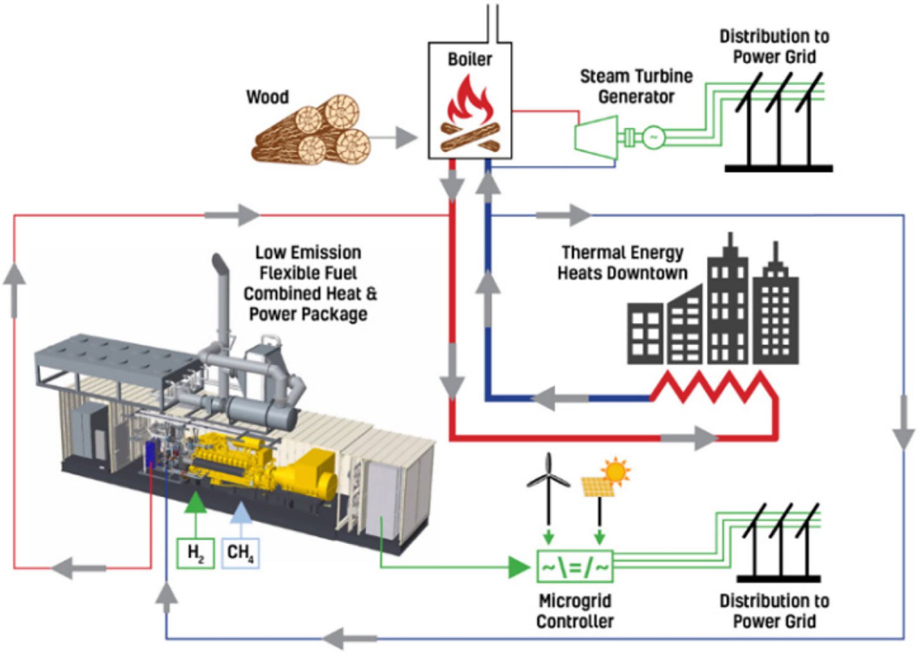
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY & RENEWABLE ENERGY



District Energy St. Paul demonstration configuration. *Diagram courtesy of Caterpillar, Inc.*

Flexible Natural Gas/Hydrogen Combined Heat and Power System

District energy systems efficiently provide thermal energy to multiple buildings and facilities through a network of shared infrastructure. Frequently, district energy systems are centered around combined heat and power (CHP) plants that generate electricity as well as heating and cooling to the local buildings. By providing both electricity and thermal energy from a single fuel source and central location, these systems use less fuel, decrease energy and operational costs, and reduce the need for heating and cooling equipment in individual buildings.

District energy systems are found throughout the world in areas such as denser downtowns, college campuses, military bases, and hospital complexes. These systems range in capacity and can utilize different fuel types and technologies. While district energy has been around for more than a century, these systems are not as common in the United States as in many other countries.

However, there is an established and growing customer base for CHP systems that support district energy systems, as well as a growing interest in alternative energy sources for CHP. (The current industry standard for engine CHP systems is internal combustion engines fueled by natural gas.) Caterpillar, Inc., and partners seek to design, develop, and demonstrate a cost-effective and scalable CHP generator set (genset) that can be powered by natural gas, hydrogen, or a combination, along with advanced microgrid/grid compatibility controls for the system. The technology will be demonstrated in a renewably fueled district energy system.

Benefits for Our Industry and Our Nation

Residents and businesses in a district energy system require reliable, efficient, high-performance power generation assets to keep operations running 24x7x365. However, district energy systems are increasingly using variable renewable energy sources to generate their electricity. This project aims to provide a power system that will complement intermittent renewables and ensure reliable power delivery. The CHP technology will not only meet baseload requirements but also automatically and seamlessly respond to variations in electric power generation within a district energy system, as well as provide a rapidly dispatchable generation asset for grid support during peak demand times.

The CHP system is also flexible, enabling the use of renewable hydrogen as an energy source and thus reducing the carbon footprint of many application demands. Moreover, during times of low demand, excess electricity from renewable systems can be used to generate green hydrogen, which can be stored onsite. The flexible gas engine system can automatically detect when hydrogen fuel is available and switch to pure hydrogen or a mixture of hydrogen and natural gas, allowing for CHP genset operation with low or no greenhouse gas emissions.

