MISSION INNOVATION HYDROGEN FUEL CELLS OFF-ROAD EQUIPMENT AND VEHICLE WORKSHOP
SUMMARY REPORT
September 22–24, 2021

ANL-22/32

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Abstract

This report serves as the proceedings of the Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicles Workshop held by the U.S. Department of Energy, the U.S. Department of Transportation, the Ministry of Energy of Chile, the Australian Renewable Energy Agency, and the European Fuel Cells and Hydrogen Joint Undertaking virtually on September 22–24, 2021. Presentations from the workshop can be found at *Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicles Virtual Workshop: https://www.energy.gov/eere/fuelcells/mission-innovation-hydrogen-fuel-cell-road-equipment-and-vehicles-virtual-workshop*.

The workshop was held to assess the state of the art for hydrogen fuel cells in heavy-duty off-road equipment and vehicle applications in agriculture, construction, and mining; to identify refueling infrastructure challenges; to discuss operational requirements and lessons learned on early equipment demonstration projects; to understand current technology gaps; and to identify potential collaborative research and development opportunities. This report summarizes the discussions and diverse opinions expressed by participants at the workshop.

Acknowledgements

We would like to acknowledge the U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office Director, Sunita Satyapal. Special thanks to Pete Devlin, Zachary Taie, Ben Gould, Greg Moreland, Charlie Myers, and Stacey Young for their support in the planning and execution of the workshop.

We would also like to thank Mission Innovation Clean Hydrogen Mission, Chilean Ministry of Energy, the Australian Renewable Energy Agency, U.S. Department of Agriculture, U.S. Environmental Protection Agency, and California Air Resources Board for their support and participation in the workshop.

The workshop organizers gratefully acknowledge those who presented talks at the workshop, including Matthijs Soede, Sunita Satyapal, Max Correa, Matt Walden, Mark Brodziski Britney J. McCoy, William Robertson, Curt Blades, Rajesh Ahluwalia, Mike Duffield, William Resende, Ismo Hamalainen, Jay Schmuecker, Brian Lowry, Michael Lewis, Martin Kirchmair, Ray Gallant, Julian Soles, Clemens Müller-Falcke, Ryan Sookhoo, Tim Sasseen, Gus Block, Rick Mason, Johan Burgren, Dave Edwards, Al Burgunder, Kyle McKeown, Michael Koonce, Paul Dawson, and Mike Peters. Last, we would like to thank all the participants for the opinions and insights they shared at the workshop. Without these contributions, the workshop would not have been a success.

Executive Summary

This report summarizes the proceedings from the Mission Innovation Hydrogen Fuel Cells Off-Road Equipment and Vehicles Workshop. This virtual workshop was organized by the U.S. Department of Energy, the U.S. Department of Transportation, the Ministry of Energy of Chile, the Australian Renewable Energy Agency, and the European Fuel Cells and Hydrogen Joint Undertaking and attended by more than 100 representatives from more than 50 organizations, representing academia, government, and industry across seven countries (Australia, Canada, Chile, Finland, Sweden, United Kingdom, United States) and four continents (North America, South America, Europe, and Australia).

The objectives of the workshop were to:

- Assess the state of the art for heavy-duty applications using hydrogen fuel cells (FCs) for agriculture, construction, and mining equipment.
- Discuss operational requirements and lessons learned from early equipment demonstration projects for agriculture, construction, and mining.
- Understand current technology gaps and identify collaborative research and development (R&D) opportunities.
- Identify refueling infrastructure challenges.

A growing number of governments worldwide consider hydrogen part of their comprehensive energy portfolio. Hydrogen can couple with many other primary energy sources and end uses to address applications in agriculture, construction, and mining that are hard to decarbonize by other means. A three-fold strategy for hydrogen is being pursued that (1) addresses scaling up hydrogen production and use; (2) supports R&D to improve performance and reduce costs; and (3) addresses enablers of hydrogen technology.

Attendees indicated that there are numerous opportunities for hydrogen and FC technologies in agriculture, construction, and mining. Compared to batteries, hydrogen and FCs in agriculture, construction, and mining have increased range and payload, higher mission flexibility, shorter refueling times, and lower lifecycle costs.

There are also challenges for deploying hydrogen and FCs in agriculture, construction, and mining. A major challenge is storing enough hydrogen onboard the vehicles to meet the operating requirements. Liquid hydrogen provides a higher volumetric energy storage density than gaseous hydrogen; however, there are concerns that even the higher volumetric energy storage density of liquid hydrogen may not be adequate for some applications. There are also operational challenges inherent in transporting, handling, and storing — including bunkering — liquid hydrogen. Workshop participants indicated that the amount of hydrogen supply infrastructure, including the number of liquefaction facilities, needs to increase to meet future demand.

FCs have their own set of challenges. The lower operating temperature of polymer electrolyte membrane (PEM) FCs compared to internal combustion engines causes thermal management issues. For example, in construction equipment where ram air is not available for cooling, more fan power and larger radiator sizes are needed for FC systems than for diesel engine systems to maintain acceptable FC temperatures. Despite these challenges, hydrogen and FCs are a promising route to decarbonizing these hard-to-decarbonize sectors.

Introduction

Government and industry technology developers worldwide are realizing the potential for hydrogen heavy-duty, off-road applications including fuel cells (FCs) for agriculture, construction, and mining equipment. This workshop was designed to help identify needed research to accelerate technology development and address barriers to industry commercialization.

This workshop was hosted by the U.S. Department of Energy; the Ministry of Energy, Chile; and the European Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) as part of the Mission Innovation Clean Hydrogen initiative. The workshop was held virtually over a 3-day period from September 22–24, 2021. It consisted of 31 invited talks organized in 6 sessions focused on government perspectives, agricultural equipment, construction equipment, mining equipment, FC developers, and onsite hydrogen production and refueling, along with breakout discussion sessions focused on equipment development and hydrogen production and refueling for each equipment sector (agriculture, construction, and mining). More than 100 attendees from more than 50 organizations participated in the workshop, representing academia, government, and industry across seven countries (Australia, Canada, Chile, Finland, Sweden, United Kingdom, United States) and four continents (North America, South America, Europe, and Australia).

The objectives of the workshop were to:

- Assess the state of the art for heavy-duty applications using hydrogen FCs for agriculture, construction, and mining equipment.
- Discuss operational requirements and lessons learned from early equipment demonstration projects for agriculture, construction, and mining.
- Understand current technology gaps and identify collaborative research and development (R&D) opportunities.
- Identify refueling infrastructure challenges.

