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Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

# 2022 Combined Heat and Power/District Energy System Portfolio Meeting

Summary Report

June 7–9, 2022

# Disclaimer

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# List of Acronyms

| | |
|---|---|
| AC | Alternating current |
| AFA | Alumina-forming austenitic |
| AFR | Air–fuel ratio |
| Al | Aluminum |
| AM | Additive manufacturing |
| AMO | Advanced Manufacturing Office |
| APC | Argon power cycle |
| API | Application programming interface |
| Btu | British thermal unit |
| CAISO | California Independent System Operator |
| CHP | Combined heat and power |
| CLI | Command line interface |
| $CO_2$ | Carbon dioxide |
| COP | Coefficient of performance |
| CPES | Virginia Tech Center for Power Electronics Systems |
| Cr | Chromium |
| DC | Direct current |
| DE | District energy |
| DER | Distributed energy resource |
| DER-VET | Distributed energy resource value estimation tool |
| DES | District energy system |
| DiTTo | Distribution transformation tool |
| DOE | U.S. Department of Energy |
| DSM | Demand side management |
| DSS | Distribution system simulator |
| EPRI | Electric Power Research Institute, Inc. |
| ERCOT | Electric Reliability Council of Texas |
| F-CHP | Flexible combined heat and power |
| Fe | Iron |
| FOA | Funding opportunity announcement |
| FY | Fiscal year |
| GEB | Grid-Interactive Efficient Buildings |
| GIS | Graphic information system |

| | |
|---|---|
| GMT | GeoJSON to Modelica Translator |
| GUI | Graphical user interface |
| GW | Gigawatt(s) |
| GWU | George Washington University |
| $H_2$ | Hydrogen |
| $H_2$+NG | Hydrogen and natural gas |
| HARC | Houston Advanced Research Center |
| HFO | Hydrofluoroolefin |
| HX | Heat exchanger |
| Hz | Hertz |
| IDEA | International District Energy Association |
| IEEE | Institute of Electrical and Electronics Engineers |
| IN718 | INCONEL® Alloy 718 (a nickel–chromium alloy) |
| K | Specific heat |
| kg | Kilogram(s) |
| krpm | Kilo revolutions per minute |
| kV | Kilovolt(s) |
| kW | Kilowatt(s) |
| kWh | Kilowatt-hour(s) |
| kW/L | Kilowatt(s) per liter |
| L | Liter(s) |
| lb | Pound(s) |
| LBO | Lean blowout |
| LHV | Lower heating value |
| LiDAR | Light detection and ranging |
| LTN | Low-temperature network |
| MAWP | Maximum allowable working pressure |
| MISO | Midcontinent Independent System Operator |
| MMT | Million metric tons |
| MOSFET | Metal-oxide semiconductor field-effect transistor |
| $MtCO_2e$ | Metric tons of carbon dioxide equivalent |
| MW | Megawatt |
| MWe | Megawatt(s) electric |
| $N_2$ | Nitrogen |
| NETL | National Energy Technology Laboratory |

| | |
|---|---|
| NG | Natural gas |
| $NO_x$ | Nitrogen oxide |
| NREL | National Renewable Energy Laboratory |
| NYISO | New York Independent System Operator |
| $O_2$ | Oxygen |
| ODS | Oxide dispersion strengthened |
| ORC | Organic Rankine Cycle |
| OSAF | OpenStudio® Analysis Framework |
| P | Active power rating |
| PCS | Power conditioning system |
| PJM | PJM Interconnection LLC (Pennsylvania, New Jersey, and Maryland) |
| psi | Pounds per square inch |
| PURPA | Public Utility Regulatory Policies Act |
| PV | Photovoltaic(s) |
| Q | Reactive power rating |
| Q&A | Question and Answer |
| RICE | Reciprocating internal combustion engine |
| RL | Reinforcement learning |
| RNG | Renewable natural gas |
| RNM-US | United States Reference Network Model |
| R&D | Research and development |
| ROI | Return on investment |
| RPM | Revolutions per minute |
| SA | Supplement A |
| $sCO_2$ | Supercritical carbon dioxide |
| SDK | Software development kit |
| SiC | Silicon carbide |
| SOFC | Solid oxide fuel cell |
| STEP | Supercritical Transformational Electric Power |
| SwRi | Southwest Research Institute |
| T | Temperature |
| TAP | Technical Assistance Partnership |
| TCCS | Turbo-compression cooling system |
| TES | Thermal energy storage |
| TRL | Technology readiness level |

| | |
|---|---|
| UL | Underwriter Laboratories |
| URBANopt | Urban Renewable Building and Neighborhood optimization |
| V | Volt(s) |
| W | Watt(s) |

# Table of Contents

# Introduction

The U.S. Department of Energy's (DOE's) Advanced Manufacturing Office (AMO) held the 2022 Combined Heat and Power/District Energy System Portfolio Meeting on June 7–9, 2022. The meeting was hosted at Southwest Research Institute (SwRI) in San Antonio, Texas. The meeting brought together approximately 50 researchers from industry, national laboratories, and research institutes; participants attended primarily in person, with a few attending virtually in response to the ongoing COVID-19 pandemic.

The meeting began with Dr. Robert Gemmer, Technology Manager of Research and Development for AMO, welcoming participants. Afterwards, Tim Allison from SwRI provided a safety and history briefing of the facility. The meeting continued with presentations on combined heat and power (CHP) and district energy (DE) systems, including an overview of the AMO CHP program and discussions of the technologies' current status. For the remainder of the event, principal investigators presented on projects that comprise the AMO CHP/DE research and development (R&D) portfolio, explaining project goals and objectives, approaches, and results to date. Each presentation was followed by a question-and-answer (Q&A) session. The meeting also included a facility tour of SwRI on the second day. The full agenda is available in Appendix A. Each presentation has been saved on the 2022 Combined Heat and Power & District Energy System Portfolio Meeting website.

The purpose of the meeting was for DOE to understand the performance of the projects being sponsored through the CHP program and the status of the technology development, which informs future program planning. The event also provided networking opportunities and fostered future collaboration.

# Presentation Summaries

## *Day One*

### Overview of CHP Program

*Robert Gemmer, Advanced Manufacturing Office*

Dr. Gemmer presented an overview of the AMO CHP activities at DOE and highlighted the potential for rapid growth in small to mid-sized CHP and DE systems.

AMO CHP efforts use a two-pronged approach: (1) the CHP Deployment Program, which provides technical assistance to stakeholders interested in CHP, including the resources necessary to identify CHP market opportunities, and (2) the CHP R&D Program, which supports the development of cost-effective CHP systems in industrial, commercial, institutional, and other applications. An important aspect of AMO's CHP work is the close integration and collaboration between the R&D and technical assistance components.

While currently deployed CHP systems are fueled mostly with natural gas, CHP is not fundamentally a fossil fuel technology but rather an energy conversion technology that can work with any fuel. Compared with other power generation methods, CHP deployment leads to increased energy usability, efficiency, reliability, and resilience. Furthermore, CHP supports increased integration of variable renewable energy sources by providing a dispatchable resource, addressing the issue of intermittency.

There are commercial and institutional opportunities for CHP, and its future in fiscal year 2022 and beyond is strong, especially given the current administration's prioritization of decarbonization. Work is being done to emphasize where CHP fits in the overall marketplace, including outside of the manufacturing space. Historically, CHP has been a one-off design approach tied to a chemical plant, but there are many small to mid-size entities, unaware of CHP, that could benefit from its adoption.

To leverage this opportunity, the CHP Deployment Program established the CHP Technical Assistance Partnerships (TAPs): ten regional groups within the United States that can provide interested entities with technical support. TAPs evaluate whether CHP, waste heat to power, or DE technologies are a good fit for a possible end user and support technology implementation. The TAPs provide screenings based on past energy use data and perform engineering analyses for CHP opportunities, including potential end users that lack in-house resources to perform these analyses (e.g., hospitals or small businesses). TAPs help potential end users navigate the various tools available, including the eCatalog. The CHP eCatalog is a national web-based catalog of DOE-recognized packaged CHP systems supported by CHP suppliers and outreach partners. This online resource allows users to search for CHP system characteristics, compare technology options, and get connected to packagers, installers, and CHP engagement programs.

In the R&D space, there are opportunities in electrification and decarbonization, CHP systems with high power-to-heat ratios, and flexible CHP (F-CHP) systems that support the future grid and its incorporation of distributed energy resources (DERs). The presentations on the first day focused on the F-CHP portion of the R&D portfolio. In this future grid, power flows will be bi-directional and managed by interconnected information and control systems. It will be an interactive matrix, with electricity produced by a variety of resources, including customers who can provide energy back to the grid to supply other customers; small and mid-sized industrials offer significant potential as suppliers. However, additional technologies are needed to integrate these entities with the grid. With increasing incorporation of renewable energy sources and sudden demand spikes, the grid will become more stressed. F-CHP systems can respond rapidly when additional power is needed. To pursue this vision, AMO is sponsoring projects that focus on CHP R&D and demonstrations, as well as DE systems.

**Key Points Raised During Q&A**

- Rather than providing a software within the eCatalog for people to do their own first-level CHP systems analysis, TAPs perform a screening and use the eCatalog to identify systems with specific performance characteristics.
- REopt, a tool used by the National Renewable Energy Laboratory, can help optimize energy systems through screenings and tools.
- An activity within AMO is looking into controlled environment agriculture with respect to the CHP market.

## CHP Markets and Decarbonization

### CHP Market Overview

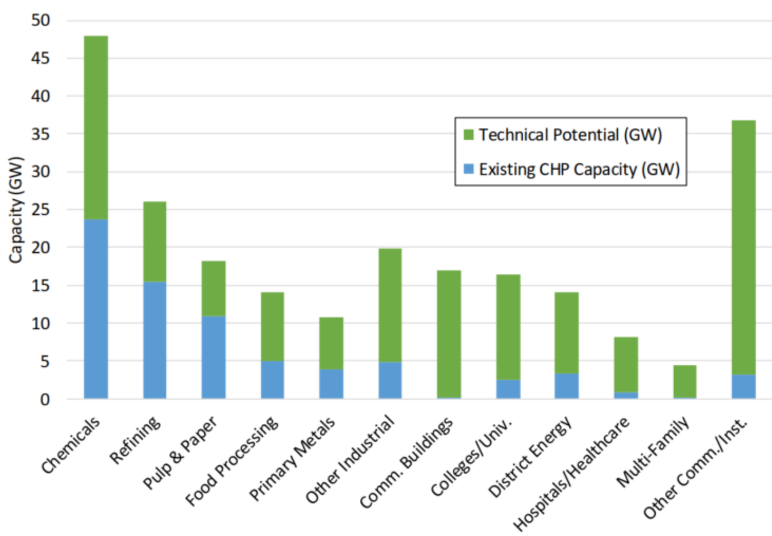
*David Jones, ICF*

By using CHP, the United States avoids over 1.3 quadrillion Btus of fuel consumption and 215 MMT of $CO_2$ emissions annually. There is 81.7 GW of installed CHP at more than 4,700 industrial and commercial facilities. Though California and New York have the highest number of CHP installations in the nation, Texas has the highest total CHP capacity, roughly double that of California (the state with the second-highest capacity). Although they have the highest existing CHP capacity, Texas and California also represent the highest remaining CHP technical potential.

Most of the existing CHP in the nation is in the industrial sector, and refining and chemicals make up nearly half (~48%) of the total capacity. The multi-family buildings market sector has the highest number of installations, but the highest capacity for energy generated from CHP is in the chemicals sector, followed by petroleum refining. Prior to 2016, the chemicals sector also had the most installations, but there was a shift between 2016 and 2020, and now there are more CHP installations in commercial and institutional sectors (e.g., multi-family buildings and hospitals) than in larger industrial/utility areas. Recent trends are also showing an increase in smaller installations in commercial markets (e.g., packaged CHP and micro CHP).

The primary CHP fuel source is natural gas (~70% of systems), followed by renewables. Renewable sources of fuel include biomass (wood or other), digester gas, and landfill gas, among others.

Natural gas CHP can reduce carbon emissions in most U.S. locations. Net on-site CHP emissions are typically in the range of 600–800 lbs per megawatt-hour of electricity produced. As noted in Dr. Gemmer's CHP overview presentation, CHP TAPs are active across the United States, engaging new stakeholders and end users to support CHP adoption. Between 2018 and 2021, 303 engagements were completed with 204 newly identified end users, and 633 technical assistance activities supported an estimated CHP capacity of 991 MW.




Source: DOE CHP Technical Potential report, 2016

*Figure 1. CHP applications and market trends.*

CHP offers 24/7 resilience from multi-day grid outages and serves as an anchor for microgrids. Paired with photovoltaics (PV) and energy storage, CHP can maximize resilience while minimizing emissions. By incorporating renewables and low-carbon fuels into CHP, carbon emissions can be further reduced. Furthermore, as more variable renewable electricity is incorporated into the grid, F-CHP systems can help support it.

While CHP is gaining ground, there is still substantial technical potential in the commercial and industrial sectors, as shown in Figure 1.

**Key Points Raised During Q&A**

- In the United States, the current payback period for CHP depends on many variables (e.g., location, electricity/gas prices, site demand). When electricity prices are high, the payback period may be five years or less; in places with low electricity prices and spark spread, the payback period can be over ten years.
- Batteries can be used for energy storage (e.g., thermal storage). They have been used effectively with CHP. The economic case for storage is expected to grow.
- Most of the microgrids that operate continuously have CHP.
- The CHP Deployment Program is working on determining a strategy to prioritize CHP deployment in places with the most emissions reduction potential. Determining whether CHP makes sense economically or logistically for facilities is the role of the TAPs.
- Currently, there are only a few examples of F-CHP systems selling excess power back to the grid. It is occurring at sites that prioritize the use of their systems based on what the grid needs. The goal is to increase using F-CHP and selling power back to the grid.
- Prior to 2006, the Public Utility Regulatory Policies Act (PURPA) encouraged large facilities to export power. After 2006, there was a policy change, and power export was no longer profitable.

