HYDROGEN PROGRAM AMR & PEER EVALUATION MEETING
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Flexible Natural Gas/Hydrogen CHP System Development & Demonstration (DOE Award: DE-EE009422)

Industrial Efficiency & Decarbonization Office (IEDO)

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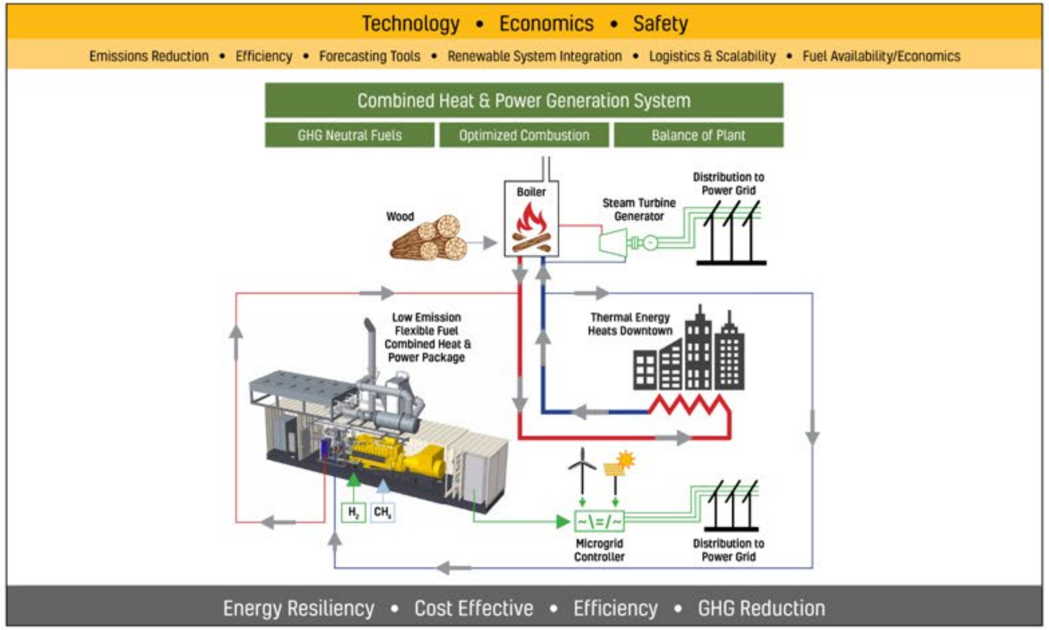