Session I: Perspectives on Hydrogen for Mining, Construction, and Agriculture Applications

Matthijs Soede, Mission Innovation 2.0 Clean Hydrogen Mission Director, European Commission, "Opening Remarks"

Dr. Soede welcomed participants and provided background information on Mission Innovation (MI). MI aims to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions, thus providing widely affordable and reliable clean energy solutions. The Clean Hydrogen Mission is part of MI's commitment to clean energy innovation that provides every country with the confidence to set ambitious clean energy and climate targets. The goal of the Clean Hydrogen Mission is to increase the cost-competitiveness of clean hydrogen to the end user by reducing end-to-end costs to $2 (USD)/kg by 2030. MI believes hydrogen has the potential to decarbonize hard-to-reach sectors in the economy. The Clean Hydrogen Mission seeks to help build a global hydrogen economy. Dr. Soede stated that it is necessary to clearly define and prioritize these activities.

Dr. Sunita Satyapal, Director, Hydrogen and Fuel Cell Technologies Office, U.S. Department of Energy, "U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office Opening Remarks"

Dr. Satyapal provided additional background on the Clean Hydrogen Mission, indicating it was launched in 2021 with 17 member countries. She reiterated that its mission is to develop a global clean hydrogen economy by reducing end-to-end costs of hydrogen to $2/kg by 2030. As part of this effort, member countries have committed to research, development, and demonstration and to building 100 large-scale clean hydrogen valleys to reduce costs and scale up clean hydrogen technology. MI and the Clean Hydrogen Mission are based on three pillars: research and innovation, demonstrations, and an enabling environment. There are three working groups within Clean Hydrogen Mission: Production, Distribution and Storage, and End Use. This workshop falls under the purview of the End Use working group, which is cohosted by Australia, Chile, the European Commission, and the United States. Member countries of the Clean Hydrogen Mission provided feedback on high-priority areas of R&D; decarbonizing mining and other hard-to-abate sectors was voted as the top priority.

Dr. Satyapal outlined the workshop objectives, which are to (1) assess the application of hydrogen and FC technologies for equipment in the heavy-duty off-road markets, focusing on agriculture, construction, and mining; (2) identify the current status and state of the art for hydrogen and FC technologies; (3) discuss operational requirements and lessons learned about early equipment demonstration projects; (4) understand current technology gaps; (5) discuss potential hydrogen refueling infrastructure pathways and challenges; and (6) assess current and future potential total cost of ownership (TCO) analysis scenarios for selected applications.

Expected outcomes from the workshop are the identification of opportunities and challenges for commercialization and R&D activities to accelerate commercialization of hydrogen and FCs in agriculture, construction, and mining. Dr. Satyapal hopes that this workshop will not be a one-of-a-kind event but will lead to further engagement and identify what the next steps should be. Dr. Satyapal provided some examples of the potential impact of hydrogen and FCs in the off-road sector, indicating that mining trucks emit 68 million tons of CO_2-equivalent (CO_2e) per year globally. In the United States, off-road transportation emissions account for 533 million tons CO_2e/year, with agriculture, construction, and mining accounting for most of these emissions.

Dr. Satyapal discussed President Biden's and the U.S. government's commitment to addressing climate change and the U.S. Department of Energy's (DOE's) Earthshot Hydrogen Shot Initiative to achieve a hydrogen production cost of $1/kg of clean hydrogen within a decade. The $1/kg Hydrogen Shot goal is consistent with the Clean Hydrogen Mission's goal of $2/kg end-to-end, which includes delivery, storage, and infrastructure costs in addition to production costs. The Hydrogen Shot Initiative considers all pathways for producing clean hydrogen, including water splitting, biological approaches, and thermal conversion with carbon capture, use, and sequestration.

Max Correa, Head for Fuel Cells and New Energy Carriers Division, Ministry of Energy of Chile, "Green Hydrogen, an Opportunity for the Decarbonization of the Mining Industry"

Mr. Correa discussed Chile's goal to reach net-zero carbon emissions and become carbon neutral by 2050. Their plan for becoming carbon neutral relies heavily on hydrogen, with green hydrogen accounting for 21% of planned reductions in emissions. Mining is an important part of Chile's economy, and their hydrogen strategy focuses heavily on the mining sector. Chile has significant solar and wind resources to produce low-cost green hydrogen. Recent estimates indicate that Chile can produce green hydrogen at a cost of about $1/kg by 2030, with the potential to produce 160 million tons of green hydrogen per year. Chile has set goals of (1) having 5 GW of electrolysis capacity operating by 2025, (2) being capable of producing 200,000 tons of hydrogen per year from at least two hydrogen valleys, (3) increasing to 25 GW of electrolysis capacity by 2030, and (4) producing hydrogen at a cost of less than $1.50/kg.

Chile's strategy to accomplish these goals involves using local applications to ramp up demand for hydrogen and initiate a domestic hydrogen industry targeting six applications: oil refining, ammonia production, mining haul trucks, heavy-duty trucking, long-range buses, and blending hydrogen into the natural gas grid. With their competitive natural renewable energy resources, they see the possibility for Chile's hydrogen industry to grow to match the size of its mining industry.

Mr. Correa next focused on hydrogen's potential uses in mining. The mining industry is growing in Chile; with efforts to combat climate change, it will grow more rapidly, as will its energy consumption. Mining will play a key role in the adoption of hydrogen in Chile; it will make up an estimated 30% of Chile's local demand for hydrogen. The cost of hydrogen is expected to be less volatile than the cost of diesel, which will benefit mining operations. Chile's national mining policy has set goals for large mining companies to operate zero-emission fleets by the end of this decade to reduce CO_2e emissions from large-scale mining by at least 50% by 2030, and to reach carbon neutrality by 2040.

Matt Walden, Investment Director, Australian Renewable Energy Agency, "The Role of ARENA in Australia's Energy Industry"

Mr. Walden discussed the role of the Australian Renewable Energy Agency (ARENA) and their mission to support the global transition to net zero emissions by accelerating the pace of pre-commercial innovation. ARENA has invested $1.7 billion in more than 580 projects valued at more than $6.9 billion, leveraging every $1 of ARENA funding with $3 of private investment. ARENA is investing in four strategic areas: (1) optimizing the transition to renewable electricity, (2) commercializing clean hydrogen, (3) supporting the transition to low-emissions metals, and (4) scaling up carbon capture and storage.

To commercialize clean hydrogen, ARENA is using R&D to reduce the cost of hydrogen produced from renewable energy to demonstrate technologies that address technical challenges along the hydrogen value chain and to prove the technical feasibility and commercial viability of hydrogen use. ARENA has invested $33 million in 12 hydrogen projects, leveraging every $1 of ARENA funding with $1.5 of private investment. Projects include feasibility studies for using hydrogen in transportation, for producing renewable ammonia and methane, for use in power-to-gas applications, for blending hydrogen into the natural gas infrastructure, and for developing a hydrogen microgrid. ARENA maintains an open-source library of reports and studies, which is available at arena.gov.au/knowledge-bank.

