Annual Report | Volume 6 | 2018

ADVANCED POWER AND ENERGY PROGRAM

BRIDGING

Engineering Science to Practical Application

Hydrogen: The Key to Our Future

DIRECTOR'S MESSAGE

Professor Scott Samuelsen

Director, Advanced Power and Energy Program

The shift to clean energy production in the United States and the world is accelerating. While solar and wind continue to be critical components, the global community has recognized that hydrogen is uniquely suited to provide the massive amounts of clean energy and energy storage needed as the movement away from combustion accelerates. The Advanced Power and Energy Program (APEP) continues to be solidly positioned at the forefront of this change as it works in close collaboration with industry, national and international agencies, universities, and laboratories. Bridging the gap between engineering science and practical application has long been a hallmark of APEP, the umbrella organization for the National Fuel Cell Research Center (NFCRC) and the UCI Combustion Laboratory (UCICL). These critical relationships have become even more valuable as the energy landscape has transformed.

For this sixth edition of our "Bridging" annual report, we not only feature APEP's continuing work in bringing the hydrogen future to the hydrogen present, but also our research into effective and reliable microgrids, and ever cleaner combustion which is needed until the shift to zero carbon-zero pollutant energy production is complete.

To address resiliency, reliability and the environmental impact of water and energy systems, APEP under the sponsorship of the U.S. DOE, is coordinating research into a new generation of power plants that can operate with high efficiency while producing water. Transforming power plants from water consumers to net-producers is an important step towards higher resiliency and reliability for both water and energy systems.

In one of our most important efforts, APEP in partnership with UCI Facilities Management successfully islanded the campus 20 megawatt-class microgrid from the Southern California Edison grid on February 12, 2018. During the one hour and fifteen minute test, the microgrid performed flawlessly in response to varying campus electrical load demands.

Many communities in California experience degraded air quality as a result of significant emissions from goods movement using heavy duty diesel trucks, cargo and materials handling equipment, ships, and rail. With funding provided by Toyota, APEP is conducting research to assess the air quality and human health impacts of replacing heavy duty diesel trucks with fuel cell electric trucks in California.

First conceived at the NFCRC in 2002, Tri-Generation was successfully demonstrated at the Orange County Sanitation District in Fountain Valley California in 2011 as a viable strategy for producing bio-hydrogen, renewable electricity, and high quality heat from human waste. In the first commercial deployment of this NFCRC technology, Toyota Motor North America and FuelCell Energy announced the deployment of a 2.3MW Tri-Generation fuel cell that is capable of producing 1200 kg/day of bio-hydrogen and a hydrogen fueling station at Toyota's Port of Long Beach operations.

Continuing its cutting edge research in the area of clean combustion, the UCICL is investigating the effects of injecting fuel/water emulsions for high efficiency clean power generation. By injecting water in liquid form with fuel into a combustion system, an increase in power output and a reduction in emissions are possible.

To address a lack of data and facilitate adoption of renewable gaseous fuels including renewable hydrogen, the UCICL is investigating the flammability limits of typical renewable gases. This knowledge is necessary for appliances to perform safely and with no degradation in emissions.

We are especially proud of the accomplishments of our students during the 2017-2018 academic year which includes 7 M.S. graduates, 3 Ph.D. graduates, and 6 internships with diverse entities such as: **Horiba Mira, Walt Disney Imagineering, Los Angeles Department of Water and Power, Tesla Power Systems and Utilities, Altura Associates, and Irvine Valley College**.

In summary, we continue to be indebted to our long standing relationships that contribute in so many ways to our research, real world demonstration projects, students, and to "bridging" from needed research in engineering science to the ultimate goal of deployment in practical application.

Scott Samuelsen

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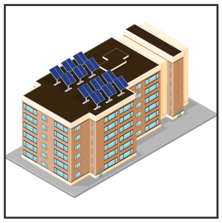
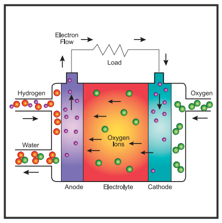
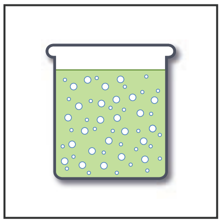
ADVANCED POWER AND ENERGY PROGRAM



NATIONAL FUEL CELL RESEARCH CENTER



UCI COMBUSTION LABORATORY



ALSO INCLUDED IN THIS ISSUE:

Evolution of the Grid:

To meet environmental and energy goals targeted for 2020, 2035, and 2050, changes in the electric grid are rapidly occurring, particularly in sharp contrast to the relatively slow evolution in the past. These changes, a result of the need to mitigate both the emission of greenhouse gases and criteria pollutants from the electric and transportation sectors, include:

- The deployment of renewable solar and wind generation at the transmission level, and the deployment of solar generation at the distribution level in the electric sector.
- The introduction of distributed energy resources (DERs)[1].
- The emergence of plug-in electric vehicles (PEVs)[2] and hydrogen fuel cell electric vehicles (FCEVs) in the transportation sector.

While the existing electric grid is absorbing these paradigm shifts in a complex puzzle of resources, evidence of adverse impacts on reliability and resiliency is starting to surface[3]. Arguably, to accommodate and manage these shifts, major structural changes in the grid must be developed and implemented to resolve the puzzle. While an important piece of the puzzle is smart grid technology, the key to the puzzle may in fact, be hydrogen.

WHY A SMART GRID? Increasing the penetration of intermittent renewable generating resources, PEVs, and FCEVs on the grid requires a strategy to absorb and manage the uncertainty introduced by these intermittent generating resources and intermittent vehicle loads. For example, managing a high penetration of PEVs requires visibility into the grid in order to (1) reduce the impact of PEVs on the load profile, and (2) use PEVs as a grid resource for energy and ancillary services. Increasing the penetration of DERs also presents the need for visibility and control of the grid. A smart grid is a grid with the intelligence necessary to (1) maintain and increase the efficiency and reliability of the grid in the face of these intermittencies, (2) provide two-way communication and controls to enable a path for grid automation and electricity markets, and (3) provide stakeholders with visibility and control over their respective responsibilities, examples of which are:

- Customers: Energy management and control by residential owners, office building managers, industrial plant managers, and campus microgrid operators.
- Utilities: Utility management and control of distribution system services and resources.
- The Independent System Operator (ISO): ISO management and control of the full portfolio of grid services and resources including electricity markets.

WHY IS HYDROGEN THE KEY TO THE PUZZLE?

There are two major reasons.

A ZERO CARBON FUEL TO REPLACE GASOLINE With renewable wind and solar generation establishing an electric grid of zero-carbon, the other major source of carbon, transportation, must move to both a zero-carbon fuel, and a supply chain that emits zero-carbon in the generation of the fuel. While electricity and plug-in electric vehicles represent an emerging example of using electricity as the "fuel" sourced hopefully one day by a zero-carbon grid, hydrogen as the fuel is the preeminent example to enable the range, fueling time, and scale required for a robust transportation system. Again we must ask why?

First, hydrogen is carbon free. Second, when used as a fuel for a fuel cell engine, hydrogen produces virtually zero emission of criteria pollutants for all scales of transportation, from light duty to heavy duty vehicles. Third, hydrogen can be generated from renewable

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[1] DERs: Examples include Distributed Generation (DG), energy storage (e.g., battery, hydrogen), demand response

[2] PEVs: Battery Electric Vehicles (BEVs), Plug-In Hybrid Vehicles (PHEVs), and Plug-In Fuel Cell Electric Vehicles (PFCEVs)

[3] Examples include (1) dynamic fluctuations in grid voltage due to the diurnal and instantaneous intermittencies associated with renewable solar and wind, (2) curtailment of renewable wind energy, (3) unscheduled and uncontrolled vehicle charging loads, and (4) demand for rapid ramping spinning reserves.