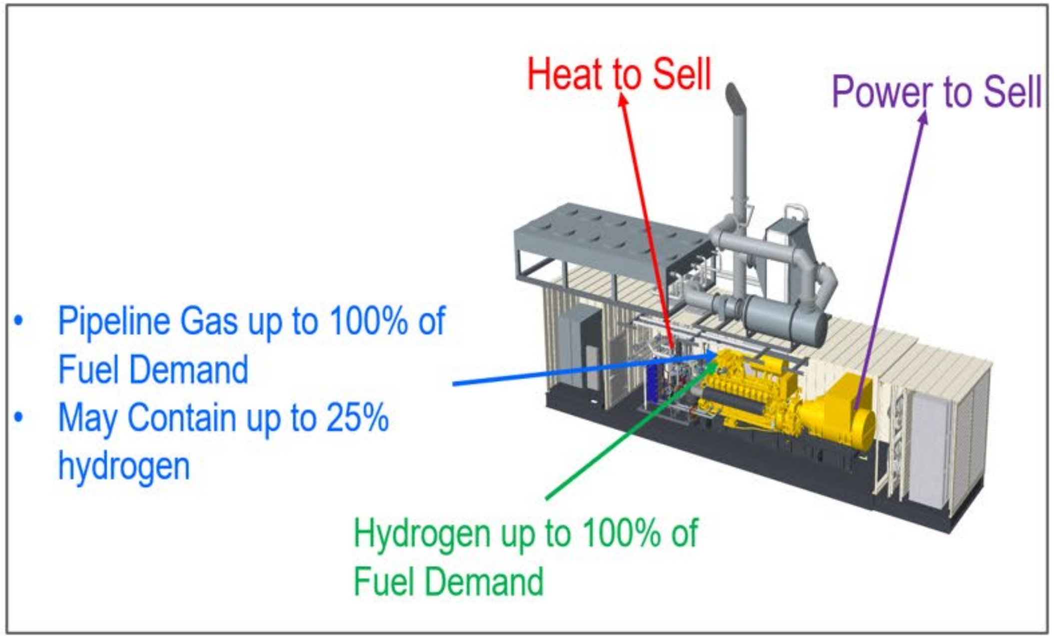

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Project Overview

- Development of a multi-megawatt flexible CHP system for distributed energy generation –
  - To serve as back-up generation asset for the grid, and
  - To stabilize a District Energy system that employs renewable power generation systems
- Utilization of low carbon and renewable hydrogen to accelerate decarbonization and improve long-term reliability and resilience of energy systems.
- Provides insight into microgrids with hydrogen-based CHP system and how they can enhance stability and improve air quality, particularly for hard-to-decarbonize sectors.
- Enables leveraging diverse domestic energy resources in U.S. industries, while strengthening environmental stewardship and manufacturing workforce by supporting innovative technologies and practices.
- Understand which social, financial, and technical barriers hydrogen-based power generation projects face e.g., low carbon intensity hydrogen availability, cost, logistics, storage, and safety, and what policymakers can do to spur more commercial investment in hydrogen projects.

Project Outline

Innovation: Flexible CHP equipment capable of utilizing low-carbon intensity fuels

Project Lead: Caterpillar Inc.

Project Partners: DESP, NREL, McKinstry LLC, Linde Inc., Ziegler Power Systems

Timeline: Sep. 2021 – Sep. 2024, progress ~52%

Budget:

	FY21 Costs	FY22 Costs	FY23 Costs (estimate)	FY24 Costs (estimate)	Total Planned Funding
DOE Funded	$0.7M	$1.3M	$2.1M	$0.5M	$4.6M
Project Cost Share	$1.3M	$2.8M	$5.0M	$1.0M	$10.1M

End Project Goal:

- Development of a hydrogen/natural gas flex-fuel CHP genset capable of running on 100% natural gas, 100% hydrogen, or up to 25% hydrogen + natural gas blends (volume basis), and
- Demonstration in a renewably fueled district energy (DE) system –
    - Automatically and seamlessly respond to variations in electric power generation by the renewable(s) to assist in maintaining base-load operation of the facility
    - Serve as a back-up generation asset for the facility/grid

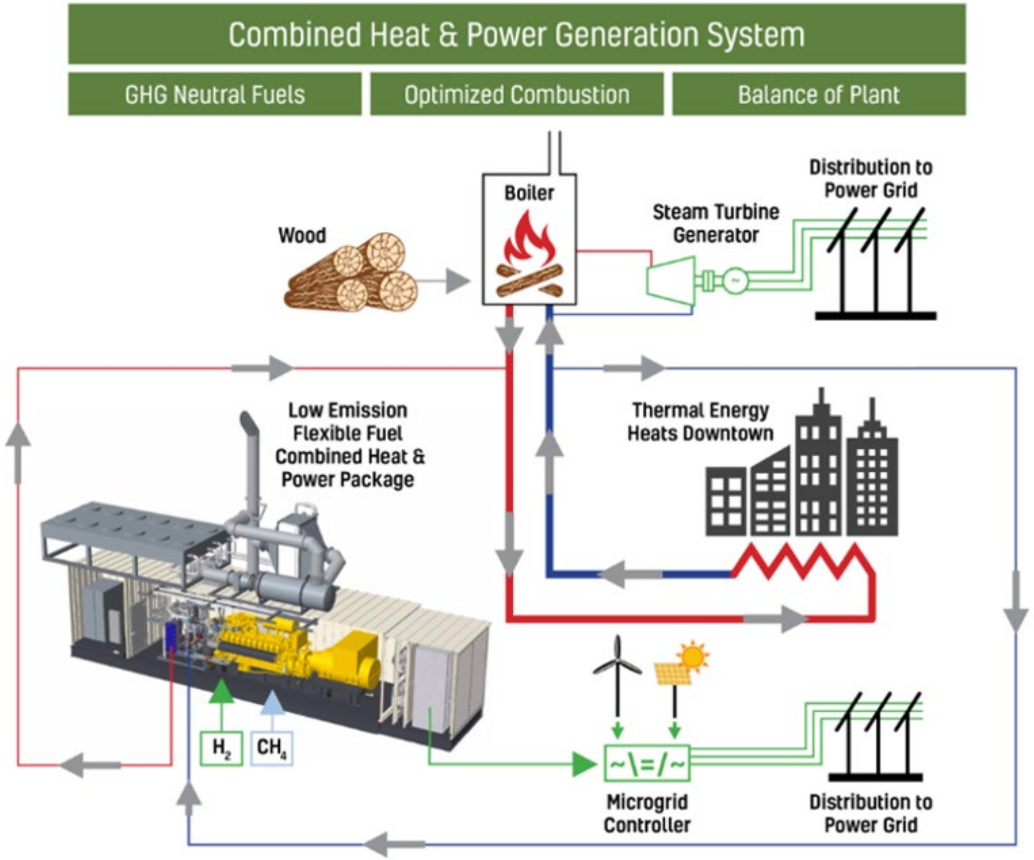
DOE Program Provides Accelerated Development Opportunities