Mark Brodziski, Deputy Administrator for Rural Business-Cooperative Service, U.S. Department of Agriculture, "Perspectives on Hydrogen for Mining, Construction, and Agriculture Applications"

Mr. Brodziski discussed U.S. Department of Agriculture (USDA) perspectives on hydrogen for mining construction and agriculture. He indicated that the U.S. government is taking a "whole of government" approach to the climate crisis, which includes leveraging the federal government's footprint and buying power to lead by example. The goals are to rebuild the nation's infrastructure for a sustainable economy and revitalize our energy communities while securing environmental justice and spurring economic opportunity.

The USDA approach includes a strategy of voluntary adoption of climate-smart agricultural and forestry practices that (1) decrease the risk of wildfires, which are fueled by climate change; (2) produce additional measurable, verifiable carbon reductions and sequestration; and (3) serve as the source for sustainable bioproducts and fuels. The USDA is pursuing decarbonization on the input side by examining programs that increase energy efficiency and the use of renewable energy and biofuels. On the output side, the USDA is looking at carbon sequestration, agricultural production, and forestry practices to produce renewable fuels and feedstocks for hydrogen.

One USDA effort that supports the supply chain for hydrogen and FC equipment for energy production through programs includes the USDA Rural Development Energy Program for producing hydrogen from biomass via processes such as biomass gasification, reforming biomass-derived liquids, and microbial fermentation. Other USDA programs support the hydrogen supply chain and infrastructure; these include programs such as the Rural Energy to America Program, the Business and Industry Program, and the Biorefinery, Renewable Chemical and Biobased Manufacturing Assistance program.

Britney J. McCoy, Center Director, Climate Analysis and Strategies Center, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, "Nonroad & H2 Fuel Cells: An EPA Overview"

The nonroad equipment market is extremely diverse. It includes over 200 categories of applications, from marine and rail applications to snowmobiles to lawn-and-garden equipment. The U.S. Environmental Protection Agency (EPA) regulates emissions from marine engines, locomotives, and aircraft separately from other non-road applications. Mining equipment is not regulated by the EPA, but by the U.S. Department of Labor's Mine Safety and Health Administration.

The transportation sector accounts for the largest amount of U.S. greenhouse gas (GHG) emissions, 29%, with the nonroad sector accounting for 20% of the GHG emissions within the transportation sector. Construction, mining, and agriculture equipment are the largest contributors (excluding marine, locomotives, and aviation) to nonroad GHG emissions; they are responsible for more than half of all nonroad GHG emissions. Hydrogen FCs can help reduce emissions from nonroad applications. However, except for forklifts, nonroad equipment using FCs is at a low technical readiness level (TRL); it is mostly in the early demonstration stages and not yet commercially available.

EPA and the National Renewable Energy Laboratory (NREL) collaborated to evaluate FC cost and performance for off-road and nonroad vehicles. As a test case, the study initially evaluated 61 yard tractors operating at five different port terminals. The study projected the energy efficiency, initial cost, and TCO for yard tractors from 2020 to 2050. Results suggested that FC yard tractors could achieve 2.6 to 3.4 times the fuel economy of diesel yard tractors. The study also concluded that FCs could be cost competitive with diesel in yard tractor applications by 2025, after which time they will cost less to operate than diesel yard tractors. FCs have the potential to replace diesel engines in a variety of port operations, including marine, rail, and nonroad applications, which could lead to significant reductions in diesel emissions at ports.

Although the EPA does not provide funding for R&D, they do fund the deployment of commercially available technologies that reduce emissions. The Diesel Emissions Reduction Act (DERA) authorizes funding assistance to reduce diesel emissions from legacy engines providing health and environmental benefits in targeted areas. FCs can qualify for DERA funding to replace certain vehicles and equipment, with the funding level based on the technology.

The audience asked whether DERA funding would be applicable to a FC tractor. Dr. McCoy responded that the EPA would need to make sure that it is a commercially viable tractor.

William Robertson, Vehicle Program Specialist, California Air Resources Board, "State-level Off Road Actions and Perspectives"

The California Air Resources Board (CARB) is the leading office in California for addressing climate. CARB's tasks fall into three areas: climate, regional air quality, and local exposure. CARB sets aggressive goals and targets for both criteria and GHG emissions. The office takes a whole-of-economy approach to address these emissions.

California is providing leadership in the areas of climate, regional air quality, and local exposure. The state has adopted targets for achieving carbon neutrality across its economy by 2045. It calls for 100% zero-emission vehicles (ZEVs) for off-road operations "where feasible" by 2035. New York recently signed a similar law. Mr. Robertson noted that workshops like this are very important in pushing boundaries and determining what is feasible.

Hydrogen provides interesting opportunities to decarbonize off-road applications. Many off-road applications have high energy demands and a high degree of utilization throughout the day. Hydrogen offers the potential to decarbonize off-road applications by providing extended operating time and/or range, and by increasing the total amount of energy stored on the tractor, excavator, or dozer compared to batteries. Hydrogen can reach beyond the grid, enabling work in remote locations. Hydrogen also provides an opportunity for mobile refueling and for relocatable micro-grids to support temporary worksites. Hydrogen and FCs do not necessarily need to be on the vehicles, because hydrogen and FCs can provide off-grid charging stations for battery electric vehicles (BEVs). The current shared fueling infrastructure also fits with hydrogen; this provides flexibility for small businesses, because it means they do not necessarily have to own the infrastructure.

The California Energy Commission is funding demonstrations of hydrogen and FCs for trucks, buses, and several off-road applications such as railroad switcher locomotives, harbor tugs, and harbor craft. The Clean Off-Road Voucher Incentive Program (CORE) is a voucher program that aims to reduce emissions in off-road vehicles and includes a proposed expansion to include zero-emission agriculture and construction. The Funding Agricultural Replacement Measures for Emission Reductions Program (FARMER) aims to reduce emissions in agriculture with the goal of eliminating the dirtiest equipment in the agricultural sector. Over $249 million has been spent on nearly 3,200 projects for replacing older diesel tractors and harvesters with newer, cleaner diesel vehicles. There is a large opportunity to replace diesel equipment with zero-emission equipment, including FCs, under this program.

The California Energy Commission has supported hydrogen and FC demonstrations for off-road applications, including a FC hybrid top loader, FC yard trucks for cargo handling, and a hydrogen FC ferry. Funding for other opportunities is expected to develop, including a proposed $40 million for GHG reduction for FYs 2021–2022, which could include projects for construction equipment, cargo handling equipment, maritime applications, and locomotives.

Curt Blades, Senior Vice President, Association of Equipment Manufacturers, "AEM – Association of Equipment Manufacturers"

The Association of Equipment Manufacturers (AEM) is the leading organization in North America for advancing construction and agriculture equipment manufacturers and their value chain partners in the global marketplace. AEM represents the agriculture, forestry, mining, and construction industries.

