine carbon char (Figure 11).

Figure 11: Moving-Bed Granular Filter Draft Tube Design and Operation

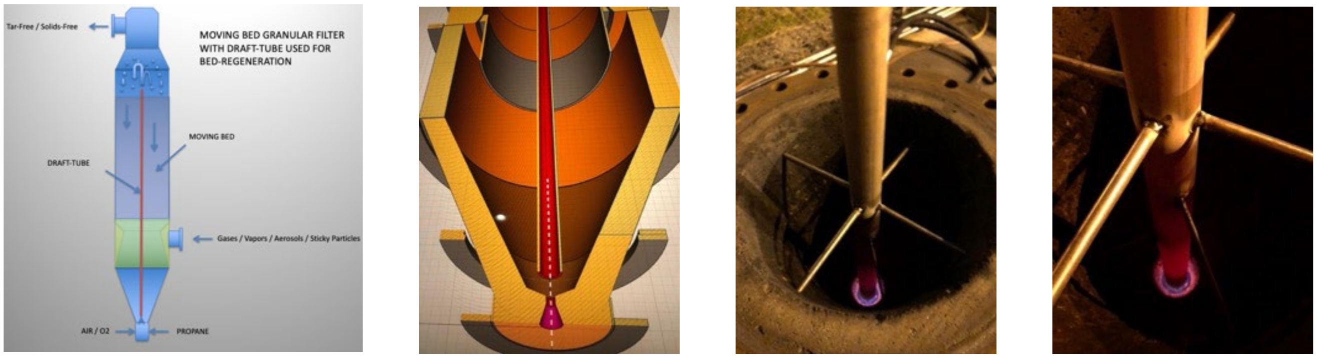


Photo Credit: Taylor Energy

Figure 12 shows the cooling and condensing system used to recover biocrude liquids; an air/water evaporative cooling system provided cooling water through a tube and shell heat-exchanger designed and constructed by Taylor Energy to condense hot pyrolysis gases recovered as biocrude liquids.

Figure 12: Bio-Crude Liquids Produced Using Biomass Gasification Methods

Photo Credit: Taylor Energy

The specific approach used for evaluating of bio-liquids production follows.

- Operate the pilot plant continuously for 4 hours using a moving-bed granular filter (MBGF) with woody biomass input of 3 pounds per minute (1.3 MMBtu per hour with energy content of 7,000 Btu per pound). The MBGF was considered a key component that would be proven first before preliminary testing of the biocrude liquids production path.
- Evaluate Path 3 by operating the pilot plant continuously for 6 hours with woody biomass input of 3 pounds per minute (1.3 MMBtu per hour with energy content of

7,000 Btu per pound), with energy output of 0.780 MMBtu per hour, demonstrating a 60 percent (by weight) net conversion efficiency of feed into bio-crude liquids as the energy output.

Selection and Testing of an Optimum Process Path

- Evaluate the preliminary operations and test data to select the optimum process configuration, and then operate an optimum thermo-catalytic gasification method for 500 hours.

The research team, with input from the technical advisory committee (TAC), selected Path 2 (biomass conversion to syngas for hydrogen production) as the most advantageous path for extended testing, and:

- Performed heat and mass balance by semi-empirical method and semi-empirical ASPEN process model development.
- Estimated the carbon footprint for the process and the products by performing a life-cycle analysis of greenhouse gases, regulated emissions, and energy use in transportation.

Technical Advisory Committee

Several experts served as standing TAC members and provided both diverse skillsets and technical and business perspectives, including:

- Samuel Young, Captain, U.S. Navy, retired
- Lyman Frost, CEO of OxEon Energy, LLC
- Nicole Davis, assistant director, Center for Environmental Research and Technology, UCR
- Harold Burnham, CEO, Advisory Energy Consulting, Inc.
- Dr. Robert Dibble, professor of chemical engineering, U.C. Berkeley, retired

The TAC assembled on March 12, 2020, to review progress on the project tasks. A 15-page summary document describing the work accomplished was provided, and TAC members were asked for feedback, especially to assess future deployment. TAC members asked questions about paths to hydrogen production and encouraged the development of gasification methods that enable low-cost hydrogen production. TAC members also concluded that the best approach for flexible power generation in California would employ hydrogen-rich syngas formation intended for production of pipeline-quality hydrogen. To complete the evaluation of the hydrogen alternative, the team agreed to test an optimized biomass-to-hydrogen process.

The technical approach endorsed by TAC members was thermal-catalytic processing of woody biomass: up to 3-weight percent potassium carbonate was added to a carbon-char fraction, which was re-injected into the gasification reactor to serve as a low-cost catalyst enabling thermal-catalytic cracking of biomass-derived volatiles into syngas composed primarily of hydrogen and carbon oxides.

The technical approach using potassium-loaded carbon-char as a gasification catalyst had been developed and demonstrated at bench-scale by a Japanese research team. This approach is promising for conversion of biomass and/or waste-plastics-derived volatiles into syngas when compared with traditional costly catalytic conversion methods because traditional catalysts are quickly deactivated by contaminants (heteroatoms).

The TAC members' overall vision was to use biomass and waste resources as the energy feed to produce renewable hydrogen gas (or liquified hydrogen) at multiple locations, each with a 500 tons per day processing capacity, the plant size permitted in California for recycling facilities.

Furthermore, interest was expressed in pursuing a novel low-cost power generation cycle optimized for the use of hydrogen or hydrogen-rich fuel-gases. The design for the subject Rotary Detonation Power Cycle is discussed in the results. Taylor Energy has proposed to demonstrate this highly innovative flexible power cycle, which would use pipeline gas to supply dynamic power on demand.

CHAPTER 3: Project Results

Path 1: Clean Fuel-Gas Production Used for Baseload Power Generation, Using a Solid Oxide Fuel Cell or Internal Combustion Engine

The team tested a biomass gasification method optimized to produce hydrogen-rich fuel gas for a baseload electric power in a dual-fuel engine/generator, an objective that was achieved. Ultimately, the project team accumulated 300 hours of baseload operation testing autothermal gasification of biomass with air while testing, developing, or improving various subsystems.

Startup testing of improved pulse detonation embodiments were integrated with the biomass gasification system using mid-range temperatures between 1,382°F and 1,742°F (750°C and 950°C), using air-blown gasification for fuel-gas production. The research team tested the produced fuel gas in a 3406-CAT engine/generator with a 14:1 compression ratio, trimmed for dual-fuel operation (Figure 13).

Figure 13: 3406-CAT Engine/Generator Used for Operational Testing

Photo Credit: Taylor Energy

To overcome the tendency for premature deflagrations resulting in cylinder knock, the team made the gas lean using excess air to minimize premature ignition and consequent engine knock. Efficient operation was limited to 600 revolutions per minute (rpm), and the 3406-CAT engine performance was derated compared with that of biodiesel at 1500 rpm.

The baseload biomass gasification power generation cycle consisted of air-blown production of hydrogen-rich fuel gases used in a dual-fuel engine. The 4-stroke Caterpillar test engine was operated using a dual-fuel approach employing biodiesel for ignition and low-idle operation. Gaseous fuel was aspirated into the turbocharger intake to increase power above idle. A resistance-type electric load bank was used to measure and consume the electric power generated during biomass-derived fuel-gas testing.

However, the hydrogen-rich fuel-gases also contained about 5 percent by volume (vol%) unsaturated gases, primarily including acetylene, ethylene, and propylene, all of which exhibit a strong tendency to auto-ignite in a high-compression engine cycle so would be characterized as very low octane. Biomass-derived fuel gases are an ideal fuel for gas turbines (>20 MWe) but are not well suited for reciprocating compression-ignition (diesel) engines that operate with high efficiency in all sizes.

The baseload biomass gasification process operated within the temperature range between 1,382°F and 1,742°F (750°C and 950°C) and was relatively easy to operate when compared to bio-crude production (Figure 14).

Figure 14: Engine Generator Connected to Baseload Biomass Gasification System

Photo Credit: Taylor Energy

Engine operation was limited to 600 rpm, employing the slowest combustion cycle for that engine, using a high moisture and lean operation to suppress pre-ignitions resulting from light olefin that are highly reactive compared to methane, for example, causing pre-ignitions during the compression stroke.

Operating a 3406-CAT engine in dual-fuel mode was not considered successful when using biomass-derived fuel-gases aspirated into the air intake (with or without turbocharging) because the 14:1 compression ratio of the 3406-CAT engine is too high for a gaseous fuel with 5 vol% unsaturated gases that include acetylene and ethylene or that are prone to pre-ignition during the compression stroke. Based on the gas composition, a compression ratio of 8.5:1 was recommended by Wakasha for use with their lean-burn engines.

Reciprocating engines are still the most cost-effective power generation method for power generation of less than 30 MWe. At greater than 30 MWe, combined-cycle gas-turbine/steam-turbine plants are more efficient. This low-octane fuel-gas problem is solved by other engine manufacturers by using a direct injection method where fuel-gases are injected directly into the cylinder at high pressure.