## CHP and Decarbonization

*Bruce Hedman, Entropy Research*

CHP can have an important role in decarbonizing the U.S. economy and U.S. industry, particularly in providing low- or net-zero-carbon energy services to applications and processes that do not lend themselves easily to electrification or need dispatchable onsite power for long-duration energy resilience and operational reliability. A key feature of CHP is its fuel flexibility. While 72% of existing CHP capacity is fueled by natural gas because of its historic availability, low emissions, ease of use, and moderate price, 15% of CHP capacity (and close to 25% of CHP installations) is fueled by renewable fuels, low-carbon waste fuels, and hydrogen where available. In the future, CHP technologies will be capable of using higher amounts of biogas, renewable natural gas (RNG), and hydrogen as these fuels become more available. Current CHP systems using natural gas do not need to become stranded assets, thanks to the fuel flexibility and ability to modify systems to accommodate emerging renewable and zero-carbon fuels.

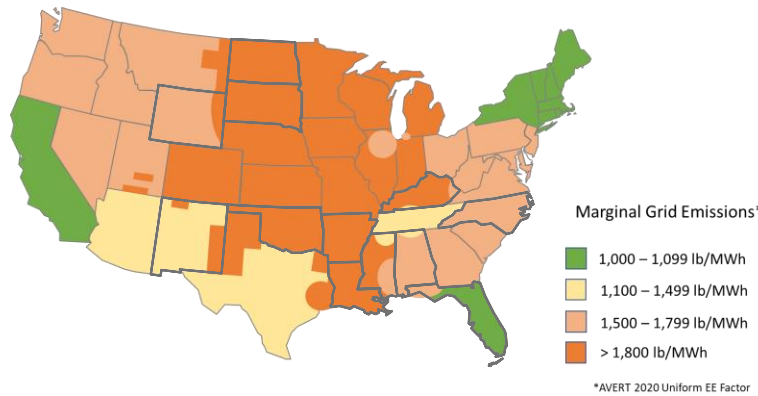


*Figure 2. The marginal grid.*

Additionally, CHP is the most efficient way to generate power and thermal energy from combustion, which results in significant $CO_2$ reductions and fuel savings. Well-designed and -operated natural gas CHP systems can produce power with lower $CO_2$ emissions (430 to 610 lb $CO_2$/MWh) than current marginal grid generation resources in all regions of the United States (see Figure 2). While economy-wide electrification and decarbonization of electricity generation are being pursued aggressively in many states and cities, fossil fuels (specifically natural gas) are likely to remain as the marginal generation resource for the near- and mid-term in many areas of the country and, in some regions, may continue to be necessary over the longer term to provide needed grid regulation services. CHP can meet future marginal grid requirements more efficiently and with lower carbon emissions than any fossil fuel central station resource. Furthermore, the efficiency and emissions advantages of using CHP will remain as the natural gas infrastructure decarbonizes and renewable and zero-carbon fuels enter the market on both sides of the meter.

While CHP is a resilient and efficient technology, the transition to renewable and zero-carbon fuels will present some challenges. The main barriers to incorporating renewable fuels such as biogas, RNG, and hydrogen into CHP are related to production, distribution, and price of these emerging resources. For example, while RNG is interchangeable with pipeline natural gas and can be used without modification to the pipeline infrastructure or CHP equipment (and can have a negative $CO_2$ emissions value, depending on the feedstock), there will be limitations on the resource base and ultimate supply. In the case of hydrogen, DOE is working on developing production and distribution networks with hydrogen hubs, but new equipment and transportation methods will be required for high levels of hydrogen use. There are several differences between hydrogen combustion and natural gas combustion, including energy density (hydrogen is roughly one-third as dense as natural gas), flame speed (hydrogen is seven times higher than natural gas), and flame temperature (hydrogen is ~500°F higher than natural gas). Because of these differences, higher hydrogen volumes are needed to deliver the same energy as natural gas, and combustion hardware must be modified. Furthermore, hydrogen's higher flame temperature has the potential to increase $NO_x$ emissions, requiring additional combustion and aftertreatment modifications.

DOE AMO's CHP program is evolving to ensure CHP continues to provide efficiency and emissions benefits as the economy decarbonizes. The work includes efforts to verify and promote the expanded use of renewable and net-zero-carbon fuels in both deployment and research activities, and continued near-term deployment support for natural gas CHP in regions of the country with heavily fossil-fueled grids. There is a focus on hard-to-decarbonize industries and critical facilities looking for long-duration resilience, as well as a goal to transition these systems to renewable and net-zero-carbon fuels as they become available. Research, design, and development investments will focus on optimizing future use of renewable fuels and hydrogen and enhancing the performance and operating flexibility of CHP systems so they can provide efficient, dispatchable support to a fully decarbonized grid.

## Flexible CHP R&D and Demonstrations

### Value of Flexible CHP to System Owners

*Peggy Ip, Electric Power Research Institute (EPRI)*

EPRI conducted a study focused on the application of a Solar Titan-130 F-CHP gas turbine and studied the outcome from a customer/owner perspective. EPRI applied a four-step DER and energy storage analysis framework: (1) scenario development (identify customer needs and solutions), (2) grid services analysis (transmission or distribution needs), (3) market and customer service analysis (value streams, DER sizing), and (4) cost–benefit analysis.

During scenario development, the researchers selected three cases and three sensitivities. The three cases were a traditional CHP, sized for the baseload, and two F-CHPs, both oversized to enable them to provide energy back to the grid. With one of the F-CHPs, 70% of the rated capacity was used for onsite generation, and 30% was for market services. With the other F-CHP, the breakdown was 50% for each use. The project was based in California, where natural gas prices are relatively high, so natural gas prices were factored as a sensitivity in this study. The other sensitivities were utility territory and fuel efficiency improvements in CHP.

For the grid services analysis, the study considered customer load management, energy time shift ("energy arbitrage"), frequency regulation and response, and spinning reserve (responding to contingency) ancillary services to the California Independent System Operator (CAISO). EPRI's distributed energy resource value estimation tool (DER-VET) was used to explore site-specific energy storage value with stacked grid services. DER-VET is a free, open-source technology, available online, that allows CHP customization and optimization simulation/co-optimization.

For the market and customer service analysis, the study identified four ways in which F-CHP systems could participate in CAISO's market for energy, spinning reserve, and frequency regulation services:

- Case 1: The turbine dispatches energy while operating at minimum capacity, which would be desired when the grid energy price is significantly high compared to turbine operational cost.

- Case 2: The turbine offers regulation up capacity while operating at minimum capacity, which would be desired when the regulation up price and the grid energy price are high.
- Case 3: The turbine offers spin capacity while operating at minimum capacity, which would be desired when the spin price is high and the grid energy price is low.
- Case 4: The turbine offers symmetric capacity of regulation up and regulation down while operating at 75% rated capacity, which would be desired when both regulation up and regulation down prices are high and when the grid energy price is significantly high.

The cost–benefit analysis showed that, for the same load, traditional CHP was the most cost-competitive, and 70% (or higher) F-CHP may be close to traditional CHP. The 70% F-CHP was more cost-competitive than the 50% F-CHP because the electric and gas bill savings dominated revenue. There was no consistency of savings found between utilities, indicating that accurate cost–benefit analysis must be site-specific. When comparing sensitivities, fuel efficiency was found to improve the benefit-to-cost ratio, and the cost of natural gas can significantly impact revenue.

For F-CHP to be widely applicable, interconnections are necessary, but interconnection requirements are site- and utility-specific. Rules/standards are being developed to help mitigate the challenge. Market signals and grid services will need to be transparent for site owners to consider F-CHP. EPRI is working to put together generic CHP profiles for hospitals, wastewater treatment plants, and industrial plants. In addition, the ongoing research from EPRI and GTI Energy in the Low-Carbon Resources Initiative explores CHP end-use and industrial applications in a low-carbon future.

**Key Points Raised During Q&A**

- The regulation and other ancillary services needed by a heavily renewables-based grid may be different from the existing grid's support needs. Some efforts are under way to identify future grid support needs, and these should be incorporated into F-CHP program planning.

## Modifications to Solar Titan-130 Combustion Systems for Efficient, High Turndown Operation

*Griffin Beck, Southwest Research Institute (SwRI)*

As gas turbines are turned down, their efficiency suffers. SwRI has been working to modify a Solar Titan-130 to enhance high turndown operations. Increased renewable power generation offers an opportunity for small- to medium-scale CHP. Operating a gas turbine CHP system at part load would allow for significant spinning reserve that could be available to local grid support. However, operating at part load presents some technical challenges. Emissions can increase at part-load operating conditions. Additionally, at high turndown operation (greater than 50%), the combustion becomes too lean and unstable, as operation is close to the lean blowout (LBO) limit. To mitigate the LBO risk, air flow through the combustor is reduced by using inlet guide vanes or compressor bleed, but both solutions yield efficiency penalties. The project's goal is to extend the operating limits of the Solar Titan-130 without efficiency and emissions penalties.

The project team first conducted atmospheric combustion tests with the existing Titan-130 combustion system to determine whether the LBO limit could be extended. Researchers used test results to investigate the load percentage, hydrogen content, and pilot flow. Previous work by Sandia National Laboratory found that the addition of hydrogen could extend the LBO limit, and the SwRI project confirmed that finding. At atmospheric conditions, the addition of hydrogen extended the LBO limit to about 20%.

The project will now focus on testing a new injector/nozzle design to see whether the flame can be stable at higher operating pressure, specifically, 115 psi. A high-pressure, single-injector rig has been designed, and fabrication is under way. The initial fabrication of the combustor liner was performed via rolling, but there was a mismatch. Therefore, current efforts are focused on pursuing additive manufacturing (AM) for the liner, made of Hastelloy X material.

**Key Points Raised During Q&A**

- Emissions measurements were not performed in the atmospheric test case but will be performed in the higher-pressure case.
- Variable speed operation has not been considered/evaluated.
- AM was used because there were tight component tolerances and traditional manufacturing was cost-prohibitive.

## Demonstration of Improved CHP Systems Utilizing Improved Gas Turbine and $sCO_2$ Cycles Using Additive Manufacturing

*Anand Kulkarni, Siemens Corporation*

This project seeks to integrate a supercritical carbon dioxide ($sCO_2$) bottoming cycle with a gas turbine to develop a CHP system that can transition rapidly between 50% and 100% load by engaging or bypassing the bottoming cycle while always maintaining electrical system efficiency above 30%. The gas turbine used for this project is a Siemens 5.3 MW A05 aeroderivative gas turbine with capability for fast cold-starts, fast ramping up and down, and multiple startups and shutdowns per day. The initial electrical efficiency is 32% at rated power, but modeling indicates that the efficiency can reach ~50% with additional steam injection and system modifications and incorporation of the $sCO_2$ bottoming cycle.

The gas turbine conditions for this project were compared at 952°F and 1000°F. The increasing gas turbine exhaust and firing temperatures improved $sCO_2$ power and CHP heat efficiency. Increasing steam injection also improved the turbine’s efficiency monotonically. Combustion concerns may limit the amount of steam that can be added, although the bottoming cycle could be used to reject excessive heat. Ongoing work is focused on developing a dynamic model that can simulate the startup and load changes for the combined gas turbine and $sCO_2$ power plant, in addition to developing an algorithm/ method to optimize efficiency and economic value.

One primary element for this project is the heat exchanger (HX) design. Oak Ridge National Laboratory and The Pennsylvania State University initiated a partnership to design new finned hexagonal tubes via AM. These laser powder bed fusion AM tubes showed creep lifetimes 3–5 times higher than their cast alloy counterparts (at 700°C–750°C), as well as superior yield strengths both along and perpendicular to the build direction. In addition to the bundle redesigns, the steam nozzle has been modified using AM.

The project has studied three $sCO_2$ system architectures for the bottoming cycle and a range of steam injection in the gas turbine cycle, with the following results:

- Rated efficiency varies between 0.47 and 0.49 based on current technology but will increase beyond 0.5 with further optimization.
- Electrical efficiency at 50% turndown (total system power) will exceed 35%.
- Overall CHP efficiency varies from 0.87 to 0.90.

Further work includes AM-printing the HX design for integrated gas turbine rig testing, as well as assembling the combustion rig setup for integrated HX–exhaust gas/s$CO_2$ interfacing.

**Key Points Raised During Q&A**

- While this project focused on using natural gas for the s$CO_2$ HX bottoming cycle, this engine's current direction is to be compatible with 100% hydrogen.
- The upcoming tests will help determine whether fouling risk is a concern for the new HX design.
- COVID-19 prevented access to Oak Ridge facilities, so the project used modeling (in lieu of hands-on testing) to compare pressure drop of this AM HX to traditional/baseline HXs.
- The HX tubes are made of IN718, a high-strength, corrosion-resistant nickel chromium alloy.

## Organic Rankine Cycle Integration and Optimization for High-Efficiency CHP Genset Systems

*Tom Brokaw, ElectraTherm, Inc.*

This project focuses on integrating and optimizing CHP and the Organic Rankine Cycle (ORC). When a CHP system is run and there is more power than the facility needs, the CHP can turn-down or reject heat to the atmosphere. Rejected heat is a loss to the system, limiting power generated and efficiency. To increase efficiency and power, an ORC can be used with CHP. ORC is a thermodynamic cycle that uses an organic fluid to convert low-temperature heat into mechanical work, and then that mechanical work is converted into electricity. This project uses the physics of ORC; the amount of power generated is based on the temperature differential across the cycle and the working fluid, which for this project is a refrigerant (with a boiling temperature lower than water's). For this project, the ORC cycle will be elevated to higher pressures and temperatures so that it can operate in multiple modes. The heat can come into the ORC and go into the building for use when the heat load is high, or the ORC can run as a bottoming cycle, rejecting heat to the atmosphere when the CHP is generating more energy than the building needs.

ElectraTherm designed the BITZER expander for integration into the ORC, and the units are capable of running with the elevated temperatures required to support CHP facilities. The maximum temperature is determined by the ORC's maximum allowable working pressure (MAWP), and the MAWP is set by the pressure rating of the expander. To achieve a higher pressure rating, a semi-hermetic expander is used; it has an integrated generator, and no shaft seal is needed. This new expander has a quick response to pressure changes, allowing the ORC to stay connected through large changes in temperature and flow, and allows for uninterrupted transitions between heating, prime power, or different load conditions.

The estimating and modeling software has been updated with a gas module that allows estimates with different heat sources: air, natural gas exhaust, steam, or a custom fluid. Through modeling, the project team can evaluate ORCs in parallel and series operation and can use water (CHP) or air on the ORC cold side/heat sink.