The AEM believes that the change to clean and zero-emission technologies can provide opportunities for innovation. Equipment designs have not changed much in the past 100 years, because they are all powered by combustion engines. Changing the powertrain provides opportunities to optimize around the new electrical powertrain. Mr. Blades stated that there is no one perfect solution to address carbon reduction in the equipment industry, but that the equipment industry is committed to working together to find the right mix of solutions.

Rajesh Ahluwalia, Group Leader for Engineering and Systems Analysis, Argonne National Laboratory, "Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-duty Applications- Preliminary Results"

Dr. Ahluwalia discussed the results of a preliminary study to (1) compare the TCO of hydrogen FC-powered tractors, wheel loaders, and excavators to the TCO for their respective diesel powered counterpart; and (2) determine what improvements in terms of cost, performance, and durability are necessary for hydrogen FC equipment to be competitive with their diesel counterparts in each of these applications. Farm tractors with engine sizes from 50 to 550 hp, wheel loaders with engines from 75 to 700 hp, and excavators with engines sizes from 50 to 500 hp were considered with the assumption that FC systems being developed for heavy-duty trucks would be used in these applications to leverage economies of scale. FC systems were sized to meet the application's power requirement at its end of life. Heat rejection was considered with the size of the fan and radiator frontal area determined based on the operating temperature, FC stack efficiency, and operating temperature. The fuel storage system was adapted from systems currently being developed for heavy-duty trucks. The size of the fuel storage was calculated to provide similar time between refuelings as the diesel equipment at end of life. Energy storage systems (batteries) were considered to improve fuel economy by recapturing regenerative energy and to extend FC stack life by enabling voltage clipping.

For the farm tractor, Dr. Ahluwalia determined that the FC drivetrain for traction power provided higher efficiency (90%) at rated power compared to the mechanical drivetrain (86%). The drivetrain efficiency for the powertrain only for the FC system (38.7-37.1%) was higher than for the diesel engine (24.4-30.9%). However, the FC system had a higher heat load than the diesel system. The FC system was 69–162% more efficient than the diesel, which allowed for a lower power FC system than corresponding diesel system, even after accounting for the higher fan power required for cooling the FC. However, the larger tractors require more than 300 kg of hydrogen onboard to match the diesel refueling schedule, and fitting this much hydrogen onboard, even as liquid hydrogen, may be an issue. Refueling frequency may need to be increased.

The TCO for tractors excluded the common cost elements of the tractor, such as the chassis, tires, labor, other attachments, and insurance, and considered only on the capital costs of the power system, energy storage (battery), fuel storage, electric drive, fuel cost, and operating and maintenance costs. Dr. Ahluwalia considered two cases for the FC and onboard hydrogen storage systems: (1) the current technology status case based on current performance, durability, and manufacturing costs for the FC and onboard hydrogen storage systems as defined by the DOE Hydrogen and Fuel Cell Technologies Office (HFTO) and (2) the ultimate targets case with the performance, durability, and manufacturing cost targets for the FC and onboard hydrogen storage system required to make the TCO for FC vehicle cost competitive with its diesel counterpart. TCO is dominated by fuel cost, with fuel accounting for 72–82% of the TCO for diesel tractors and 70–77% of the TCO for the hydrogen FC tractors in the ultimate FC case. FC tractors are the lower cost option for compact, utility, and row-crop tractors (tractors with less than 265 hp diesel engines), if the ultimate cost targets are met for hydrogen, the FC system, and the onboard hydrogen storage system. The TCO for the largest four-wheel-drive FC tractor is slightly higher than the TCO for the diesel, primarily due to the high cost of the onboard liquid hydrogen storage system.

A similar analysis was performed for the wheel loaders based on the efficiency for travel and work with the actuator over a representative duty cycle. The FC wheel loader exhibited 90–180% higher efficiency than the diesel wheel loader. To meet the same refueling schedule as its diesel counterpart would require storing 164 kg of hydrogen onboard the largest wheel loader. The TCO for the FC wheel loader is competitive with that of the diesel for all the sizes investigated at the current FC technology status level and would be a lower cost option for all wheel loader sizes considered if the ultimate FC targets are met.

FC excavators were analyzed in a similar way. The FC excavators were determined to be 71–142% more efficient than the diesel excavators. They are cost competitive in the current status case with diesel engines for compact, medium, and standard/full excavators, even at fuel costs of $5/kg hydrogen and $3.25/gal diesel. FCs are lower cost options for all excavator sizes considered if the ultimate targets case is met.

Dr. Ahluwalia determined that FCs provide a substantial (40–180%) gain in lifetime operating efficiency for the off-road applications investigated compared to their respective diesel counterparts. The increase in efficiency can lead to significant fuel savings, resulting in a potentially competitive TCO. However, challenges for integrating FCs into the off-road equipment investigated were associated with heat rejection. This resulted in a 28–74% higher heat load, requiring 43–132% larger fans and radiators compared to their respective diesel counterparts. There were also challenges with storing enough hydrogen onboard to provide the same operating hours as diesel counterparts.

Session II: Agricultural Equipment

Mike Duffield, Module Lead-Energy Storage, John Deere, "John Deere"

John Deere is organized into four business units: production and precision agriculture, small agriculture and turf, construction and forestry, and enabling businesses. Within these units, the company is organized by production system, for example in production and precision agriculture, production systems include corn and soy, small grains, sugar cane, and cotton. This ensures products are designed to work together (for example, the tractor, planter, and harvester).

John Deere has been interested in developing hydrogen and FC equipment for some time and demonstrated a FC Pro-Gator in 2002. John Deere has a wide variety of products, ranging from large harvesters to small all-terrain vehicles, each with their own requirements and duty cycles. Each product and application in the range must be addressed and using generalities to describe the applications is not sufficient. One thing the John Deere products have in common is that they operate off-road, which exposes the equipment to quite different and, in many ways, harsher conditions than on-road vehicles. While on-road equipment works in a relatively clean environment on smooth roads, off-road equipment operates in an environment that can be filled with debris (dirt, chaff, etc.) and on unpaved surfaces, which can lead to severe vibrations. On-road equipment travels at speed and can use ram air for cooling, while off-road equipment generally travels at low speeds (5 mph) and fan power provides the cooling.

Demands on the engine for production agriculture applications are quite different than for on-road highway truck applications. For a highway truck, the contact area is very low, and high power is not needed during cruising, so the engines operate at relatively low rotations per minute (RPM) and require moderate torque most of the time. In agriculture applications, the tractor or harvester operates at the limit of the engine under high-torque, high-RPM conditions most of the time. Space is also more limited on a tractor and finding space to put adequate hydrogen storage is challenging.

John Deere's view is that current hydrogen and FC technology does not compare with diesel. They estimate that this new technology would have an installed cost 7.5 times that for diesel, would require refueling 10 times as often, and would have fuel costs 4 to 5 times higher than diesel on a $/kW basis. In addition, agriculture tractors are often refueled in the field, and there are concerns about how hydrogen refueling can take place there.