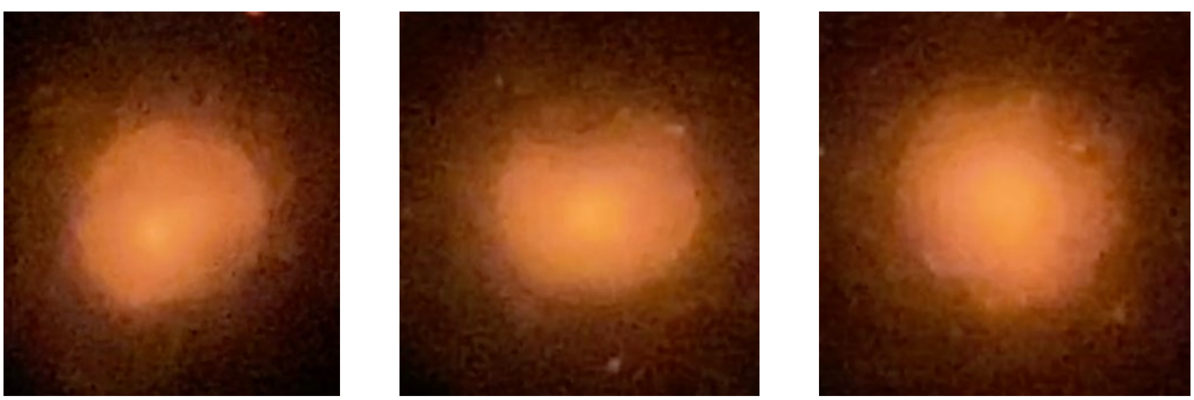
Initially, the project team performed the engine tests with the intent of proving that operation at medium speed (600 rpm to 750 rpm) allows enough combustion time within the cylinder (the duration of the crank-angle) to complete the oxidation process when the input air and fuel-gas are saturated with moisture to suppress the tendency to pre-ignition during compression. Test objectives were achieved; however, a path forward using the 3406-CAT or similar medium-speed engines requires the use of direct in-cylinder injection, which solves all pre-ignition problems. Therefore, the project team decided not to select Path 1 for more testing.

Path 2: Converting Syngas Into Hydrogen Intended for Pipeline Blending and Storage for Flexible Power Generation

After selecting this path as the optimum method, the team operated the system successfully for 300 hours using low-pressure blower-air in the range of 1.5 pounds per square inch gauge (psig) to 3.5 psig for biomass gasification, which is an order of magnitude lower than traditional biomass gasification systems. During the testing campaign, the Covid-19 pandemic necessitated closure of the site facility, preventing additional hours of testing.

The technical results demonstrated successful gasification of biomass in a jet spouted bed reactor, shown in Figure 15, and further identified synergistic benefits using pulse-detonation methods likely to enable the economical production of hydrogen-rich fuel gases. The synergistic benefits attributed to pulse-detonation methods in gasification are intensified chemical reactions. (For more extensive explanations, see Appendix A).

Figure 15: First Images of Pulse Detonation Burner



Driving Jet Spouted Bed

Photo Credit: Taylor Energy

The gasification system was successfully optimized to produce hydrogen-rich syngas (Figure 16) suited for recovery of pipeline-quality hydrogen for energy storage as a compressed gas (in salt-caverns, depleted gas wells, or renewable-gas pipelines), or liquefied for transportation or used as a cryogenic liquid. The hydrogen produced through gasification, with a partial oxidation environment followed by carbon monoxide shift reaction with the injection of water, has been modeled by researchers at Jadavpur University, India (Bhattacharya, 2012).

Figure 16: First Images of Biomass Derived Syngas Using Pulse Detonations

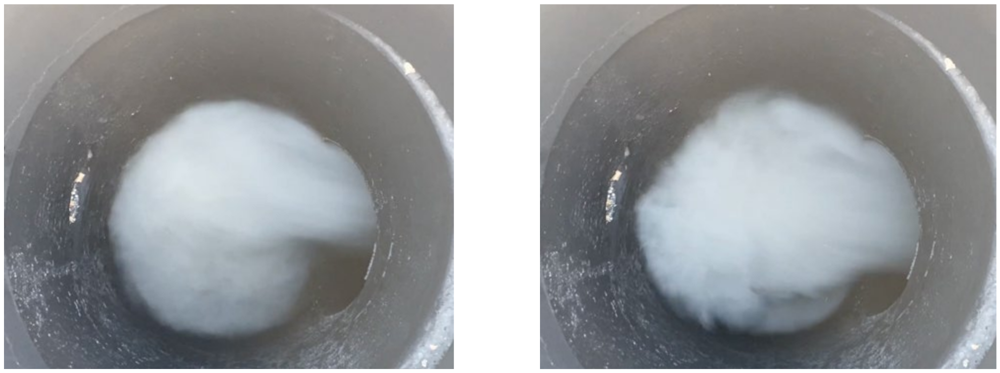
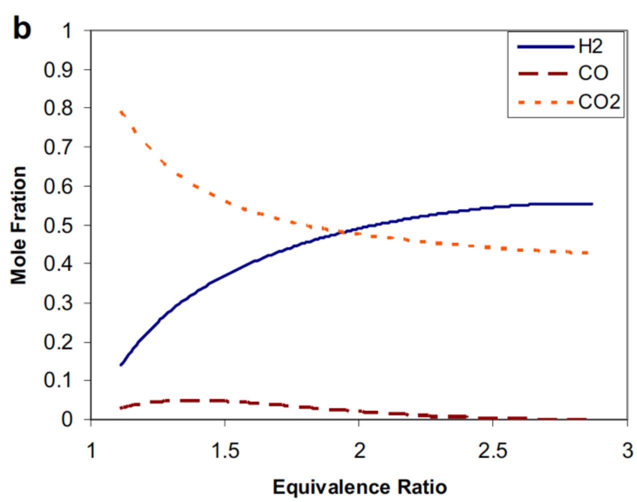


Photo Credit: Taylor Energy

The project team used an oxygen enrichment approach (adding gaseous oxygen to the blower air input) to increase the hydrogen yield. At atmospheric pressure, the optimum Equivalence Ratio (ER) was found to be between 2.0 and 2.5 for gasification temperatures of 1,382°F and 1,742°F (750°C and 950°C) to obtain the optimal hydrogen mole fraction. In this case, the objective was to operate with an ER of about 2.5. The biomass gasification tests using O_2 enrichment clarified the need to minimize the nitrogen (N_2) content, and the need to carefully control air infiltration to prevent the ER from falling below about 2.5.

The project team evaluated the effects of operating conditions such as the gasifier equivalence ratio and the shift reactor condition on the hydrogen concentration in the product gas from biomass. The process can generate 1 kilogram (kg) hydrogen per 10 kg of biomass, resulting in a cold gas efficiency of 65.4 percent (Bhattacharya, 2012). The graph following indicates that (before performing the waste-gas shift, $CO \rightarrow H_2$), the hydrogen content can reach 60 percent mole fraction operating at an equivalence ratio above 2.5 (Figure 17).

Figure 17: Mole Fraction Versus Equivalence Ratio



Source: Bhattacharya, 2012

The maximum conversion efficiency from biomass to hydrogen is about 53 percent. On the other hand, when the project team integrated the high-pressure gasification system with a water gas shift and used pressure swing adsorption (PSA) methods to produce hydrogen, the net conversion efficiency is 65 percent, producing significantly more hydrogen, as supported by studies (Ishaq, 2019).

At present, life cycle analysis projections for gasification-based biomass-to-hydrogen systems (without carbon or carbon dioxide [CO_2] capture) range from about 5 grams carbon dioxide equivalent per megajoule (gCO_2eq/MJ) to about 100 gCO_2eq/MJ, depending on complex factors. For example, some studies model the use of grid-mix electric power to operate biomass gasification plants, where plants consume power for both cryogenic O_2 production and for PSA purification to recover high-purity hydrogen (Susmozas, 2015). In the project team's case, the parasitic electric power requirements are to be generated from residual biogases after the PSA separation of hydrogen.

The result envisions the use of woody biomass that is collected, dried, and transformed into high-purity hydrogen for pipeline distribution through existing utility pipeline systems, and additionally for production of carbon-negative industrial fuels for both heat and power. Life cycle analysis for biomass-to-hydrogen via gasification presently range from negative-200-gCO_2eq/MJ to positive-200-gCO_2eq/MJ, depending on how biomass is sourced and mixed grid electric use (Salkuyeh et al., 2017). A higher-level analysis would add incremental syngas use for production of cryogenic liquid hydrogen production, a high-value transportable product.

Path 3: Direct Production of Crude Bio-Liquids for Storage Intended to Fuel a Slow-Speed Engine Used for Flexible Power Generation

The researchers were able to produce relatively clear bio-liquids using two hot-cyclones operating in series to separate entrained solids. The bio-liquids contained 3-percent fine matter that was removed and recycled to the gasifier. The fines were agglomerated with a small tar fraction (using a cyclonic spinning action), then skimmed off the surface of the denser biocrude liquids (which includes 20 percent water) after several days of flotation time.

The bio-crude liquids can serve as a storable liquid, although 30 days is approaching the maximum storage period because the viscosity increases with time through polymerization reactions that cross-link the hydrocarbon chains. The length of time available for storage is dependent upon water content: the lower the water content, the faster the viscosity increases. Minerals present in carbon char also tend to catalyze cross-linking reactions, causing bio-crude viscosity to increase more rapidly than completely clear bio-liquids. The addition of 10 percent methanol enables bio-crude storage of up to 12 months, with only a modest increase in viscosity.

The research team was also successful in producing a pump-able storable biocrude liquid, processing 10 tons of woody-biomass pellets and generating a bio-crude liquid fraction that included 25 percent water, rich fuel gases, and carbon char. Bio-crude liquids were stored in four 275-gallon portable liquid storage containers.

Bio-crude was not tested in an engine generator since industrial gas turbines (>20 MWe) already burn heavy fuel oils. Significant efforts were expended in the selection of an optimum

IC engine and 2-stroke power cycle with 3 MWe output, which would likely operate successfully and economically using a low-cost bio-crude product.

Considering the properties of bio-crude, the opposed-piston engine (made by Fairbanks-Morse and others) is an engine type proposed for use with difficult liquid fuels. This 2-stroke engine-generator selected for evaluation is considered the most robust and reliable of all engine types, shown in Figure 18. This 2-stroke design uses opposed pistons that uncover the intake and exhaust valves at bottom dead-center, eliminating the need for valves and valve trains, thereby cutting in half the number of moving parts required for power generation.