The lessons learned from the initial integration have led to a new design of a larger next-generation ORC system that utilizes a shell and tube condenser and results in better pairing with large gensets. The increased sizing was needed because many engines were larger than could be handled with one ORC. Thanks to the larger expander, the project has doubled the capacity of what was previously the largest ORC. The design is complete, and prototype fabrication has started. Initial modeling work shows that this new system:

- Can run with a traditional genset.
- Combines power generated and heat rejected by the ORC for use at a facility.
- Adds flexibility in power output when excess heat—beyond the needs of the building—is produced.
- Meets the electric and CHP efficiency targets set by the DOE program goals.

**Key Points Raised During Q&A**

- The working fluid currently modeled in this project is R245FA. As ElectraTherm moves toward a higher operating envelope, the project is evaluating whether other working fluids will yield higher efficiency, specifically hydrofluoroolefins (HFOs) and blends.
- Currently, a steady state model is used for the outlet estimates and some component designs, whereas previous models used empirical data. ElectraTherm performs this modeling in-house and has transitioned into a machine learning algorithm that is trained with empirical data. The project team is interested in doing more university outreach and training.
- The ElectraTherm ORC has lower efficiency than turbine-based ORCs because the ElectraTherm ORC operated as a bottoming cycle and has been focused on lower temperature. The ElectraTherm expander is also capable of much greater turndown, adding to the overall system flexibility. The expander unit has thermal efficiency of 8%–11% and an isentropic efficiency/ pressure rating of 70%–80%.
- Smaller ORCs (~30–120 kW) are currently commercially available; the larger sizes (300 kW) are expected to be on the market within the next year.

## Silicon-Carbide-Based Modular Transformerless Megawatt-Scale Power Conditioning System and Control for Flexible CHP System

*Fred Wang, University of Tennessee*

Compared to other materials, silicon carbide (SiC) results in lower loss, higher voltage, faster switching, and better control. Low voltage (e.g., less than 1.2 to 1.7 kV) SiC-based power electronics are quite mature and have been applied to applications like electric vehicle and PV inverters with improved efficiency and system cost. Medium voltage (e.g., more than 3.3 kV) SiC with potential for grid and facility applications are undergoing development with huge potentials. This project is developing a 10 kV SiC-based, modular, transformer-less, megawatt-scale power conditioning system (PCS) and a corresponding F-CHP control system. The PCS and controller are designed to meet the Institute of Electrical and Electronics Engineers’ (IEEE’s) standards for DER interconnections and microgrid controllers (IEEE 1547 and 2030.7). The F-CHP controller must be able to work with variable energy sources (including renewables) and cooperate with local storages and loads, while being able to support grid functions and operate under abnormal grid conditions. If successful, this work would result in an increased market acceptance of megawatt-scale SiC-based PCS and F-CHP, and accelerated adoption of CHP for grid applications.

The project has already designed the PCS and F-CHP controller. To meet the requirements to support unbalanced grid operation and abnormal grid transients like lightning and faults, additional hardware and control software had to be introduced. Faster switching 10 kV SiC devices could also introduce more power losses due to parasitic capacitances as well as noise and insulation challenges. Novel design mitigations were developed to solve these issues. Based on the design, the project developed and tested a 13.8 kV/100 kW PCS converter prototype. The converter hardware converts 13.8 kV AC on the grid side to 800 V DC on the CHP facility side utilizing a modular structure cascading an AC/DC converter with a DC/DC converter, which will facilitate future scaling to higher voltages and higher power.

The project team ran four full scale tests on the technology. A hardware assessment was conducted to evaluate the insulation and the AC side full power rating, and the performance was tested for power quality and control bandwidth. The project then conducted a full rating evaluation of the DC/DC stage (active power), as well as an efficiency test that used a power analyzer to measure both the low voltage DC side input power and the medium voltage AC side output power. In the third test of the PCS converter prototype, a grid was emulated to test converter performance and grid requirements/functions. The test used four-quadrant operation at grid normal and abnormal conditions, in both grid-connected mode and islanded mode. Results showed that power requirements were met but targeted efficiency was not achieved. The fourth test evaluated the F-CHP system controller design and implementation, including scalable PCS operation. The project team used a F-CHP controller hardware testbed, which emulated a grid source and used hardware to run the system test in the laboratory. This assessment evaluated nine scenarios across four different categories: (1) F-CHP system start, (2) grid-connected mode operation, (3) islanded mode operation, and (4) transitions and transient operation. This work demonstrated that when there is a grid interruption, the PCS allows some power use beyond the local load, and when grid power returns, the PCS resumes its grid-connected mode.

Next, the project plans to build a second 13.8 kV/100 kW PCS converter prototype with better efficiency and power density to run in parallel with the first prototype and validate PCS scalability.

**Key Points Raised During Q&A**

- The PCS interface to the grid uses a grid-following inverter. The DC side does not need an advanced inverter.
- The PCS can assist in stabilizing the grid by providing equivalent impedance.

## High-Efficiency Silicon-Carbide-Based Flexible CHP Interface Converter with Advanced Grid Support Functions

*Rolando Burgos, Virginia Tech Center for Power Electronics Systems (CPES)*

Wind and solar power in the United States have grown increasingly popular and successful. Today's electric grid interconnects and serves residential, commercial, and industrial loads with a growing number of intermittent renewable energy sources, which have stressed the operation of the power grid significantly. That is why the flexible combined heat and power (F-CHP) generation vision came into place: to aid and reinforce the grid. In effect, F-CHP generation seeks to tie into the existing electric grid through a full converter power electronics interface while providing electricity and thermal energy to medium-size industrial plants, using its excess generation capacity to offset the inherent variability of renewable energy sources; and also to provide grid support services, such as voltage and frequency regulation, through the power converter interface.

Further empowering the F-CHP vision, the goal of this project is to develop a modular, scalable grid interface medium-voltage power converter featuring stability-enhanced grid support functions. The technology will be fully compliant with IEEE 1547 Category B (for operation in local areas with high aggregated DER penetration) and IEEE 2030.7 (specifications of microgrid controllers). The proposed F-CHP converter and stability-enhanced functions will be attained by enabling the converter to measure the local grid impedance and hence to monitor the local stability conditions. In addition, the proposed converter will adopt grid-forming controls, enabling renewable energy sources operating in proximity to maximize their power generation and consequently their revenue. Furthermore, to maximize the performance and efficiency of the F-CHP converter, wide-bandgap SiC power semiconductors will be adopted.

Overall, F-CHP converters will provide the following key advantages from a dynamic standpoint:

- Reduce the equivalent grid impedance seen by renewable energy sources operating in proximity (e.g., PV inverters)
- Effectively mitigate the onset of dynamic interactions between local renewable energy sources and the grid
- Increase the power generation ability of local renewable energy sources
- Can monitor grid stability conditions through measurement of the F-CHP converter terminal impedances (grid and self)

**Key Points Raised During Q&A**

- The F-CHP monitors stability and can dynamically change its own terminal impedance.
- An F-CHP plant connected to the grid via this advanced power converter and control system can allow the local system operator to incorporate additional PV generation into the electrical system. This could promote the use of F-CHP plants as an enabler for greater PV integration.

## Converter-Interfaced CHP Plant for Improved Grid Integration, Flexibility, and Resiliency

*Ibrahima Ndiaye, GE Research*

With standards becoming more stringent, traditional distributed generation resources will most likely have a hard time meeting grid compliance (e.g., IEEE 1547) compared to inverter-based solutions such as PV. Enabling implementation of converter-interfaced CHP requires both economic viability and technical ability. For this project, the goal was to develop grid interface converter controls and microgrid controller algorithms for a seamless interconnection and operation of small- to medium-sized CHP plants to the distribution grid. The converter has been targeted to meet key interconnection standards, including IEEE 1547 and 2030.7. The cost of the converter has been targeted at 3–4 cents/W. Compared to the base case, this approach (see Figure 3) interconnects CHP systems using a grid-ready inverter that already incorporates the key grid functions. Based on the presence of the interface converter, a microgrid controller was developed to enable operational flexibility.

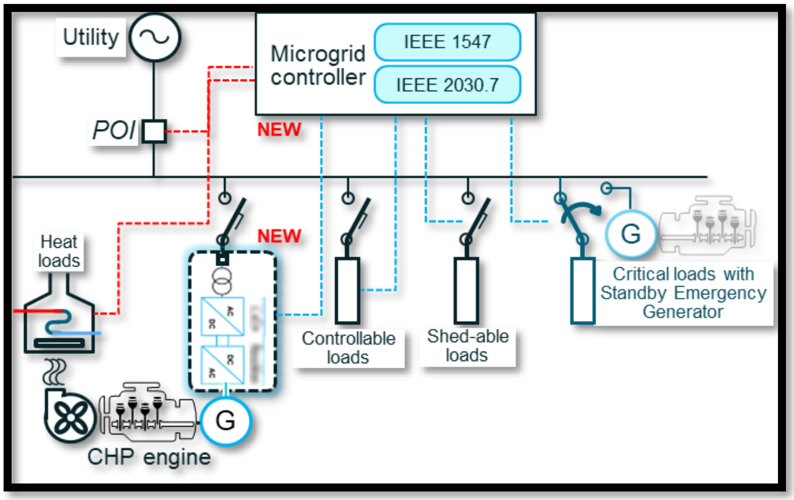


*Figure 3. GE's proposed technology.*

For this project's approach, an evaluation of return on investment (ROI) and a sensitivity analysis were performed to compare the effects of several critical parameters: energy price, voltage support price, converter cost, generator cost, converter-to-engine-size ratio, and interconnection delay. The economic feasibility analysis compared 25 use cases: five applications (commercial buildings, colleges/universities, water reclamation, hospitals, and hotels) in five independent system operators (CAISO, MISO, NYISO, PJM, and ERCOT).[1] The results of the sensitivity analysis showed that profitability is most responsive to energy price, converter cost, and specifically interconnection delay. Indeed, it was found that if the interface converter accelerates the interconnection by 6 months or more, converter-interfaced CHP becomes more profitable than directly coupled in more than 85% of cases. Using a commercial microgrid controller, the project validated compliance with IEEE standards 1547 and 2030.7. The project built a 700 kW power hardware-in-the-loop testbed and performed simulations to demonstrate unity power factor operation of the CHP generator, power factor control at the point of interconnection, and seamless transition between heat following and power following. Results validated the technical benefits and proved that the converter-interfaced CHP had superior steady-state and transient performances compared to directly coupled CHP.

This project is promoting CHP penetration by increasing flexibility of CHP plants for improved resilience and grid support services, lowering installation costs, and reducing delays. Future work aims to (1) optimize the CHP engine (leveraging asynchronous operation with the grid) to further reduce system costs and (2) develop a converter for coupling CHP with PV and a battery energy storage system to streamline the integration of renewable DERs and optimize revenue streams.

**Key Points Raised During Q&A**

- This project would allow larger, synchronous, generator-based CHP systems up to 20 MW to be "seen" by the grid as essentially inverter-based systems. This should make the interconnection process with the grid easier and potentially less costly, reducing a significant barrier to CHP project economics in this size range.

[1] California, Midwest, New York, PJM Interconnection (Pennsylvania–New Jersey–Maryland), and the Electric Reliability Council of Texas.

## High-Speed Medium-Voltage CHP System with Advanced Grid Support

*Randy Collins, Clemson University*

Because of power electronic limitations and required applications, the current state of the art in multi-megawatt medium-voltage power electronic systems does not normally support advanced grid functions. The goals of this project are to enable a technology readiness level (TRL) 5 demonstration of a 1 MW, 500 Hz, 15,000 RPM, high-frequency CHP generator and electric machine system, using advanced grid support functions required by IEEE 1547-2018 and Underwriter Laboratories (UL) 1741 SA.[2]

Traditionally, electrical generators use rotating machines that connect to the power grid directly, operate at relatively low speeds, and have limited controls. In this project system, a high-speed rotating machine (generator) is utilized, coupled directly to the turbine axle in the system (without a gearbox), and the electric generator is coupled to the electric grid via a medium voltage power electronic converter without a transformer. The converter is equipped with advanced controls to (1) enable flexible operation of the system for electrical qualities and (2) allow the generator to remain connected to the grid and provide grid support during electrical anomalies, such as voltage excursions caused by short circuits (faults).

Furthermore, the project is demonstrating island-mode transitions and resynchronization for reconnection with the power grid with the fully coupled system prototype setup. So far, islanded mode has resulted in some harmonic distortion not experienced in grid-following mode, but the transitions are working well overall.

This system provides several advantages:

- The multi-level medium-voltage converter and induction generator are directly scalable to 20 MWe.
- The high-speed generator and drive, without a gearbox, simplify mechanical designs and maintenance.
- The power electronic grid interface with SiC devices improves advanced grid support functions.
- The footprint size is considerably smaller than that of a comparable electrical generator system.

The primary step left to perform in this project is to simulate/test the fully coupled system in power hardware-in-the-loop utilizing existing eGRID capabilities. (eGRID is Clemson's grid emulator.)

**Key Points Raised During Q&A**

- The rationale for the high-speed generator was to have active power to put into the grid system while having independent regulation of reactive power. The generator is an induction machine, and the generating speed can be varied, providing load-following generation in compact spaces.

[2] UL 1741: Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources. SA stands for Supplement A.

## Megawatt-Scale, Multi-Source Heat Recovery System with a Flexible Grid Interconnect

*Randy Collins, Clemson University*

This project builds upon the above-noted one, “High-Speed Medium-Voltage CHP System with Advanced Grid Support.” This project uses a multi-source heat recovery system, with a single turbo expander, to drive the ORC. Multiple heat sources are aggregated into a single collection stream that powers the ORC, controllably proportioning electrical generation and district heating/cooling requirements. Recovering waste heat to generate electricity can be done by heat of compression, biomass-fired boilers, geothermal sources, and hydrogen electrolyzers. The ORC uses propane as a working fluid (selected because it is the best fit—propane is easily obtained and cheap).

The system leverages technological developments of high-speed induction machines and high-frequency power conversion to streamline grid integration and increase overall efficiency. The project’s system uses a variable-speed (rather than a fixed-speed) ORC design and can ramp electrical power output based on the ramp rate of any one of the heat sources, as needed, to help stabilize the grid. The goal of this work is to generate 1 MW at a cost of $1800/kWe and connect that power back to the grid via power electronics.

The current focus is commercialization, so where possible, some improvements and simplifications to earlier models are being made. For example, the initial system required expensive Litz wires for stator coils in the induction machine; the updated system uses standard wires. A key task of this project—and a cost driver—is right-sizing the air condenser base. Ambient conditions must be used, but as ambient conditions increase, the system gets larger and more expensive. The project team is focusing on this in addition to system modeling, control system development, and demonstration objectives.