THE MISSING PIECE IN THE PUZZLE

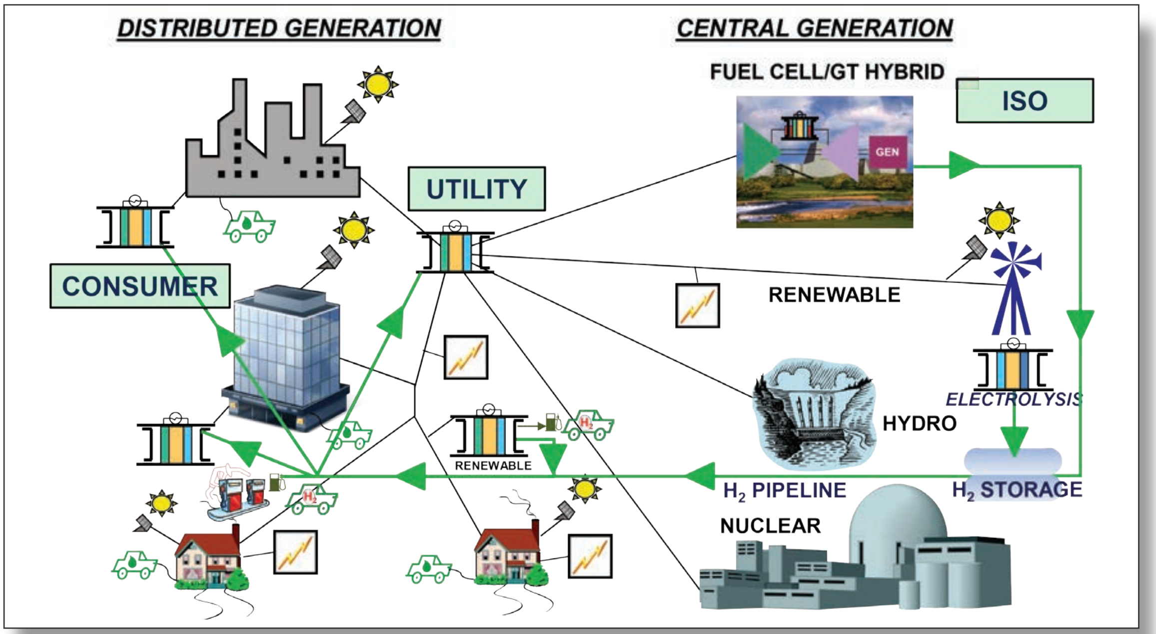
sources and thereby remove the emission of carbon from the supply chain. Fourth, hydrogen can be locally generated and help achieve the goal of fuel independence and thereby separate fuel sourcing from geopolitics.

THE CAPACITY TO STORE MASSIVE ENERGY The high penetration of renewable wind and solar into the electric grid results in the curtailment of these renewable resources during many hours of the day when the generation of electricity exceeds the need for the electricity. Fortunately, instead of being curtailed, these renewable resources can be utilized to generate renewable hydrogen and thereby become a major source of zero-carbon fuel for the transportation sector.

And very importantly, while electric batteries will serve a role, the generation of zero-carbon hydrogen through electrolysis is emerging as a compelling strategy for capturing and storing the massive amount of energy that would otherwise be lost.

In the initial years, the renewable zero-carbon hydrogen produced can be injected into natural gas pipelines and both stored and conveyed to natural gas appliances such as stoves, water heaters, space heaters, clothes dryers, gas turbines, and boilers. This already is occurring in Canada and Europe. In the future, dedicated hydrogen pipelines will likely evolve and be added to the already thousands of miles of hydrogen pipelines that are deployed around the world to support industry and the refining of gasoline. The energy stored can then be recovered to power fuel cell electric light duty, medium duty, and heavy duty vehicles, locomotives, ships and fuel cells to generate electric power when the load demands.

The Advanced Power and Energy Program (APEP) is actively involved in the evolution of the electric grid, the merging of transportation with the grid, and identifying and addressing the pieces of the puzzle required to achieve a 100% renewable electric sector and a 100% renewable transportation sector. Various planning tools such as HiGRID and STREET have been developed by APEP to analyze and guide the future, and major activity has been directed to smart grid technology. Not surprisingly, a pivotal focus of APEP is directed to hydrogen, from the generation of zero-carbon renewable hydrogen, to fueling the next generation of zero-carbon vehicles, to the utilization of renewable hydrogen for the generation of zero-carbon electricity through fuel cells.



A Schematic Depicting the Elements of the Evolving Electric Grid

The AIR QUALITY and Human Health Benefits of Fuel Cell Electric Trucks

Many communities in California experience degraded air quality as a result of significant emissions from goods movement activity by on-road and off-road diesel equipment such as heavy duty diesel trucks, cargo and materials handling equipment, ships, and rail. In particular, heavy duty diesel trucks used for short distance transportation or "drayage" such as for transporting cargo from ports to regional warehouses and distribution centers are a key source of pollutant emissions due to the use of older, higher-emitting vehicles. The use of zero emission Fuel Cell Electric Trucks (FCETs) to replace these heavy duty diesel trucks can achieve significant reductions in criteria pollutant emissions.

With funding provided by Toyota, APEP is conducting research to assess the air quality and human health impacts of using fuel cell electric trucks (FCETs) to provide drayage services in California. The focus is on the South Coast Air Basin (SoCAB) due to existing air quality challenges and the presence of substantial drayage activity from the Ports of Los Angeles and Long Beach.

Sets of future vehicle scenarios have been developed spanning a range of possible FCET fleet penetrations and are assessed to quantify how emission reductions from FCETs provide improvements in air pollutant concentrations, and how changes in air pollution impact human health.

Max 8-hour Average

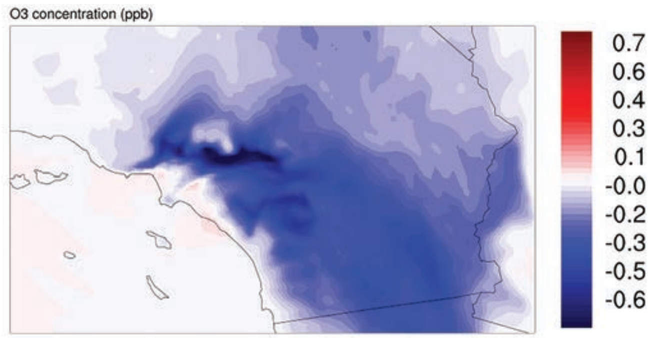


Figure 1 (A)

24-hour Average

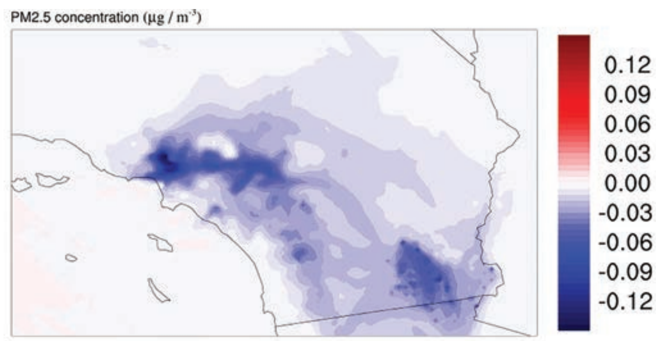


Figure 1 (B)

Figure 1. Predicted improvement in summer (A) max 8-hr ozone and (B) 24-hr average PM2.5 for a FCET Case relative to a Base Case comprised of diesel trucks.

