U.S. Department of Energy (DOE)

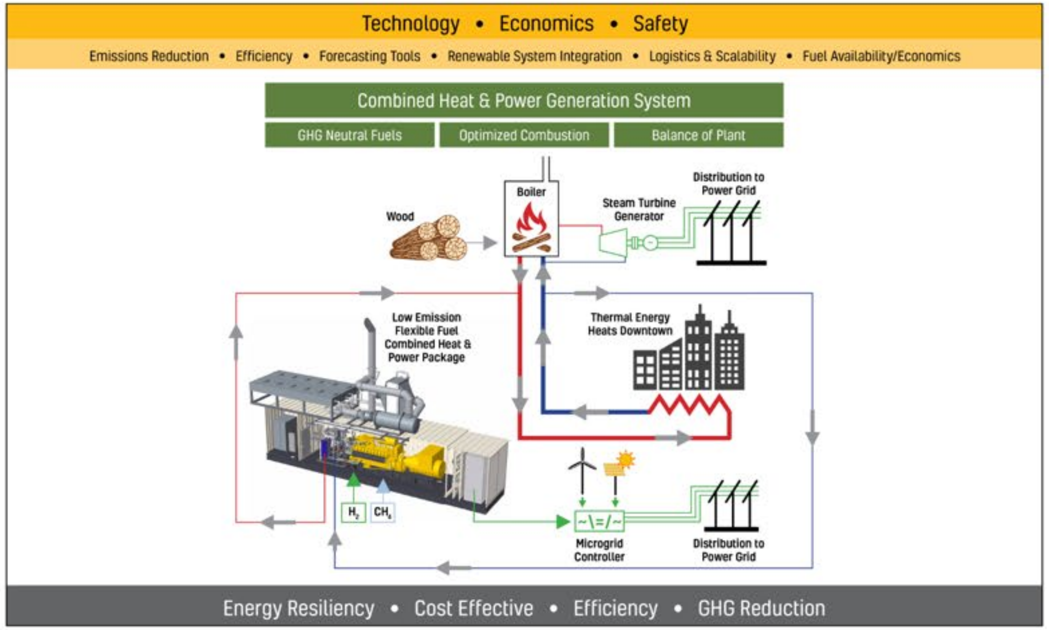
Combined Heat and Power/District Energy (CHP/DE) System Portfolio Meeting

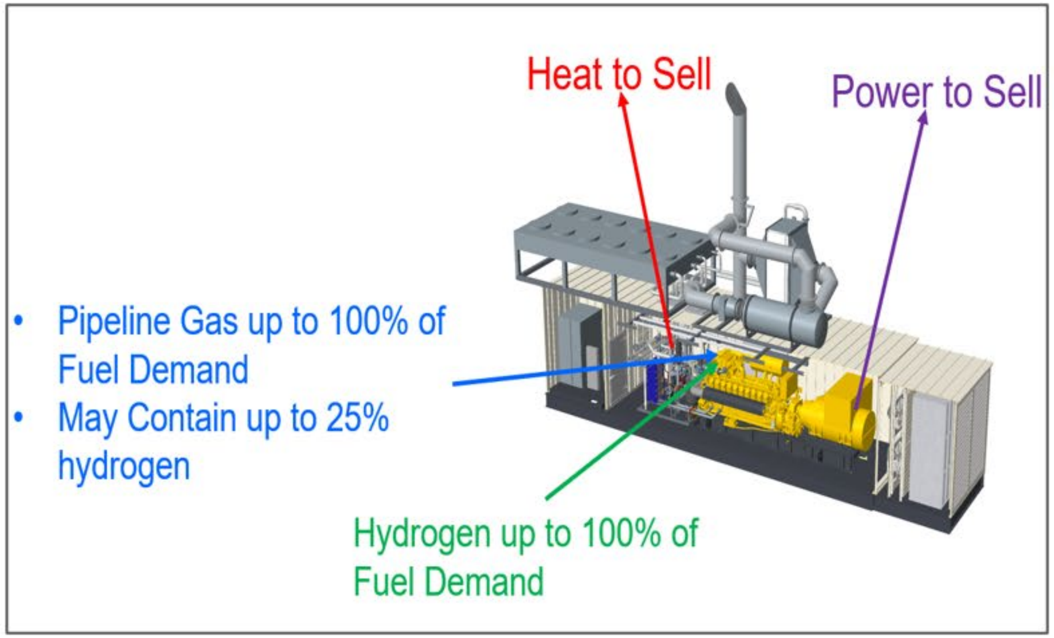
(June 7-9, 2022)

Flexible Natural Gas/Hydrogen Engine for Combined Heat and Power Applications

Flexible Natural Gas/Hydrogen CHP System Development & Demonstration

(DOE Award: DE-EE009422)





Principal Investigator & presenter:

Jas Singh, Caterpillar Inc.

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AGENDA

- Program overview & objectives
- External partners
- Single-cylinder engine testing results
- Demo site and preliminary design
- Significant results and next steps

DOE-Caterpillar CHP-Hydrogen(H2) Program

Duration: April 2021 – March 2024 (three years)

JAN 2021	MAR 2021	APR'21-MAY'22	JAN 2022	MAR-DEC '22	AUG 2023
DOE Award	Start-at-Risk	SCTE Work	Contract Execution	MCTE WORK	Demo at DESP

Budget: $12M (Caterpillar share: $7.45M, DOE share: $4.55M)

Key deliverables:

- Development of a hydrogen/natural gas flex-fuel 2.0 eMW 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.
  Capability to automatically and seamlessly:
  - respond to variations in electric power generation by the renewable(s) to maintain base-load operation of the facility, and
  - serve as a back-up generation asset for the grid

DOE-Caterpillar CHP-H2 Program:

Two Major Development Components

Flex-fuel Gas Genset System Development

A natural gas genset that also runs on:

- Blends of hydrogen + natural gas,
- 100% hydrogen,
- Meets performance requirements, and is
- Emission and safety compliant

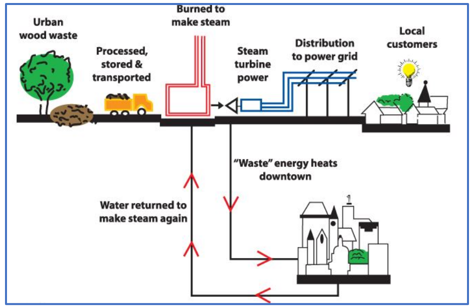
Power Electronics and Controls Development

- Enable CHP system integration into and coordination with the District Energy system power microgrid
- Compliance with grid/micro-grid codes
- Remote asset monitoring
- Cybersecurity

Program Team (External Partners)