**Key Points Raised During Q&A**

- Propane was selected as the working fluid after surveying ~18 oil and gas users, all of whom preferred using propane because of its historical use and accessibility. Isobutane was the next most popular option because it is also readily available.
- Propane flammability has not been an issue at the laboratory scale.
- There is no maximum change in temperature (T) for this system. The minimum delta T is estimated to be 195°F; this estimate will be tested when the facility/test location is set up.

## Flexible Natural Gas/Hydrogen CHP System

*Jas Singh, Caterpillar, Inc.*

This project is developing a 2.0 MWe CHP genset capable of running on 100% natural gas, 100% hydrogen, or up to 25% hydrogen + natural gas ($H_2$+NG) blends (volume basis). The resulting system, also referred to as the $CHPH_2$ system, will be demonstrated in a renewably fueled DES. To be successful, the system needs to be able to respond to electric power variations automatically and seamlessly, maintaining baseload operation for facilities, and serve as a back-up generation asset for the grid. This project has two major development components: (1) the flex-fuel gas genset system and 2) controls systems (e.g., for engine-genset, CHP, and master micro-grid controller).

The project team developed hydrogen port fuel injection technology to allow the use of hydrogen as a fuel. Once that was completed, a single-cylinder engine model was used to test hydrogen and $H_2$+NG fuels. As hydrogen is highly flammable, running on 100% hydrogen necessitated the "Hydrogen Sandwich" approach (see Figure 4). This approach is as follows: as soon as the intake valve opens, some fresh air is let in ("cooling air"); $H_2$ is injected in the middle of the intake stroke; then injection of $H_2$ is stopped, and air is allowed in again ("purging air") before the intake valve is closed. With this approach, no hydrogen is present at the start of the next cycle, mitigating the risk of ignition.

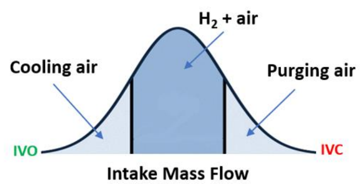


*Figure 4. The "Hydrogen Sandwich" approach.*

Preliminary testing of the G3501 flex-fuel engine, comparing $H_2$+NG blends to natural gas alone, has shown that combustion speed increases as hydrogen concentration increases. The tests also look at maintaining NOx levels, whether the system is running natural gas or hydrogen. The project has shown that, to attain the lower NOx levels while using hydrogen blends, the spark timing must be retarded. When comparing $H_2$+NG blends to natural gas, a leaner air–fuel ratio (AFR) is required at a given spark timing, and brake thermal efficiency is high.

Preliminary testing of the G3501 flex-fuel engine running on 100% hydrogen has shown faster combustion with richer lambda. Testing has shown that 10–90 burn duration trends down with richer lambda, but not always with retarded spark timing. More stable combustion occurs with richer AFR and advanced spark timing and, to a certain extent, higher brake thermal efficiency is possible with retarded spark timing and richer AFR.

For the G3501 flex-fuel engine with 100% hydrogen, the project team has performed engine operating space mapping and defined operating boundaries based on detailed single-cylinder engine testing.

Demonstration testing of the 2.0 MWe flex-fuel ($H_2$+NG) genset and CHP system will be performed at District Energy St. Paul in an enclosure. This system will connect to the same power and heat network as the district's existing wood-fired steam turbine, which provides up to 33 MWh electricity and 65 MWh heat (enough to heat 200 commercial buildings, heat 300 single-family homes, and cool 119 buildings). The site load will be able to accept all the power and heat delivered from the CHP$H_2$ system, even in the summer months.

The project team performed a preliminary total cost of ownership analysis and found that the gas engine modified for running on hydrogen (40% derate) is competitive against a proton exchange membrane hydrogen fuel cell. Some of the next steps are to perform greenhouse gas emissions analysis and technoeconomic analysis; the National Renewable Energy Laboratory will assist with these efforts.

**Key Points Raised During Q&A**

- During engine development, some changes were made involving the combustion chamber – the piston compression ratio was slightly reduced, and the Miller amount was reduced (so the closing of the intake valve was a little delayed compared to the baseline NG engine).
- Green hydrogen, a byproduct of the plastic manufacturing process, is used in this project; it is also called low-carbon-intensity hydrogen.
- The controller used in this work is an off-the-shelf microgrid controller that was modified for the demo site and was not specifically developed for this project.

## Turbo-Compression Cooling System for Ultra-Low-Temperature Waste Heat Recovery

*Derek Young, Colorado State University*

Low-grade waste heat recovery can substantially improve energy efficiency for a variety of industries. Unfortunately, implementation of heat-driven chillers (absorbers) is sparse, as commercially available ones are expensive; therefore, extra waste heat is typically lost rather than captured. This project aims to help with this issue by developing a low-cost turbo-compression cooling system (TCCS) that couples cooling and power cycles using a high-efficiency turbo-compressor. A TCCS is an ORC directly coupled to a vapor compressor through a turbo-compressor.

This project utilizes the working fluid R1234ze(E) and uses an economizing HX as a preheater upstream of the waste heat boiler. The project turbo-compressor must realize technology advances, including high speed and high efficiency (at least 80% isentropic) and compact HXs that are low-cost and highly effective (utilizing aluminum when possible); these enhancements are especially critical for the technology's successful transition to commercialization. The project used shell and tube HXs for the evaporators (cooling cycle) and the condensers (power and cooling cycles) because they were commercially available, while aluminum brazed plate-fin HXs were used for the boilers and recuperators.

During baseline design, auxiliary loop temperatures were established to match commercial absorption systems for direct comparisons, and high efficiencies for turbomachinery were based on designs from the project partner. The system was modeled and designed for a thermal coefficient of performance (COP) of 0.6.

Actual data showed a COP of 0.56 +/- 0.01. Lower-than-design turbine efficiency caused higher mass flow through the power cycle (to get the desired power output), a greater change in pressure through the cycle, and a choked flow through the turbine. Additionally, the condenser was undersized, which resulted in lower turbine pressure ratio (less power output) and higher compressor pressure ratio (less flow delivered and reduced evaporator cooling capacity), in addition to a two-phase fluid exiting the cooling cycle condenser, which left less enthalpy of vaporization available in the evaporator for chilling. Some of the turbine efficiency and condenser sizing challenges were outweighed by performance improvements from heat integration.

Future work includes test facility modifications to enable repeatable startup and shutdown, more testing to generate detailed turbomachinery performance maps, and turndown testing. Additionally, the shell and tube condenser will be replaced with an HX with a larger surface area. Looking ahead, a TCCS will be designed and tested for U.S. Navy ships to capture low-grade waste heat from ship service gensets, with the aim of improving fuel efficiency by 10% without changing the footprint (TCCS sizing is the same as the existing baseline chillers).

**Key Points Raised During Q&A**

- At the beginning of the project, a study was performed to search for a working fluid with low global warming potential and no ozone depletion potential. Working fluid R1234ze(E) was a reasonable choice, given the operating temperatures and pressures of the cycle being used. (If the project increased temperatures, the critical temperature of this fluid would be a challenge.) Additionally, this working fluid posed no safety concerns.

# Day Two

## Introduction to Day Two

*Robert Gemmer, Advanced Manufacturing Office*

Day Two began with an introductory presentation from Dr. Gemmer, welcoming meeting participants, giving a brief overview of the first day's presentations, and summarizing what would be discussed during the second day's presentations. He noted that the first two presentations of the day were national laboratory research projects (from a 2018 laboratory call) that support more efficient turbines for CHP. These projects are important because turbine efficiency is a critical factor for CHP success.

The last three presentations of the day discussed three AMO-sponsored R&D projects that are developing CHP systems with high power-to-heat ratios. Today's CHP systems are thermally driven; sites with low thermal demand are often not a good fit for CHP. Using waste heat for electricity generation (one or two bottoming cycles) could produce ultra-efficient distributed energy generation systems. These projects are contributing to future CHP systems that produce more electricity and less thermal energy, which would expand the potential CHP market to other commercial and institutional facilities, including sites with lower thermal demand.

## National Laboratory Projects

### Advanced Airfoils for Efficient CHP Systems

*Doug Straub, National Energy Technology Laboratory (NETL)*

Between 2020 and 2025, the U.S. market for small-scale (less than 20 MW) CHP systems is expected to grow by 637 MW. This potential equates to an estimated 3 million tons of avoided $CO_2$. This project aims to increase the efficiency of small gas turbines (5–10 MW) suitable for CHP applications, thus improving the business case for installing smaller CHP systems that match the potential domestic CHP markets.

The project goal is to increase the gas turbine firing temperature 100°C (over a 2015 baseline) using advanced materials, AM, and advanced cooling designs. The estimated benefit of this technology improvement is a reduced payback period for CHP plants. In addition, a 100°C increase in turbine inlet temperature could increase power by 20%, increase efficiency by 2% (relative to a 33% baseline), and increase steam production by 10%–15%. Additionally, this technology is estimated to reduce $CO_2$ emissions and fuel consumption by 36% relative to a conventional non-integrated power/boiler configuration and 7% relative to a baseline CHP plant.

This project addresses two primary technical challenges. The first challenge is that AM has not produced materials with better properties than the base alloy. Oxide-dispersion-strengthened (ODS) alloys have better high-temperature properties, but traditional AM powder processing cannot produce ODS powders containing $Y_2O_3$ or $Al_2O_3$ because of the high melting points. In this project, a different powder processing approach has been used to produce ODS powders that can be used to additively manufacture parts with better high temperature properties than the base alloy. The second challenge is the lack of a common airfoil cooling design for small (5–10 MW) gas turbines that can be used to quantify benefits of more advanced cooling architectures. Public data on integrated airfoil cooling are limited and largely focused on large gas turbine engines. Additionally, test protocols for integrated airfoil cooling performance are also limited. In this project, a baseline airfoil cooling design has been defined and advanced cooling designs have also been designed, additively manufactured, and tested.

To resolve these challenges, the project has three primary focus areas: (1) system modeling and market benefits, (2) internal cooling using AM, and (3) ODS AM materials. First, to establish a common baseline, a "virtual" model was created based on a 2015 generic CHP gas turbine. The upgraded engine was then compared to this baseline model. The upgraded engine increased power, thermal efficiency, and exhaust temperature. Based on this virtual gas turbine model, improvements in the cooling design were needed to maintain the same, or lower, metal temperatures at the higher turbine inlet temperature. The overall cooling effectiveness (measured as non-dimensional surface temperature) would need to increase from 0.28 to 0.42.

Next, several internally cooled airfoil designs were developed, additively manufactured, and tested. Cooling technology curves were produced for each airfoil design by varying the coolant flow and measuring the temperature distribution on the airfoil surface using infrared thermography. One design, the NETL double wall, was found to be significantly more efficient than the baseline. The NETL design achieved the upgraded engine cooling effectiveness targets at the same coolant flow that the baseline used to achieve the current cooling effectiveness target. In addition, the NETL double-wall design had a lower pressure drop than the baseline.

The project also demonstrated a powder processing method for ODS for 0.5% $Y_2O_3$ in IN718. Samples were manufactured using two approaches: direct energy deposition and laser powder bed fusion. Experimentation and comparison of IN718 with and without $Y_2O_3$ addition has shown that adding 0.5% $Y_2O_3$ has little effect on ultimate tensile strength properties. Future work will focus on higher concentrations of $Y_2O_3$. Results are encouraging because the distribution of yttrium was uniformly distributed throughout the powder and the additively manufactured parts.

In the second phase of this project, these technologies will be advanced to gain industry "buy-in."

**Key Points Raised During Q&A**

- For the virtual engine model, when the turbine inlet temperature was increased, the pressure ratio was also increased to avoid affecting only the exhaust temperature. The combination of higher pressure ratio and higher turbine inlet temperature increased the power and efficiency and resulted in a small increase in exhaust temperature.
- The NETL double wall design did not have many negative tradeoffs. The wall thickness was ~1 mm.
- Two different heat treatments were performed on the IN718 with 0.5% $Y_2O_3$.

## High-Performance, High-Temperature Materials to Enable High-Efficiency Power Generation

*Bruce Pint, Oak Ridge National Laboratory*

The goal of this materials-science-focused project is to increase CHP system efficiency by developing lower-cost materials that offer higher performance and higher-temperature capabilities. The project comprises four separate tasks, described below.

The first task is to develop lifetime modeling and alloy evaluations for high-temperature, thin-wall components, including the primary surface recuperator and combustor liner. Recuperators are essentially compact HXs that significantly increase the efficiency of microturbines. This task uses a combination of modeling and experiments to develop model parameters and validate model predictions to compare new materials. The model predicts oxidation kinetics, compositional changes, and wall thickness loss as a function of time, temperature, specimen thickness, thermal cycle duration, and atmosphere. The model is able to predict experimental plots of time versus net specimen weight change (weight of scale vaporized subtracted from weight of metal oxidized). A metric of $t_{10}$, which is the time at which chromium content is 10% at the metal–oxide interface, was developed as an end-of-life criteria. At $t_{10}$, the chromium content is no longer sufficient to form a protective chromium-rich oxide, and accelerated attack begins. The model has been able to predict lifetimes of over 100,000 hours. Model validation was performed via field exposures with Solar Turbine's Mercury 50 engine (4.6 MW) at 643°C, in air with 4%–7% water, and at a velocity of 10–20 m/s (lab velocity of ~2 cm/s). Field tests were performed for 106,360 hours, approximately 10 times longer than laboratory exposures, and used an alloy 709 (Fe-20Cr-25Ni+Nb) test panel.

The project also uses modeling to examine the behavior of candidate materials when used with green hydrogen, an energy source gaining in popularity. Green hydrogen's anticipated increased utilization makes testing particularly important, as 100% hydrogen fuel will create extreme environments in its transportation, generation, and combustion. In particular, the project examined whether the higher flame temperature and higher $H_2O$ exhaust associated with hydrogen affected material performance. The project modeled a system running higher $H_2O$ levels at 700°C, comparing HAYNES® alloy HR-120 (Fe-25Cr-35Ni, used by Capstone) to Inconel 625 (used by Solar Turbines). In terms of chromium loss, HR-120 performed better than alloy 625. Alloy 625 formed a chromium-rich oxide, but it evaporated throughout the process; whereas HR-120 formed an iron-rich oxide, which inhibited evaporation.