William Resende, Manager Electrified PWT Fuel Cell Engineering, CNH Industrial, "Technology Challenges for Hydrogen Fuel Cells in Agricultural Applications"

CNH Industrial believes that hydrogen and FCs provide several advantages for agricultural applications, including zero emissions, reduced noise and vibrations, fast (10–15 minutes for larger vehicles) refueling, and up to 9 times lighter powertrain than batteries (for a large vehicle with liquid hydrogen storage). The ability to make hydrogen from a variety of energy sources, including biomass, wind, and solar energy, which are available on farms, and the integration of hydrogen and FCs with distributed energy generation is also seen as a potential advantage.

Three use cases were described: small utility tractors in the range of 50–100 kW, typically used on small farms; 100–200 kW tractors used on medium-sized farms and for dairy and livestock; and large tractors 200–450 kW and above used for crop farming on large farms. Small utility tractors can be built with FCs and hydrogen storage technology available today. However, hydrogen provides the most benefits for large tractors. More development is needed for hydrogen storage and FC technology for these applications.

CNH has previous experience with FC tractors and developed and demonstrated early phase hydrogen FC tractors. They found that runtime was insufficient in these demonstration tractors, because only a small amount of hydrogen was stored onboard. They also found that FC power was frequently de-rated due to cooling issues, and that it was very hard to test the FC tractors in real customer areas because they were remote and there was a lack of hydrogen infrastructure. There were also hydrogen safety aspects that needed to be dealt with both onboard and off-board. Cost was also a challenge, especially at the prototype stage. CNH indicated that the drivetrain cost would be 15 times more expensive than a diesel powertrain (due largely to low production volumes). The hydrogen storage cost was the main cost factor for the FC drive train, driven mainly by the cost of carbon fiber. CNH took a modular approach, which duplicates the balance of plant, adding to cost.

CNH identified several challenges for hydrogen and FCs for agricultural applications:

(1) The power density of the FC system is a challenge, and it needs to be increased. Packaging space is limited on a tractor and power density for the FC system (~175 kW/m^3) was lower than that for a typical diesel engine (~275 kW/m^3). Increasing FC power density while increasing efficiency is key (i.e., power density at 0.7 V/cell).

(2) Hydrogen storage energy density and specific energy are also a challenge, with the energy density being the main barrier to achieving the same run time as a diesel tractor.

(3) Cooling the FC is a challenge. A FC system of 300 kW would require a radiator with 5 times more heat rejection capacity than ones currently available. Adding more radiators, increasing fan power, and/or increasing FC stack operating temperature are potential solutions.

(4) Powertrain lifetime was also identified as a challenge, particularly for equipment such as sugar cane harvesters where the current diesel powertrain lifetime is 20,000 hours. The lifetime in agricultural operations is expected to be impacted by the higher percentage of time it will be operated at higher power and higher temperature compared to on-road applications. Development of durable materials operating at higher temperatures is key to achieving targets.

(5) Another major challenge is the fuel supply and hydrogen infrastructure. Passenger car hydrogen refueling stations are mainly located in non-farming locations, which limits synergy of farms with current infrastructure and the potential for hydrogen delivery to the farms by truck. Hydrogen could be produced on the farm; however, that will require high investment costs that are likely to be untenable for small and medium farms.

(6) Safety is also a challenge. Existing standards have been successfully implemented for on-road applications, the same level of standardization and best practices needs to be implemented for off-road, including hydrogen infrastructure at farms.

CNH believes hydrogen and FCs can play an important role in the electrification of agricultural machines. CNH has already worked on two FC tractor demonstrators and has experience with the challenges to be solved to enable widespread adoption. The main challenges are in powertrain cost, hydrogen storage energy density, FC durability, cooling, and refueling infrastructure availability. CNH believes funding should be directed toward increasing the energy density and reducing the cost of hydrogen storage systems, reducing the FC system cost while increasing power density and efficiency, and enabling operation at higher temperatures. They believe that support should be provided to build up infrastructure to produce hydrogen on farms or to have a distribution network for other applications that can be used by farms. It is likely that the infrastructure will need to go to liquid hydrogen to make delivery to farms cost effective.

Ismo Hamalainen, R&D Manager, AGCO Power, Finland, "H2@Off-Road"

AGCO's leading brands include Challenger, Fendt, Massey Ferguson, Valtra, and GSI. They have four engine factories, located in Argentina, Brazil, Finland, and China, and produce 3-, 4-, 6-, and 7-cylinder engines.

Hydrogen provides a 100% CO_2-neutral fuel (based on tailpipe emissions). It can be used in both FCs and hydrogen internal combustion engines. FCs provide high efficiency (45–55%) and an electric powertrain in the vehicle, but have challenges related to system price, maintenance, and service, and are sensitive to fuel impurities. Hydrogen ICEs have lower efficiency (40–45%) but use a conventional powertrain in the vehicle. Hydrogen ICEs will also require mission after-treatment. Electrolyzers could be used for local hydrogen production on farms; however, this scenario faces challenges associated with financial feasibility and with ensuring safety and quality of the hydrogen. Storing enough hydrogen onboard is also a challenge. Larger (175- and 300-kW) tractors operate 12 or more hours a day and require 1,050 to 1,800 kWh of energy over this period. This would require 64 to 110 kg of hydrogen, or 4.2 to 7.3 m^3 of space for the hydrogen tanks (assuming hydrogen is stored at 700 bar pressure).

Mr. Hamalainen explained that hydrogen can be a CO_2-neutral fuel for agricultural purposes and can be used with either FC or ICE power sources. Challenges for hydrogen in agriculture include developing the hydrogen infrastructure and the amount of hydrogen that can be stored onboard. Reliability, efficiency, and ease of use are main drivers for farmers, and Mr. Hamalainen indicated that they must be addressed.

Jay Schmuecker, President, Schmuecker Renewable Energy System, "Schmuecker Renewable Energy Hydrogen-Ammonia Fueled Tractor"

Mr. Schmuecker described his experience with decarbonizing his farm tractor. Based on the length of the growing season, he indicated that he needed to produce hydrogen at a rate of 10 lb./day and would need 77 kW of solar panels and 80 composite storage tanks. His farm uses ammonia as fertilizer for the corn crop, so the project expanded to also produce hydrogen for ammonia production and to produce CO_2-free ammonia.

A tractor was purchased with a dual fuel (hydrogen or ammonia) combustion engine, and four hydrogen storage tanks were installed on the tractor. The tractor was first demonstrated in 2015. Upgrades and dyno testing were completed in 2021 to optimize tuning and improve the power output. The ammonia generation system developed achieves 27% efficiency. Most of the energy consumption (64%) is associated with the production of the hydrogen used in the ammonia production. An additional 23% is used for nitrogen production, and 12% for the ammonia production step and for powering the controls.