Figure 1(a) shows the predicted change in ozone and Figure 1(b) the change in PM2.5 air pollution for a FCET Case relative to drayage continuing to be provided by heavy duty diesel trucks. Improvements in summer ozone range from -0.76 ppb to -1.09 ppb with peak improvements occurring in areas of San Bernardino and Riverside Counties associated with the highest baseline ozone levels. Reductions in summer and winter PM2.5 are predicted up to -0.19 ug/m3 and -0.35 ug/m3 24-hour average, respectively. Locations of PM2.5 reduction are more localized to truck activity and is again associated with communities that are heavily impacted by poor air quality, notably those surrounding the Ports of Los Angeles and Long Beach.

Improvements in air quality result in health benefits for residents of the Southern California Air Basin. The predicted magnitude of these avoided costs demonstrates the important benefits to California by attaining air quality improvements through FCET deployment in the drayage fleet.

The results of this work demonstrate that displacing heavy duty diesel trucks used in drayage applications with zero-emission vehicles is not limited to reducing pollutant emissions in urban regions where impacts on PM2.5 are more localized to truck activity at the ports of Los Angeles and Long Beach. The resulting air quality improvements also include areas not directly co-located to sites of the emission reductions. For example, Riverside and San Bernardino, areas that are currently impacted by poor ozone air quality show the largest ozone improvements despite emission reductions being centered in Los Angeles and Orange Counties. Both of these outcomes are desirable from an air quality and human health standpoint.

UC Irvine Microgrid Islanding Event is a Resounding Success

Today, because the UCI Microgrid serves a community of more than 50,000 and includes a large research portfolio, the University is especially sensitive to ensuring a reliable, uninterrupted provision of electricity. The UCI Microgrid encompasses a wide array of:

- Building types such as residential, office, research, and classrooms.
- Transportation options that include automobiles, twenty electric buses, a fuel electric bus and a shared-car program.
- A significant number of distributed energy resources.

Through various prior and current research programs, the Advanced Power and Energy Program has teamed with UCI Administration and UCI Facilities Management to integrate key microgrid hardware, software, and simulation assets into the UCI Microgrid.

As part of a Generic Microgrid Controller project funded by the U.S. Department of Energy, and in close collaboration with Facilities Management, the UCI Microgrid was islanded on February 12, 2018 as a part of a partnership between APEP, UCI Administration, Facilities Management, Schweitzer Engineering Laboratories (SEL), Southern California Edison (SCE) and Solar Turbines. Before the historic event, the controller was tested in Hardware in the Loop (HIL) on an OPAL-RT platform to ensure success and to identify operational limits for a successful transition from grid-connected to islanded mode and vice versa.

The Microgrid was islanded from the SCE grid at 5:00 am, and resynchronized and reconnected to the grid at 6:15 am. During this 1 hour and 15 minutes of islanded operation, step loads were changed including the addition of three 200 hp pumps and campus building loads, and the dropping of a 500 kW chiller. This test demonstrated the ability of the UCI Microgrid to disconnect from the SCE grid and island, operate in islanded mode under conditions of load changes, and resynchronize and reconnect to the grid (Figure 1).

As the frequency of extreme weather events increase due to climate change, reliability in serving critical loads becomes crucial in assuring public safety. This demonstration was an important step in establishing UCI as a fully functioning microgrid capable of seamless disconnection, resynchronization and reconnection, and stable islanded operations that increase the reliability and resiliency of serving campus loads and the University community.

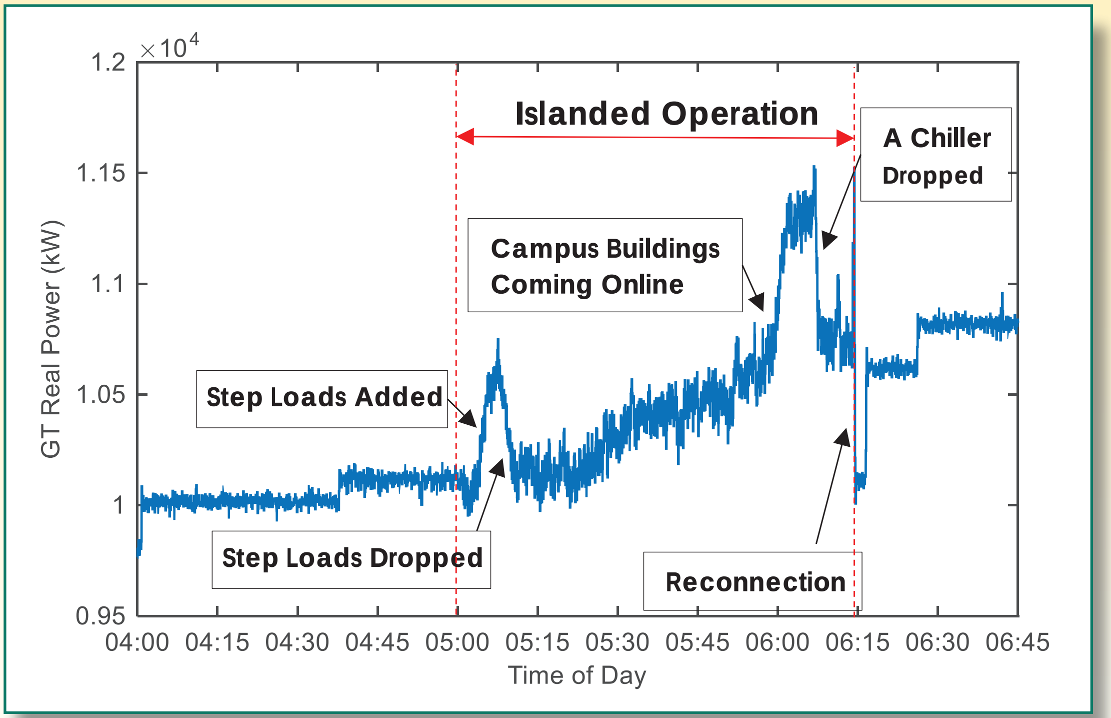


Figure 1. Gas Turbine Real Power Output

Transforming Water Consuming Power Plants Into Water Producing Power Plants

Flick a switch and the bathroom lights up, a few more steps to turn on the faucet and water pours out; a lifestyle we take for granted, not just at home but in almost every aspect of our lives. At first glance, there doesn't seem to be interconnectedness between the two, however in reality the resiliency of water and energy systems are strongly coupled. While thermoelectric electricity generation requires enormous amounts of water primarily for heat rejection, water distribution and treatment systems require electricity for pumping and purification. The growing importance of renewable biomass in electricity generation and the associated water demand add further complexity to the interconnectedness between water and energy. An illustration of the interplay between the different systems affecting the water-energy nexus is shown in Figure 1.

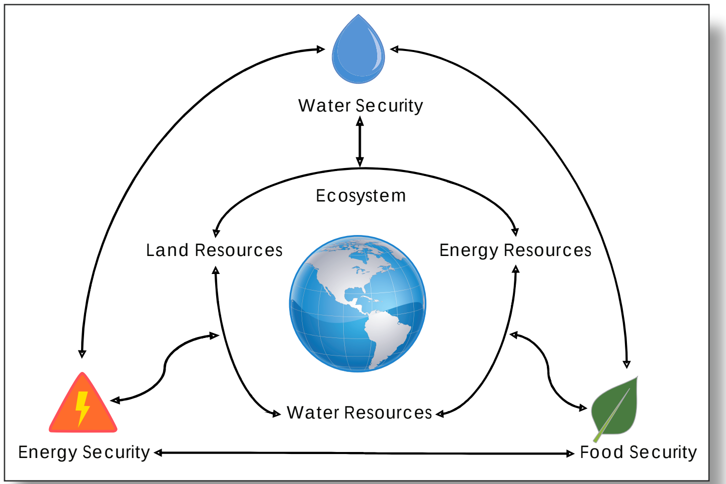


Figure 1. Water - Energy - Nexus

In the future, climate change and policies addressing greenhouse gas emissions will exacerbate the stress on our water and energy systems as many CO2 capture technologies increase water consumption and reduce plant efficiency. To address resiliency, reliability and the environmental impact of water and energy systems, the Advanced Power and Energy Program (APEP) at the University of California, Irvine (UCI), under the sponsorship of the U.S. DOE, is coordinating with the Research Center for Power and Energy at the Chinese Academy of Sciences (CAS) and the National Engineering Research Center for Clean Coal Combustion at Tsinghua University. Together they are investigating a new generation of power plants that can operate highly efficiently while producing water. In this regard, researchers from APEP are studying solid oxide fuel cell hybrid systems of various scales and feed stocks for grid support on both the transmission and distribution levels. In contrast to thermoelectric power generation, fuel cells are scalable and can reach very high efficiencies even in small scale applications, making them ideal candidates for distributed power generation while maintaining superb environmental performance. Transforming power plants from water consumers to net-producers of water is an important step towards higher resiliency and reliability for both water and energy systems.