This DOE co-funded program –

- Helps Caterpillar:
  - Expedite production release of hydrogen capable flex-fuel gensets that can provide 100% hydrogen capability with fallback capability to partial or full natural gas fueling in times when hydrogen supply is not adequate or not available
  - Develop and test cost competitive electronics and controls for easy “plug-n-play” flexible CHP system integration with a variety of Distributed Energy power systems
  - Gain and document understanding of how a hydrogen power profile would compare to that of traditional fuels (e.g., diesel, natural gas) and futuristic power systems (e.g., fuel cell, battery) in terms of power density, efficiency, transient response, GHG emissions profile, and TCO
- Helps project partners:
  - Advance their know-how about hydrogen fueling and storage systems, and CHP systems using hydrogen as fuel
  - Enables them to bid for other hydrogen related projects, as well as share their experience with others in similar industries through consultancy and participations in the conferences and workshops

District Energy St. Paul, Demo Config: CHPH2 System Integration

- Nonprofit utility, well-known district energy site
- Biomass-fired CHP
  - Tree waste from over 115 communities in 22 counties - 260,000 tons of wood chips/year
  - Produces approximately 25 MW of electricity and 65 MW of heat
  - Helps avoid 100,000 tons of CO2 emission each year
- Natural gas fired boilers and electric chillers also used
- Currently cools 119 buildings and heats 200 buildings and 398 single-family homes in downtown Saint Paul and adjacent areas through a network of hot- and cold-water distribution pipes
- The containerized flex-fuel genset CHP system (CHPH2) will connect to the existing power and heat network at the DESP demo site
- Site load will be able to accept all the power and heat from the CHPH2 system, even in summer months



Flex-fuel Genset/CHPH2 System Development and Demo Activities

Key Project Activities

- Engine System Concept Evaluations: 1-cyl Testing & 1D/3D Simulations

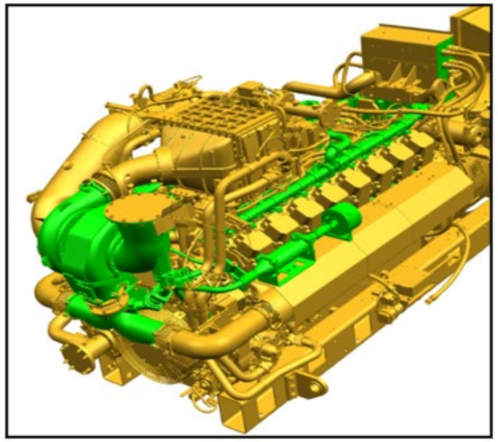
- 2MW multi-cylinder Engine/Genset Testing,
- Hydrogen Safety Planning

- Controls Work: Engine, Genset, CHP System, MMC
- CHP Power System Containerization/Testing