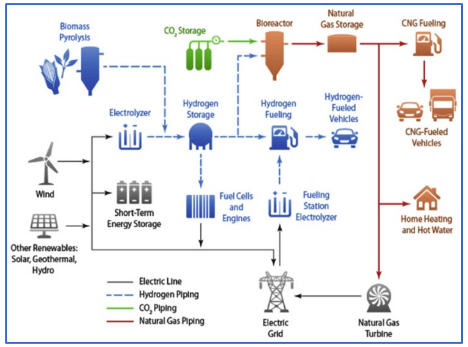
➢ District Energy St. Paul (DESP), MN

- Flex-fuel CHP power system demonstration site
  - We are finalizing the subcontractor agreement
  - We plan on leaving the containerized CHP plant for DESP to use after the demo is complete



➢ National Renewable Energy Lab

- Hydrogen safety/regulations experts, GHG & TEA analysis
  - Kickoff meeting held, planning to meet regularly



➢ McKinstry, LLC, and Ziegler Cat®

- Demo site permitting, preparation, and equipment installation
  - We are finalizing the subcontractor agreement w/McKinstry
  - Cat® dealer will help service the genset/CHP plant as needed

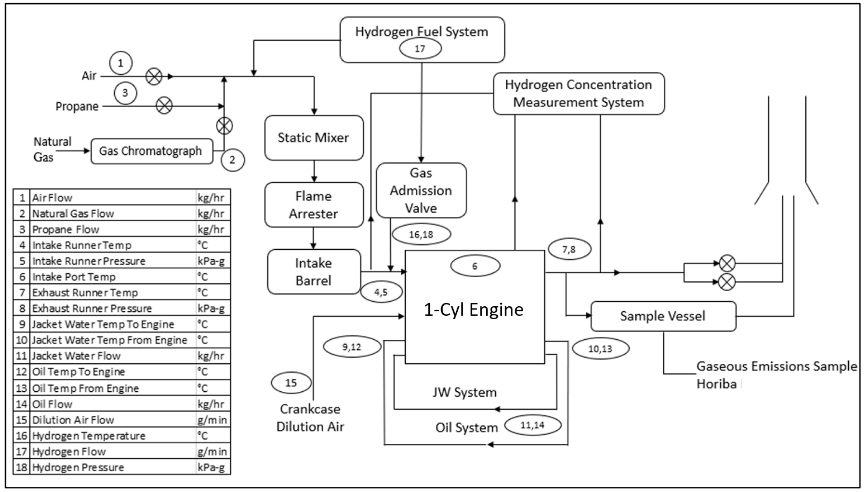
➢ Linde/PRAXAIR

- Green hydrogen fuel and fueling infrastructure supplier

1-cyl Engine Test Cell Prep: Engine Testing with H2 and NG+H2

➢ Key Systems and Considerations Put in Place

- Test cell & hydrogen supply systems
- High speed data acquisition systems
- H_2 port fuel injection system
- Generic instrumentation: Pr, Temp, Flow-rates
- Engine H_2 concentration measurement in test cell
- Engine exhaust emission measurement systems
- Instrumentation for complete JW & Oil HR measurement
- Lube oil quality evaluation plan
- Engine flame arresters
- Component temperature measurement
- Test cell safeties/trainings
- H_2 Safety: Regulations & Certification Requirements

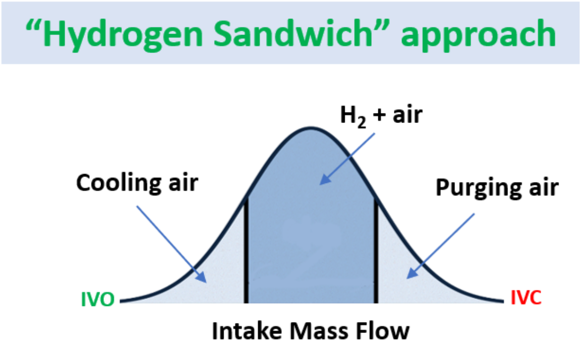


1	Air Flow	kg/hr
2	Natural Gas Flow	kg/hr
3	Propane Flow	kg/hr
4	Intake Runner Temp	°C
5	Intake Runner Pressure	kPa-g
6	Intake Port Temp	°C
7	Exhaust Runner Temp	°C
8	Exhaust Runner Pressure	kPa-g
9	Jacket Water Temp To Engine	°C
10	Jacket Water Temp From Engine	°C
11	Jacket Water Flow	kg/hr
12	Oil Temp To Engine	°C
13	Oil Temp From Engine	°C
14	Oil Flow	kg/hr
15	Dilution Air Flow	g/min
16	Hydrogen Temperature	°C
17	Hydrogen Flow	g/min
18	Hydrogen Pressure	kPa-g

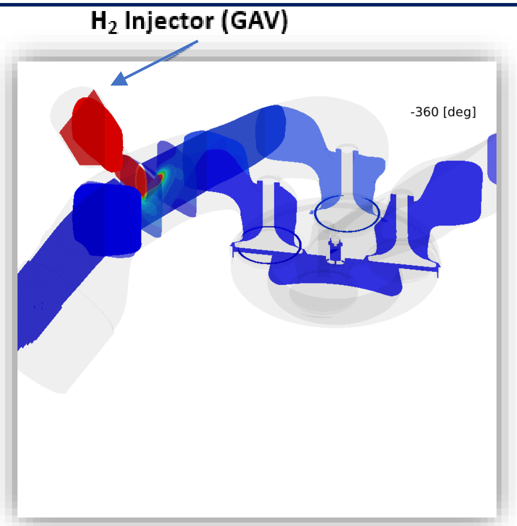
A schematic of the single cylinder engine laboratory.