Figure 18: Opposed-Piston Engine

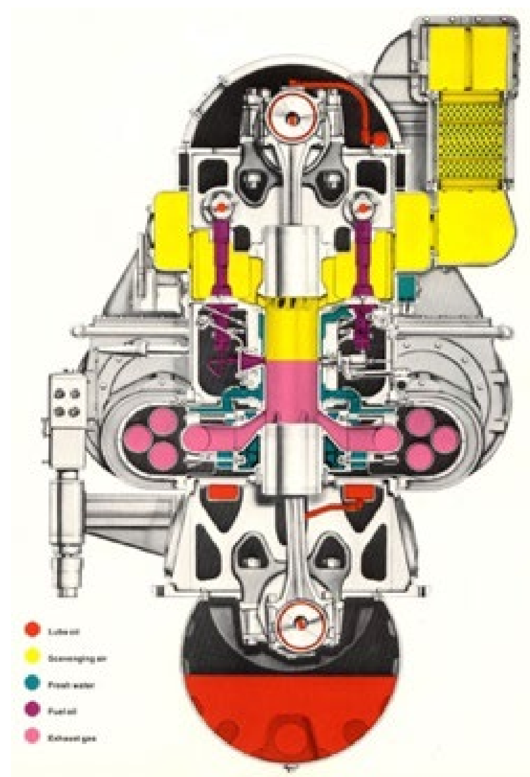


Photo Credit: Fairbanks Morse

The objective was to accumulate a significant quantity of bio-crude (from relatively small inter-mittent pilot-scale operations) for testing a bio-crude product using a commercial scale engine, (an opposed piston engine owned by Farabee Mechanical). Bio-crude tests and air emissions tests were planned as part of a test campaign in Hickman, Nebraska, in the heart of the Corn Belt, with co-founding provided by Farabee Mechanical.

However, this objective was partially achieved: a series of 21 tests was performed, operating for approximately 6 hours during each test session. The equivalence ratio was about 3.0 for gasification temperatures in the range of 977°F to 1,157°F (525°C to 625°C), which resulted in the formation of bio-crude liquids collected and stored from multiple runs, accumulating 1,000 gallons of bio-crude, which were then collected in 250-gallon quantities for truck transport to Farabee Mechanical: a company specializing in opposed-piston (OP) engine acquisition, sales, parts, maintenance, and testing located in Hickman, Nebraska (Farabee Mechanical, n.d.)

Representatives from MAN Diesel & Turbo (MAN) in Copenhagen, Denmark, agreed to perform the fuel analysis on multiple 2-liter samples of "biomass pyrolysis oil." A quotation for the testing of approximately $10,000 per sample was received, with the understanding that MAN was potentially interested in biocrude liquids as a renewable fuel appropriate for their large and medium low-speed engines. MAN also recommended testing 10 representative biocrude liquid samples, each two liters.

However, when MBGF failed to operate, funds for biocrude testing were not committed to MAN. The biocrude liquid product was expected to exhibit a high-acid number along with other less desirable fuel properties. This is in comparison to hot-filtered biocrude liquid, which has been proven by others to have superior fuel properties compared with biocrude liquids produced by filtering condensed liquids.

Nevertheless, the biocrude liquid product was screened and filtered as a condensed liquid to remove solids in preparation for engine performance and emissions testing in an OP engine provided by Farabee Mechanical. These engines are proven to use the most difficult fuels, including heavy heating oils.

The research team produced biocrude liquids, which were stored in 275-gallon portable liquid storage containers as shown in Figure 19.

Figure 19: Production and Storage of Biocrude Liquids

Photo Credit: Taylor Energy

The team concluded that bio-crude is easily produced using Taylor Energy's biomass gasification technology at medium-temperatures using a simple jet spouted bed gasifier. Biomass was converted into a medium viscosity bio-crude liquid that was successfully pumped, stored, and transported. However, bio-crude liquid is a difficult alternative because of its narrow operating temperature range, deviations from which caused heavy bio-tar fraction that coated internal pipe surfaces with sticky polymers that solidified.

Rapid heating of biomass requires small feed particle sizes (1 millimeter) for uniform particle heating, for which fast-fluidization methods provide efficient heat and mass transfer. Fluidized bed pyrolysis processes utilize well-established technologies and have been scaled up to several hundred tons per day. Taylor Energy tested a traditional type of oxidative pyrolysis methodology. According to Robert Brown, "Recent research has shown that fast pyrolyzers can also be operated auto thermally by admitting air at equivalence ratios of 0.06 to 0.12, accompanied by dramatic intensification of pyrolysis while suffering only minor losses in oil yield. The possibility of autothermal operation of fast pyrolyzers received little attention until recently, probably because it seemed likely that oxygen would preferentially oxidize the vapors intended for bio-oil production. In fact, in a fluidized bed reactor, the oxygen preferentially oxidizes char with only a small penalty on bio-oil yield. Not only does autothermal pyrolysis simplify reactor design and operation, but it also achieves several-fold process intensification in reactor throughput by overcoming the heat transfer bottleneck of conventional (non-oxidative) pyrolysis." (Brown, 2021).

Analysis of the carbon cycle for biomass-to-hydrogen for the subject technology is based on previous studies performed by UCR and published in reports (Taylor & Raju, 2020). For example, the GHG emissions for baseline diesel-fuel production were estimated to be 29.8 kg CO_2e/MMBtu. Diesel used for heavy vehicles is assumed to be replaced by hydrogen fuel cell vehicles. The project team estimated that the approximate GHG emissions reductions for hydrogen produced from biomass via gasification are about 69.9 kg CO_2e/MMBtu-H_2.

Lesson Learned

This lesson learned section is applicable to all pathways that the project team evaluated. The primary advantage that the project team expected to provide is a thermal conversion system design (initially with 20 to 40 tons per day capacity, and ultimately with 500 to 1000 tons per day capacity) that offers a fraction of installed cost compared to commercialized gasification systems that operate in the 500 to 1000 tons per day range. This objective can be achieved by exploiting the fundamentals proven in this project:

- Near-atmospheric pressure operation of the gasifier assures a low-cost reactor.
- Pulse detonation system controls are integral with the gasification reactor control.
- A jet spouted bed configuration is used, but without the bed material.
- Pulse detonation power is used to input superheated oxygen mixed with superheated steam at high velocity, propelled by supersonic shockwaves that build some internal head pressure along with intense mixing and ablative action caused by compression waves that pass through the gasification reactor.

Regarding the ignition system used to achieve cyclic detonations, the research team used an after-market automotive system. There are several well-developed spark-ignition control systems used in racing engines of all types. Much of this equipment is robust and well suited for industrial service. For example, the team used the same iridium sparkplugs used in the principal investigator's personal utility vehicle that has traveled 300,000 miles. Automotive spark ignition systems provide a cost-effective technology that will enable successful pulse-detonation systems. The research team tested two other costly high-energy ignition systems and found auto ignition to be the most reliable.

Regarding materials of construction for the detonation-burners, while aluminum was used extensively in early prototypes because it is easy to work and the heat transfer is high, the research team tested carbon steel, stainless steel, highly conductive refractory, copper, and aluminum. A critical factor in the successful operation was that no internal surfaces, corners, or edges, became hot enough to radiate. Any spot that glowed red within the detonation chamber would void the ignition sequence because hot spots became a continuous primary ignition source. Eliminating hot spots was mostly a matter of selecting materials with suitable heat-transfer capabilities. The internal architecture of the mixing, ignition, detonation, and expansion chambers also affected the formation of hot spots, but the materials of construction were critical. Copper would be the obvious choice; however, copper was costly to purchase, expensive to machine due to its density and friction, and difficult to weld because of high heat losses.

Regarding fail-safe engineering of the oxygen/propane mixing chamber, inlets were designed for choked-flow operation (sonic flow) to limit the maximum oxygen input. For example, while testing a detonation burner in gasification service, the research team experienced a failure of the liquid-oxygen control valve, which instantly boosted the oxygen pressure from 7 psig up to 70 psig. Because oxygen flow into the mixing chamber was choked at about 10 psig, the impact on the detonation-burner performance was minimal. Engineering of the fail-safe gas-flow restrictions was critical in managing the safe operation of the oxygen/methane detonation system.

Ultimately, the team operated using a fifth-generation oxygen/propane detonation burner that, until this last generation, required a great deal of trial and error to achieve successful detonations that were repeatable and controllable over a meaningful range. Four advanced technologies were employed to control the pulse-detonation burners:

- Digital delay generators provided the control sequence (commercial instruments).
- High-speed electromagnetic solenoid valves (commercial gas-direct-injection).
- Peak and hold drivers used to control fuel injectors (peak and hold instruments).
- Integrated spark-electrode/spark-ignition system (automotive racing electronics).

Path 1

- Results from evaluating a biomass-to-biopower baseload path informs us that existing gasification systems operating continuously to produce baseload power can use biomass both efficiently and economically.
- Additionally, advanced gasification power cycles, typically operating 24-7 for baseload generation, can co-produce high-purity hydrogen for blending hydrogen into existing gas pipelines to enable gas storage for subsequent flexible biopower.

Path 2

- Operating the biomass gasification system with parameters identified during project testing (biomass oxygen equivalence ratio of 2.5 with a steam to carbon ratio of 3:1), will generate hydrogen-rich syngas.
- Soon 99 percent high-purity hydrogen can be separated from low partial pressure hydrogen sources, including fuel-gases derived from biomass gasification with 50 vol% H_2.
- Based on utility pipelines becoming sources of fuel gases with hydrogen content, a low-cost peaking cycle is proposed using advanced rotary detonations power.
- The concept for a novel rotary detonation power cycle intended for flexible power generation is reported in Appendix C, Rotary Detonation Power Cycle.