The second task is to investigate materials for a temperature increase of at least 100°C. Alumina-forming austenitic (AFA) steels were tested at 850°C in wet air, and the results showed that $Al_2O_3$ was less affected by the presence of water than $Cr_2O_3$. These AFA steels showed adequate creep and corrosion resistance for 850°C thin-walled applications.

This project also developed a new oxidation-resistant nickel-based alloy for turbine combustor liners for use at temperatures of 1100°C–1150°C (two patents were awarded for this alloy, one in 2019 and one in 2020). This material exhibits an excellent combination of creep strength and oxidation resistance. Thus far, the project has performed scale-up, characterization, and oxidation testing at 1100°C in wet air. Due to the ongoing COVID-19 pandemic, there have been delays in the mechanical testing to verify high temperature tensile, creep, and fatigue properties.

The third task is to evaluate and test the performance of high-temperature coatings for fatigue and corrosion resistance. This phase addresses an important issue, especially for aerospace and industrial applications: significant blade degradation due to hot corrosion in gas turbines. Hot corrosion is a common issue when burning opportunity and renewable fuels, so higher-temperature durability is key to improving gas turbine efficiency and reducing $CO_2$ emissions. Therefore, there is a need for coatings that offer hot corrosion resistance at temperatures above 700°C without compromising other properties (e.g., fatigue resistance). Oak Ridge National Laboratory is working with Siemens Corporation and Tennessee Technological University to develop such coatings. The project team has developed a new experimental rig and conducted initial fatigue testing in a hot corrosion environment. However, this task has been delayed by personnel changes and will require a no-cost extension to complete.

The fourth task, which is led by Argonne National Laboratory, is helping to characterize these new materials and coatings. To characterize the properties of the new nickel-based AFA alloy referenced in the second task, high-energy synchrotron x-ray diffraction (XRD) has been conducted using the Advanced Photon Source. Additionally, Argonne has been studying the iron-rich oxides formed on alloy 709 after long-term laboratory exposures.

**Key Points Raised During Q&A**

- The project used 10% water content/vapor in air used for testing. Though velocity has a significant effect on the results, if a lower water content had been used, it would have taken longer to see the damage effects. These tests must be run for a long time; for example, 1,000 hours is insufficient to see any damage.
- The project needs to perform additional analysis regarding the impact of moisture content to better understand whether AFA steel at 850°C can withstand green hydrogen and biofuels (which have higher moisture content).

## High Power-to-Heat Ratio CHP Development

### Robust Combined Heat and Hybrid Power for High Electrical Efficiency Cogeneration

*Comas Haynes, Georgia Tech*

This project builds upon the NETL's high-electrical-efficiency, Brayton-cycle-style, recuperative solid oxide fuel cell (SOFC)/gas turbine cyberphysical system. Cyberphysical systems are a cost-effective way to test a system's behavior by combining physical components with virtual simulations. The project is developing a CHP hybrid system with high electrical and cogeneration efficiency. The system exhibits dynamic robustness through the operation of a high-temperature bypass valve across the hot side of the recuperator. The bypass valve offers the site flexibility on how much process heat to generate, compared to dedicating the thermal energy to increase the electrical efficiency in the power block. The system is ideal for efficient, dynamic onsite power and heat production at manufacturing facilities with high power-to-heat ratios.

For this work, Georgia Tech is conducting system-level simulations and analyses across variable power, heat loads, and bypass valve settings to determine their effects on heat supply, electrical efficiency, and cogeneration efficiency. The fuel cell, post-combustor, and reformer have been simulated in MATLAB, while all other components have been modeled with Ebsilon software. The University of Texas at El Paso is physically designing, developing, and characterizing the recuperator bypass valve. NETL is providing simulation capabilities, including a baseline for the system simulation, and access to a cyberphysical system to test the bypass valve within realistic flow conditions.

Compressed air increases fuel cell voltage and is required for turbine expansion to atmosphere. Fuel cells efficiently and directly convert fuel energy into DC electricity by allowing air to electro-oxidize fuel, although the air and fuel streams do not mix. SOFCs can utilize a variety of fuels and can better tolerate impurities than lower temperature fuel cell systems; the SOFC is currently set up to run on (fuel processed) natural gas, but it is an easy transition to renewables (e.g., biofuels and hydrogen). Most fuel cells oxidize approximately 80% of the fuel, but this fraction of fuel consumption can be an optimized design input. Electrochemical reactions act as an additional heat source to the cycle, and the combustor burns any residual fuel to further heat air. The turbine and generator convert thermal energy of compressed hot air into AC electricity. The recuperator reclaims some of the thermal energy that is not converted to power by the turbine and generator. Bypass valves are crucial to get heat downstream, but more thermal energy bypassed results in less energy used in the power block. The hybrid fuel cell and turbine power allow the system to achieve high electrical efficiencies. The fuel cell nominally generates 65% of the power, so the bulk of the efficiency comes from the fuel cell and not the turbine. The system uses a new reformation approach that is more efficient than the current state of the art; a lower heating value set point of 90% efficiency is used, whereas electricity efficiency is ~75% when not bypassing. The bypassing fraction is between 0.0 and 0.8. Figure 5 shows a flow diagram of a CHP system utilizing a SOFC/gas turbine with a recuperator bypass valve.

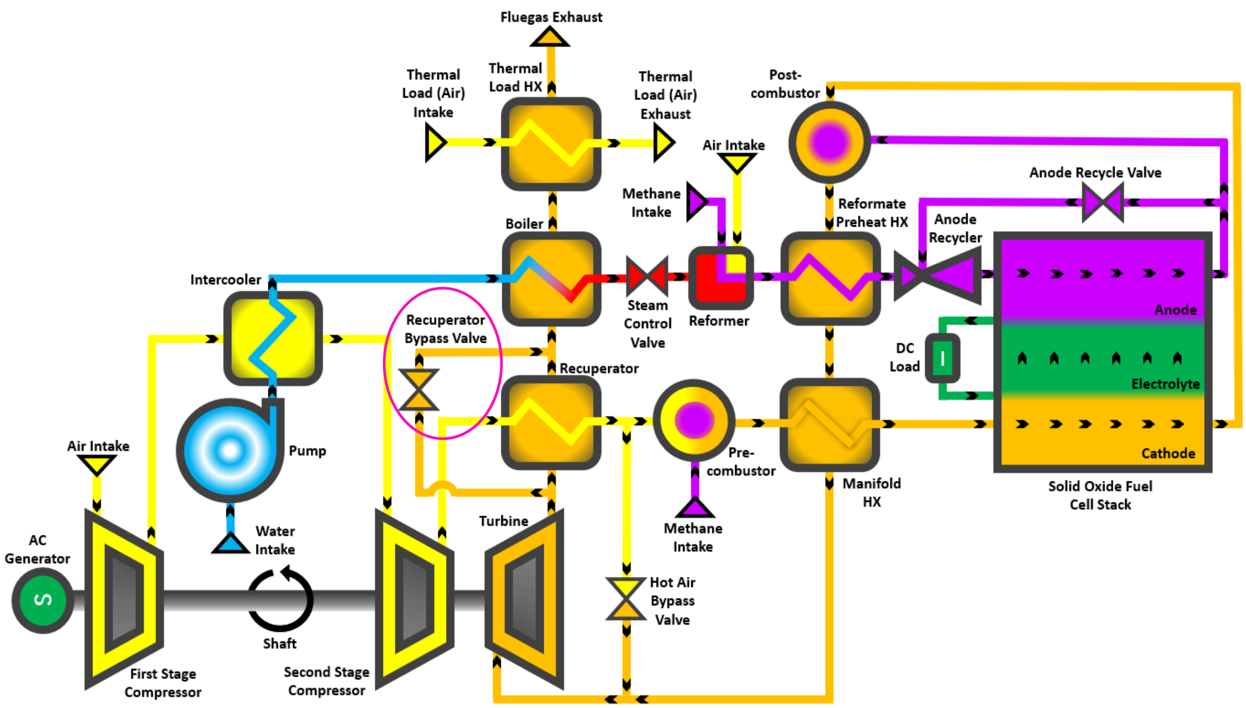



*Figure 5. Simulated CHP system with the recuperator bypass valve circled in pink.*

Cyberphysical systems use external stimuli from real, physical components as inputs to numerical models of virtual components that operate actuators and hardware within the physical side of the system to mimic the behavior of real versions of virtually simulated components. HyPer is the NETL's SOFC/gas turbine cyberphysical system. It contains a real compressor, turbine, generator, and recuperator, as well as a virtual SOFC stack that computationally predicts SOFC transport phenomena such as electrochemical current (hence power) and heat. The SOFC is physically represented in Figure 5 by a storage tank. The University of Texas at El Paso used computer-aided design to develop the recuperator bypass valve (circled in pink in Figure 5) and initially tested it under low-temperature and low-mass-flow-rate conditions. The valve is going to be inserted into NETL's HyPer for operation and testing under more realistic temperatures, pressures, and mass flow rates. After being implemented in HyPer, the valve will be characterized and modeled.

**Key Points Raised During Q&A**

- The size (in kilowatts) of the currently targeted power rating is in the order of hundreds.
- In Figure 5, the “Manifold HX” represents the fuel cell inlet, rather than a separate HX. It is represented as a HX because there will be some heat transfer in the manifold (though a small quantity).
- Fuel cell degradation will occur via voltage degradation over time, which can be modeled but has not yet been.
- If hydrogen is the fuel, an endothermic reformer will not be used, and the boiler will not be needed. So far, modeling has input only natural gas as a fuel.
- Modeling was performed with quasi-steady-state dynamics in mind, except for the fuel cell, which uses a transient model.
- Cost is a major constraint for this system, which is expensive. The goal is to demonstrate a unique and innovative system, and it is currently an early-stage design. The system is not considered to be a traditional topping and bottoming cycle; instead, it uses a hybrid cycle to reduce the size of the fuel stack. As a result, the overall capital cost decreases as the turbine compensates for the higher cost of the fuel cell, and the price per kilowatt-hour is made more comparable to turbomachinery.

## Additive Manufactured Supercritical $CO_2$ Heat-to-Power Solution

*Dan Thoma, University of Wisconsin*

This project’s primary goal was to determine whether a high-efficiency turbine could be manufactured using AM. More specifically, the project aims to increase thermal/heat-to-power efficiency in power generation by developing a new design that targets 65% fuel-to-electricity efficiency and 70% overall efficiency. To attain these objectives, the project is evaluating advanced turbine and rotating mechanics, new generator and power electronic concepts, increased functionality through AM, and system integration on power cycle testbed. A key deliverable of this work is the demonstration of turbine design within a power cycle testbed facility.

AM has been used to demonstrate functionality and scale up the technology. Process parameters for the new materials have been determined using high-throughput laser powder bed fusion, and a hexagonal shape was chosen to make it easy to remove with a wrench. Consistent and acceptable material properties were exhibited in the as-processed and as-used states. Successful scale-up of the process parameters resulted in AM turbines, which are quite small at only 2.5" diameter.

The innovative generator has integrated thermal management. To select the best design, multiple slot/pole combinations were explored at low (25 krpm) and high (100 krpm) speeds. It was found that the bearingless generator could achieve very high efficiency (at least 96%) and power density (~14 kW/kg), and the performance was comparable to the highest-performance electric machines. The next steps for the generator portion of this project are to assemble the generator, characterize the parameters, build the control system, and demonstrate it.

The system uses $sCO_2$ as the working fluid, which provides the advantages of small turbomachinery, high efficiency, and lower capital costs compared to conventional steam cycles. Initial work using the testbed demonstration focused on turbine inlet temperatures of ~800°C, but the longer-term project models and tests at ~1300°C. At a turbine inlet temperature of 1300°C, the high-performance testbed model demonstrated a net power output of 32 kW and an efficiency of 66%. However, the actual testbed demonstrations performed at 800°C revealed a 50% cycle efficiency. The heater is being modified to run this system at hotter temperatures. The improved heater design will have a thin-walled heating element made of Inconel 625, with $CO_2$ running inside/the length of the pressure vessel. There are several challenges associated with this update, but the proposed design has considered them, and the solutions will be tested.

**Key Points Raised During Q&A**

- High-temperature and high-pressure conditions make it challenging for recuperators to function, and it is difficult to manufacture turbines for these conditions. This system needed to be more easily manufactured and to work at high temperatures, high pressures, and with $sCO_2$. AM seemed the best option to meet these needs.
- An electric heater was selected as the heat source because it was best suited for the controls and the project objectives.
- If this work eventually goes to commercialization, Raytheon Technologies Research Center would lead the effort.
- To date, testing has been done using Haynes 282. Material changes are being considered to reach higher temperatures; specifically, coating technologies are being discussed with Raytheon.
- The current testbed is inefficient, and as a result, more power input has been required to test the turbine. A $CO_2$ pump would not be used in a real-life system because it is inefficient.

## Ultra-Efficient CHP with High Power/Heat Ratio using a Novel Argon Power Cycle

*Miguel Sierra Aznar, Noble Thermodynamics*

This project is based in California, a state that prides itself in its unique effort transitioning to a zero-emissions economy; the state's approach is to decarbonize the energy supply and electrify the energy demand. Though reciprocating internal combustion engines (RICEs) continue to serve a crucial role in maintaining the grid's reliability with growing renewables, they are also responsible for over 70 million $MtCO_2e$ emissions annually, in addition to other air-pollutants such as $NO_x$ and particulate matter.

The argon power cycle (APC) promises an affordable, efficient, and feasible approach to the decarbonization of the grid, particularly RICE. In this project, APC technology is integrated within a CHP framework, targeting the realization of ultra-highly efficient, zero-emission power generation. An APC-CHP system can potentially deliver single-cycle chemical-to-mechanical energy conversion efficiencies as high as 65% and overall combined plant efficiency of at least 70% at nominal CHP system scales, all the while, delivering emission-free electricity from natural gas. The core concept behind the APC is a high-pressure, closed-loop argon recirculated thermodynamic cycle. Thermodynamic efficiency of a RICE strongly depends on the ratio of specific heat (K) of the working fluid. Using argon gas (highest K) allows dramatic RICE efficiency improvements. Additionally, because of the APC's closed-loop nature, capturing the generated $CO_2$ emissions is straightforward and efficient, and subsequently, in the absence of $N_2$, no $NO_x$ emissions are generated. Altogether, the APC offers an efficient, versatile, and intrinsically clean power generation solution that is retrofittable onto GW of existing electrical generation assets across the U.S. and worldwide.