100% Hydrogen Port Fuel Injection (PFI)

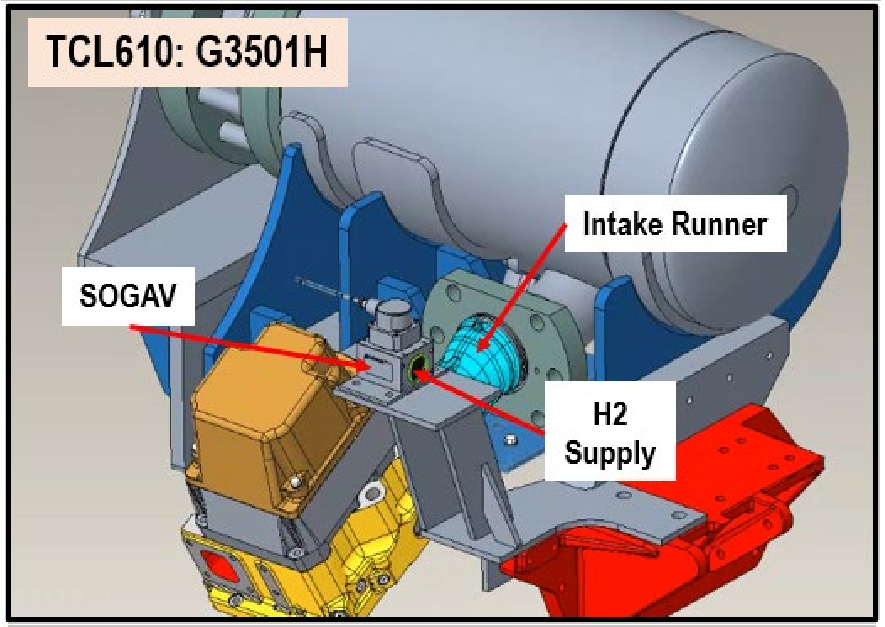
- Hydrogen port fuel injection through –
  - The side of cylinder head into intake port, and
  - Intake runner
- H2+NG blends will use modified premixed or fumigated system
- 1D/3D CFD simulation used to optimize design

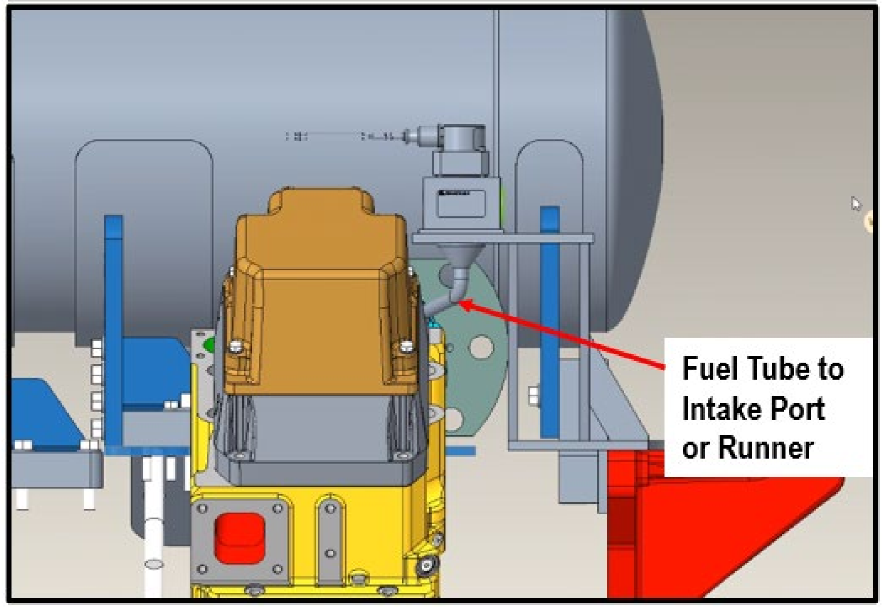


1. Cooling air mixes with exhaust residuals and cools off combustion chamber
2. Hydrogen is injected
3. Hydrogen injection stops, intake runner purged



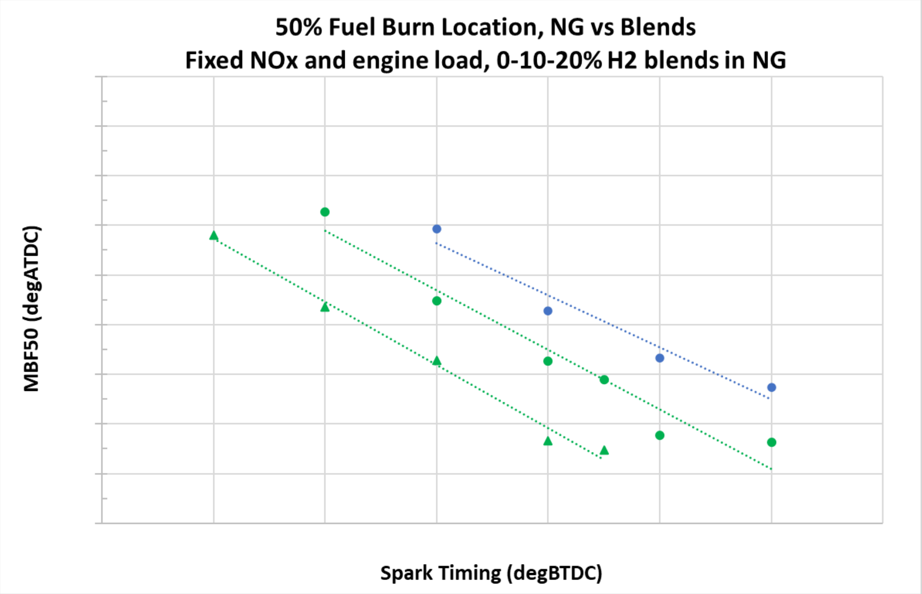
- Minimum leftover hydrogen in intake port with acceptable in-cylinder mixing