The source of water lies in the fuel bound hydrogen. As the fuel undergoes oxidation in the fuel cell, water vapor is formed. Several factors have to be considered to reduce water consumption of power plants and convert them into a source of water. First considerations include the implementation of highly efficient flue gas cooling and heat rejection technologies while minimizing wet cooling systems. Further reductions in water use can also be achieved on a system integration level by replacing steam usage with water rich process streams.

A generalized flow sheet for such a net-water power plant is illustrated for a fuel cell-gas turbine hybrid system in Figure 2. In this type of plant, power produced by the fuel cell can approach 90% of total system power produced, and due to its high efficiency and generation of minimal waste heat, no active cooling is required. Additionally, rather than wasting the remaining unconverted fuel, it is combusted in the gas turbine to increase total system efficiency while utilizing dry-cooling and recycling of water vapor rich anode off-gas to the fuel cell. This process also eliminates the need to employ direct steam injection, since water vapor is required in solid oxide fuel cells operating on carbonaceous fuels to promote reforming and to avoid carbon deposition on catalyst surfaces and the anode.

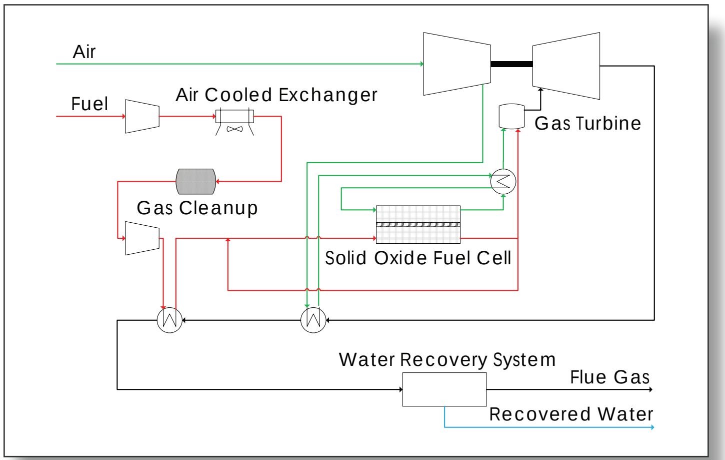


Figure 2. Fuel Cell - Gas Turbine Hybrid System

Net-water power plants in the 10 MW-scale operating on natural gas with greater than 72% lower heating value (LHV) efficiencies and generating 48,000 liters/day of water have been identified. Such plants can supply about 8000 residential customers with electricity and enough water for irrigation of approximately 35,500 square meters of farm land.

Thus, highly efficient fuel cells in combination with advanced water recovery technologies can transform water consuming power plants into net-producers of water and substantially increase the resiliency and reliability of our water and energy infrastructure. Exploitation of such new water sources will be essential to assure sufficient food and water supplies, especially with an increasing world population and with the future severe drought events expected due to climate change.

Tri-Generation FUEL CELL AND ENERGY STATION Provides World Changing "Firsts"

Since 1998, the National Fuel Cell Research Center (NFCRC) has worked closely with the fuel cell industry in deploying unusually efficient and clean fuel cell technology for both vehicle and power generation applications, and in developing advanced fuel cell systems such as Tri-Generation. The NFCRC deployed the first Fuel Cell Electric Vehicle in the United States in collaboration with Toyota on December 2, 2002 and thereby established a longstanding relationship in systematically exploring the hydrogen fueling infrastructure, and the public perspective of both hydrogen vehicles and the fueling of hydrogen vehicles.

A TECHNOLOGY FIRST

The technology for the Tri-Generation of bio-hydrogen, electricity, and high quality heat from human waste was first conceived at the National Fuel Cell Research Center in 2002, and was further developed through a collaboration fostered by the NFCRC that included Air Products and Chemicals Inc. and FuelCell Energy Inc., founding members of the NFCRC. It would prove to be a viable strategy and serve as a major example of the opportunity to source the vehicle fuel of the future from a renewable source, and contribute to U.S. fuel independence.

A DEMONSTRATION FIRST

The first real-world demonstration of this revolutionary technology utilized a stationary fuel cell deployed at the Orange County Sanitation District (OCSD) in Fountain Valley, California. Funded by the U.S. Department of Energy, the California Air Resources Board, the South Coast Air Quality Management District, and the Southern California Gas Company, the deployment was commissioned on August 5, 2011. In its 4 years of operation, the demonstration proved to be overwhelmingly successful and attracted tours from around the world. On a daily basis, it was capable of producing high quality heat for use in the plant digester, 300 kilowatts of electricity for plant operations, and 120 kilograms of renewable hydrogen, enough to fill on average 30 fuel cell vehicles. Toyota, Honda, General Motors, Mercedes Benz, and Hyundai vehicles that were undergoing on-road testing in the hands of California drivers fueled their Fuel Cell Electric Vehicles (FCEVs) with the bio-hydrogen produced at a publicly accessible dispenser.

A COMMERCIAL DEPLOYMENT FIRST

Fast-forward to November 30, 2017 and the Los Angeles Auto Show when, Toyota Motor North America and FuelCell Energy Inc. announced the first commercial deployment of this NFCRC conceived and nurtured technology to generate on-site hydrogen at the Port of Long Beach. **The Tri-Gen facility will use bio-waste sourced from California agriculture to generate hydrogen in addition to heat and electricity.**

When operational in 2020, the Tri-Gen plant will generate approximately 2.35 megawatts of electricity and 1200 kilograms of hydrogen a day, enough to power the equivalent of 2350 average sized homes, and fuel nearly 1500 vehicles. The facility will provide the fuel for all Toyota fuel cell vehicles moving through the Long Beach port facility including the Toyota hydrogen fuel cell heavy duty truck, heat for hot water to wash the vehicles arriving at the port, and electricity for port operations. To support these refueling operations, Toyota will build with the help of Air Liquide, one of the largest hydrogen fueling stations in the world.

With the adoption of Tri-Gen technology Toyota has taken a significant step forward in the shift to a hydrogen economy.

Photo Credit: Paul Kennedy

SOLID OXIDE FUEL CELL
Combined Power and Cooling

According to the American Lung Association, forty-seven percent of Americans live in counties with unhealthy ozone or particle pollution, and nearly three-out-of-four Californians live in polluted cities. The residential sector is responsible for 18 percent of total U.S. emissions. California will require all new home construction in 2020 to be Zero Net Energy (ZNE). In ZNE buildings the net energy produced by on-site renewable sources must be equal to that consumed annually by the building.

Eventually all energy and power demands must be met by renewable and sustainable sources. However, the availability of most renewable energy sources including solar and wind are uncontrollable and intermittent, resulting in a significant need for energy storage and complementary resources that can be dynamically dispatched to match demand with supply.