Nonetheless, realizing the APC is not a trivial endeavor. Combustion in argon-rich working fluids results in higher temperatures and pressures than combustion in air. For RICE, this translates into higher knocking tendencies (undesired and uncontrolled autoignition), higher heat losses (which can be reduced by the size of the engine), and as a result, a narrower feasible operation range.

Solving the challenges around knock and range needs creative strategies and the use of all available tools at one's disposal. Synthetic working fluids (e.g., argon and $O_2$) allow for fine control over cylinder-charge composition, expanding the toolset beyond that of injection and ignition timing. Additionally, the use of argon gas also affords substantially higher flame speeds at a wider range of equivalence rations. These combined aspects result in at least three additional degrees of freedom for combustion control, providing additional dimensions where knock-free operation can be found.

Unlike conventional air-breathing engines which are constrained by combustion stability, knock, and $NO_x$, argon-breathing engines are not subject to $NO_x$ emissions, nor by a fixed air-to-fuel ratio, so there is a broader realm of feasible operating points for performance optimization (e.g., controlling knocking vs. operating range, vs. misfiring). In other words, one can understand the operational map is two-dimensional for an air-breathing engine, while it is n-dimensional for the argon-breathing counterpart.

Figure 6 shows a flow diagram with the actions involved in APC. The steps in orange are related to ultra-efficient power generation, where the use of a monoatomic gas (i.e., argon) as the working fluid greatly increases the system's conversion efficiency and prevents the formation of harmful nitrogen oxides. The steps in blue are related to heat and water recovery, which reduces cooling water consumption and improves overall plant efficiency. The steps in green are related to carbon capture and purification; control over the recycled argon stream composition enables the lowest-cost carbon capture, in addition to efficient hydrogen blending.

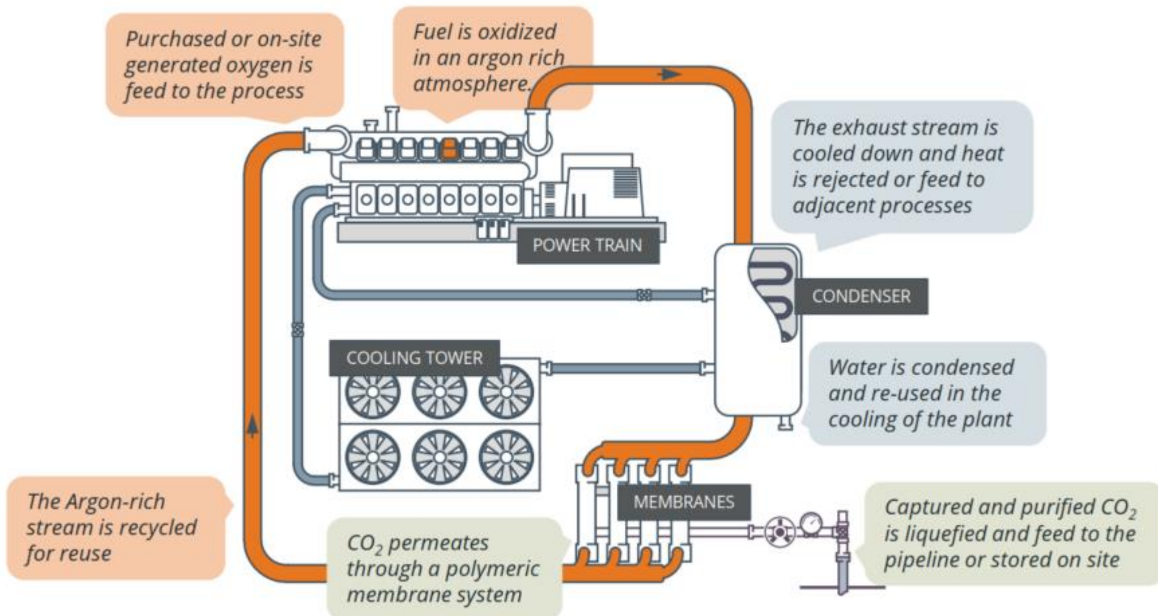



*Figure 6. Argon power cycle process flow diagram.*

To further expand the operating range and optimize performance of the argon-breathing RICE, a $CO_2$ separation membrane system can be used to capture/remove $CO_2$. Membrane separation is ideal in closed-loop configurations because they conform to a continuous plug-flow reactor model, they add no consumables to the process, there is no complex chemistry, and there is no need to capture all the $CO_2$ in a single pass. Additionally, compared to amine separation systems, closed-loop configurations are less expensive and generally easier to operate and maintain. Though the membrane causes a pressure drop, active management of the system pressures allows for tuning the amount and purity of $CO_2$ within a wide range. The membrane separation system enables fine control over the composition of the recirculating system. Additionally, membranes act as controllable buffers between engine exhaust and intake conditions.

When operating with 100% hydrogen fuel, no $CO_2$ capture is required, and thus the penalty of capture is eliminated. As a result, the net benefit of the $H_2$-fueled APC is estimated to be 15%, whereas the net benefit from a natural gas system is estimated to be 5%–10%. The APC's relationship to RICE can be equated to that of the relationship of supercritical $CO_2$ to a gas turbine: both power systems yield higher efficiency for their corresponding prime movers by drafting a cycle with a higher average cycle peak temperature.

In search for the highest possible efficiency, this project also explored whether, and by how much, net plant efficiency could be increased by adding a bottoming cycle. Because of the higher performance of the RICE with the APC, exhaust temperatures drop by comparison. On the other hand, as engine bore size increases, the heat losses to the cooling jacket decrease slightly, balancing the quality of the exhaust heat. The DOE goal is a power-to-heat ratio of 1.5 and overall CHP thermodynamic efficiency of 80%. Two bottoming cycle cases were tested, the first using water as a refrigerant (for cases in which the exhaust exergy was high) and the second using R245FA (for cases in which the exhaust exergy was low). The results showed that the use of an ORC increased the efficiency gains slightly at low exhaust gas temperatures (limited to less than 2%) and reduced the heat available for district heating, hurting the overall CHP efficiency of the plant compared to water. The water cycle delivered 73 kW more power than the ORC, with 1.4 MW of useful heat, an overall efficiency of 90%, and a power-to-heat ratio of 1.68. On the other hand, the 88 kW ORC and 3 MW engine delivered 1.2 MW of useful heat and an overall efficiency of 87%.

The next steps in this work are to demonstrate that the thermodynamic efficiency of the RICE can be increased by as much as 18% through integration of the APC. Once the APC has been implemented in a CHP framework, the objective will be to exhibit RICE efficiencies of 65% or more and overall system efficiency of 70%.

**Key Points Raised During Q&A**

- Argon was selected as the working fluid because it was the practical business choice. Argon is relatively cheap compared to the other noble gases, and it has good conductivity/ insulation properties, so it is easier to seal and reduces heat losses. If performance were more important than cost-effectiveness, a heavier noble gas would be used.
- During the membrane purification process, 100% of the $CO_2$ is recovered at a purity of 95%, with the other components being mainly argon.
- No NG upgrading (reduced $CO_2$ content) is needed for this system.

## Tour of Southwest Research Institute

*Hosted by SwRI*

Day Two concluded with an optional tour of the host site, SwRI. The tour included the following:

- The first stop for the meeting participants was the Supercritical Transformational Electric Power (STEP) Facility. The STEP pilot plant is a collaboration between SwRI, GTI Energy, GE Research, and DOE NETL. The facility is designed to demonstrate $sCO_2$ power cycles, a new form of power generation that is considerably more efficient and cost-effective than traditional steam cycles. Figure 7 is a photograph of participants taken during this part of the tour.
- The next stop in the tour was the power train engineering facilities. Meeting participants were shown a single-cylinder engine test stand that is currently being used to research the use of hydrogen fuels in reciprocating engine applications. Additionally, meeting participants were given tours of the large engine test facility. At this facility, researchers test the performance of stationary engines, many of which can be employed in CHP and DE applications.
- The final stop in the tour was the turbomachinery laboratory. Participants were shown several advanced machinery systems that have been developed by SwRI to support $sCO_2$ power cycles and carbon capture and sequestration. Additionally, participants were given tours of two combustion test facilities. The HEAT facility is being used to develop and test combustion system improvements that will allow for improved high-turndown efficiency and promote the use of F-CHP. The second facility is demonstrating oxy-fuel combustion that will further improve $sCO_2$ power cycle efficiencies.


*Figure 7. Photograph of meeting participants at the STEP facility during the SwRI tour.*

## *Day Three*

### Introduction to Day Three

*Robert Gemmer, Advanced Manufacturing Office*

Day Three began with an introductory presentation from Dr. Gemmer, who welcomed participants back for the final day of the workshop. Dr. Gemmer then provided a brief summary of the preceding day's presentations and facility tour, gave a high-level overview of AMO's DE activities, and introduced the presentations for the third day.

Since fiscal year (FY) 2018, AMO has received direction from Congress to support R&D on DE systems. As a result, the following activities were initiated:

- FY 2018 laboratory call
  - A national laboratory project to incorporate DE systems in the URBANopt tool (National Renewable Energy Laboratory and Lawrence Berkeley National Laboratory)
- FY 2019 funding opportunity announcement (FOA)
  - Five projects to perform verification and validation on the performance of DESs
- FY 2020 FOA
  - Two projects to demonstrate F-CHP systems in a renewably fueled DES
- FY 2021 FOA
  - A solicitation for projects that will advance technologies in a renewably supplied DES. At the time of the meeting, the solicitation was closed, and selections were pending. Three selections were announced after the meeting (in July 2022).

In addition to the above research activities, AMO has also supported a Report to Congress on District Energy Systems (issued in July 2019), and DE was included in the CHP Potential Study prepared for DOE by ICF International (issued in March 2016).

On Day Three, six presentations were given that focused on DESs, particularly modeling and verification/validation of these systems. The results from the 2018 laboratory call were presented first, followed by presentations of five projects selected through the 2019 FOA.

**Key Points Raised During Q&A**

- Dr. Gemmer defines a F-CHP system as one that produces electricity for a local facility, in addition to producing electricity for the grid.

## District Energy Systems Modeling and Verification/Validation

### Simulation-Based Design and Optimization of Waste Heat Recovery Systems

*Nicholas Long, National Renewable Energy Laboratory, and David Blum, Lawrence Berkeley National Laboratory*

The motivation for this work is to progress into the "fifth generation" of DES, in which DES can be energy-efficient and allow bidirectional heating/cooling at approximately ambient temperatures (~15–25°C). To aid in this transition/transformation, this project's goal is to develop analytical models for DESs, extend existing tools to enable easier modeling of DESs, and integrate additional waste heat sources (e.g., sewer and wastewater treatment, data center cooling, condenser water, etc.) into the analytical framework. The project is working with a private third-party company to integrate the analysis into their systems so that, for example, developers of community-scale construction projects can evaluate DESs and their potential application.

Developing a fifth-generation DES poses a major challenge: addressing the low-temperature network (LTN), which is close to ambient temperatures. LTN requires local temperature-boosting to heat and cool buildings, which leads to more complex energy transfer station designs. Bidirectional mass or energy flow is needed to enable network-wide heat recovery, which requires tighter hydronic coupling between network components. Additionally, low-temperature lifts increase the magnitude and sensitivity of mass flow to load changes, which places a greater emphasis on pump energy and control and pipe designs. As a result, LTN presents control challenges for stable and efficient operation. Dynamic modeling, including explicit pressure flow and control, is required; load-based modeling alone is insufficient to aid practical design and operation and is unable to capture control issues.

To try to resolve these matters, Modelica Buildings Library was used and expanded upon for developing the underlying component models for the analysis. Modelica is an object-oriented, equation-based language that integrates and models heterogeneous physical systems through time. This software has been used in automotive, energy, and aerospace industries, and its open specification allows commercial and open-source compilers. Modelica separates modeling from simulation, enabling equation-solving even in nonlinear equations, which allows modeling of pressure-flow networks and controls in DESs. The Modelica Buildings Library contains over 2,000 models, including ones for heat transfer between rooms and the outside. The Spawn of EnergyPlus—also employed by the project—uses the Modelica Buildings Library in its simulation engine coupled with EnergyPlus for building and control energy systems.

The Urban Renewable Building and Neighborhood optimization (URBANopt) software development kit (SDK) is a simulation platform that can be used to analyze urban centers including DESs. The SDK includes three major components: building core modules, district thermal system modules, and grid interactivity modules. Figure 8 shows the technologies utilized for each capability. Each building is modeled separately, the thermal loads are modeled by thermal zone in the individual buildings, and then the buildings are combined in the model. REopt can be incorporated into the grid interactivity module.

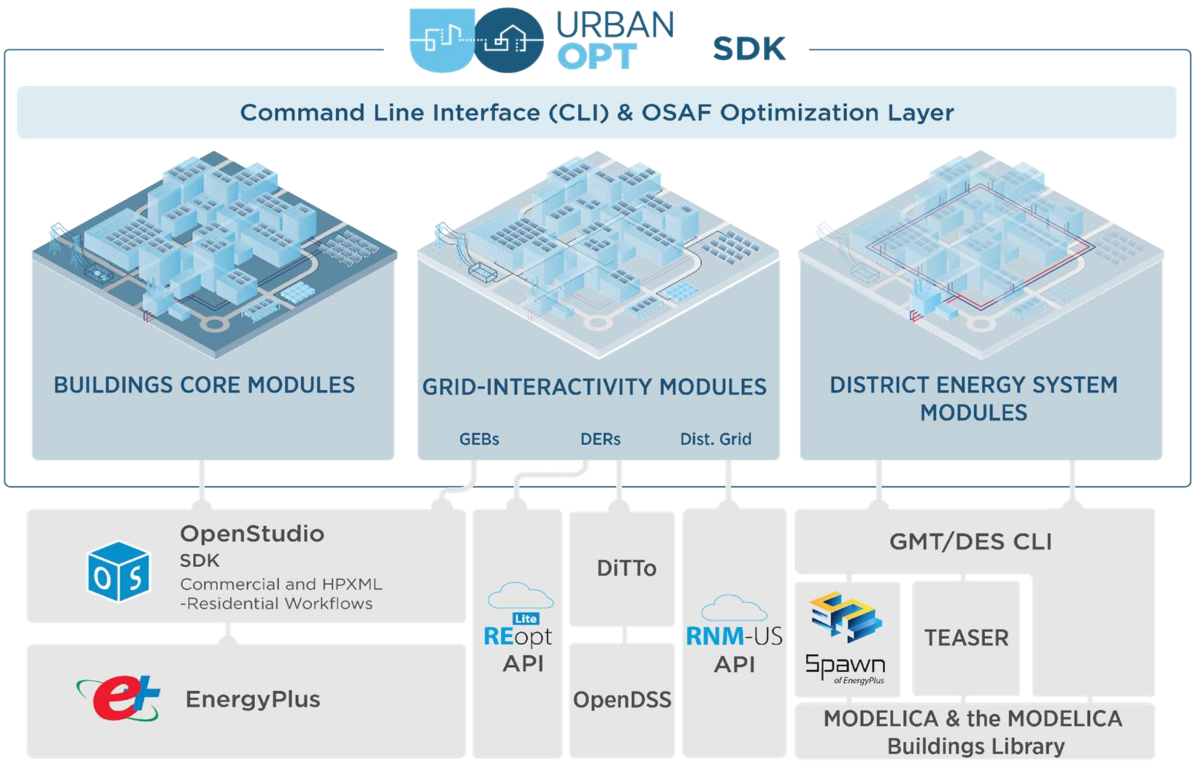



*Figure 8. The URBANopt SDC Architecture.*

Fourth-generation models have been integrated into a tool called the GeoJSON to Modelica Translator (GMT) that is able to automatically connect buildings together using the loads and layout from URBANopt. Fifth-generation models have also been integrated but are still under verification. Work is continuing to provide more robust integration, access to additional district generations, tighter integration with third-party tools, and implementation of additional network component models in Modelica.