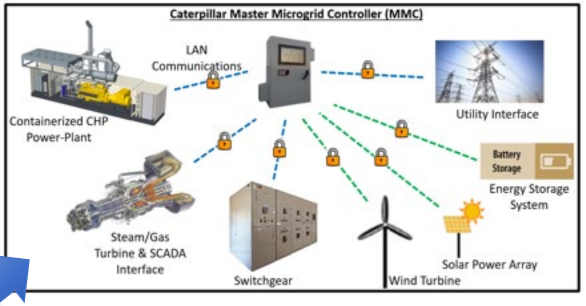
- Demo Site Design, Permits, and Construction
- Flexible CHP Genset Sys. Install, Integration & Demo

Hydrogen Engine Specific Updates

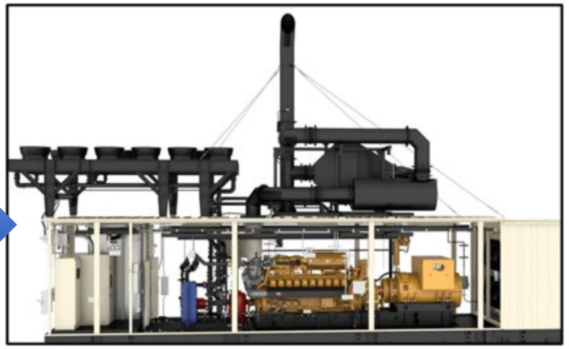
- 100% hydrogen port fuel injection valves and fuel train
- Hydrogen compatible pre-mixed fueling system that is now capable of handling hydrogen + natural gas blends
- Turbo change to meet leaner operation with 100% hydrogen
- Finer mesh flame-arrestors per cylinder
- System for crankcase ventilation with 100% hydrogen operation
- Engine controls to handle variations in hydrogen%, and in-cylinder pressure sensing system for cylinder balancing
- Updated several engine components/seals (metal and non-metal) for hydrogen compatibility



- Caterpillar MMC that is capable of interfacing with multiple Distributed Energy Resources, utility grid, industrial power inverters, and complex switchgears.



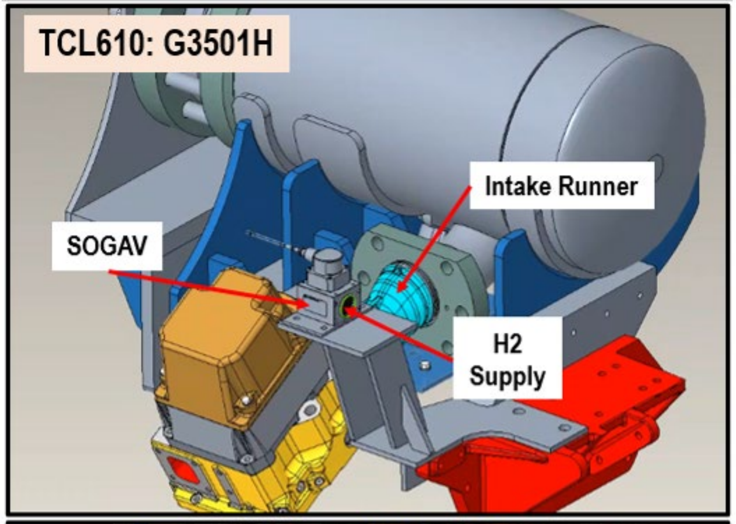
- Standard CHP enclosure design updates for hydrogen genset integration and MMC interface
- Includes hydrogen safety systems - H2 leak detection and auto-shutoff, improved ventilation and explosion pr. relief, etc.



G3501 Single-cylinder Engine R&D for Flex-fuel Engine Recipe Dev.

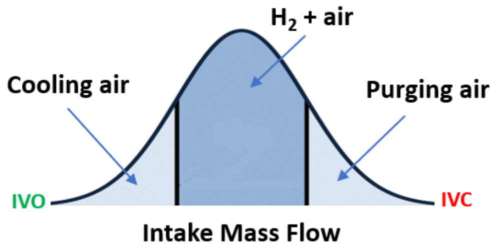
Completed

- Engine testing and 1D/3D simulation used to down-select recipe for a flex-fuel engine
- Determined optimum parameters for H2 port injection valve operation
- Investigated pre-ignition issues and developed controls logic for mitigation
- Evaluated performance with NG and H2+NG blended fuel (25% H2 blend)
- Designed and tested flame arrester for H2+NG blended fuel operation
- Tested for and measured combustion chamber component temperature values
- Identified optimum engine operating space/boundaries