Solid Oxide Fuel Cell (SOFC) technology could provide the required dynamic dispatch needed, along with high fuel-to-electricity efficiency, zero criteria pollutant emissions, and use of renewable fuels such as biogas or renewable hydrogen. With high quality exhaust heat, the SOFC capability of combined heating, cooling and power could enable novel applications with overall system efficiencies exceeding 80%. The heat from the fuel cell can be captured and processed through an Absorption Chiller (AC) to provide cooling. Or an Organic Rankine Cycle (ORC) can be used when low temperature heat is available to make additional electricity (see Figure 1).

Solid Oxide Fuel Cell technology could provide the required dynamic dispatch needed

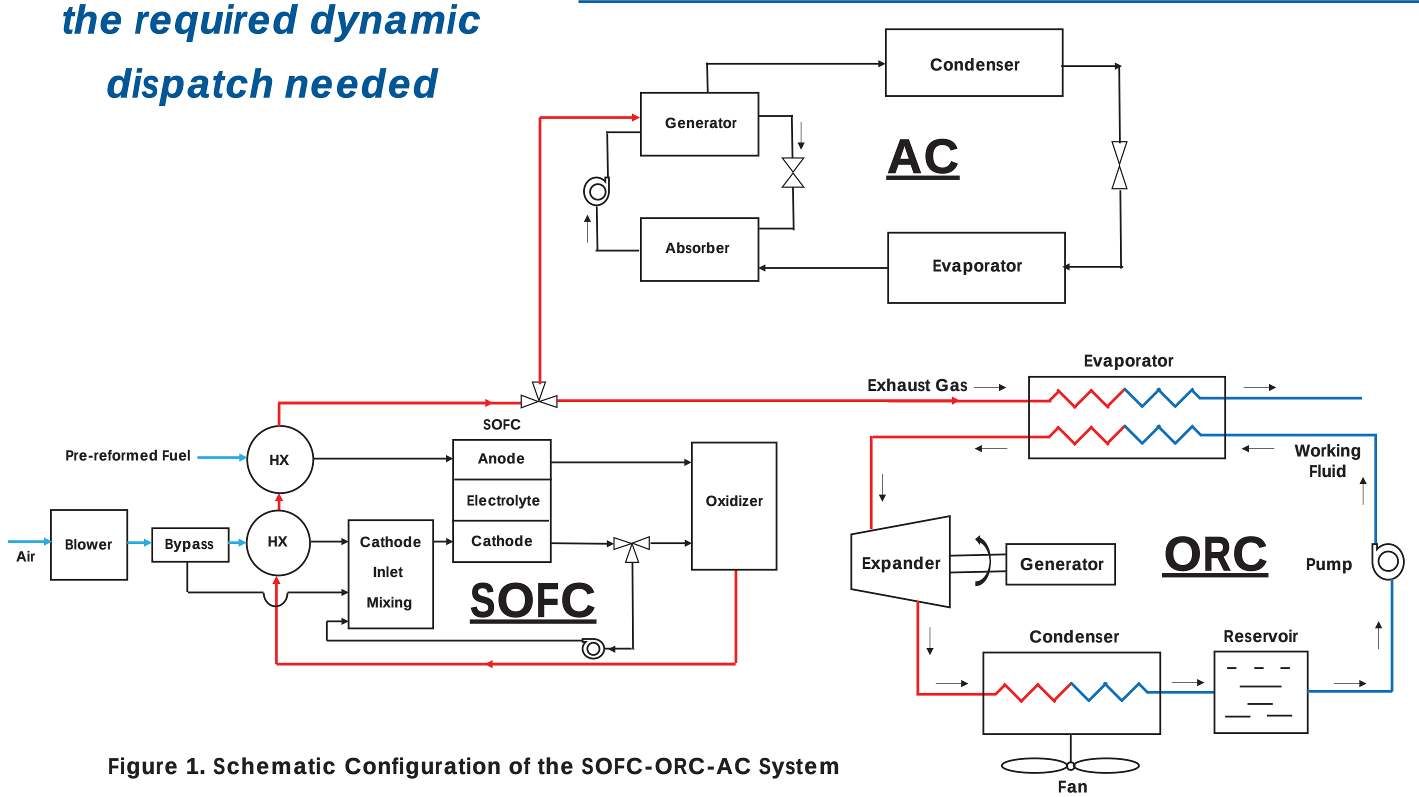


Figure 1. Schematic Configuration of the SOFC-ORC-AC System

To investigate the application of an integrated SOFC system for dynamic stationary power generation application for ZNE buildings, APEP developed an integrated dynamic model of a Solid Oxide Fuel Cell-Organic Rankin Cycle-Absorption Chiller (SOFC-ORC-AC) system (Figure 1) to study its dynamic operating characteristics and performance. This model has been used to evaluate the efficiency, capacity, and dispatchability of the system, based upon meeting measured real-world load profiles of residential buildings.

The initial results have established that the SOFC system can follow highly dynamic demands quite accurately with small deviations from the demand profile due to the balance-of-plant power consumption. Results also show that an integrated SOFC-ORC/SOFC-AC may be a good option for dynamic operation to meet future residential applications in terms of system performance and overall efficiency.

The advancement of this innovative technology will significantly reduce fuel consumption, climate impacts, and greenhouse gas and criteria pollutant emissions while at the same time enabling much greater use of intermittent renewable power. As a result, air quality will improve and energy sustainability may be more easily attained.

UCI Combustion Laboratory Investigates the Effect of INJECTING FUEL/WATER EMULSIONS for High Efficiency, Clean Power Generation

The UCI Combustion Laboratory (UCICL) has an extensive portfolio of work in fuel injection and atomization for a large variety of power generation and propulsion systems. These atomization studies aim to improve performance and to reduce harmful pollutants. By injecting water in liquid form with fuel into a combustion system, the added mass can boost power output for a given amount of fuel used, thereby increasing efficiency. While this is an inherent benefit, important benefits regarding emissions reduction are also possible.

Current liquid fueled combustion systems are cleaner than ever, and boast high reductions in pollutants such as NOx and soot, compared to legacy systems. Yet, it is desired to reduce these pollutants further and to bridge the gap between current power generation systems and future, even cleaner systems. A possible means to reduce such emissions is to add water to the fuel to create a water-in-fuel "emulsion." Small droplets of water are suspended in a continuum of fuel and when the emulsion is injected and atomized into a combustor, large fuel droplets are occupied by an array of smaller water droplets, as shown in Figure 1. The resulting benefit of adding water into the fuel stream is at least twofold; (1) water reduces flame temperature which reduces NOx formation and (2) water can improve atomization through so-called "microexplosions."

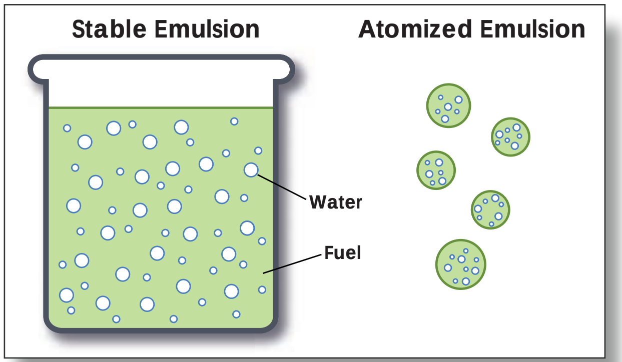


Figure 1. Water-in-Fuel Emulsions

Although benefits of utilizing emulsions have been demonstrated in the laboratory, questions remain which have inhibited widespread use. Therefore, the focus of the UCICL's current studies are to determine what effects injecting emulsions are likely to induce when implemented on a practical system.

To investigate this:

- A plain jet-in-crossflow setup was used which is commonly found in power generation systems.
- The emulsions are pressure injected into a transverse air crossflow.
- This air crossflow then atomizes the liquid jet and delivers the droplets into a combustion chamber.

Figure 2 shows a high-speed experimental image of this system.