Several case studies have been performed:

- The National Renewable Energy Laboratory demonstrated a campus expansion using URBANopt to model a 4G system and Modelica Buildings Library for a lower-temperature 5G system. The 5G system only used ~25% of the heating power input required by the 4G system because it leveraged waste heat off the laboratory’s supercomputer.
- A new 5G DES LTN topology was proposed, a so-called reservoir network, to overcome control challenges observed in bi-directional networks. The two network topologies were

modeled (including waste heat from a sewer system and geothermal storage) with the Modelica Buildings Library. The topologies showed similar energy performance, with the reservoir network showing better control stability and an opportunity for modularity.

- A model was created to integrate waste heat loads into the Modelica and URBANopt DES. The model includes data center water cooling, data center air cooling, wastewater, refrigeration, and laundry.

**Key Points Raised During Q&A**

- Several factors can lead to model error (compared to actual operation), such as occupant behavior, equipment size, and ground modeling accuracy. For example, heat transfer of pipes running underground varies with ground conditions, affecting the accuracy of heat transfer calculations.
- The REopt model has seven building types, and a specific load profile can be uploaded to the model. In the URBANopt model, the building energy modeling is specified, and then EnergyPlus is used.
- It is important to validate individual models by calibrating with known data or with other simulations. These component-level tests are performed, similar to ASHRAE Standard 140 validation testing, to mitigate error of propagation. This team is always interested in working with partners who have existing validated models or real data so that component models can be validated.
- The framework does not currently include future weather years, but these data can be incorporated into GeoJSON, a tool that can be used and integrated for further analysis.
- Modelica is a promising framework for analyzing buildings. It has shown success and growth in the automotive industry and can be viewed with similar potential for building and DESs.

## Advances on CHP District Energy and Microgrid Deployment: Simplified Tool for Rapidly Deploying Feasibility Analytics for the Non-Technical User

*Gavin Dillingham, Houston Advanced Research Center (HARC)*

The purpose of this project is to develop a free, cloud-based, user-friendly, and easily accessible tool for stakeholders to expedite feasibility analyses of community CHP-based DESs and microgrids. The vision is that this software will be available for non-technical users (e.g., investors) and will also provide advanced features for technical users. Overall, the project will increase adoption of community microgrids and DESs by reducing the time and cost needed to run feasibility analyses (e.g., so more microgrids and DESs can be evaluated by investors and more potential solutions explored). Increasing onsite generation will improve energy resilience and reliability.

The tool operates by creating a digital twin with geographic information system (GIS) capabilities (3D environment for navigation) by using light detection and ranging (LiDAR). The tool’s architecture integrates three major components: the customized graphical user interface (GUI), the computational engine, and the middleware/cloud service. The tool helps the user understand key economics, such as return on investment or rate of return, to make the best investment decision. The approach is not one-size-fits-all, and the tool uses AI-based algorithms to analyze thousands of potential technology combinations and configurations, removing unconscious biases in the engineering process. The assessments have increased accuracy because data about future climate scenarios is being integrated into the model.

The model has been built for an area of 25 square miles around the center of Houston, Texas. The user can select buildings that would be included in the DES or microgrid and input the financial, environmental, and resilience goals. The output will return the most optimized model and benchmark the result with the user's goals.

The project is now developing the report structure and style. In the coming months, the project team expects to finalize the reporting capabilities and incorporate them into the GUI and the computational engine, validate the first version of the computational engine (expected to be ready November 2022), test the middleware, make the microgrid part of the tool available, and run intensive testing.

**Key Points Raised During Q&A**

- The tool is developed in MATLAB and uses an hourly timeframe for its fidelity.
- The tool enables the integration of both new and existing buildings into community energy systems.
- The user inputs the detailed utility data that the tool will use. The more granular the data, the better the model output.
- HARC is in contact with different manufacturers collecting as many data as possible (e.g., cost of system components) to maximize model accuracy and the number of scenarios.
- When selecting a building to include in the model, the digital twin contains some information on sizing and other building specifications, but the user can customize if desired. The user selects which buildings are connected in the network, and the tool optimizes the structure, cost, and center location to connect the system. The model output shows system information (e.g., operational costs).
- The ultimate project goal is to drive interest in taking the first step, which seems to be the biggest hurdle, toward DESs and microgrids. This work enables the user to be an informed consumer when they arrive at an engineering company for further evaluation of their potential application/system.
- Rice University ramps up its microgrid system in response to ERCOT pricing and the market.

## Advanced District Energy Controls for Improved Efficiency and Resilience

*Julian Lamb, Paragon Robotics*

The goal of this project is to model, install, and verify a community-based (municipal, multi-customer) DE demand and generation control system that reduces undelivered energy. The project aims to investigate monitoring and controls that can improve both the efficiency and resilience of centralized CHP/storage addition or remote CHP generation. This work is dedicated to keeping real-world applications in mind and making sure that proposed solutions are reasonable and feasible.

The initial focus was largely on survey and social science work, with the aim of better understanding what drives customers and how CHP can be implemented in a real-world system. A survey on energy efficiency was sent to approximately 40 end users on Cleveland Thermal's DES; about half responded. This survey examined end-user attitudes about energy efficiency, costs as a factor in end-user decision making, and end-user interest in/open-mindedness about DESs. A wide net was cast for this first survey; a more targeted respondent questionnaire will be conducted later.

The survey revealed that cost is a primary driver for end-user decision making in terms of efficiency improvements. Operating and maintenance costs are the most important, followed by upfront capital costs. From a list of potential behind-the-meter efficiency improvements, lighting was the most popular choice. Responses were widespread regarding how best to pay for DE. Over half of the respondents preferred payback periods of less than five years for energy efficiency investments; only 18% of the respondents would consider a payback period of more than five years.

Respondents were informed about demand side management (DSM) and demand response programs, and they can reduce costs. DSM programs (including electricity programs) were unfamiliar to 44% of respondents, but upon learning about DSM, 94% would likely participate if the program could save them money. Some respondents (40%) noted that they could reduce heating or cooling load during peak demand events. The survey also explained how microgrids within a DE footprint can deliver additional value for electrical and thermal loads. Of all respondents, 62% were familiar with the design and operation of microgrids, and 90% thought that microgrids could be useful to their companies. Most respondents stated that they were willing to pay 7 cents per kWh for electricity from a microgrid that could deliver 99.999% uptime; however, the prevailing cost is currently 11 cents per kWh.

Next, this project looked at steam and associated energy losses. In the summer months, much energy is lost in the steam system. The losses are determined by calculating the difference between steam energy sendout and steam energy sold. The steam energy losses vary from 13% to 58%, with the highest losses typically in July, when steam energy efficiency is only 25%. In addition to the heat loss through piping, loss due to flow discharge in traps and leaks could decrease efficiency. The project team researched using steam traps but determined that they are impractical, as piping is buried and manholes are not widely accessible. Furthermore, getting data from inside manholes (regardless of accessibility) is not really feasible because temperatures and humidity are high (~85°C), which has impacts on instrumentation (in terms of both functionality and maintenance costs). As a result, the project focus for steam efficiency improvements is on real-time flow rate (typically condensate flow rate) and optional pressure sensing at some customer sites. Real-time data will be integrated from the entire network, and AI analysis will be used against the system model to look for discrepancies and make suggestions to operators regarding those discrepancies (e.g., implementing a smart control system).

In its final phase, the project will demonstrate additional renewable, CHP, or microgrid equipment.

**Key Points Raised During Q&A**

- Utilities are interested in installing turbines at the customer level, so this project is trying to better understand and quantify the practical consumer-level applications.
- The steam network was selected for evaluation for three reasons: it is large (~80 customers); steam is distributed at any time, so the steam pipes are always live; and there is a variety of customers. (For comparison, the chilled water network has only ~20 customers.) In the summer months, mostly industrial customers need steam for process heat (e.g., using steam in the food industry or as a reheat for humidity control).
- Using real-time data is greatly improving analysis and modeling. Genetic algorithms (running tens of thousands of models) are being used to run multiple variables which has generated a lot of data.

## Verification and Validation of Performance with Dissemination of Best Practices in District Energy and CHP for Enhanced Resilience, Energy Efficiency, and Cybersecurity

*Henry Johnstone, International District Energy Association (IDEA)*

This project aims to increase stakeholder awareness of the role of DE, CHP, and microgrid assets in supporting and participating in the grid of the future. In addition, the project is verifying, validating, and analyzing performance metrics (for DE, CHP, and microgrid systems) and identifying industry best practices.

Project researchers emailed a survey to 42 sites, each with a history of participating with IDEA. The survey focused on one or more of the following topics, as applicable to the specific site: CHP and microgrids, renewables and thermal energy storage, management, and cybersecurity. The sites were chosen to represent different climate zones, different markets and rate structures, and different sizes. A large sample of those surveyed were on university campuses, but respondents also included medical centers, municipal systems and utilities, and airports.

Email responses to the survey varied in levels of detail provided, so the project team decided to interview each site to gather more information. These virtual interviews take place with a participant team, which could include (for example) engineers, energy managers, plant operators, and utility directors. The survey questions are used as a starting point, and the conversation is relatively unstructured, which encourages the participant team to share best practices and lessons learned. The interview is documented in a written summary, and a system line diagram is created to help characterize the information. About half of the participant interviews have been completed so far, and the results are being analyzed to identify best practice themes. Several have already emerged:

- There is a growing use of chilled water thermal energy storage with renewables for load balance and decarbonization.
- CHP is being utilized as a key system element in the transition to zero carbon emissions.
- Information sharing and communication between operations management, organization, and leadership are important for overall system efficiency.
- Building efficiency is being integrated into DES optimization.

The project has also discovered that some respondents with CHP have inadequate heat load in the summer. Facilities have absorption chillers, but they are slow-moving, have a slow thermal response, and require a good deal of maintenance. One solution is to add ORC to CHP. This idea is gaining traction and could avoid the absorption chiller issues.

Furthermore, respondents feel that there is some friction and that utilities are not promoting local CHP. Decisions are driven by ROI (rather than energy or carbon emissions). ROI is historically evaluated through master planning (e.g., a 20-year look-ahead) and lifecycle analysis to evaluate alternatives. However, uncertainty about future technologies (e.g., hydrogen availability) and costs (e.g., carbon and gas rates) make it challenging to do these analyses.

**Key Points Raised During Q&A**

- A DES's physical boundary (e.g., chilled water loop, heating, electricity) differs depending on the service or utility in which the DES is used. The main challenge is interconnection; for example, steam transactions are easier than electric.
- Within the respondent group, the majority of existing CHP systems are 5–15 MW gas turbines.
- Europe has done a good job of implementing district heating. Many regions have good pipe distribution, and the pipe material is corrosion resistant.
- Often, solar is being implemented through a power purchase agreement.

## Urban Combined Heat and Power with Integrated Renewables and Energy Storage

*Saniya LeBlanc, George Washington University (GWU)*

This project aims to determine how to effectively integrate and enhance electricity generation and energy storage components into an urban DES to impact resilience, reliability, vulnerability, and ROI. The project evaluates two DE cases, one real (the GWU DES) and one fabricated (DES "synthetic case"). The synthetic case contains a mixture of different site types, including homes, businesses, hotels, schools, a hospital, and a park. The DES was built from load data, and the loads were evaluated based on the city-block square footage occupied by the building and the total building square footage. The real-life case was based on the GWU DES, which supports two academic buildings and three dormitories. The GWU DES has 7.4 MW combined-cycle CHP. The campus has 497 kW of rooftop solar, in addition to 52 MW of solar from a power purchase agreement comprised of three solar farms on the PJM grid; this agreement supplies half of the university's energy. Additionally, there are two electric vehicle charging stations and four solar water heating systems.

To make decisions about the utilization of different energy systems, the project team considered existing energy management systems but ultimately opted to develop a new one that can also be used as a modeling tool. The system currently looks at electric, thermal, and cooling loads; fuel cells could be added. This energy management system takes inputs such as historical data and utility status to perform and output forecasting. Two modes are considered—baseline and emergency—for both the synthetic and GWU DES studies. In the baseline case, the objective function minimizes operational cost and has a heavy penalty for any outages. In emergency mode, operational cost is also minimized, but there is a mild penalty for not having stored energy (power and thermal) and a heavy penalty for shedding the critical load. The critical load is defined by the user; the current implementation assumes 20% of the load is critical. In the GWU case study, the most challenging project task was obtaining data for all GWU energy systems.

To achieve its objectives, the project adds new technologies to the model to gauge their impacts. For both the synthetic and GWU DES cases, researchers compared the base case to the base case plus PV generation, battery storage, and thermal storage technologies. Historical load data is used to predict upcoming load. Negative power indicates that charging is taking place. The model, using the energy management system, shows how the DES should be operated for electrical, cooling, and heating functions. In the GWU DES case, the GWU CHP is oversized; it was originally sized (in 2014) to supply the needed load and avoid pulling from the grid. As a result, the synthetic case provides more useful information in this study. In the hardware-in-the-loop testbed demonstrations, hardware simulates operation of the energy systems such as the battery charge/discharge of cycling.