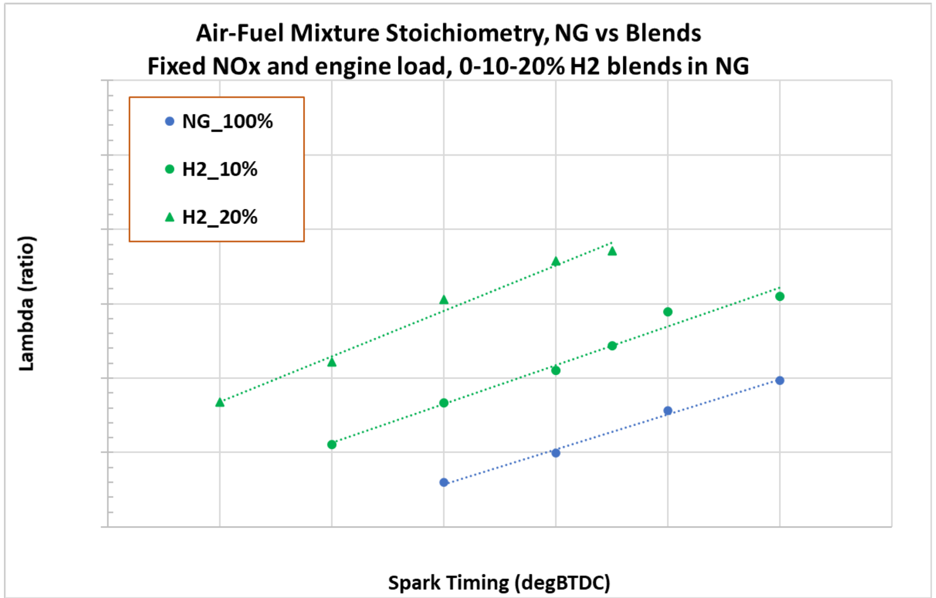


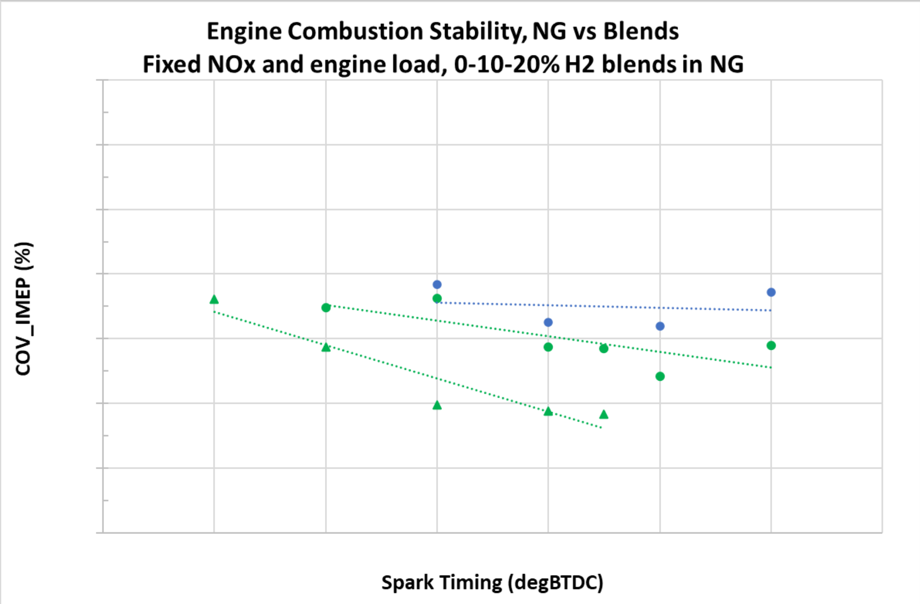


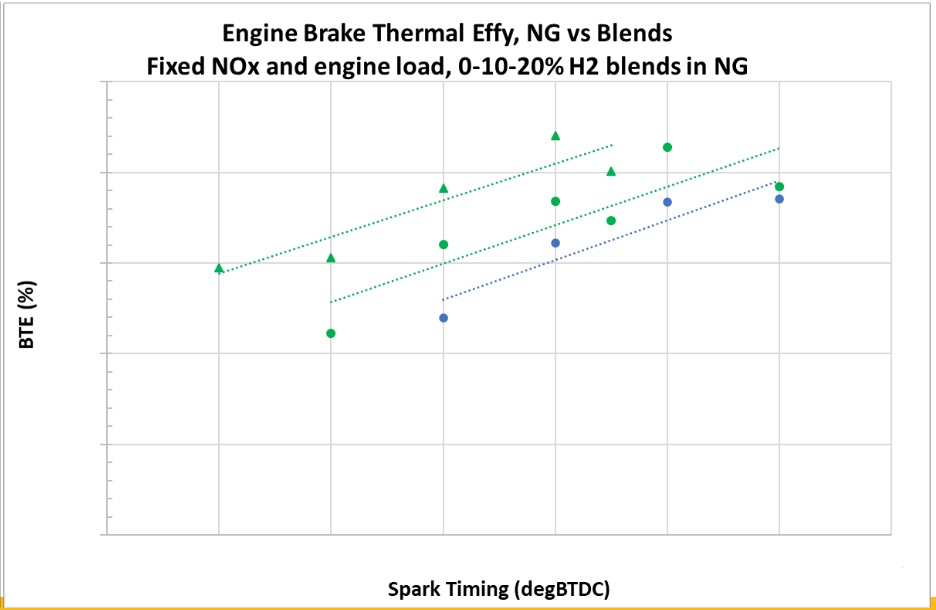
G3501 Flex-fuel Engine Performance with Hydrogen + NG Blends

Spark timing sweeps with NG and NG+H2 blends - fixed engine out NOx and engine load