Path 3

- Oxidative pyrolysis tests have been performed using Ponderosa pinewood pellets in a pilot-scale test facility at 932°F to 1,292°F (500°C to 700°C), with equivalence ratios from 0.09 to 0.25.
- The results have been compared with those reported in the literature for in pyrolysis in a dual fluid bed using fast-fluidization methods; bio-crude liquid yield from oxidative pyrolysis (autothermal pyrolysis) is within about 1 percent of indirectly heated flash pyrolysis systems.
- The bio-oil yield in the conical spouted bed reactor is very high because of this reactor's features that maximize liquid yields, namely, high heat and mass transfer rates, low volatile residence time, and continuous removal of char from the bed.

CHAPTER 4: Technology/Knowledge/Market Activities

In accordance with technology transfer tasks, Taylor Energy prepared a video that summarizes project objectives and progress reports. This video, as well as information about Taylor Energy technology, potential applications for biomass-to-hydrogen, and recent project advancements, is available to the public at https://taylorenergy.org/.

Taylor Energy actively shared the technology in a formal presentation to a colloquium sponsored by the UCR Center for Renewable Gas, which was attended by renewable energy stakeholders within both government and industry. The colloquium focused on thermochemical renewable natural gas production using renewable feedstock, hydrogen production through water electrolysis using renewable electricity, methanation, and systems-level techno-economic and life cycle analyses to evaluate and optimize technology pathways.

In January 2021, Taylor and Raju presented a technology and program overview to representatives of CEMEX USA, communicating with executives based in Houston, Texas, regarding the development and demonstration of the subject biomass gasification technology and its potential integration with cement production in California, specifically considering the Victorville plant as a possible venue for a renewable clean-fuel demonstration project. No EPIC funds were used for travel to Texas.

In April 2021, Taylor presented a technology overview to representatives from the UCR Office of Sustainability who are responsible for achieving carbon neutrality. The focus of the technology discussion was comparing hydrogen to renewable methane regarding the production, application, and testing of renewable hydrogen distribution and potential for adoption university wide.

In August 2021, Taylor and Raju presented a technology overview to representatives from the Port of Long Beach under the direction of Heather Tomley, managing director of Planning and Environmental Affairs, who guides the Port's environmental, transportation, and master land use planning divisions. The details regarding current project research and future deployments potentials were discussed.

Taylor Energy's technical advisory committee concluded that the subject biomass-to-hydrogen technology should be developed at demonstration scale before firm commercial relationships are established that will advance the technology to full commercial deployment. Nevertheless, the technology has been actively shared with a potential commercial partner, Sims Ltd.

The project has received a letter of interest from the Chief Technology Officer at Sims Limited, whose business divisions include: (1) Sims Metal, a leading metal recycler that buys, processes, and sells ferrous and non-ferrous metal to manufacturers in 30 countries; (2) Sims Municipal Recycling, a processor and marketer of more than 600,000 tonnes of municipal curbside material annually for NYC, Palm Beach County, and portions of New Jersey, Long Island and Chicago; and (3) Sims Resource Renewal, a leading circular business that operates in line with the waste hierarchy by removing all recoverable material from auto shredder residue before it is used in the energy recovery process.

In September of 2021, Taylor and Raju presented a technology overview at the Los Angeles County Department of Public Works, which has provided a letter expressing interest in biomass gasification technologies. The county supports development of conversion facilities capable of managing the county's green waste by providing technical assistance with permitting, finance, outreach, market research, and feasibility studies to facilitate the development of biomass conversion facilities (Figure 20).

Figure 20: Biomass-to-Hydrogen Technology Proposed for California

Photo Credit: Kosti Shirvanian

CHAPTER 5: Conclusions/Recommendations

The research team, along with the TAC, identified Path 2 as the optimal path for biomass conversion to hydrogen pipeline distribution through existing utility systems. The life-cycle analysis for Path 2 biomass-to-hydrogen via gasification to syngas presently ranges from negative-200-gCO_2eq/MJ to positive-200-gCO_2eq/MJ, depending on how biomass is sourced for mixed-grid electric use. The team envisions the use of woody biomass transformed into high-purity hydrogen using this path. The team expects to show that 1 ton of woody-biomass produces about 21,000 standard cubic feet of renewable hydrogen. California has about 76,000 tons per day of biomass available for conversion into renewable gases including forest residues, agricultural residues, and separated biomass. Based on an average energy content of 6,000 Btu per pound, the energy content is about 912,000 MMBtu per day. The state's biomass and organic waste residues can be used to build a recycling industry that employs thousands of people by advancing economically viable biomass conversion methods.

A Path 2 project would use oxidizing agents O_2, H_2O, and CO_2. Operating at 1,742°F (950°C), the syngas compositions can be accurately estimated based on equilibrium outputs. A typical syngas is composed of 60 to 65 percent CO, 24 to 27 percent H_2, 2 to 4 percent CO_2, and 2 to 5 percent H_2O (plus N_2 and other minor species). High-purity hydrogen with 99 percent H_2 can be recovered using commercially available PSA technology. Both the ease of hydrogen production (via biomass gasification) and the ease of hydrogen separation (via PSA and proton-pump type electrochemical membranes) are the primary factors that favor Path 2. Due to the Covid-19 pandemic, and the closure of the site facility by the University of California, the team collected 300 hours of testing for Path 2 instead of 500 hours.

The Path 2 simplicity of a biomass-to-hydrogen process with the fewest working parts is the most desirable methodology predicated on the availability of pipeline blending contracts.

A Path 1 baseload approach could make economic sense in today's market where there is a continuous need for both heat and power. For example, both cement and glass plants operate 24-7 and could be supplied via a continuous biomass gasification process, which could include a topping-cycle used to recover high purity hydrogen employed for pipeline blending and subsequent flexible power.

A Path 3 could be deployed in more complex supply-chain scenarios where an important part of the solution would be the de-centralized pre-treatment of biomass to obtain an intermediate energy carrier of high energy density, which can be transported economically over long distances to supply an industrial plant of reasonable size for synthetic fuel production.

Path 1, Path 2, and Path 3 all appear technically feasible, although each path would be favored under highly varied conditions to benefit ratepayers. The biomass-to-biofuels market is presently limited by high-cost equipment systems, high operating and maintenance costs, and unexpected system outages, typically resulting in poor online availability.

The TAC concluded that the subject biomass gasification technology must be successfully developed to demonstration-scale (40 tons per day) to quickly advance the technology for commercial deployment.

Allocation of CEC funds to demonstrate biomass conversion projects is highly desirable to overcome the economic barriers that otherwise prevent commercialization of advanced conversion technologies that can help California achieve multiple environmental, economic, and energy-security mandates.

Thus far, the project has set the groundwork for future near-term deployment of low-cost renewable energy sourced in California from forest residues or separated biomass, which is a low-cost energy feed that could potentially produce biofuels that are cost-competitive with fuels imported to the state through interstate pipelines.

Incidental Results

The research team evaluated a novel power cycle based on opposed impulse engines, a power production method of historic significance, from Hero's first steam engine to the Hiller Hornet, a post-WWII ramjet helicopter. This work was not included in the project's original scope. Recognizing that renewable H_2/CH_4 gas mixtures will emerge as a dominate fuel source, and the need for backup power, peak power, and flexible power, compelled the research team to consider low-cost electric power generation cycles that would use state-of-the-art CH_4/H_2-propulsion engines (using advanced detonation methods that presently operate above 20,000 Hz, continuously generating thrust at high efficiency).

Policy changes favor renewable hydrogen and renewable methane as low-carbon fuels. New electric power generation cycles become possible when hydrogen-enriched methane becomes available as the dominant pipeline fuel. The team considered the benefits of hydrogen and/or hydrogen/methane mixtures in various air-detonation power cycles. One novel electric power generation cycle using opposed detonation engines to provide impulse power is discussed in the Lessons Learned section of this report.

Significant data gaps still exist. Taylor Energy has not proven the benefits of shockwave enhanced gasification compared to traditional gasification methods. An optimum method using oxygen-steam (to produce hydrogen-rich synthesis gases) was not tested. A hydrogen method was nearing operational testing when seven months of site limitations due to COVID-19 prevented vetting of the shockwave gasification process using oxygen/steam for partial oxidation. Whereas autothermal gasification of biomass with air was successfully tested for production of fuel gases with significant H_2 and CO content while also including methane, which averaged about 5 vol%, and light olefins that likewise averaged about 5 vol%; N_2 averaged 40 to 49 vol% using air as the oxidant.

Thermal conversion of woody biomass into fuel-appropriate bio-crude liquids was proven to be technically feasible, albeit with some production difficulties. However, the market impetus to optimize existing medium-speed reciprocating engine/generator technology to support efficient use of bio-crude for flexible power production is presently replaced by a more universal interest in renewable hydrogen. Recent policy decisions favor hydrogen production (via electrolysis) as a means of storing intermittent electricity that is derived from both wind and solar power.

Consequently, the gas utility pipeline distribution system is open to limited testing of hydrogen injection, potentially including the use of hydrogen produced from renewable biomass.

The TAC identified the emerging technical potential to produce high-purity hydrogen from relatively low-quality syngas, including hydrogen recovery from low-pressure gas streams, and potentially from gas mixtures with relatively low hydrogen partial-pressure; the catalytic synthesis methods (Fischer-Tropsh and the methanation paths) require high-purity syngas and high pressure (greater than 30 atmospheres) for efficient production. Therefore, the research team elected to focus on biomass-to-syngas methods using near-atmospheric pressure thermos-catalytic partial-oxidation to enable steam-reforming of biomass, initially to form a medium-quality syngas using air or O_2-enriched air as oxidant.

CHAPTER 6: Benefits to Ratepayers

Benefits to California

Taylor Energy assumes that it will have a 1 percent market penetration within 10 years, and that other companies will likely apply the technology as well. When adopted at scale, the technology offers multiple environmental and economic benefits to California ratepayers.