Ammonia has advantages in that it is not flammable, while other fuels are. Farmers are also familiar with handling ammonia. If spilled, ammonia vapors rise and dissipate. However, ammonia is hazardous; as a gas it can cause lung damage, and if spilled as a liquid it can cause burns and eye damage. Ammonia is hazardous at 50 ppm but can be smelled and detected at 5 ppm.

Session III: Construction Equipment

Brian Lowry, Engineering Manager, Caterpillar, "Caterpillar"

Caterpillar is focused on three sectors: resources (mining), construction, and energy and transportation. Across these sectors, Caterpillar's customers are looking to transition to equipment with reduced emissions. Caterpillar is looking at renewable fuels, including hydrogen and hydrogen blends, FCs, electric and hybrid powertrains, batteries, and microgrids to accomplish this transition. Caterpillar currently has turbine generators that run on hydrogen blends, which can operate on up to 85% hydrogen, and reciprocating engines that can run on up to 100% hydrogen. Caterpillar will have generator sets that can run on 100% hydrogen available to order this year.

Mr. Lowry noted that there are key challenges for hydrogen in construction and mining. Infrastructure and delivery to the mining or construction site and the availability of hydrogen is a challenge. The volumetric energy density of hydrogen also presents a challenge for storing enough hydrogen on the equipment, as does the cost of compressed or liquid hydrogen. The efficiency of making and compressing or liquifying hydrogen is also a challenge, as some are looking at onsite generation of the hydrogen. Last, the refueling rate can also be a challenge.

Michael Lewis, Technical Director — Technology, Komatsu, "Decarbonization Approaches Construction Equipment"

Komatsu is committed to minimizing environmental impacts. They are focusing on decreasing CO_2 emissions from product use and production by 50% by 2030 and increasing the rate of renewable energy use to 50% by 2030. Komatsu focuses on 5 of the 17 Sustainable Development Goals the United Nations has created for global entities: decent work and economic growth; industry, innovation, and infrastructure; sustainable cities and communities; climate action; and partnerships for achieving these goals.

Komatsu has multiple products in the construction equipment, mining equipment, and utility equipment sectors. Significant investment and R&D are required to develop zero-emission versions of this equipment. This will be the largest energy transition in Komatsu's history. Previously, the biggest transition was to Tier 4 emissions technology. Battery electric and hydrogen FCs are competing for the same resources and prioritization is mandatory. Serialization of development may result in a slower transition of key models than desired. Mr. Lewis stated that incentives from governments will be necessary to increase the pace of equipment development. He noted that significant investment will be required to create and deploy critical supporting technologies such as the infrastructure for green hydrogen production, distribution, storage, and refueling.

Battery technology has challenges associated with cost, long charging times, and limited operational hours/duration, while FCs have high component costs and require large hydrogen tanks to achieve the desired operating times. To achieve fast penetration, the TCO of zero-emission machines must be lower than that of diesel ICE machines. Mr. Lewis said that a greenhouse tax on diesel ICE machines and subsidies on zero-emission machines will support the spread of zero-emission machines.

The construction market presents challenges for hydrogen FC equipment, including the job site, which can be in rural, suburban, or urban locations in cold (-30°C), hot (>50°C), dry (desert) or humid (rainforest) environments. Safety is of prime importance.

Durability is also a challenge. Mr. Lewis explained that the lifetime of hydrogen-related components should be longer than 10,000 hours (i.e., longer than the warranty time of present construction machinery maintenance programs). The operation time provided without refueling for a 20-ton ICE excavator is 24 hours, while a 20-ton FC excavator using current technology provides less than 8 hours of operation. Hydrogen tank and machine system R&D will be necessary to extend hydrogen machine operating time.

Mr. Lewis noted that construction machinery regulations, standards, certification systems, recycling systems, and so forth are currently geared toward ICE equipment and would need to be revised for hydrogen-powered machines. Hydrogen infrastructure still needs to be developed. The establishment of on-demand hydrogen delivery service at a reasonable cost will be indispensable for the spread of hydrogen construction machinery.

The audience asked about the TRL for Komatsu's hydrogen construction equipment and if Komatsu is also looking at ICE for hydrogen and hydrogen blends. The response indicated that the TRL is low, and the equipment is not there today, but that Komatsu expects to have solutions available by the end of the decade. Komatsu is looking at hydrogen ICEs and indicated blends would be difficult for construction sites.

Martin Mirchmair, Technical Director, Prinoth, "Zero Emission. Perfect Slopes"

Prinoth is a manufacturer of tracked utility vehicles, and its main markets are snow groomers and for vegetation management. Their equipment operates in extreme conditions, with temperatures ranging from -40°F to 104°F, vibrations up to 10 Gs peak loads, and at elevations up to 14,800 feet above sea level. The power requirements of their snow-grooming equipment range from 170 to 380 kW.

Prinoth is looking at zero emission in two segments: (1) a small segment for vehicles with lower runtime hours (~3 hours) and lower power requirements, which focus on small ski hills, cross country trails, and indoor facilities; and (2) the big segment, which requires full shift operation (8 hours) with a high power demand. They are looking to address the small segment with BEVs and the large segment with hydrogen FCs. Even with hydrogen, the second segment may require refueling during the shift because it is hard to fit 8 hours' worth of hydrogen on the vehicle. Prinoth has developed a proof-of-concept FC vehicle, the Leitwolf h2Motion, which has a ~200-kW FC, a 150-kWh battery, and ~40 kg of onboard hydrogen, stored at 700 bar. The target is 4 hours of operation between refueling (or half of a shift).

The challenges for hydrogen and FCs in the snow-grooming application include durability, because a lifetime of 10 years/10,000 hours of operation is required to match existing diesel equipment; the hydrogen storage capacity onboard the vehicle; and the TCO. Infrastructure challenges include getting the hydrogen supply to the remote locations at the needed cost and onsite hydrogen storage. Snow-groomer garages are in remote locations without winter road access. For example, the hydrogen requirements for one site with a fleet of 10 groomers was estimated at 600 kg/day. Standards for hydrogen and training and education are also a challenge. Mr. Mirchmair noted that snow groomers are one of the hardest applications for tracked drivetrains and an interesting platform for testing new technology.

Session IV: Mining and Loader Equipment

Michael Lewis, Technical Director — Technology, Komatsu, "Komatsu"

Mr. Lewis explained that decarbonizing the mining industry will be challenging. Doing so will require abating 70 megatons of CO_2 emissions, with surface mining accounting for 50–80% of the emissions. The journey is not a one-step process; it has already started with Tier 4 engines to reduce NO_x emissions.