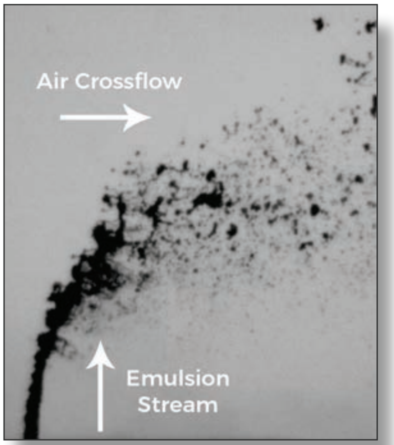


Figure 2. Liquid Jet in Crossflow

Following an experimental investigation using laser and high-speed video diagnostics, numerous valuable insights were found:

- Due to the inherent instability of emulsions, where the water and fuel repel each other, increased atomization and spray instabilities were found in comparison to non-emulsions.
- As emulsions are delivered to the injector, it is difficult to maintain a stable mixture which leads to large structural oscillations in the liquid atomization process.
- Although improved atomization could be achieved using emulsions, this was not consistent and only occurred over small intervals of operation.

Based on our findings so far, it is evident that more work must be done to address mixing effects on the resulting atomization process to assure a certain level of steadiness. The dynamic behavior may prove beneficial or detrimental to combustion performance.

UCI Combustion Laboratory Develops Test Apparatus for Determining Flammability Limits of RENEWABLE GASEOUS FUELS at Elevated Temperatures and Pressures

To facilitate adoption of renewable gaseous fuels, a wide range of factors must be considered, including safety aspects. These fuels can be produced using various technologies including gasification and anaerobic digestion of waste feedstocks, as well as Power-to-Gas, which uses excess electricity from renewable sources to produce renewable hydrogen. A key safety factor to be considered is the so called "flammability limits" of these fuels in air. Flammability limits are the concentration limits of a homogeneous combustible gas/oxidizing gas mixture within which a flame can propagate through the mixture. Gas mixtures are deemed flammable if concentration of the combustible gases lies between the lower flammability limit (LFL) and the upper flammability limit (UFL). A key factor for preventing an explosion is to eliminate the formation of a flammable atmosphere, hence knowing the flammability limits of a substance relative to an oxidizing agent is necessary to work safely with any fuel. However, because renewable fuels are not as ubiquitous as fossil fuels, there is a need for information regarding their flammability limits. Additionally, information is needed regarding flammability limits of these fuels at elevated temperatures and pressures because specialized test equipment is required.

To address this need for data, a study has been conducted to determine the lower flammability limits of mixtures of the major components found in typical renewable gases. These components consist of methane, hydrogen, carbon monoxide and blends of these gases in various proportion depending on the technology used. Mixtures of methane/carbon dioxide are used to simulate typical biogas compositions, while mixtures of hydrogen/carbon monoxide simulate typical syngas compositions. These blends were chosen as they represent the usual composition for both renewably-derived biogas and syngas. Finally, mixtures of methane/hydrogen were investigated as they are widely reported in literature and also represent potential fuel compositions of methane enriched with renewable hydrogen produced from Power-to-Gas technology.

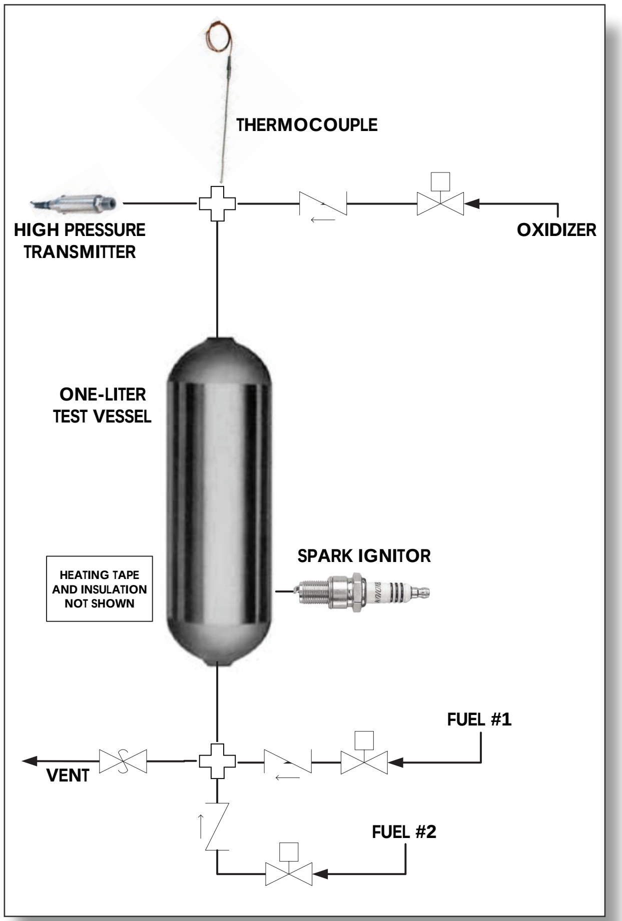


Figure 1. Schematic Diagram of UCICL Test Apparatus

The experimental methodology involved developing a test setup similar to those found in pertinent standards and other flammability studies, with emphasis on the role of elevated temperatures and pressures. ASTM E918, developed by the American Society for Testing and Materials, was selected as the most appropriate standard for these tests, and an experimental setup was assembled and prepared according to this standard. The results from the experimental tests were compared with available flammability data for the previously mentioned renewable gaseous fuel mixtures at a given specified test temperature and pressure.

Key results include a decrease of the lower flammability limit with an increase in the initial test temperature for all gas mixtures tested across all test pressures, as well as a general increase of the lower flammability limit with an increase in the initial test pressure. After repeating the flammability tests to ensure accuracy of the results, conclusions were drawn and recommendations were made to update the ASTM E918 standard.

Recommendations provided included:

- An increase of the test vessel size from 1-liter to 5-liters to improve the consistency of flammability data for a wider range of fuels.
- Using a 5% pressure rise instead of the suggested 7% pressure rise criterion to improve reliability of flammability results.
- Various modifications to the experimental setup to reduce the number of auxiliary components such as valves and pressure transmitters.

Overall, this work has established new understanding of the safe working limits of renewable fuels which helps to facilitate the adoption and increased use of these fuels in future low carbon fuels systems.

GRADUATES AND INTERNSHIPS

GRADUATES

Ali Azizi (Ph.D.)
Dissertation: Solid Oxide Fuel Cell-Gas Turbine Hybrid Power Systems: Energy Analysis, Control Assessments, Fluid Dynamics Analysis and Dynamic Modeling for Stationary and Transportation Applications

Alirezza Kalantari (Ph.D.)
Dissertation: Boundary Layer Flashback of Turbulent Premixed Jet Flames at Elevated Pressures and Temperatures

Derek McVay (Ph.D.)
Dissertation: Evaluation of Dynamic Reversible Chemical Energy Storage with High Temperature Electrolysis

Scott Lee (Ph.D.)
Dissertation: A Real-Time Simulation Methodology to Enable Seamless Microgrid Islanding

Aaron Cheng (M.S.)
Thesis: Evaluating the Impacts of Centralized and Decentralized Electric Vehicle Smart Charging Algorithms on the Electric Grid

Alejandra Cervantes (M.S.)
Thesis: Air Quality and Greenhouse Gases Impacts Associated with Zero and Near-Zero Heavy-Duty Vehicles in California

Alex MacDonald (M.S.)
Thesis: Scalable Method to Model and Calibrate the Building Energy Demand of the Mixed-use Residential, Commercial, and Industrial Community for Use in District-scale Solar Planning

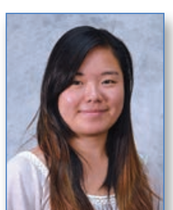
Blake Lane (M.S.)
Thesis: Plug-in Fuel Cell Electric Vehicles: A Vehicle and Infrastructure Analysis and Comparison with Alternative Vehicle Types