Environmental Benefits

- The project team estimated that the approximate GHG emissions reduction for hydrogen produced from biomass via gasification is about 69.9 kg CO_2e/MMBtu-H_2.
- Improved energy reliability by using local energy feedstock sources and providing flexible power generation to provide backup for intermittent wind and photovoltaic resources.
- Reduced the local criteria pollutants carbon monoxide, nitrogen oxides, and particulate matter when compared to air-curtain furnaces presently used to burn forest wastes.
- Energy savings by using separated biomass as a renewable feedstock. The quantity of refuse-derived biomass feedstock available in California is approximately 76,000 tons per day, which contains energy content equal to about 912,000 MMBtus per day. Assuming a reasonable 60 percent net conversion to renewable gas means that 532 million standard cubic feet per day of renewable gas could be produced using existing waste biomass.
- Diversion of valuable waste resources intended for landfill and used instead as plentiful and low-cost renewable energy sources.
- Diminished risk of forest fires by using forest residues as feedstock.
- Ability to compress and store high-purity hydrogen in pipelines, salt caverns, and depleted gas wells for future use.

Economic Benefits

- Lower cost of California's abundant forest residue and separated biomass as low-cost energy feeds compared with gaseous fossil fuels imported to the state through interstate pipelines.
- Expected savings of $998 million per year based on California's approximate 912,000 MMBTUs of available energy per day and a savings of $3 per million BTUs using the biomass-to-hydrogen thermal conversion method based on Taylor Energy's anticipated confirmation of ongoing findings.
- Potential to lower the cost of renewable power by $32 per megawatt by providing on-demand power generation that provides back up for intermittent wind and photovoltaic resources.
- Potential to build an advanced recycling industry that employs thousands of people.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Btu	British thermal units
California ISO	California Independent System Operator
CEC	California Energy Commission
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
ER	equivalence ratio
GHG	greenhouse gas
gCO_2eq/MJ	grams carbon dioxide equivalent per megajoule
H_2	hydrogen gas
H_2O	water
HSS	highly superheated steam
Hz	hertz
IC	internal combustion
JSB	jet spouted bed
kg	kilogram
kWh	kilowatt hour
MAN	MAN Diesel & Turbo
MBGF	moving-bed granular filter
MMBtu	million British thermal units
MSW	municipal solid waste
MWe	megawatt electrical
N_2	nitrogen
O_2	oxygen
PSA	pressure swing absorption
PSIG	pounds per square inch gauge
RDB	refuse-derived biomass
RENEW LA	Recovering Energy, Natural Resources, and Economic Benefits from Waste for Los Angeles
RPM	revolutions per minute
TAC	technical advisory committee
UCR	University of California, Riverside
vol%	percent by volume

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Appendix A: Pulse Detonation Gasification of Organic Wastes

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APPENDIX A:
Pulse Detonation Gasification of Organic Wastes

In 2011, Dr. Serge M. Frolov, at the prestigious Semenov Institute of Chemical Physics in Moscow, developed a "new generation of industrial burners" based on the detonation of methane-air mixtures within a 3.7-inches diameter tube with a 10-foot run-up tube.

The possibility of controlled cyclic deflagration-to-detonation transition (DDT) within a length of 3.0-m in an open-end tube (94-mm in diameter) with a separate continuous supply of natural gas and the air was demonstrated for the first time. Based on experimental studies, a workable pulse detonation burner, a prototype of a new generation of industrial burners, was developed. It can produce a combined effect on the objects blown on with combustion products—shockwave (mechanical) and thermal (Frolov S. M., 2021).

During the performance of CEC contract EPC-14-45, "Advanced Recycling of MSW," the PI reached out to Dr. Frolov to license his new industrial burner technology for emerging applications in waste gasification. Dr. Frolov was unable to license his institute's air-methane detonation technology. Still, after that, his research team became interested in "gasification of organic municipal and industrial wastes," using methane--oxygen--steam mixtures, according to a research paper on this subject published by Serge M. Frolov et al., in 2020.

It is proposed to produce highly superheated steam (HSS) for environmentally friendly steam-assisted gasification of organic municipal and industrial wastes using cyclic detonations of ternary methane–oxygen–steam mixtures. Systematic experiments to determine the detonation limits of such mixtures in terms of steam dilution have been conducted. The experiments are performed in an innovative pulse-detonation steam superheater (PD-SSH) with cyclic detonations of ternary mixtures at variation of fuel-to-oxygen equivalence ratio (from 0.3 to 1.84 in methane mixtures) and steam volume fraction (from 0 to 0.7) at normal atmospheric pressure. The experiments are supplemented by thermodynamic calculations.

Cyclic detonations of ternary methane–oxygen–steam mixtures are proved to generate highly superheated steam (HSS) with temperature exceeding 2250 K, when expanded to the atmospheric pressure. The detonation products of stoichiometric ternary mixtures under consideration can contain up to 80% HSS and up to 17% CO_2 with trace amounts of CO, O_2, and H_2. As a result of deep thermal processing (gasification) of organic wastes by such exhaust products, a gaseous mixture of CO and H_2 is obtained, which can be used to produce synthetic fuels such as renewable CH_4. Due to periodic filling with the cool ternary gas mixture, the temperature of PD-SSH walls and inner elements increases insignificantly, so that conventional (not heat-resistant) construction materials can be used for its production (Frolov S. M., 2021).

As indicated above, industrial applications are emerging for this "new generation of industrial burners," such that "objects (are) blown on with combustion products—shockwave (mechanical) and thermal." Pulse-detonation-engines provide discharge velocities on the order of 2,000-meters per second, and the instantaneous pressure-gains are 20-times the input pressure.

Figure A-1 shows the pulse-detonation power-cycle Taylor Energy constructed from a water-cooled tube that receives cyclic O_2/fuel inputs followed by cyclic ignitions leading to detonations.

Figure A-1: Pulse-Detonation Power Cycle — Principal of Operation

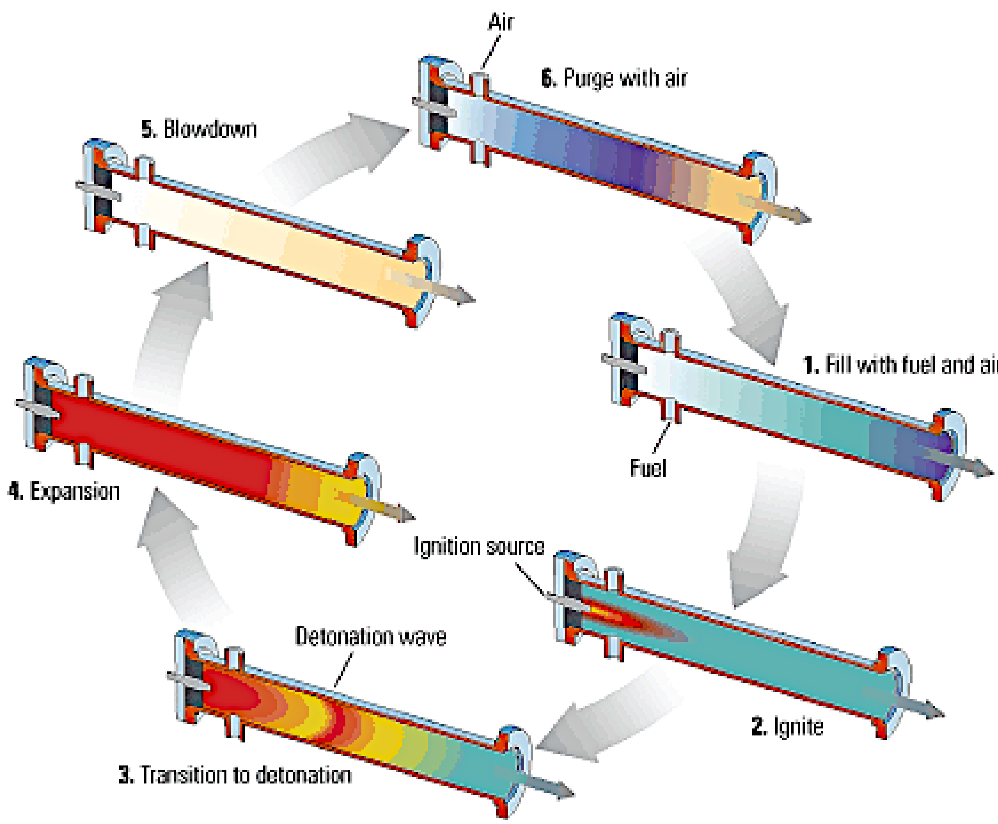


Photo Credit: Pratt & Whitney MMI

The detonations are fuel rich: the target is Phi = 1.33 for the oxygen-methane (O_2-CH_4) detonations. During gasification, oxygen continues to flow during a short purge cycle; therefore, the detonation burner exhaust goes lean for the instant between fuel-injections, providing an excess of O_2, along with and CO_2, which all participate in partial oxidation reactions with biomass (POx reactions.) Carbon dioxide (CO_2) can likewise be recycled and injected into the downstream side of the detonation tube and used for "dry reforming" of organic feeds. Injection of recycle-gases and/or steam injection is controlled separately and input into the run-up tube through an annular nozzle discharging in the direction of the hot exhaust gas flow.

Oxy-fuel mixtures used successfully for detonations included air-propane (Figure A-2), air-propylene, oxygen-propane, and oxygen-propylene. While propylene mixtures tended to be more reactive than propane (because of the reactive double bonds), propylene showed a propensity to deposit carbon on the ignition electrode, causing the iridium sparkplug to fail when operating rich, at Phi is greater than 1.0.