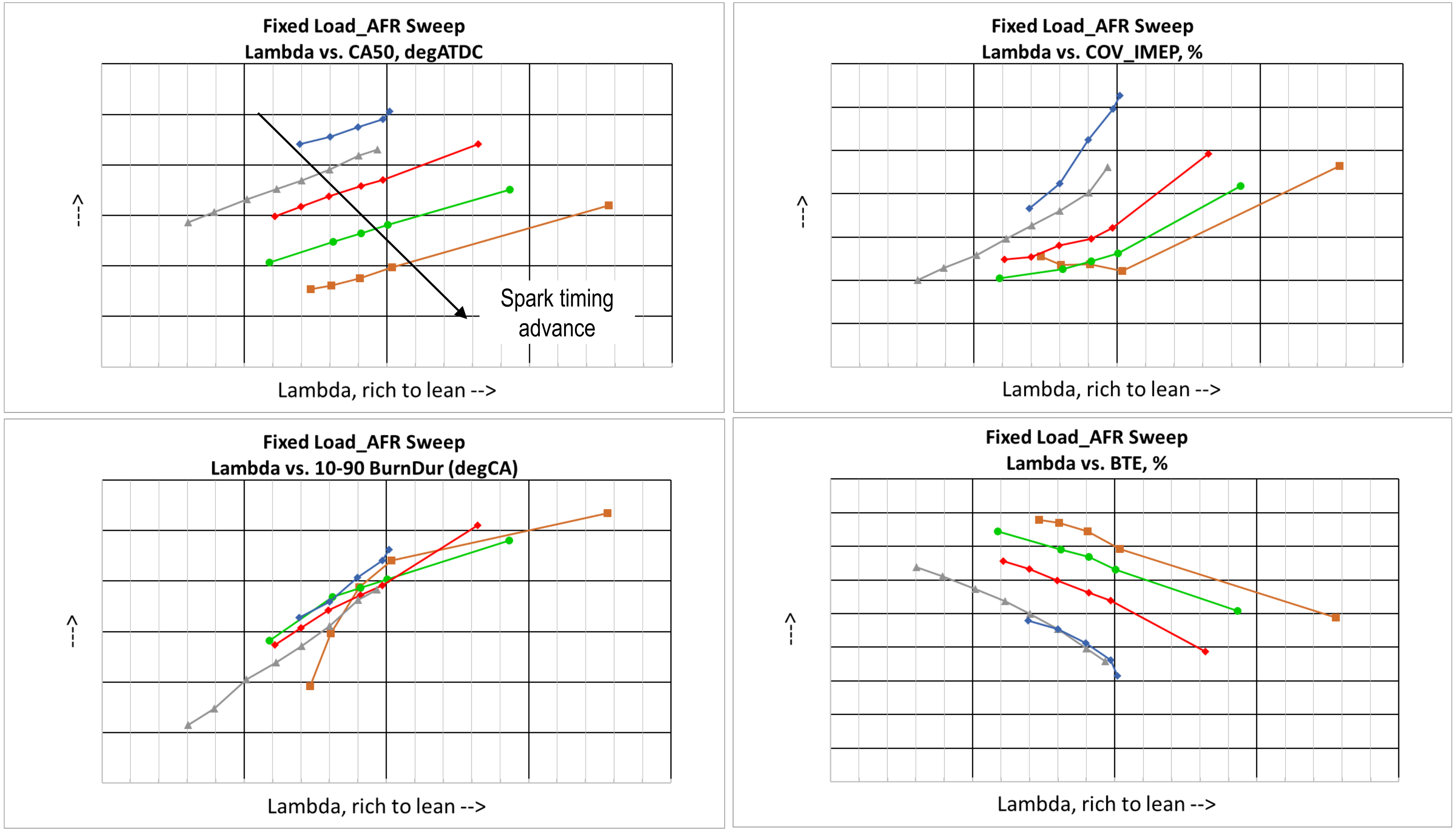




- Preliminary testing
- Faster combustion with increase in hydrogen conc., as shown by CA50 advance
- In order to maintain same NOx level as NG, spark timing retard required to keep same CA50, when running with hydrogen
- At a given spark timing, leaner AFR required with H2+NG vs with NG alone
- Similar, high BTE with NG+H2 blends as with NG alone

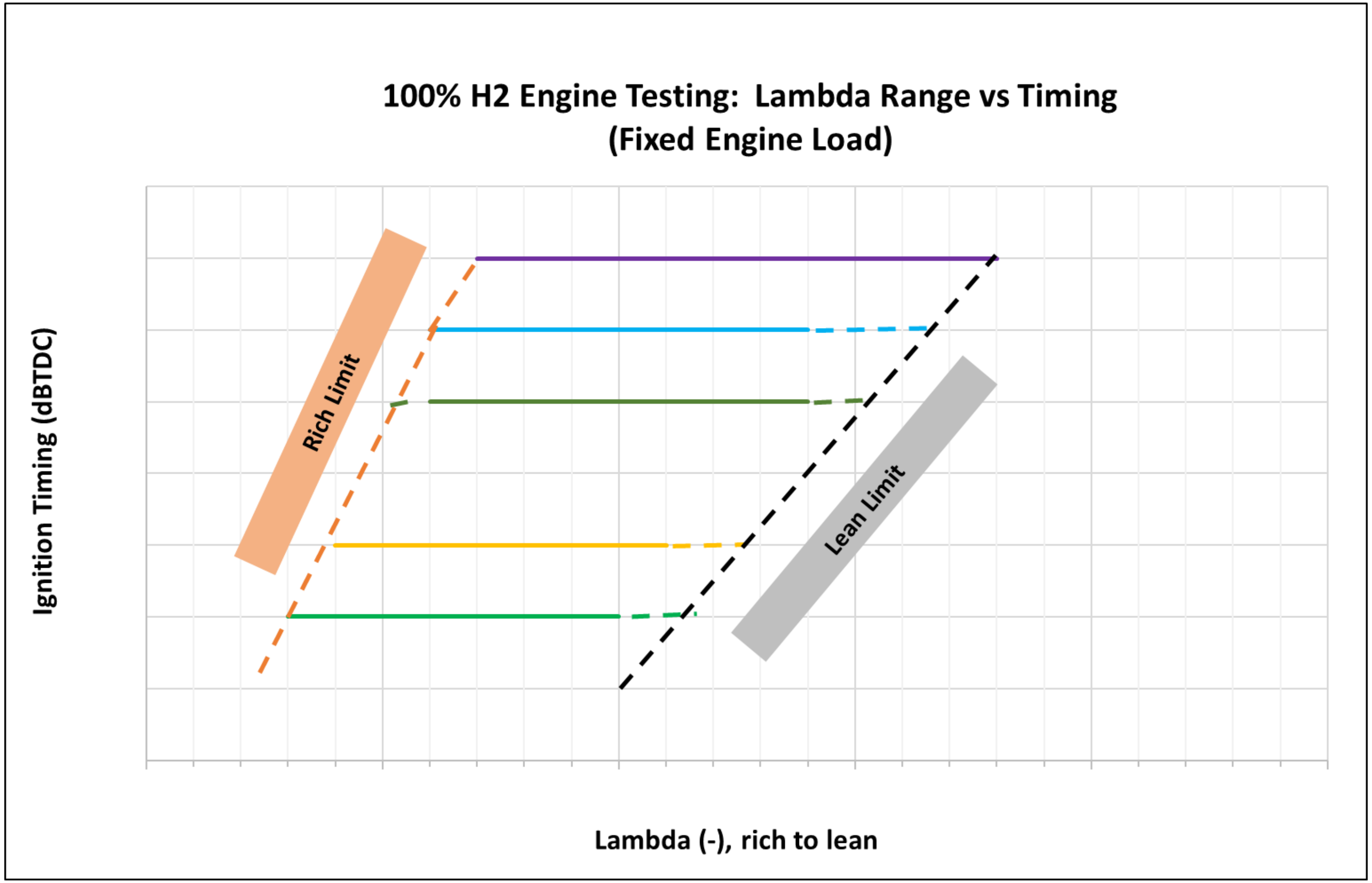
G3501 Flex-fuel Engine Performance with 100% Hydrogen

Fixed load AFR (or Lambda) sweep at various spark timings



- Faster combustion with richer lambda, as shown with CA50 advance and shorter 10-90 burn duration
- 10-90 burn duration trends down with richer lambda, but not always w/retarded ST
- More stable combustion with richer AFR and advanced spark timings
- Higher BTE, as with more advanced spark timing, is possible with retarded spark timing and richer AFR, to some extent