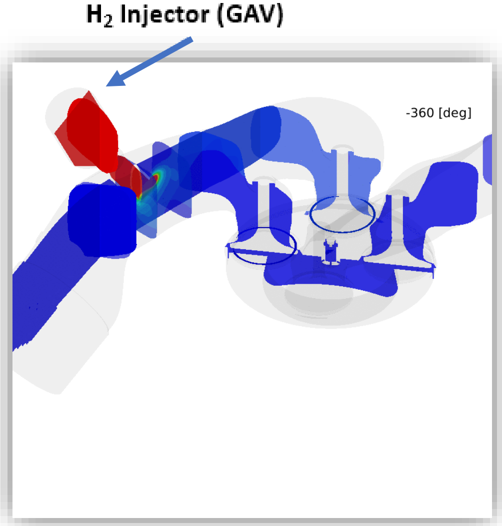


100% Hydrogen Port Fuel Injection (PFI)

"Hydrogen Sandwich" approach



1. Cooling air mixes with exhaust residuals and cools off combustion chamber
2. Hydrogen is injected
3. Hydrogen injection stops, intake runner purged



- Minimum leftover hydrogen in intake port with acceptable in-cylinder mixing

G3516 2MW Flex-fuel Genset Testing/Development

Completed

- A G3516 2.0 eMW natural gas engine-genset was modified for flex-fuel capability for use in this testing
- Testing included genset startups, steady state performance and emission, and transients
  - Detailed engine testing/calibration was done with 100% H2, H2+NG blends, & NG
  - Engine/genset controls evaluation and tuning carried out during testing
  - Hydrogen compatible port-fuel injection system and pre-mixed fueling system were also evaluated extensively
  - During NG and blended fuel operation: The genset delivers 2.0 MW electrical power output with exhaust NOx emission at 1.0 g/hp-hr
  - During 100% hydrogen operation: The genset power output limited to 1.0 MW, with exhaust NOx emission below 0.1 g/hp-hr
  - Independent of the type of fuel used, the genset can ramp up and down between 50% and 100% rated electrical capacity in less than two minutes, and
  - At both 50% and 100% of rated electrical capacity the combined heat and power efficiency is up to 80 - 85%

***H2*: Hydrogen, *NG*: Natural gas**

Demo Site Hydrogen Safety Plan and Risk Analysis

In-progress

Hydrogen Safety Considerations

1. Hydrogen Safety Plan 1st Draft: Hydrogen Safety Panel (or HSP, of the Center for Hydrogen Safety) reviewed the 1st draft of our plan in Oct-2022
2. Preliminary PHA: Completed Nov-2022
3. Final PHA: HAZOP methodology will be used. Will include NREL, other project partners, and appointed members of the Hydrogen Safety Panel (May-Jul 2023)
4. Hydrogen Safety Plan Final Draft: Will be submitted for Hydrogen Safety Panel review and approval (Apr-Dec 2023)
   - Will address the detailed HSP comments and include hazard analysis results, hydrogen risk planning, and detailed data on hydrogen fueling system design
5. PSSR (Pre-Startup Safety Review): To be held at the demo site, possibly with NREL and HSP involvement (Jan-Feb 2024)