Figure A-2: Air-C3H8 Detonation Experiments Expansion Phase

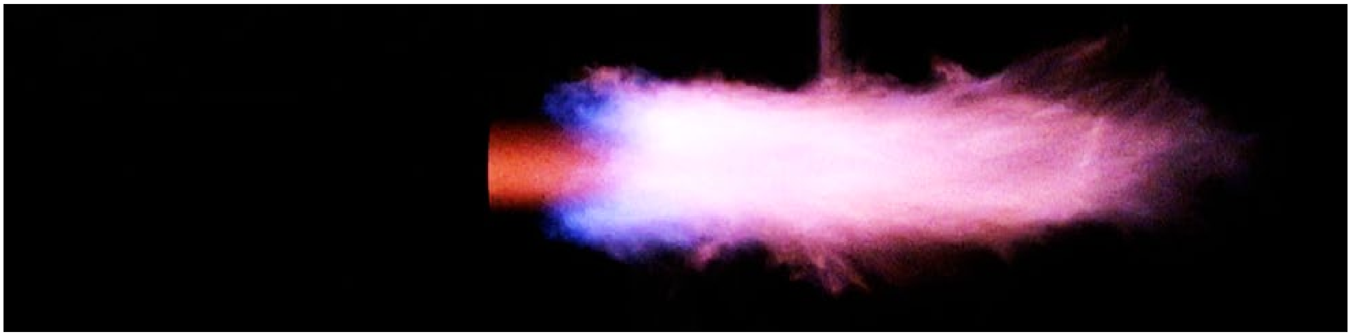


Photo Credit: Taylor Energy

Initially, a 4-inch diameter x 5-foot-long detonation burner was tested to accomplish biomass gasification (Figure A-3).

Figure A-3: 4-Inch ID Detonation Burner

Photo Credit: Taylor Energy

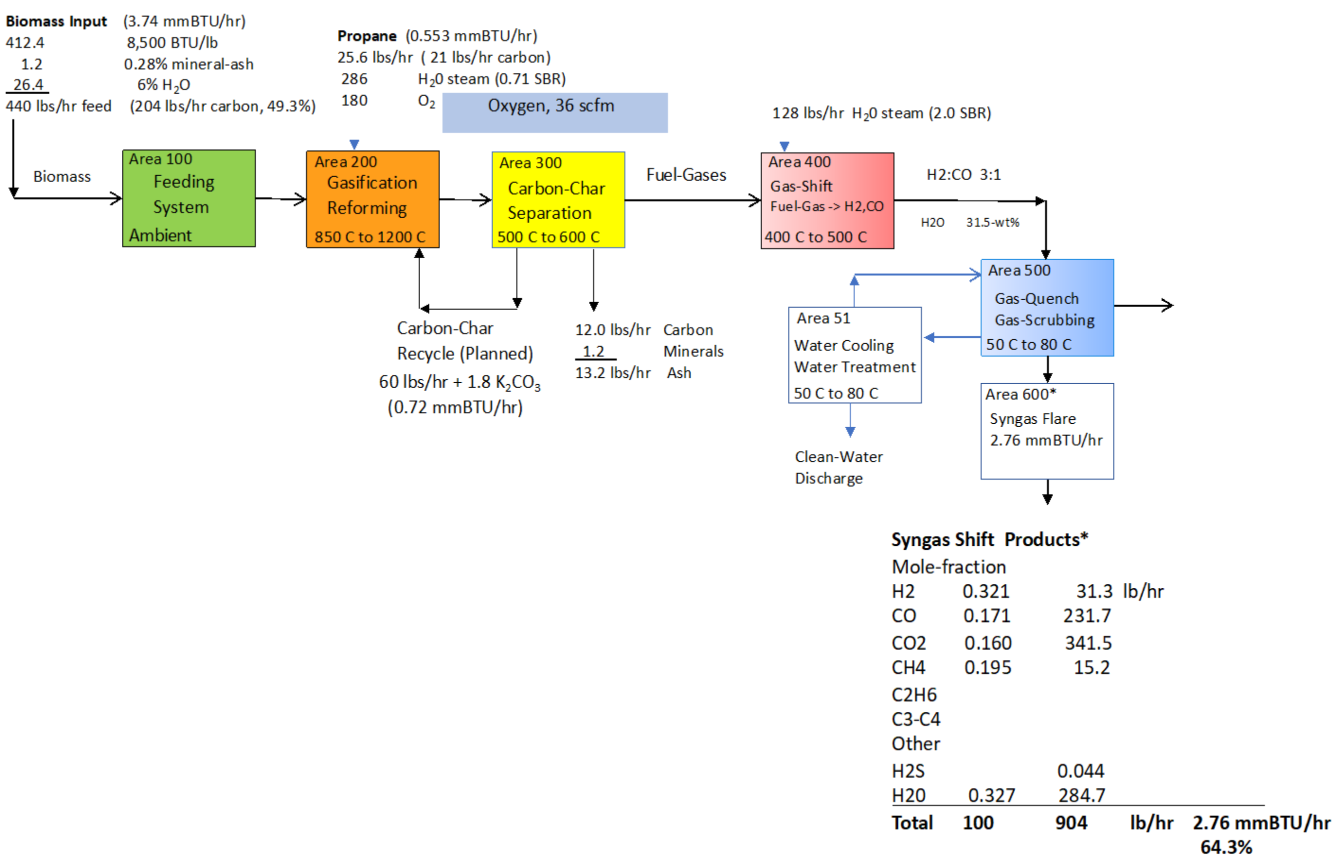
During this project, we developed two different oxy-fuel mixing heads for the detonation burner: one for liquid fuels using a cone and another for gaseous fuel using a micro-cyclone. During development of the pulse detonation burner technology, we tested four different fuels, using both the gaseous and liquid forms -- ethane (gas and liquid), propane (gas and liquid), propylene (gas and liquid), and H_2 (gas).

Initially, we used propane liquid for testing and development because of the simplicity, availability, relative low-cost, and its ability to form mixtures with air and oxygen that detonate with small cell size. However, syngas (resulting from biomass gasification) is the ideal gaseous fuel for pulse detonation because of the H_2, acetylene, and ethylene -- these three molecules being the best at exciting cascading detonations.

Regarding the quantity of fuel consumed to achieve self-sustaining gasification, relatively small amounts of fuel were consumed compared to the biomass energy input. Please see the mass and energy balance below (Figure A-4).

Biomass input is 3.74 MMBtu/hr; Propane input is 0.553 MMBtu/hr. For testing and development, propane energy consumption was about 15% of the biomass energy input (0.553/3.74 = 0.147).

Figure A-4: Present Mass & Energy Balance



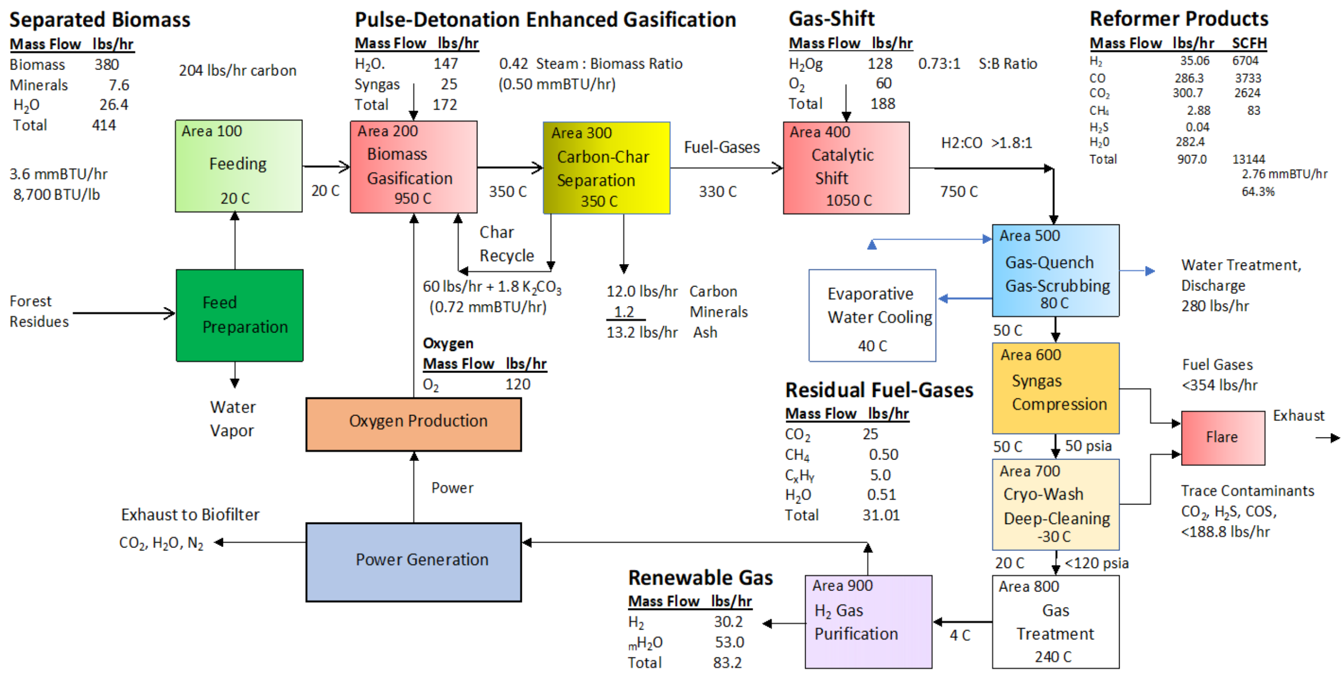
Source: Taylor Energy

For commercial operation, the syngas product stream will be recycled back into the pulse-detonation burner. Carbon char will be recovered as a product or recycled into the discharge end of the detonation run-up tube, where the shockwaves are most intense, and where the gasifier pressure can be reduced to sub atmospheric pressure.

At the discharge end of the detonation tube, we have created a low-pressure zone where gases or carbon can be reintroduced into the gasification system, reacting most effectively with the superheated O_2/H_2 input. In future embodiments, recycle gases or carbon-char will be used as the primary fuel for partial-oxidation to heat the gasification process.

Figure A-5 shows the projected energy balance for a future test embodiment that would include carbon char recycle and operation using syngas products.

Figure A-5: Planned Mass & Energy Balance – Using Syngas & Carbon Char



Source: Taylor Energy

Competitive advantages were achieved using a jet spouted bed reactor because of its ability to tolerate highly variable feedstocks, notably biomass and separated biomass.