G3501 Hydrogen Engine Performance with 100% Hydrogen

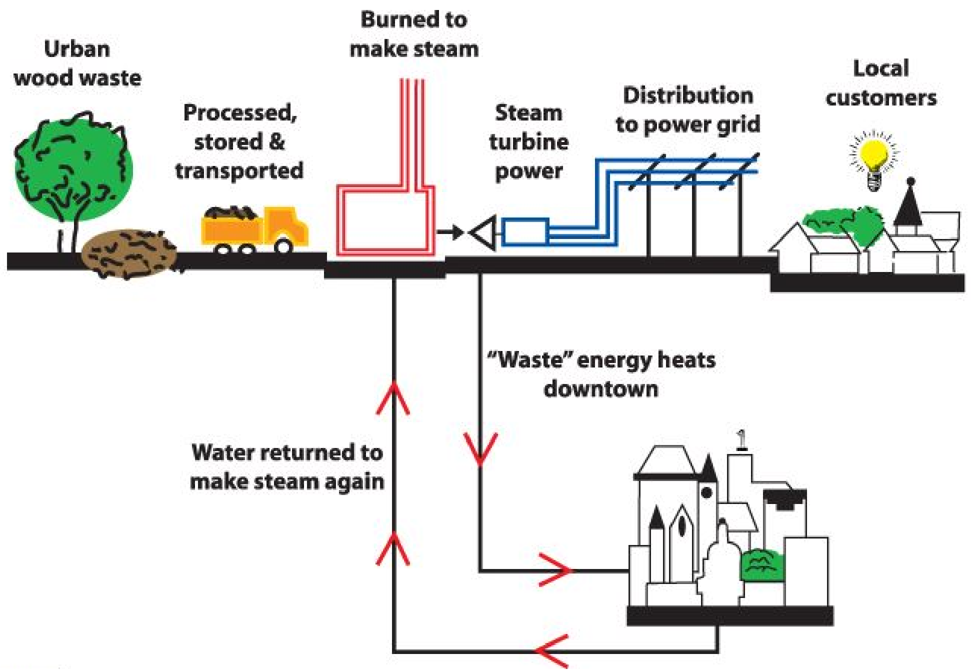


- Engine operating space mapping has been done, or operating boundaries have been defined based on detailed single-cylinder engine testing
- Rich and lean limit boundaries are shown here for various engine operating conditions of spark timings and lambda (or AFRs) at a given engine load

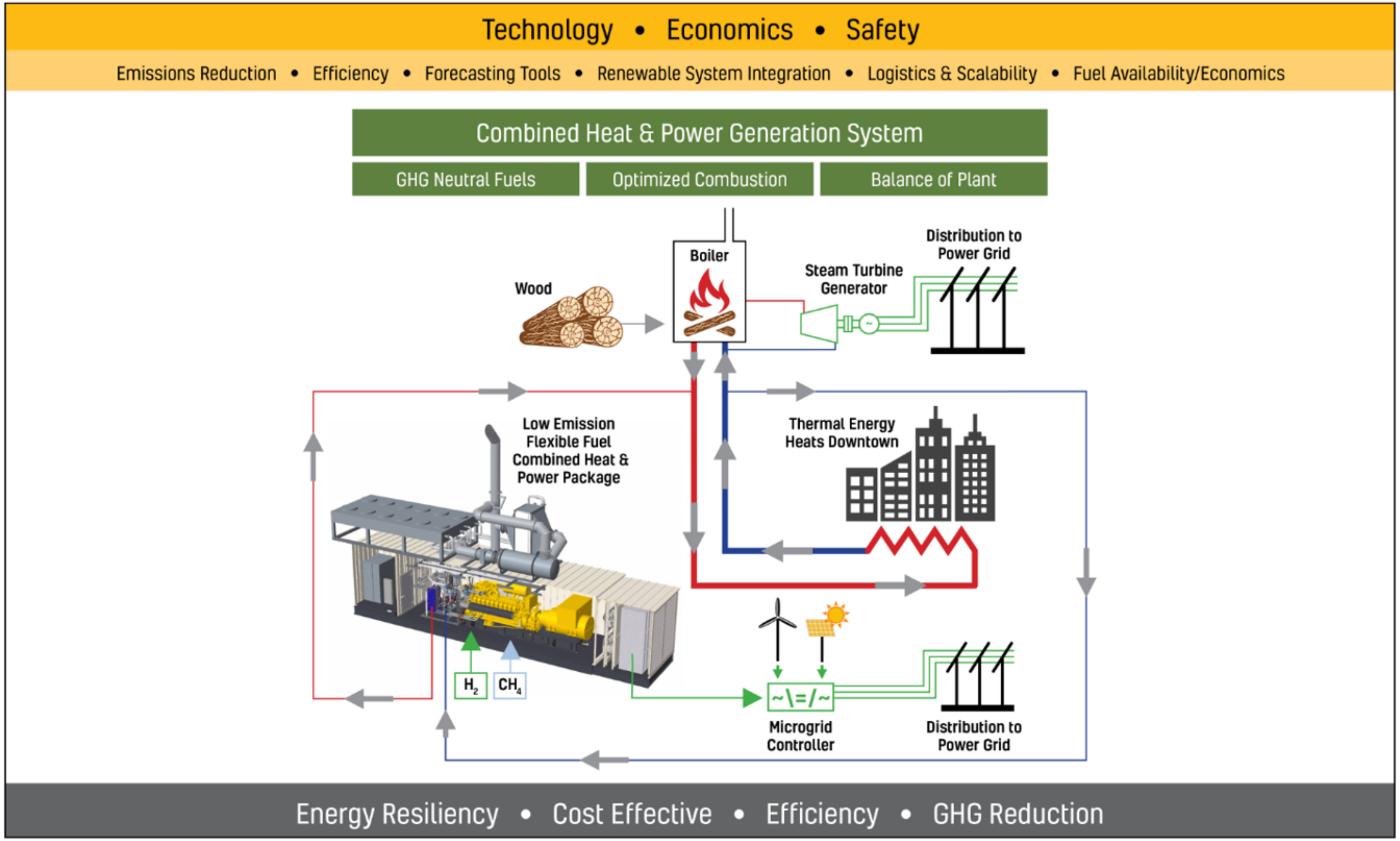
Demo Site: District Energy St. Paul (DESP)

- Nonprofit utility, country's best-known district energy systems
- Biomass-fired CHP, and solar thermal
  - Tree waste from over 115 communities in 22 counties - 260,000 tons of wood chips/year
  - Produces approximately 33 megawatts of electricity and up to 65 megawatts of heat
  - Helps avoid 100,000 tons of carbon each year
- 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 cool water distribution pipes
- The district heating network uses medium temperature (180 degF to 250 degF) hot water (typical hot supply at 210 degF & return 140 degF)