The technoeconomic framework of this study calculated and evaluated the following metrics:

- Reliability
  - Loss of energy expectation – the expected number of days in which the daily peak load exceeds the available generating capacity
  - Probability that energy needs are met – the percentage of simulations where the demands of the system are adequately met and do not fail the system
- Resilience
  - Probability of recovery – the percentage of time intervals in which the system, previously operating in deficit, is now meeting demand
- Vulnerability
  - Average failure – average failure load deficit divided by the average load during a failure
- ROI
- Cost per significant unit
  - Storage cost – capital cost of the technology divided by the storage capacity
  - Generation cost – capital cost of the technology divided by the generation capability

This evaluation can be performed for any DES to determine its reliability, resilience, vulnerability, and cost-effectiveness. In the analysis, the "status quo" scenario allowed DE to buy energy from the grid. A flat rate was used for electricity pricing. When compared to REopt, REopt showed that none of the new technologies were cost-effective. Specifically, PV generation and battery storage were expensive, revealing that a DES with CHP might not benefit from additional distributed generation and storage depending on the size (capacity) of the energy systems. The next iteration will have dynamic pricing for electricity, which will more closely resemble real-life scenarios.

**Key Points Raised During Q&A**

- Currently, GWU is not planning to connect its CHP system to the grid to sell excess electricity; the current agreement with the utility does not allow the CHP to feed into the grid.
- The synthetic case contained seven different building types. The sizes of the energy systems were specified as inputs to the energy management system.
- The minimum import requirement in the simulation was initially 700 kW, but discussions are underway with the utility to try to lower it to 200 kW.
- Optimization variables will include cost, as well as other parameters.

## Optimal Co-Design of Integrated Thermal–Electrical Networks and Control Systems for Grid-Interactive Efficient District Energy Systems

*Kyri Baker, University of Colorado, Boulder, and Wangda Zuo, Pennsylvania State University*

Fundamentally, microgrids are different from conventional power grids. Microgrids are more challenging to operate and optimize because a microgrid must supply demand locally and keep frequency at 60 Hz, which requires a sub-second balance of supply and demand. Additionally, microgrids have less redundancy than conventional power grids. Therefore, the objectives for microgrids are to achieve energy efficiency and to shift some energy consumption to periods of lower demand to relieve the supply–demand strain. When in island mode, microgrids cannot simply “draw from the grid” when supplies run scarce, so multiple energy sources are used (e.g., batteries and thermal generation). To achieve efficiency while limiting carbon emissions, microgrids aim to minimize fuel use from CHP plants and maximize local renewable generation.

This project seeks to create a holistic open-source modeling platform to optimize design and retrofit of grid-interactive efficient district energy systems and microgrids via integrating thermal and electrical systems and their controls. The goal is to increase system efficiency and resilience by 25%. To this end, Modelica models for the microgrid have been developed to perform fully dynamic simulations rather than using steady-state, as other tools do.

As referenced during the presentation on “Simulation-Based Design and Optimization of Waste Heat Recovery Systems,” Modelica is an equation-based, object-oriented, multi-domain modeling language for dynamic systems. It was developed in 1996 and has over 100 free libraries and over 2,100 models available. There are currently 16 countries working together to increase its modeling capabilities. Modelica can be used for simulation, optimization, or computing.

For this project, Modelica has been used to simulate and test several scenarios. The first is testing the performance of different chillers in district cooling systems. The model-based control optimization led to a 15% reduction in energy, 9% reduction in cost, and 15% reduction in $CO_2$ emissions. The research team has also found strategies to model more efficiently, using a new approach in Modelica to model a district heating system for a network with 180 buildings. Computing time was reduced from 33 hours to 1.3 hours, with a relative error of less than 0.08%.

The research team then moved on to the next industry application and the primary project focus: the integration of an electric–thermofluid system, for which no model is currently available. A hierarchical model was constructed in Modelica to couple electric and thermofluid systems so that, when there is a change in the thermal load, the impact on the electrical system can be evaluated.

To optimize the system, reinforcement learning (RL) was applied so that the model automatically updates its controls based on past experiences. An initial case study using DymolaGym showed success with improved voltage regulation (e.g., eliminating huge voltage swings), reduced line losses, and reduced overall generation. DymolaGym allows for rapid prototyping of RL environments using Modelica-based models. Over time, RL made the system more efficient.

To further optimize and improve efficiency, the research team is using both Modelica and URBANopt. The URBANopt SDK integrates multiple analysis tools including OpenStudio, OpenDSS, REopt, and the GeoJSON to Modelica Translator (GMT). The GMT currently handles two levels of model construction, Level 1 (the focus of this project) and Level 3. Level 1 enables string substitution into Modelica files to create models that can be simulated. Level 3 dynamically generates couplings and currently works only for 4G and 5G systems. Loads are dynamically created and connected and include Spawn, TEASER, and time-series data (which can be sourced from URBANopt SDK’s OpenStudio simulations). Based on the inputs from URBANopt, the GMT replaces some default design and sizing parameters in existing Modelica system template models.

The next step is to demonstrate whether the proposed platform can achieve a 25% total system energy efficiency improvement (from source to delivered energy), in addition to a 25% increase in the number of continuous operational hours in a simulation environment (resilience). First, a demonstration will be performed using the campus at the University of Colorado Boulder (with 92 buildings). Subsequently, the study will be expanded to test 160 buildings and a harsher summer climate at the University of Texas at Austin.

**Key Points Raised During Q&A**

- Currently, computation cost is limiting RL to offline use, but in the future, some may be done online. Some of the RL algorithms can be deployed online through cloud-based training. Overall, system reliability is a higher priority than system optimization.
- In case of system failure, having a backup is recommended so that the system can default to something that is safe, if not optimal.
- The initial case study used RL-10 and RL-50, but they will likely be merged in future studies. The tool can simulate +/- 5% transmission-level control.

# Closing Remarks

*Robert Gemmer, Advanced Manufacturing Office*

Dr. Gemmer ended the portfolio meeting with a few closing remarks. These included announcing his upcoming retirement, planned for October 2022. Dr. Gemmer noted that the projects will continue with support from AMO, under a new technical manager. He encouraged everyone to visit the AMO website for program and personnel updates and other information.

# Appendix A. Agenda

| 2022 Combined Heat and Power/District Energy System Portfolio Meeting | | | | |
|---|---|---|---|---|
| Southwest Research Institute, June 7–9, 2022 | | | | |
| **Day 1** | **Start** | **End** | **Presenter** | **Topic** |
| | 730 | 800 | Breakfast | |
| | 800 | 815 | Bob Gemmer, DOE<br>Tim Allison, SwRI | Welcome and Agenda Summary<br>SwRI Safety Briefing |
| | 815 | 900 | Bob Gemmer<br>DOE | Overview of CHP Program |
| | 900 | 930 | David Jones<br>ICF | CHP Market Overview |
| | 930 | 1015 | Bruce Hedman<br>Entropy Research | CHP and Decarbonization |
| | 1015 | 1030 | Break | |
| | 1030 | 1100 | Peggy Ip<br>EPRI | Value of Flexible CHP to System Owners |
| | 1100 | 1130 | Griffin Beck<br>Southwest Research Institute | Modifications to Solar Titan-130 Combustion Systems for Efficient, High Turndown Operation |
| | 1130 | 1200 | Anand Kulkarni<br>Siemens, Inc. | Demonstration of Improved CHP Systems Utilizing Improved Gas Turbine and $sCO_2$ Cycles Using Additive Manufacturing (AM) Components |
| | 1200 | 1300 | Lunch | |
| | 1300 | 1330 | Tom Brokaw<br>ElectraTherm, Inc. | Organic Rankine Cycle Integration and Optimization for High Efficiency CHP Genset Systems |
| | 1330 | 1400 | Fred Wang<br>University of Tennessee | SiC Based Modular Transformerless MW-Scale Power Conditioning System and Control for Flexible CHP System |
| | 1400 | 1430 | Rolando Burgos<br>Virginia Tech | High-Efficiency SiC-Based Flexible CHP Interface-Converter with Advanced Grid Support Functions |
| | 1430 | 1500 | Ibrahima Ndiaye<br>GE Research | Converter-Interfaced CHP Plant for Improved Grid-Integration, Flexibility and Resiliency |
| | 1500 | 1515 | Break | |
| | 1515 | 1545 | Randy Collins<br>Clemson University | High Speed Medium Voltage CHP System with Advanced Grid Support |
| | 1545 | 1615 | Randy Collins<br>Clemson University | Megawatt Scale, Multi-Source Heat Recovery System with a Flexible Grid Interconnect |
| | 1615 | 1645 | Jas Singh<br>Caterpillar, Inc. | Flexible Natural Gas/Hydrogen CHP System |
| | 1645 | 1715 | Derek Young<br>Colorado State University | Turbocompression Cooling System for Ultra Low Temperature Waste Heat Recovery |

| Day 2 | Start | End | Presenter | Topic |
|---|---|---|---|---|
| | 830 | 900 | Breakfast | |
| | 900 | 915 | Bob Gemmer | Introduction to Day Two |
| | 915 | 945 | Doug Straub<br>National Energy Technology Lab | Advanced Airfoils for Efficient CHP Systems |
| | 945 | 1015 | Bruce Pint<br>Oak Ridge National Lab | High Performance, High Temperature Materials to Enable High Efficiency Power Generation |
| | 1015 | 1030 | Break | |
| | 1030 | 1100 | Comas Haynes<br>Georgia Tech | Robust Combined Heat and Hybrid Power (CHHP) for High Electrical Efficiency Cogeneration |
| | 1100 | 1130 | Dan Thoma<br>University of Wisconsin | Additive Manufactured Super-Critical $CO_2$ Heat to Power Solution |
| | 1130 | 1200 | Miguel Sierra Aznar<br>Noble Thermodynamics | Ultra Efficient CHP with High Power/Heat Ratio using a Novel Argon Power Cycle |
| | 1200 | 1300 | Lunch | |
| | 1300 | 1700 | Griffin Beck<br>SwRI | Tours of Southwest Research Institute |

| Day 3 | Start | End | Presenter | Topic |
|---|---|---|---|---|
| | 800 | 830 | Breakfast | |
| | 830 | 845 | Bob Gemmer | Introduction to District Energy Systems |
| | 845 | 915 | Nicholas Long, NREL<br>David Blum, LBNL | Simulation Based Design and Optimization of Waste Heat Recovery Systems |
| | 915 | 945 | Gavin Dillingham<br>Houston Advanced Research Center | Advances on CHP District Energy and Microgrids Deployment: Simplified Tool for Rapidly Deploying Feasibility Analytics for the Non-Technical User |
| | 945 | 1000 | Break | |
| | 1000 | 1030 | Julian Lamb<br>Paragon Robotics | Advanced District Energy Controls for Improved Efficiency and Resilience |
| | 1030 | 1100 | Henry Johnstone<br>International District Energy Assoc. | Verification and Validation of Performance with Dissemination of Best Practices in District Energy and CHP for Enhanced Resiliency, Energy Efficiency and Cybersecurity |
| | 1100 | 1130 | Saniya LeBlanc<br>George Washington University | Urban Combined Heat and Power with Integrated Renewables and Energy Storage |
| | 1130 | 1200 | Kyri Baker, University of Colorado, Boulder<br>Wangda Zuo, Penn State University | Optimal Co-Design of Integrated Thermal-Electrical Networks and Control Systems for Grid-interactive Efficient District (GED) Energy Systems |
| | 1200 | 1215 | Bob Gemmer | Closing Comments and Adjourn |

# Appendix B. Workshop Participants

| Name | Organization |
|---|---|
| Mark Anderson | University of Wisconsin–Madison |
| Kyri Baker | University of Colorado Boulder |
| Guillaume Beardsell | Noble Thermodynamic Systems, Inc. |
| Griffin Beck | Southwest Research Institute |
| Mahabir Bhandari | Oak Ridge National Laboratory |
| David Blum | Lawrence Berkeley National Laboratory |
| Thomas Briggs | Southwest Research Institute |
| Tom Brokaw | ElectraTherm |
| Rolando Burgos | Virginia Tech – Center for Power Electronics Systems |
| Randy Collins | Clemson University |
| Elizabeth Collins | National Renewable Energy Laboratory |
| Payman Dehghanian | The George Washington University |
| Gavin Dillingham | Houston Advanced Research Center |
| Sebastien Dryepondt | Oak Ridge National Laboratory |
| Matt Franke | U.S. Department of Energy, Advanced Manufacturing Office |
| Carlos Gamarra | Houston Advanced Research Center |
| Robert Gemmer | U.S. Department of Energy, Advanced Manufacturing Office |
| Comas Haynes | Georgia Tech Research Institute |
| Bruce Hedman | Entropy Research, LLC |
| Peggy Ip | Electric Power Research Institute (EPRI) |
| Henry Johnstone | International District Energy Association |
| David Jones | ICF |
| Fernando Karg Bulnes | Southwest Research Institute |
| Meegan Kelly | U.S. Department of Energy |
| George Khawly | Southwest Research Institute |
| Anand Kulkarni | Siemens Corporation |
| Julian Lamb | Paragon Robotics |
| Saniya LeBlanc | The George Washington University |
| Paul Lemar | Resource Dynamics Corporation |
| Nicholas Long | National Renewable Energy Laboratory |
| David Montgomery | Caterpillar Inc. |

| | |
|---|---|
| Kashif Nawaz | Oak Ridge National Laboratory |
| Ibrahima Ndiaye | GE Research |
| Kristin Paulsen (virtual) | Energetics |
| Bruce Pint | Oak Ridge National Laboratory |
| Shanti Pless | National Renewable Energy Laboratory |
| Dean Sarandria | TECO Westinghouse |
| Chad Schell | U.S. Department of Energy, Advanced Manufacturing Office |
| Larry Shadle | U.S. Department of Energy, National Energy Technology Laboratory |
| Miguel Sierra Aznar | Noble Thermodynamic Systems, Inc. |
| Jaswinder (Jas) Singh | Caterpillar Inc. |
| Doug Straub | U.S. Department of Energy, National Energy Technology Laboratory |
| John Tabacchi | U.S. Department of Energy, National Energy Technology Laboratory |
| Yong Tao | Cleveland State University |
| Dan Thoma | University of Wisconsin–Madison |
| Fred Wang | University of Tennessee, Knoxville |
| Derek Young (virtual) | Colorado State University |
| Wangda Zuo | Penn State University |

Note: A total of 48 individuals participated in the workshop.

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