The pulse-detonation burner exhaust provides three key inputs to the gasification reactor:

- Hot oxygen, which reacts quickly to generate more heat and CO, CO_2, and H_2.
- Hot steam, which also reacts (above 1,517 [825°C]) with carbon forming H_2 and CO, CO_2.
- Power, as supersonic shocks, and gas momentum measured as internal pressure.

Production of high-purity oxygen will use most of the parasitic energy consumed for biomass gasification. The research team successfully demonstrated biomass gasification using a 2-inch diameter pulse-detonation burner (Figure A-6) that operated successfully at 7 Hertz (Hz) enabling gasification of biomass at 3 pounds/minute.

Figure A-6: Pulse Detonation Burner, 2-Inch Inside Diameter

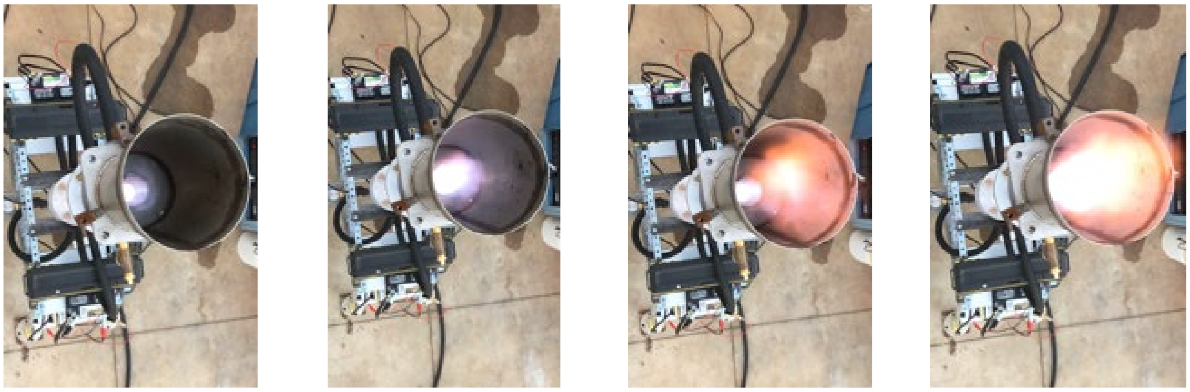


Photo Credit: Taylor Energy

The application of shockwave power to biomass gasification is unique. The pulse-detonation technology — passing supersonic compression waves through the gasification reactor — increases the comminution of friable solids, thereby increasing gas solids mixing intensity. Ultimately, carbon-char residues were recycled to the pulse-detonation burner and fired as an oxygen/carbon/H_2 mixture, which should produce the most powerful detonations, according to the literature. Primary gasification processes within a jet spouted bed, using pulse-detonation power to increase the gasification rate, will assure a low-cost embodiment and subsequent commercialization if demonstration projects and commercial scaling are executed successfully.

The control systems that operate the pulse-detonation burner also provided the de facto control of the biomass gasification process. During routine gasification system start up, the detonation burner was operated to generate inert exhaust gas products; thereby, the gasification system was heated to increase temperature with an inert atmosphere.

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Appendix B: Reciprocating Engine Cycles

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APPENDIX B: Reciprocating Engine Cycles

Engine as CO_2-Reformer, generating a relatively pure syngas product (H_2 + CO) that includes 5 percent methane and almost no other light fractions. This path is old and long tested but not exploited commercially. Renewable electric power would be a co-product resulting from power recovered from partial oxidation reactions, while the exhaust gases are a primary product.

The reciprocating engine can be classified as a type of "continuous batch reactor." As such, the reciprocating engine has to be acknowledged as one of the most successful thermal reactor types ever invented. IC engines remain attractive for distributed power generation, particularly when fueled with renewable fuel-gases. For example, the simple-cycle efficiency is very high, approaching 50 percent, while the installed cost is typically about $750/kW for large-bore engines that are supplied in standard sizes up to 98 MWe. However, the persistent problem of NOx-formation has precluded IC engines use for most new distributed power installations in California, even when applying Best Available Control Technology.

Therefore, we considered ultra-rich operation – employing a partial-oxidation cycle – using a fuel-gas-oxygen mixture of $CH_4/CO_2/O_2$ to eliminate NOx emissions, by removing nitrogen (N_2) from the power cycle, and by operating at an Equivalence Ratio greater than 3.5, the engine exhaust becomes a value-added syngas, ideal for H_2 production by using a catalytic water-gas shift to convert CO into H_2 on a 1:1 using off-the-shelf technology.

Using high-purity oxygen (O_2) to replace air extends the operating limits for a compression ignition engine well into the ultra-rich regime. The power generated by the IC engine (as a prime mover) is sufficient to produce excess power available for export to the utility grid. The IC Engine-Reformer is thereby employed as a "continuous batch reactor," well suited for fuel-gases derived from autothermal gasification of biomass; NOx emissions well below 0.1 g/bhp-hr would be achieved for the power generation part of the power cycle.

Modeling data shown below (Table B-1) informs the selection of parameters needed to operate a test engine in partial-oxidation mode. The engine exhaust products are composed mostly of H_2 and carbon monoxide. For example, as shown below, biogas (BG) and oxygen (O_2) are reacted in the mole ratios shown; note that the CO content approaches 40 percent molar exhaust volume. This importance modeling data shows that CO_2 can supply oxygen atoms for partial oxidation, with only a small amount of oxygen added to reach the desired equilibrium temperature.

Table B-1: Ultra-Rich Engine Exhaust Modeling

BG:O_2	1:0.3	1:0.34	1:0.35	1:0.36	1:0.37	1:0.4	1:0.5	1:0.75	1:1
H_2	0.183	0.248	0.250	0.247	0.242	0.226	0.176	0.052	0.0130
CO	0.332	0.393	0.394	0.391	0.387	0.373	0.323	0.197	0.0793

$BG:O_2$	1:0.3	1:0.34	1:0.35	1:0.36	1:0.37	1:0.4	1:0.5	1:0.75	1:1
CO_2	0.139	0.104	0.104	0.108	0.112	0.126	0.176	0.301	0.392
H_2O	0.287	0.246	0.248	0.252	0.257	0.273	0.323	0.445	0.445

Molar Ratio of Biogas: Oxygen Compared to Molar Volume of Exhaust Components

In addition to the modeling data above prepared at UC Berkeley Engine Laboratory for Taylor Energy, there are a dozen credible research papers that report on using IC engines as batch steam reformers. South Korea and China, both manufacturers of heavy engine, are most recently interested in the process for NOx-free generation of electricity and syngas intended for production of high-value synthetic products.

Proof-of-concept would require operating a compression-ignition engine, testing partial oxide-tion of ultra-rich mixtures of fuel-gases with oxygen. A prototype research-engine would be needed to prove an advanced ignition cycle called "steam-compression ignition," which was patented by General Motors in 1974, but never commercialized. Direct Injection of high-pressure superheated steam (near top-dead-center) would be used to initiate compression-ignition, which would serve to increase engine efficiency by two percentage points by starting the power cycle at higher initial pressure; steam addition would also improve the quality of the syngas product.

The Engine-Reformer concept was evaluated by Taylor Energy as a part of this project. Ultra-rich combustion with oxygen is considered a key enabling technology. The Taylor Energy/UCR research team considered the R&D issues, including the Aspen computer modeling and engine testing presented herein.

A zero-emissions IC-engine reformer technology that generates electric power and high-value CO-rich syngas intended for integration with emerging renewable H_2applications is technically feasible. This study was more the focus of our research effort compared to operational testing of the 3406-CAT engine in dual-fuel more.

For example, CO_2 is an essential component in the $CH_4/CO_2/O_2$ combustion mixture; fuel-gases, including a CO_2 fraction, is employed to maximize the CO content in the synthesis gas product, which is essential to maximize H_2 formation with the minimum consumption of oxygen. CO_2 serves as a source of oxygen for the partial oxidation reactions. This approach is sometimes called "dry reforming" in the technical literature, because CO_2 replaces H_2O to some degree, whereas reforming with H_2O is typically called steam-reforming.

Gasification derived fuel-gases are relatively low-value products. The value is increased significantly when integrated with co-production of power and clean fuels. The added cost for oxygen (O_2 enables the Engine-Reformer cycle to operate ultra-rich) is justified by the value-added of H_2 produced using CO-rich syngas. The unique property of fuel-gases derived from biomass gasification containing CO_2 and methane (and low-molecular weight hydrocarbon gases resulting from biomass gasification), is thereby exploited for economic advantage.

We studied the feasibility of using a Compression-Ignition (CI) engine, operated with a $CH_4:O_2$ molar ratio near 1:0.35 to achieve ultra-rich-combustion, to reform fuel-gases into CO-rich syngas, considering the economic suitability of the Engine-Reformer for production of power and syngas.

We also considered the reciprocating engine as high-speed batch reactor, with the ability to freeze the chemical equilibrium through rapid cylinder expansion, which quench-cools the in-cylinder gas mixture, creating process conditions that enable direct production of ethylene, for example, from a diverse mixture of fuel gases. Based on our research, the engine required to test that path would be high compression, at least 24:1, and operate at high rpm, at least up to 3,600 rpm. Under these conditions light olefines can like be produced directly within a reciprocating engine operated as a batch reactor with the surprising ability to provide very high rates of heat transfer resulting from rapid-compression combined with mildly exothermic reactions, followed by a rapid expansion within the cylinder that enables heat removal via quench-cooling. This approach is very promising, but quickly goes beyond the project scope because the net power output would be marginal, while the primary products would be high-value ethylene and propylene monomers.

However, co-production of electric power and syngas with 5 vol% CH_4 using an off-the-shelf IC engine was considered as a possible opportunity technology. One considers the ability to replace air with oxygen/steam within the IC engine, the process being similar in essence to the O_2/H_2O partial oxidation of biomass in a gasification reactor.