Applications in Our Nation's Industry

The project will develop and demonstrate a unique-to-the-industry power delivery and controls system. Demonstration results will provide key insights into the capability of systems to serve future hydrogen applications, helping to fill knowledge gaps in technology, scaling, and supply chain expansion of renewable hydrogen and hydrogen-capable CHP systems. Demonstration data from this project will help answer questions about converting renewable hydrogen to electric power and thermal energy—including comparisons with established fossil and methane-based renewable fuels—in terms of power density, transient response, greenhouse gas emissions profile, and efficiency. A successful demonstration will be an important first step in development of renewable-hydrogen-powered CHP solutions for many applications.

Project Description

The project comprises two major development components. First, a spark-ignited natural gas engine system design will be optimized to enable flex-fuel operation on natural gas, hydrogen, or mixtures thereof while maximizing performance and response and minimizing emissions.

Second, power electronics and controls will be developed to enable CHP system integration into and coordination with the district energy system power microgrid. The system will be scalable to multiple applications that will offer grid needed flexibility, quick start-up, precise load following, and high efficiency across the load range.

Barriers

The key challenges involve adapting natural gas engine designs for pure hydrogen and mixing/switching fuels.

- The turbocharger/air system is optimized for the narrow operating range for natural gas, but hydrogen requires dilute mixtures. The properties of hydrogen fuel require significantly higher compressor work, resulting in higher turbine work and pumping loss.
- The energy in the exhaust gas recirculation (EGR) stream can be recovered for power and heat, but the EGR delivered is cool and dry, demanding higher EGR rates to dilute and control the rapid in-cylinder flame speed of hydrogen. Most production engines use ≤25% EGR. Extreme intake dilution will result in lower exhaust temperatures, presenting a challenge to obtain a turbo match.
- A fumigated pre-mixed fueling system works well with 100% natural gas or mixtures of natural gas and hydrogen, but with pure hydrogen, the power output of the engine is severely limited. Because hydrogen is highly combustible and requires higher pumping work, there is a backfire risk.
- Direct injection (DI) of hydrogen can improve efficiency and power output, eliminate air displacement effects and back-flashing, and offer flexibility in injection parameters that even allow diffusion burn of injected hydrogen. DI's drawback is higher cost and higher engine-out NOx.
- The air–fuel ratio (stoichiometric vs. lean) must be balanced to achieve the least impact on efficiency without adding significant cost.

Pathways

- The project will conduct single-cylinder engine testing and simulation to minimize development challenges while finalizing decisions on the engine hardware for achieving flex-fuel capability and validating control strategies.
- The team will identify the limits of the air system with pure hydrogen combustion and design the system for optimum performance across the full range of fuel blends. Assist technologies (additional blowers, batteries, etc.) will be considered to address shortcomings.
- The team will conduct 1D/3D simulations to optimize combustion chamber compression ratio and turbulence intensity and to select an optimum piston and camshaft design.
- Key control parameters (such as spark timing, air fuel ratio, etc.) for the combustion phasing, cylinder-to-cylinder variation of combustion, and abnormal combustion will automatically be adjusted by using cylinder pressure sensing.

Milestones

This three-year project began in April 2021:

- Modify the design of an existing 2.0 MW spark-ignition (SI) natural gas engine to make it capable of operating on 100% natural gas, 100% hydrogen, or any mixture (2021–2022)
- Develop controls for managing the combustion fuel mixture in response to fuel availability and desired fuel blend ratio (2022)
- Install a 2.0 MW engine genset for conversion of natural gas and renewable chemical energy to electric power and heat for use in a municipal district CHP system currently using renewable-wood-fired combustion (2022–2023)
- Develop power electronics and controls for the engine genset to comply with grid code requirements and microgrid compatibility (2023)
- Analyze the environmental impact of hydrogen power systems for CHP (2023)
- Develop safety and protection systems for hydrogen storage (to manage flammability and cryogenics), high-voltage electric power, and cybersecurity threats (2023–2024)
- Procure permits for system installation and operation (2024)

Technology Transition

Caterpillar has decades of experience bringing engine and machine solutions to production—and then to the marketplace. The company already supplies engines and gensets to multiple industries through the Cat dealer network. After a successful demonstration, Caterpillar can leverage this solution into the distributed energy markets the company already serves. Caterpillar can also use its extensive dealer network, which employs 160,000 people and reaches nearly 200 countries, as well as a robust marketing and salesforce to bring the final product to market.

Project Partners

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