Fabian Rosner (M.S.)
Thesis: Techno-Economic Analysis of IGCCs Employing Novel Warm Gas Carbon Dioxide Separation and Carbon Capture Enhancements for High-Methane Syngas

Gi Jung Lee (M.S.)
Thesis: Modeling Power Plant and Electric Grid Dynamics with High Renewable Use and Climate Change in the United States and Asia

Katie Leong (M.S.)
Thesis: The Effect of Centerline Enrichment for Flexible Low Swirl Burner Flame Stabilization

Ryan Ehlig (M.S).
Thesis: Development of Closed Loop Emissions Control for Use in Dispatchable, Distributed Generation Systems Using a Low Cost, State-of-the-Art, Solid-State Nitric Oxide Sensor



Sarah Wang (M.S.)
Thesis: A Holistic Analysis of Renewable Hydrogen Production and Usage in Order to Minimize Otherwise Curtailed Power

INTERNSHIPS

Maryam Asghari
Altura Associates, Inc.
(Summer 2018)

Blake Lane
Horiba Mira,
United Kingdom
(Summer 2018)

Philipp Ahrend
Irvine Valley College,
California Community Colleges Internship Program
(2018-2019)

Zahra Heydarzadeh
Los Angeles Department of Water and Power
(Summer 2018)

Laura Novoa
Tesla, Power Systems and Utilities
(Summer 2018)

Matthew Clower
Walt Disney Imagineering
(Summer and Fall 2018)

PUBLICATIONS

JOURNALS

THE ROLE OF NATURAL GAS AND ITS INFRASTRUCTURE IN MITIGATING GREENHOUSE GAS EMISSIONS, IMPROVING REGIONAL AIR QUALITY, AND RENEWABLE RESOURCE INTEGRATION (2018). Progress in Combustion and Energy Science, Vol. 64, pp. 62-92 (Michael A. Mac Kinnon, Jacob Brouwer, and Scott Samuelsen).

ASSESSING FUTURE WATER CONSTRAINTS ON THERMALLY-BASED RENEWABLE ENERGY RESOURCES IN CALIFORNIA (2018). Applied Energy, Vol. 226, pp. 49-60. (Tarroja, Brian, Chiang, Felicia, Aghakouchak, Amir, and Samuelsen, Scott).

SURFACE STABILIZED COMBUSTION TECHNOLOGY: AN EXPERIMENTAL EVALUATION OF THE EXTENT OF ITS FUEL-FLEXIBLITY AND POLLUTANT EMISSIONS USING LOW AND HIGH CALORIFIC VALUE FUELS (2018). Applied Thermal Engineering, Vol. 136, pp. 206-218 (A. Colorado and V.G. McDonell).

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PROGRESS IN SOLID OXIDE FUEL CELL-GAS TURBINE HYBRID POWER SYSTEMS: SYSTEM DESIGN AND ANALYSIS, TRANSIENT OPERATION, CONTROLS AND OPTIMIZATION (2018). Applied Energy, Vol. 215, pp. 237-289 (Azizi, Mohamed Ali and Brouwer, Jacob).

EXPLORING COMPUTATIONAL METHODS FOR PREDICTING POLLUTANT EMSSIONS AND STABILITY PERFORMANCE OF PREMIXED REACTIONS STABILIZED BY A LOW SWIRL INJECTOR (2017). Combustion Science and Technology, Vol. 189, No 12, pp. 2115-2134 (A. Colorado and V.G. McDonell).

COMPARISON OF TWO METHODS TO PREDICT BOUNDARY LAYER FLASHBACK LIMITS OF TURBULENT HYDROGEN-AIR JET FLAMES (2017). Journal of Flow, Turbulence, and Combustion, https://doi.org/10.1007/s10494-017-9882-2. (V. Hoferichter, C. Hirsch, T. Sattelmayer, A. Kalantari, E. Sullivan-Lewis, and V.G. McDonell).

EMISSIONS AND STABLITY PERFORMANCE OF A LOW-SWIRL BURNER OPERATED ON SIMULATED BIOGAS FUELS IN A BOILER ENVIRONMENT (2017). Applied Thermal Engineering, (A. Colorado and V.G. McDonell).

STALL/SURGE DYNAMICS OF A MULTI-STAGE AIR COMPRESSOR IN RESPONSE TO A LOAD TRANSIENT OF A HYBRID SOLID OXIDE FUEL CELL-GAS TURBINE SYSTEM (2017). Journal of Power Sources, Vol. 365, pp. 408-418 (Azizi, M. Ali, and Brouwer, Jacob).

SOLID OXIDE FUEL CELL SHORT STACK PERFORMANCE TESTING - PART A: EXPERIMENTAL ANALYSIS AND M-COMBINED HEAT AND POWER UNIT COMPARISON (2017). Journal of Power Sources, Vol. 371, pp. 225–237 (Mastropasqua, L., Campanari, S., and Brouwer, J.).

SOLID OXIDE FUEL CELL SHORT STACK PERFORMANCE TESTING - PART B: OPERATION IN CARBON CAPTURE APPLICATIONS AND DEGRADATION ISSUES (2017). Journal of Power Sources, Vol. 371, pp. 238-248 (Mastropasqua, L., Campanari, S., and Brouwer, J.).

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ECONOMIC ANALYSIS AND IMPLEMENTATION STRATEGIES FOR SOFC SYSTEMS IN RESIDENTIAL APPLICATIONS (2017). Transactions of the Electrochemical Society, Vol. 78, pp. 275-285 (Zhao, Li and Brouwer, Jack).

PAPERS

EVALUATION OF SOLID-STATE ELECTROCHEMICAL SENSORS FOR REAL TIME MONITORING OF NO AND O2 IN THE EXHAUST OF A COMMERCIAL 60kW GAS TURBINE (2018). Paper GT2018-75065, Presented at TurboExpo 2018, Oslo, Norway, June 11-15 (R.A. Ehlig, M. Takahashi, and V.G. McDonell).

EXPERIMENTAL DETERMINATION OF LEAN FLAMMABILITY LIMITS OF RENEWABLE AND PROCESS GAS MIXTURES AT ELEVATED TEMPERATURE AND PRESSURE CONDITIONS (2018). Paper GT2018-75064, Presented at TurboExpo 2018, Oslo, Norway, June 11-15 (D. Jaimes, V. McDonell, and S. Samuelsen).

EMULSION JET IN CROSSFLOW ATOMIZATION CHARACTERISTICS AND DYNAMICS (2018). Paper GT2018-75818, Presented at TurboExpo 2018, Oslo, Norway, June 11-15 (S.B. Leask, V.G. McDonell, and S. Samuelsen).

TOWARDS IMPROVED BOUNDARY LAYER FLASHBACK RESISTANCE OF A 65kW GAS TURBINE WITH RETROFITTABLE INJECTOR CONCEPT (2018). Paper GT2018-75834, Proceedings of TurboExpo 2018, Oslo, Norway, June 11-15 (A. Kalantari, V. McDonell, S. Samuelsen, S. Farhangi, and D. Ayers).

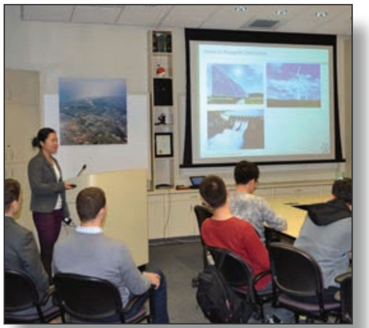
CRITICAL EVALUATION OF MOMENTUM FLUX RATIO RELATIVE TO LIQUID JET IN CROSSFLOW (2018). Proceedings of the 14th International Conference on Liquid Atomization and Spray Systems (S.B. Leask and V.G. McDonell), Chicago, IL July 22-26.