Circling back around to bio-crude production, the use of two-stroke reciprocating engines as thermochemical batch reactors, the OP engine test campaign proposed with Farabee Mechanical, and one may see that an overarching objective was to test a medium-speed engine, operated ultra-rich, using a bio-crude/oxygen/steam mixture to produce syngas (H_2 + CO with about 5 vol% CH_4) and electric power.

It quickly became apparent that the 3406-CAT engine was not right compression ignition engine for our purposes, for example, being too large to operate on oxygen without first performing single-cylinder or two-cylinder tests. Moreover, modeling indicates that a slow-speed ship engine (250 rpm) with a high compression ratio (>18:1) would provide optimum performance. Whereas the 3406-CAT is designed to operate efficiently at 1500 rpm, and the compression ratio (14:1) is too low for ideal use as an engine-reformer.

An indirect result of the efforts expended to elucidate this path was that the research team was compelled to consider alternative power cycles. Without the complexity of coproducts, what is the simplest and most cost-effective means of converting H_2/CH_4 into electricity? We developed the concept for a power cycle based on the use of two opposed impulse engines that generate thrust using rotary detonations at 20,000 Hz.

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix C: Rotary Detonation Power Cycle

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APPENDIX C:
Rotary Detonation Power Cycle

The concept for a novel rotary detonation power cycle intended for flexible power generation was conceived and designed to enable use of the products of biomass gasification in a detonation cycle using air/H_2 mixtures (Figure C-1).

Figure C-1: Ramjet Helicopters Provide the Concept for Low-Cost Rotary Power

Photo Credit: U.S. Army

The concept for this type of low-cost flexible power generation would require pipeline or other gas storage methods that would deliver a methane/H_2 mixture, the gas is thereby stored for on-demand electric power generation (Figure C-2).

Figure C-2: Concept for Gas Storage and Low-Cost On-Demand Power Generation

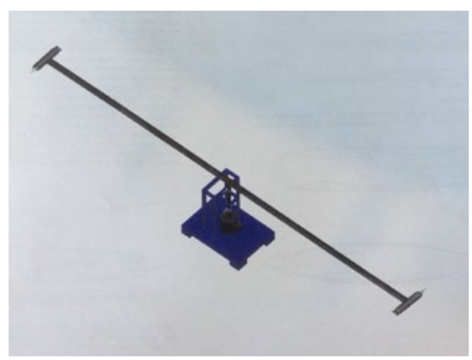

Photo Credit: Taylor Energy

The research team developed the concept for this novel low-cost power generation cycle for on-demand power, peak-power generation, and three-day back-up power, providing 40 percent net conversion efficiency, with an installed cost of $100/kW (Figure C-3).

Figure C-3: Power Cycle Using Two Opposed Rotary Detonation Engines

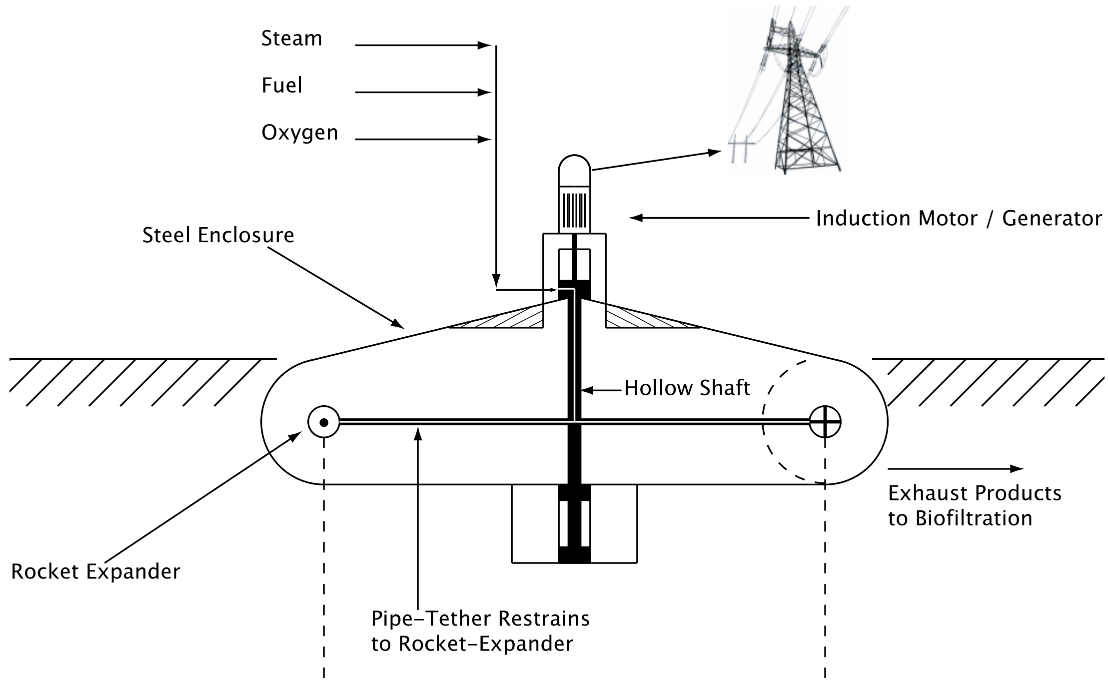

Photo Credit: Taylor Energy

One U.S. patent application for a rotary power cycle has been submitted by Taylor Energy, exemplified by the graphic image included in the application as FIG. 1A, presented below (Figure C-4).

Figure C-4: Flexible Power Cycle using Opposed Rotary-Detonation Engines

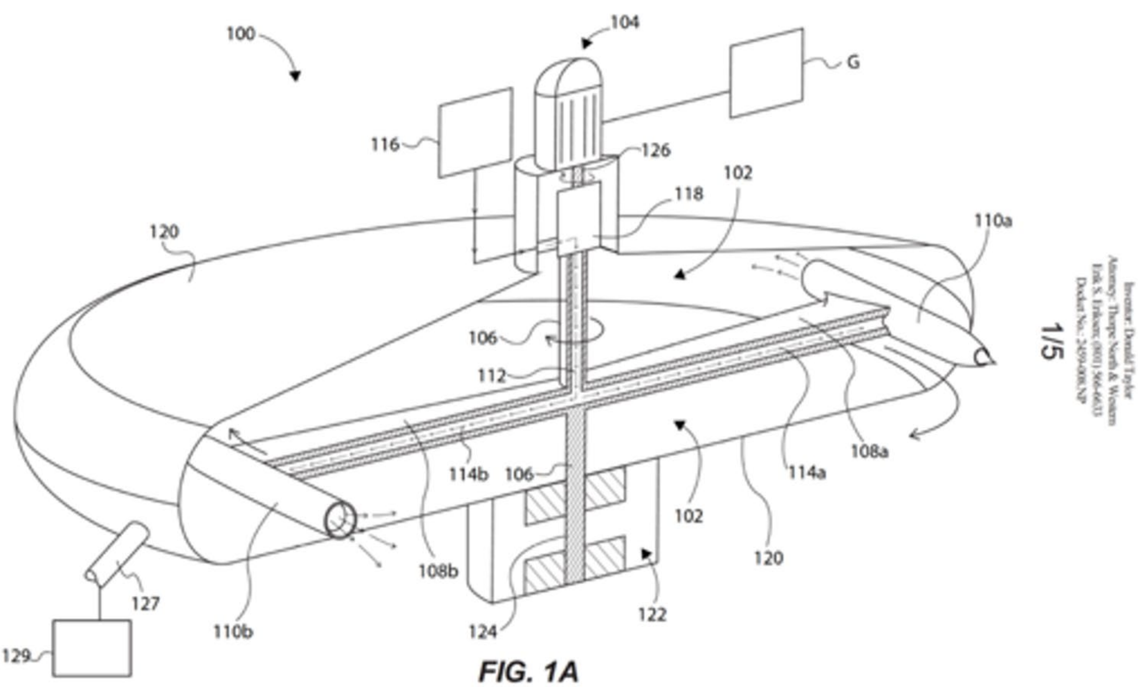

Photo Credit: Taylor Energy

H_2-rich fuel-gases produced by biomass gasification are well suited to form air/NG/fuel mixtures that will detonate using the subject detonation engine. When pulse-detonation engines replace traditional ramjet engines -- the PDRE's velocity at the tips of the blades can be subsonic and still provide high-efficiency; whereas, a ramjet only becomes efficient in the Mach-3 to Mach-4 range, rotating at speeds which are more challenging to accommodate in a simple power cycle.

There are two reasons why innovative power generation means and methodology are needed to use H_2-rich fuel-gases derived from waste biomass streams:

- H_2-rich fuel gases produced using thermal gasification technologies contain, in addition to H_2, contain light-olefins (ethylene and propylene) that exhibit extremely "low octane" because these molecules tend to be very reactive, and therefore, are not useful as an efficient gaseous fuel in reciprocating engines, which require in-cylinder deflagrations, not detonations. These low-octane fuel-gases are not used efficiently in reciprocating engines due to the requirement for low compression ratios. Reciprocating engines are still the most energy-efficient and most cost-effective power generation method for systems (for integration with biomass gasification) with capacities less than 20-MWe; above 20-MWe, combined-cycle turbine plants become more efficient.
- However, the capital cost for reciprocating engines with high-efficiency is about $1000-kWe installed; the cost for combined cycle plants is about $1200-kWe; the capital cost for high-efficiency fuel-cells higher still. PEM fuel-cells cost $200/kWh installed for back-up power; efficiency is 40%; however, the useful life of PEM fuel-cells is only 5-years, then the electrode is recycled for about $80/kWe. Consequently, there is a need for a low-cost back-up power and peaking power cycle with 40% net efficiency, having an installed capital cost of $100/kWe, with maintenance <1/4-cent per kWe.