There are challenges for hydrogen and FCs for mining equipment. Mining operations are remote and mining equipment is large and lasts a long time. Customers want decarbonization, but they also want green technologies to perform the same as ICE technology. Diesel engines last 3–5 years, with equipment lifetimes lasting 10 to 15 years. Mining equipment must be able to operate under a wide range of conditions. Diesel engines have been optimized over the past 100 years to provide reliable and easy-to-maintain service. FCs must provide similar benefits. FC-powered equipment in a typical mine operation will require 800–1,200 kg of H_2 per day per vehicle. The current TCO for FC-powered equipment is not competitive with ICEs, but Mr. Lewis expects it to become more competitive with improvements in technology. If the TCO does not become cost-competitive, then a carbon tax will be needed, he noted.

Ray Gallant, Vice President Product Management and Productivity, Volvo, "Volvo Group Journey to Sustainability: Hydrogen Solutions"

According to Mr. Gallant, the easy challenge is getting machinery to run on hydrogen. The tough challenge is getting the infrastructure in place. Several innovations will be required, with evolution of technologies driving the solutions. BEVs and FC electric vehicles will form the larger market share of new trucks from 2040 on, but the legacy of fossil fuel–burning equipment will still remain after 2040. Hydrogen ICEs are viewed as a favorable alternative to BEVs because they have a weight advantage (the higher weight of batteries reduces the payload) and faster refueling times compared to BEVs. Furthermore, hydrogen ICEs allow for the use of conventional powertrains. Hydrogen FCs provide some advantages; for example, compressed hydrogen can be transported to off-road sites without the need for additional infrastructure, and rapid refueling is possible. Hydrogen FCs also present some challenges, including the lower energy density of hydrogen compared to diesel, heat management and heat rejection, and safety, particularly where combustible gases are present.

Volvo's roadmap to electrification of trucks has multiple solutions including battery electric for refuse and city distribution trucks, battery-FC hybrid electric for construction and regional haul trucks, and FC electric vehicles for heavy transport and demanding long-haul trucks. When designing electrified equipment, matching the kilowatt-hours of onboard energy storage to the BTU of diesel stored onboard will not work; the secret is to maximize energy efficiency through energy recuperation.

Mr. Gallant noted that a main challenge for hydrogen is that the maturity and cost efficiency of the equipment is not at a point where the technology and infrastructure can be rolled out, and hydrogen refueling infrastructure is lacking. Hydrogen availability is also an issue, and hydrogen produced using the current grid electricity mix does not provide much of a GHG savings. From the customer's perspective, sustainability is required, and the TCO must be competitive.

Julian Soles, Head of Technology Development Mining and Sustainability, Anglo American "Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicle Workshop"

Mr. Soles noted that each mine is unique, but the objectives remain the same: the TCO of hydrogen FC vehicles must be equivalent to that of diesel vehicles while providing the same operational flexibility. Mining equipment operates in harsh environments that require high vehicle utilization and reliability.

Today, many trucks are already electrified — except for the diesel engine. Trucks that require long-term energy storage using batteries are not feasible in mines. Mines are constantly moving, and mine operators do not like to locate infrastructure in the mine pit to support the vehicles. Recharging times for batteries result in long downtimes, which is costly.

Hydrogen FCs offer advantages such as zero emissions if using sustainable energy sources to generate the hydrogen, hydrogen can be generated locally, refueling rates are comparable to diesel refueling rates, and they outperform batteries in heavy-duty, high-utility mobile applications. Hydrogen FCs, however, do have challenges. Hydrogen is not as energy dense as diesel and is more expensive. Adoption of hydrogen technologies is not widespread.

Clemens Müller-Falcke, Partner, McKinsey & Company, "Decarbonization in Mining"

The pressure for mining companies to decarbonize comes from a variety of avenues including customers demanding cleaner products, investors devesting of stocks based on climate risk, lower capital cost as bond financing becomes more tied to environmental performance, increasing regulatory pressure, clean technologies developing faster than expected, and employees searching for jobs targeting companies with clear sustainability goals.

Today, about 35% of mine emissions come from trucks used for haulage, with an additional 30% coming from electricity used in processing. With increased availability of renewable electricity and battery and hydrogen technologies rapidly developing, Mr. Müller-Falcke anticipates that by 2030 solutions for addressing most of the emissions at the mine will become economic. Pantographs in combination with sustainable fuels will play an important role in the transition to battery and hydrogen technologies. He expects that BEV haulage trucks will be cost competitive with diesel fueled trucks by 2025. Which technology will be the most economical in the long term will depend on how the technology develops; however, the specific mine site, lifetime of the mine, and the economics of capital expenditures may limit technology options.

Session V: Fuel Cell Developers

Ryan Sookhoo, Director New Initiatives, Cummins "Fuel Cell Off-Road Equipment and Vehicles"

Cummins is investing in the entire hydrogen value chain, including developing hydrogen and FC technologies for agriculture, construction, and mining vehicles. However, it must make absolute sense for them to deploy hydrogen and FC technologies in an application. The TRLs for the PEM FC and the solid oxide fuel cell (SOFC) systems are high enough for deployment today; however, the applications in which these FCs are used are still at too low a TRL. Markets are emerging for FC-powered vehicles for use in rail, marine, mining, construction, agriculture, fire and emergencies, and defense, especially in Europe. The use of FCs in rail has a high TRL, with rail traditionally being 5 to 7 years ahead of mining in adopting new technologies.

Mr. Sookhoo noted that bringing down the cost of hydrogen is key for deploying FCs in the transportation sector. For mining, the hydrogen infrastructure that supports the vehicles must be flexible and able to move as the mine moves. Today, the TCO for FC-powered vehicles is not competitive with diesel. The TCO is expected to become more cost-competitive with diesel as the power density increases, production becomes automated, and demand increases production volumes, which will drive down cost.

Tim Sasseen, Market Development Manager, Ballard, "We Deliver Fuel Cell Power for Sustainable Mining Operation"

Ballard has more than 40 years of experience in developing FC technologies. It focuses on the heavy-duty motive market, where FCs deliver the strongest value proposition. Commercialization of FC technology has been highest in the bus market but is quickly transitioning to trucks and other heavy-duty transportation applications, with FC trucks expected to be commercialized in the next few years. Ballard FCs currently power thousands of heavy-duty vehicles across the globe with over 100 million km of road experience.

For mining applications, getting enough FCs onboard to meet the operational requirements is not a challenge. The challenge is hydrogen — whether it is gaseous or liquid — and refueling needs need to be addressed. Ballard is working with JCB to power a 20-tonne 220X excavator and AngloAmerican to power a 300-tonne mining truck, both with FCs.

Gus Block, Director of Marketing and Corporate Development, Nuvera, "Fuel Cells for Off-Road Equipment, What Matters?"

Off-road equipment operators are facing significant challenges to meet emission reduction requirements. Zero-emission high-performance vehicles and machinery are needed where access to the electric grid is limited or nonexistent, and where diesel emissions are unacceptable, Mr. Block explained. Meeting application demand, code requirements, and an acceptable TCO are critical for successful deployment of hydrogen and FC technologies in off-road equipment.