District Energy St. Paul
76 W Kellogg Blvd, St Paul, MN 55102

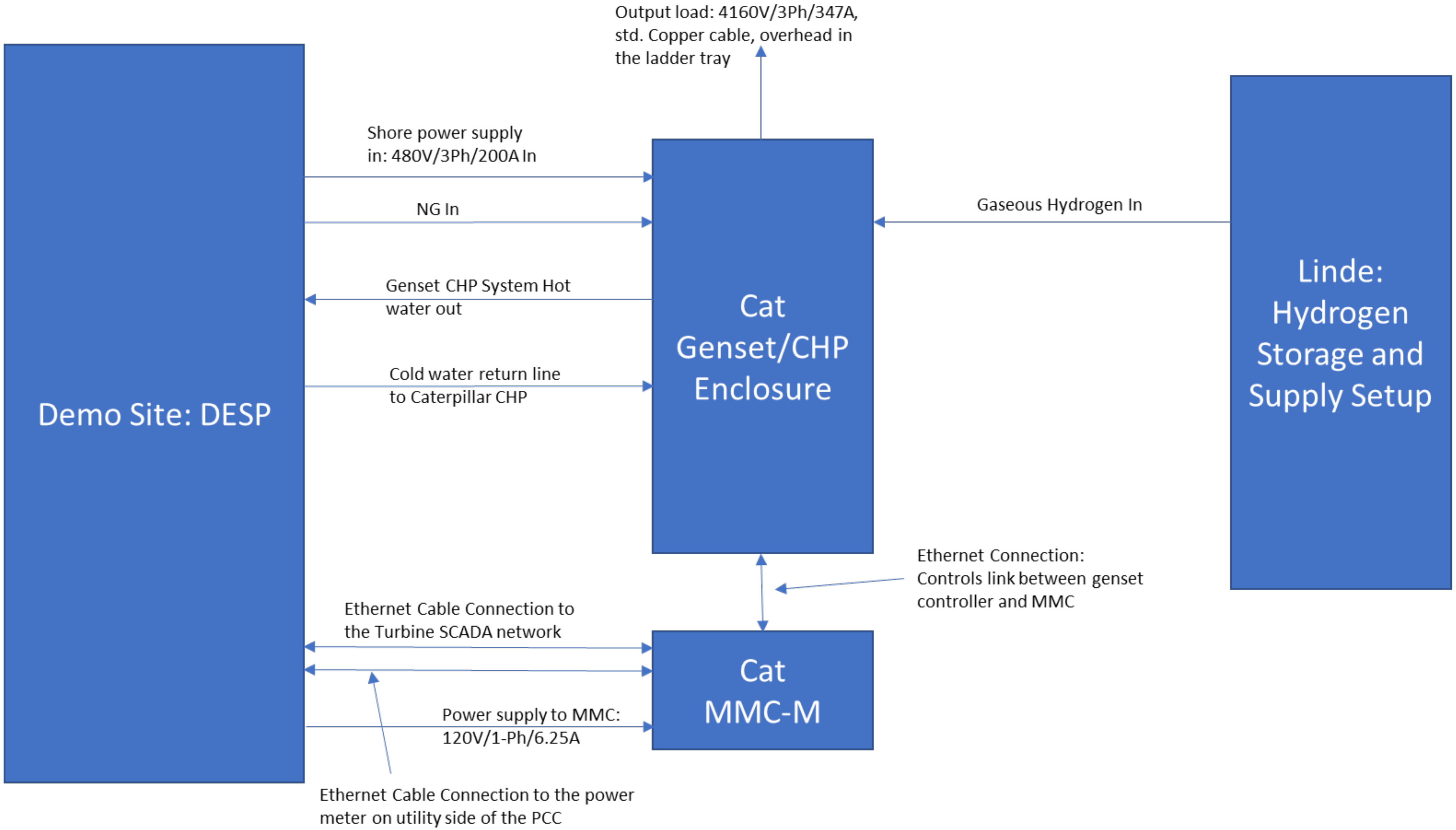


District Energy St. Paul, Demo Config: Integrated Cat® DOE CHP-H2 System



- *2.0 eMW flex-fuel (hydrogen and natural gas) genset and CHP system in an enclosure (aka CHPH2 system)*
  - *CHPH2 system will connect to the same power and heat network as the existing wood fired steam turbine*
- *Site load will be able to accept all the power and heat we can deliver from the CHPH2 system, even in summer months*

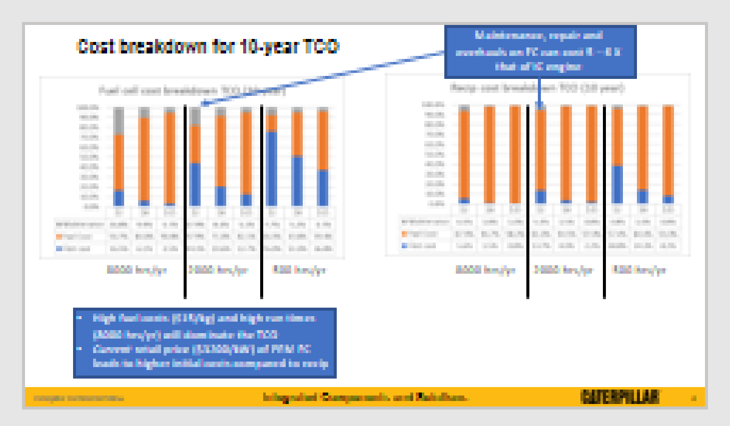
Cat® DOE CHPH2 Demo Site High-level Schematic

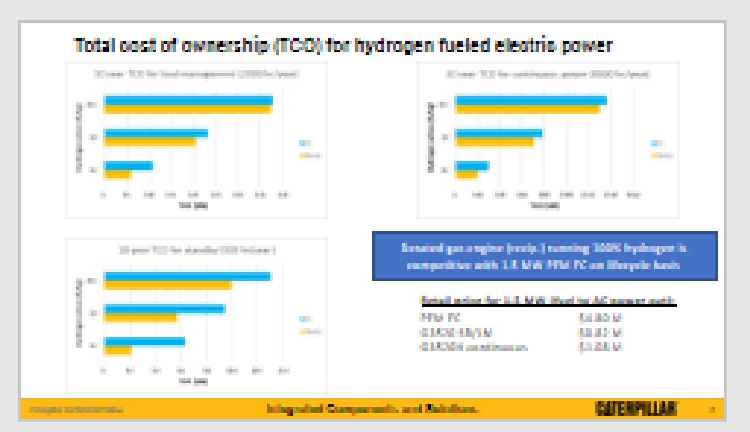


Preliminary Total Cost of Ownership (TCO) Analysis: Hydrogen PEM Fuel Cell vs. Reciprocating Engine (Recip.)