Hydrogen Safety Plan

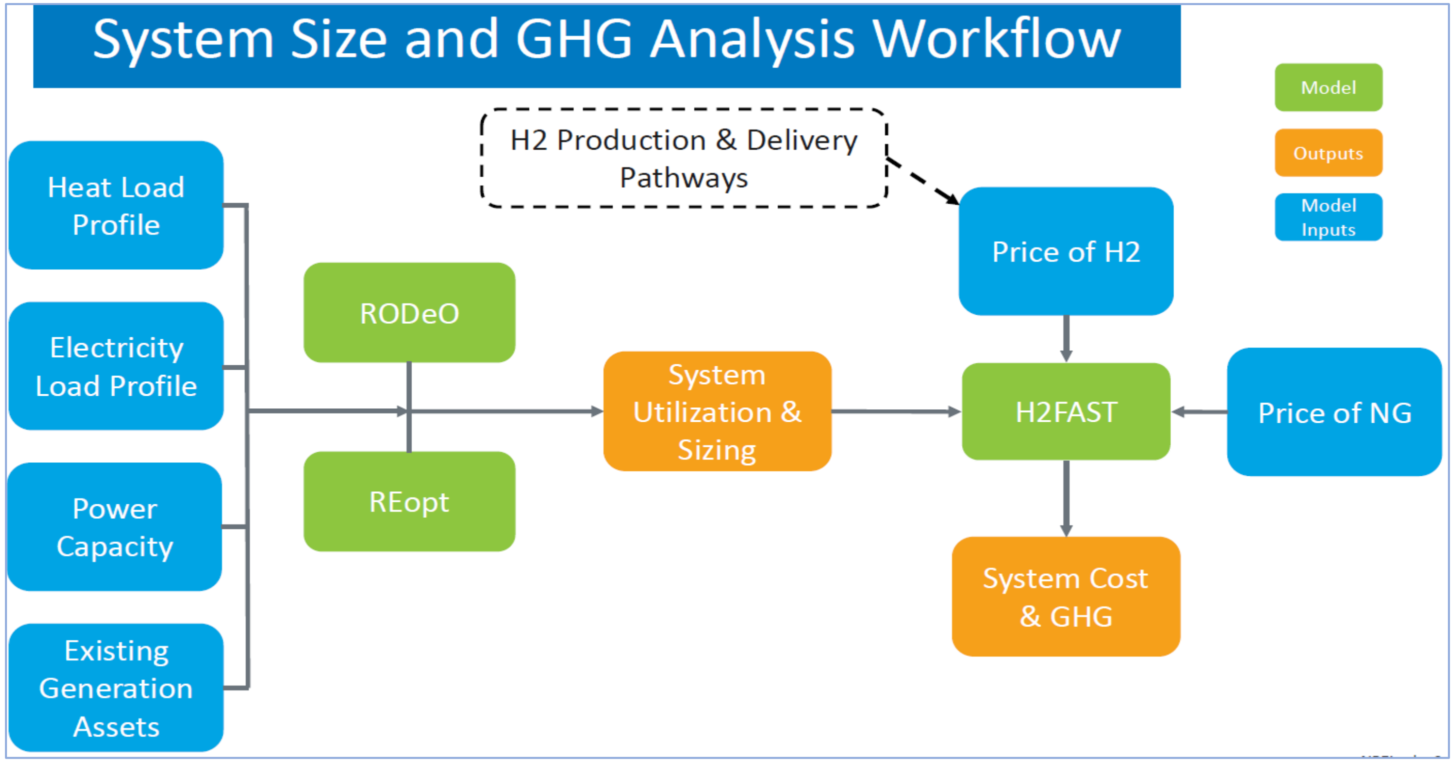
Key Contents

1. *Project Roles*
2. *Description of Work*
3. *Participants' Organization Policies and Procedures*
4. *Participants' Hydrogen Experience*
5. *Identification of Safety Vulnerabilities (ISVs)*
6. *Risk Reduction Plan*
7. *Applicable Code and Standards*
8. *Participants' Safety Procedures*
9. *Mechanical Integrity of Equipment Used*
10. *Management of Change (MOC) Procedures*
11. *Project Safety Documentation*
12. *Personnel Safety Training*
13. *Safety Events and Lessons Learned Documentation*
14. *Emergency Response Plan*

PHA: Process Hazard Assessment
HAZOP: HAZard and OPerability study

TEA and GHG Analysis: Work-flow and Tools and Inputs

- The GHG and TEA analysis focuses on the economic and environmental benefits of a flexible fuel (NG/H2/blends) engine-genset with several infrastructure options including –
  - Combined Heat & Power or CHP, renewable hydrogen production & storage, renewable power sources, energy storage system (ESS), fuel cells, micro-grid, etc.
- Analysis encompasses the system sizing, economics and emissions impacts of different system designs and operation modes.