EVALUATION OF RESEARCH SIMPLEX ATOMIZERS AS A MEASUREMENT STANDARD (2018). Proceedings of the 14th International Conference on Liquid Atomization and Spray Systems (S.B. Leask, A.K. Li, V.G. McDonell, and S. Samuelsen), Chicago, IL July 22-26.

HIGHLIGHTS of the 2017-2018 Academic Year

SUMMER 2017

SOUTHERN CALIFORNIA GAS COMPANY HOSTS SUSTAINABILITY MANAGERS MEETING AT APEP—JULY 2017 Attendees from the University of California and California State University campuses met to discuss reaching their de-carbonization and carbon neutrality goals. Following the meeting, the Advanced Power and Energy program provided a visit to the Power-to-gas (P2G) demonstration site.



APEP HOSTS STUDENT TOURS—JULY AND AUGUST 2017 Members of both local and international student organizations had the opportunity to learn about energy production, utilization and sustainability while visiting APEP's research laboratories. Over the summer students from UCI's ASPIRE/INSPRE program, Henry Samueli School of Engineering's OAI Scholars, and General Motor's E-STEP Program for Military Veterans attended presentations and tours. International students were hosted from SOKA High School, Tokyo, KAUST University, Saudi Arabia, and Yonsei University, South Korea.

FALL 2017

NFCRC DEDICATES THE UC IRVINE MEDICAL CENTER FUEL CELL AND ABSORPTION CHILLER—OCTOBER 18, 2017 The 1.4 MW power plant provides approximately 30 percent of the electricity and 25% of the cooling needs of the UCI Medical Center's Douglas Hospital. Fuel cells provide virtually zero pollutant operation, and reduced greenhouse gas emissions, while the addition of an absorption chiller further offsets pollution and greenhouse gas emissions.

INCOMING FRESHMEN VISIT THE NATIONAL FUEL CELL RESEARCH CENTER—SEPTEMBER 2017 The NFCRC hosted a group of mechanical and electrical engineering students who were given an overview of fuel cell technology and a tour of the alternative fuels fleet of vehicles.

WINTER 2018

RECORD YEAR FOR THE UC IRVINE HYDROGEN FUELING STATION—JANUARY 2018 For 2017, a total of 48,636 kilograms of hydrogen were dispensed which is more than double the 23,910 kilograms provided in 2016. While two hydrogen fuel cell electric buses also refueled at the station, the majority of the increase was from light duty fuel cell electric vehicles.

BENDING THE CURVE APEP Director Scott Samuelsen, professor of mechanical and aerospace engineering, Steven Davis, associate professor of earth system science; and David Feldman, professor of urban planning and public policy and political science taught the inaugural course: "Bending the Curve: Climate Change Solutions," in winter quarter 2018. The cross-disciplinary class is based on "Bending the Curve: Ten scalable solutions for carbon neutrality and climate stability," a report published in 2016 by more than 50 UC scholars and researchers. The course will be expanded to three additional UC campuses later in 2018.

ADVANCED ENERGY COMMUNITIES PROJECT APEP partnered with graduate students from CSU Fullerton and the Energy Coalition to offer an afterschool program at the Oak View Branch Library to teach local children about energy and the environment. The 10-week program included activities such as building a simple electric motor, creating minute amounts of hydrogen using batteries, pencils, and water, and simulating the California aqueduct system.

SPRING 2018

NATIONAL FUEL CELL RESEARCH CENTER CELEBRATES ITS 20TH YEAR – FEBRUARY 25, 2018 Established in partnership by the University of California, Irvine, the California Energy Commission, and Southern California Edison, the NFCRC is dedicated to the acceleration of the development and deployment of clean non-combustion fuel cell technology for both transportation and stationary power generation. Today fuel cell vehicles are being marketed by Toyota, Honda, Hyundai and soon Mercedes Benz with UCI being the first University to add a Fuel Cell bus to its fleet. In California there are more than 220 megawatts of electricity being generated by fuel cells, enough to power more than 220,000 homes

ICEPAG 2018: MICROGRID GLOBAL SUMMIT—MARCH 27-29, 2018 In its eighteenth year, this three-day summit hosted by the Advanced Power and Energy Program brought together global experts from Industry, Government, and Academia to examine and share cutting edge information on real-world, on-the-ground Microgrid developments. Major topics included the need to integrate sustainable energy resources, enhance the performance of the electrical grid, and increase grid resiliency and reliability.

GAS TURBINE COMBUSTION SHORT COURSE—MARCH 19-22, 2018 The four-day course offered by the UCI Combustion Laboratory provides detailed instruction on the emissions, design, performance, theory, and regulations associated with gas turbine combustion systems. Special attention is paid to methods of minimizing pollutant emissions, regulatory forces, and the experimental and computational methods used to delineate combustor behavior.

ATOMIZATION AND SPRAYS SHORT COURSE—MARCH 23-24, 2018 The UCI Combustion Lab Course provides an introduction to the theory of atomization and evaporation and how these concepts connect to practical devices used in various applications including fuel injection, coatings, and pharmaceuticals. Lectures and presentations were complemented with a hands-on experience that involved applying various diagnostic methods to representative sprays in the test cells of the UCI Combustion Laboratory

SHENZHEN CHINA FUEL CELL ASSOCIATION—APRIL 2018 The NFCRC hosted the Shenzhen Hydrogen and Fuel Cell Association for an overview of research on fuel cells and hydrogen presented by Director Jack Brouwer. The group also toured the NFCRC test laboratory, followed by a visit to the NFCRC hydrogen station.

ENGINEERING LABORATORY FACILITY CELEBRATES 30TH ANNIVERSARY—JUNE 2, 2018 The ELF as it is affectionately known by the Professors, Students, and Staff who work in the building, was dedicated on June 2, 1988. Comprised of research laboratories, meeting rooms and office space, it is home to the Advanced Power and Energy Program, the National Fuel Cell Research Center, and the UCI Combustion Laboratory.

www.apep.uci.edu

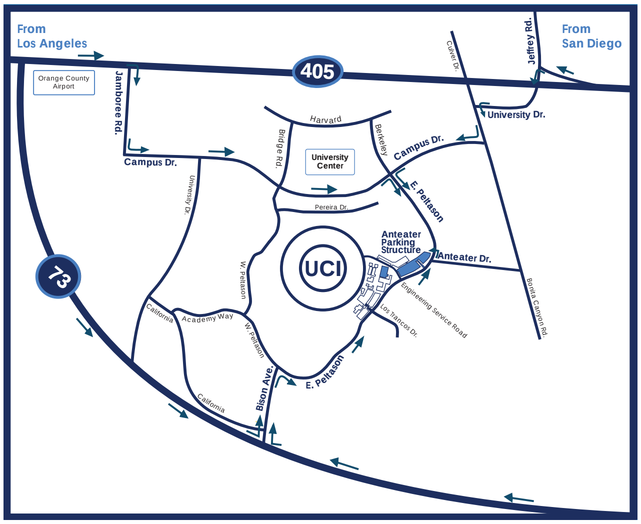
Advanced Power and Energy Program
University of California, Irvine
Irvine, California 92697-3550

The Advanced Power and Energy Program (APEP) encompasses three organizational elements: the National Fuel Cell Research Center, the UCI Combustion Laboratory, and the Pacific Rim Consortium on Combustion, Energy, and the Environment.

APEP advances the development and deployment of efficient, environmentally sensitive, and sustainable power generation, storage, and conservation. At the center of APEP's efforts is the creation of new knowledge brought about through fundamental and applied research and the sharing of this knowledge through education and outreach.

The connection of APEP's research to practical application is achieved through our close collaboration with industry, national agencies, and laboratories to "bridge" engineering science and practical application.

APEP is affiliated with The Henry Samueli School of Engineering at the University of California, Irvine and is located in the Engineering Laboratory Facility (Building 323) near East Peltason Drive and Engineering Service Road.



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