Inputs for TCO Analysis

- The total cost of ownership (TCO) over 10 years for hydrogen fueled electric power are estimated:
  - Proton Exchange Membrane (PEM) Fuel Cell (FC)
  - G3520 long stroke engine with modifications (Recip)
- Customer requirement of zero GHG emissions at point of generation
- Hydrogen fuel price range: $2/kg (futuristic) - $15/kg (current production)
- Electric power applications:
  - Continuous power (8000 hours/year)
  - Load management (2000 hours/year)
  - Standby (500 hours/year)
- Waste heat recovery is not considered in this initial analysis and not suited for PEM FC
- Current PEM fuel cell prices are high and are projected to decrease to < $400/kW
- TCO comparison for both technologies (PEM FC, recip) will continue to mature throughout the DCPEM and CHPH2 programs





Summary of Findings

- The gas engine modified for running on hydrogen (40% derate) is ***competitive*** against the ***current*** PEM FC from a TCO perspective
- Buying decisions are not solely driven by TCO. Other influences could be driven by regulatory requirements.
- TCO comparison for both technologies (PEM FC, recip) will continue to mature throughout the DCPEM and CHPH2 programs

National Renewable Energy Lab (NREL) Proposal For The Technoeconomic & GHG Impact Analysis (TEA/GHG)

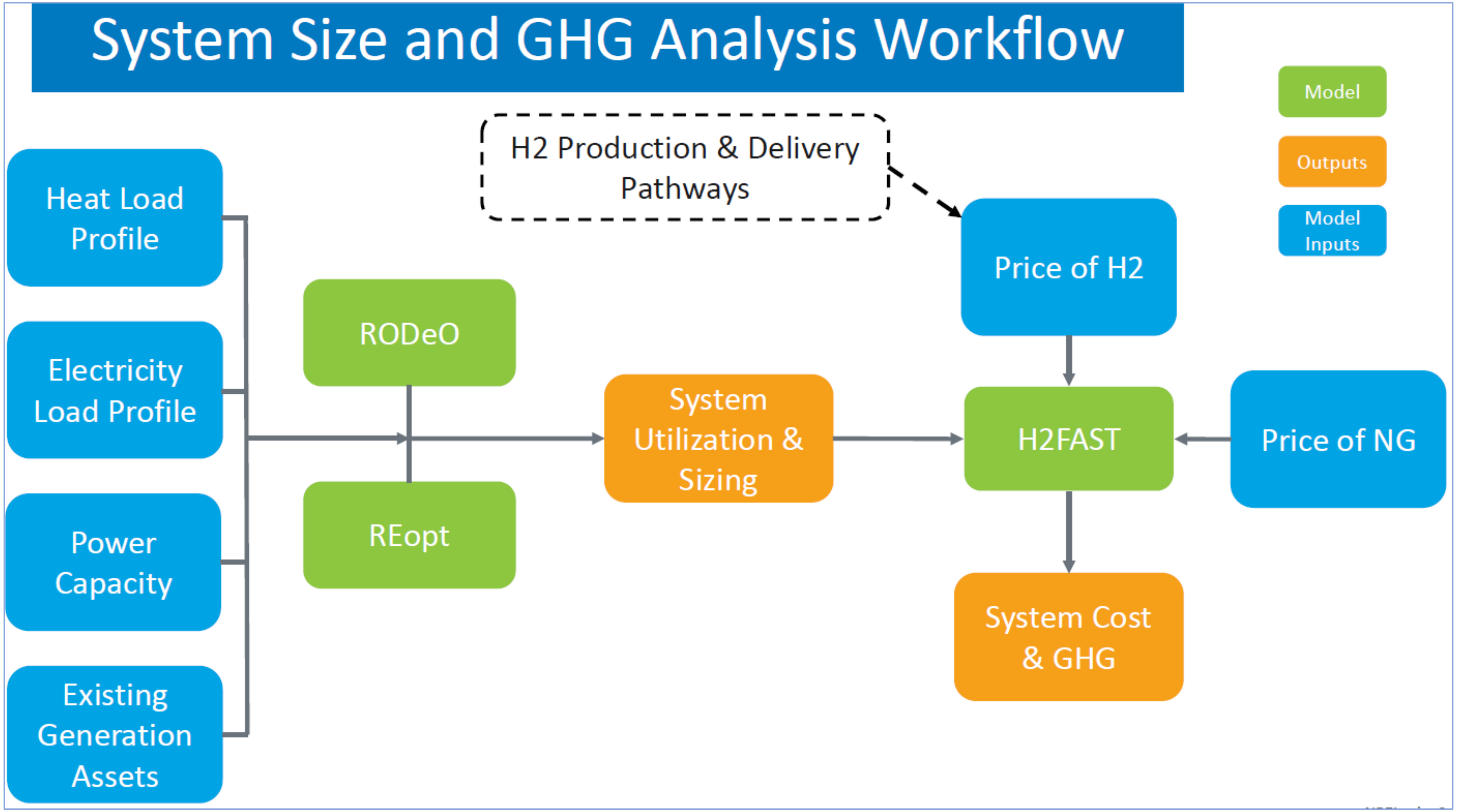
- The TEA will focus on the economic and environmental benefits of a flexible fuel (NG/H2/mix) combustion engine with several infrastructure options including Combined Heat & Power or CHP, renewable power sources, energy storage system (ESS), renewable hydrogen production & storage, fuel cells, micro-grid, etc.

- Analysis will encompass the system sizing, economics and emissions impacts of different system designs and operation modes.

  Specific aspects that the analysis will include:

  - Regionalized analysis of wind/solar resources and impact on H2 production
  - Regional and seasonal variation of natural gas prices, high/low spark spread
  - Impact on operation and costs with different NG/H2 blends
  - Performance and reliability of onsite infrastructure and power production to meet targeted load profiles
  - Potential for grid auxiliary services on top of primary demands
  - Cost optimization to minimize total system cost and maximizing GHG reduction

System Sizing & TEA/GHG Analysis Workflow w/various Required Inputs & Tools



Significant Results To-date

Following Subtasks and Milestones Have Been Completed:

- Single cylinder test cell upgrades and testing with hydrogen
- Design and development of Port Fuel Injection (PFI) for hydrogen
- Prototype engine hardware preparation and procurement
- Multi-cylinder Test Cell upgrades for hydrogen
- Initial H2/NG combustion controls logic developed for use on both single- and multi-cylinder prototype engine

SOPO Tasks: Plan for Rest of 2022

We plan to work on following tasks to accomplish other goals of the program:

- Single cylinder engine testing on NG and NG+H2 blends
- Engine Controls Dev for hydrogen/natural gas/and blends
- Prototype flex-fuel engine/genset build and instrumentation
- Flex-fuel genset development - steady state and controls work
- Genset Transient/Controls work
- Power electronics and Controls sub-systems development for the demo unit
- Get permits for the demo site
- Define various CHP scenarios, develop tools for TEA

THANKS!