<u>TEA:</u> Techno-Economic Analysis
<u>GHG:</u> GreenHouse Gas
<u>H2</u>: Hydrogen, <u>NG</u>: Natural gas

Status of Various SOPO Subtasks and Milestones

Completed:

Subtask 1.1: System requirements
Subtask 1.2: H2 market opportunity, value proposition and regulations
Subtask 1.3: Single cylinder test cell upgrades
Subtask 1.4: 1D/3D Simulation for hydrogen injection/delivery to engine
Subtask 1.5: Detailed single cylinder engine R&D
Subtask 1.6: Design/development of Port Fuel Injection (PFI) for hydrogen
Subtask 1.7: Assessment of Direct Injection (DI) system for hydrogen engine
Subtask 1.8: 1D simulation for flex-fuel engine design and performance
Subtask 1.9: Engine Controls for H2/NG/H2+NG
Subtask 1.10: Identify scenarios, tools, plans for TEA & GHG Impact Analysis
Subtask 2.1: Prototype engine hardware design and procurement
Subtask 2.2: Multi-cylinder Test Cell upgrades for hydrogen
Subtask 2.3: Engine prototype build and instrumentation
Subtask 2.4: Prototype flex-fuel genset-engine SS perf dev & controls work
Subtask 2.5: Prototype flex-fuel genset-engine transient/controls dev

Reached:

Milestone 1.1: TRL 4 review
Milestone 1.2: Down selection of H2 fuel system
Milestone 1.3: Initial H2/NG controls logic developed
Milestone 1.4 TRL 5 Review
Milestone 2.1: Test cell upgrades complete
Milestone 2.2: Prototype engine build complete
Milestone 2.3 Genset rating dev complete

In-progress:

Subtask 2.6: Controls sub-system development, acceptance testing (M19 – M23)
Subtask 2.7: Systems Integration: Flexible CHP System (containerized) (M22 – M27)
Subtask 2.8: Prelim. modeling/analysis CHP scenarios, tools refinement (M13 – M24)
Subtask 3.0: Design and Permitting for CHPH2 demo site (M7 – M21)
Subtask 3.1: Demo site preparation including safety regulations (M22– M28)
Subtask 3.2: TEA, GHG, and TCO estimations (M28 – M30)

To be Started:

Subtask 3.3: Fuel (H2, NG) supply infrastructure installation (M28 – M29)
Subtask 3.4: Installation of CHP Genset Enclosure etc. on Demo Site (M30 – M31)
Subtask 3.5: Integrate MMC, RAM, Cybersecurity, and Commissioning (M31 – M32)
Subtask 3.6: CHPH2 System demo and data collection (M31 - 33)
Subtask 3.7: Final technical review and report (M35 – M36)
Subtask 3.8: Decommission of the system (M34 -36)

To be Reached:

Milestone 2.4: TRL6 review (Q8)
Milestone 2.5: CHP system build complete (Q9)
Milestone 3.1: Initial TEA, GHG and TCO numbers developed (Q10)
Milestone 3.2: Demonstration of CHPH2 completed (Q11)
Milestone 3.3: SMART Goal (End of project) TRL7 Review and final report completed (Q12)

10 Patent applications have been filed.

Future Work, Technology Transfer, & Impact

Future Work:

- Over 50% of the SOPO Tasks and Milestone have been completed
- In-progress: Demo site development, CHP genset integration, MMC Controls, Hydrogen Safety Plan, Field-follow and hydrogen supply agreements, GHG & TEA analysis, etc.

Technology Transfer:

- Caterpillar Hydrogen Based Power Generation Offerings Available:
  - Cat® G3516H DTO (Design To Order) for 100% hydrogen fuel for 50 or 60 Hz applications
  - Staged roll-out of commercial gas gensets configured for 25% hydrogen blended with natural gas
  - Retrofit kits to enable hydrogen fuel usage on existing natural gas engines
- 10 Patent applications have been filed

Impact:

- US made flex-fuel and hydrogen genset CHP systems available for sale throughout the world
- Environmental and economic benefits: Working with NREL to document these for a flex-fuel (NG/H2/blends) genset system with several infrastructure options

Questions?

Flexible Natural Gas/Hydrogen CHP System Development & Demonstration

- PI Jas Singh, Caterpillar Inc.
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Demo Site DESP, St. Paul, MN