Reliability in terms of longer mean time between failure and durability (i.e., stack lifetime), low-cost/high-volume manufacturing capability, ease of integration into existing applications, and a competitive TCO are what matters to Nuvera for deploying FC systems in off-road equipment. Nuvera has more than 25 years of experience developing FC motive power. Its E-series FC engine provides performance like that of a diesel and provides original equipment manufacturers (OEMs) a FC system that is easy to integrate into existing applications.

Rick Mason, Vice President of Business Development and Product Management, Plug Power, "H2 Off Road"

Plug Power provides a complete hydrogen ecosystem, from production and delivery of hydrogen to FC applications that use the hydrogen. Plug Power is building the first green hydrogen generation network across the United States. Its goals are to provide 500 tons per day (tpd) of hydrogen by 2025 and to double production to 1,000 tpd by 2028.

FC trucks provide an increased range and payload compared to battery electric trucks with a considerably shorter refueling time compared to the recharging time. For ranges greater than 200 km, BEVs do not fulfill the minimum user requirements.

Johan Burgren, Business Manager, Powercell, "Off-Road. Be Part of the Next Evolution of Power Generation for Off-Road Vehicles"

Powercell is a leading global FC technology company with more than 25 years of R&D experience. Powercell supports its customers through the entire transition from ICEs to hydrogen electrification. Its current projects include a FC mining truck.

Mr. Burgren explained that opportunities for hydrogen electrification of off-road vehicles include the emergence of CO_2-free zones in urban areas that will impact construction zones. Longer range and less downtime favor hydrogen electrification over battery electrification, and the ability to produce hydrogen onsite helps to resolves issues associated with high energy consumption and transportation costs in mining. Open-pit mining machines are already electrified, which helps to facilitate the transition to hydrogen electric machines.

Challenges include general lack of experience with hydrogen electric off-road vehicles, the uncertainty of hydrogen future defers OEMs from making the investments needed to bring the technology to market, and the logistical challenges and availability of a hydrogen infrastructure.

Session VI: Hydrogen Onsite Production and Refueling

Dave Edwards, Director and Advocate for Hydrogen Energy, Air Liquide, "Hydrogen Supply to Mining Operations."

Air Liquide is a global company that has nearly 50 years of experience in hydrogen development for industries and supplies 14 billion m^3 of hydrogen annually to its customers. Air Liquide is investing two new hydrogen production facilities in North America: one north of Las Vegas, Nevada, and the other in Bécancour, Québec. The Nevada facility is the first large-scale renewable liquid hydrogen production plant dedicated to the hydrogen energy market. It will produce 30 tpd of hydrogen for mobility use on the West Coast. Construction began in 2020, and it is expected to be operational in 2022. The Bécancour facility will be the world's largest PEM electrolyzer when it comes online later this year. It will produce 8 tpd of hydrogen for the Canadian and East Coast markets.

Mr. Edwards presented an example of supplying hydrogen to meet the demand for a large mining operation site. A typical large mine consumes about 37 million liters of diesel per year to support its operations, equivalent to 12 tpd of hydrogen, assuming all vehicles and equipment were converted to FC power. Producing the hydrogen onsite would require steam methane reforming (SMR) plant about $1/8^{th}$ the size of a world-class industrial SMR plant. Producing the hydrogen onsite by electrolysis would require a plant about twice the size of the Bécancour plant. Producing the hydrogen off-site and transporting it to the mine would require three trailers per day for liquid hydrogen delivery and 25 trailers per day for gaseous hydrogen delivery. Onsite storage capacity of 20–30 tons would be required to provide 2 to 3 days of backup. Production costs for liquid hydrogen would exceed costs for gaseous hydrogen; however, the transportation costs for liquid hydrogen would be lower than for gaseous hydrogen.

Al Burgunder, Director Clean Hydrogen, Linde, "Hydrogen On-Site Supply and Refueling"

Linde is a global company that formed in 2018 with the merger of Linde AG and Praxair, Inc. Linde is involved in all aspects of the hydrogen value chain, including production, processing, distribution, storage, and applications providing integrated offerings.

Mine sites can be considered "mini cities," Mr. Burgunder explained. Hydrogen at the mine site should not only be considered for mobility but also for stationary power generation to support operations. SMR is currently the best option for providing low-cost hydrogen. Alternatively, hydrogen can be produced by electrolysis using technologies such as ITM Linde modular electrolyzer technology.

There are a few hydrogen pipelines across the United States, and hydrogen could be supplied by pipeline; however, it might require additional purification to meet FC purity requirements. Because pipelines provide gaseous hydrogen, small-scale liquefaction systems could be deployed at the mines to provide liquid hydrogen. Mines should consider using delivered liquid hydrogen, said Mr. Burgunder. Liquid hydrogen is readily available and requires onsite storage and dispensing systems but has the smallest capital commitment.

Kyle McKeown, Application Engineering Manager, Nel, "H2 Offroad"

Mr. McKeown stated that the global hydrogen market is expected to grow by a factor of 8 by 2050, with the growth being driven by decarbonization regulations and the electrification of mobility. Reducing the cost of hydrogen is critical for increasing the acceptance of hydrogen, he said.

Electricity accounts for about 70–80% of the cost of hydrogen. As the levelized cost of electricity from wind and solar continues to fall, explained Mr. McKeown, the cost of producing green hydrogen will follow the same path. Green hydrogen is on a trajectory to reach cost parity with hydrogen derived from fossil fuels in the 2025–2030 timeframe.

Nel's target price for green hydrogen is $1.50/kg by 2025. The cost target will be achieved through lower manufacturing costs as production volumes increase, engineering advancements improve the technology, and production costs are reduced through standardization of components. Nel's Herøya factory is fully automated and will have more than 500 MW nameplate production capacity when its expansion is complete, with room to expand to 2 GW of production capacity.

Nel is supplying a 3.5-MW alkaline electrolyzer to produce hydrogen for AngloAmerican's FC-powered mining truck demonstration project in Moglakwena, South Africa. The electrolyzer will produce 1,510 kg of hydrogen per day using electricity from the grid and a local solar farm. If successful, Nel estimates that over 400 mine hauling trucks could be rebuilt to use hydrogen fuel at the mine and more than 10,000 trucks rebuilt globally.

Mr. McKeown explained that challenges for hydrogen infrastructure for off-road applications include the need for vehicle standards such as onboard storage pressure and fueling interface; reducing the capital cost of hydrogen fueling systems, which are higher than liquid fossil fuel–fueling systems; costs associated with the use of grid or off-grid power; and the power connections required. Low- or no-carbon fuel credits will also be required, he said. Agriculture — with its smaller demand — may benefit from smaller production/compression solutions with larger storage (i.e., cascade fueling), whereas mining — with its greater demand — may benefit from large production/compression systems with less storage (direct fueling).

Michael Koonce, President, Bayotech, "Distributed Hydrogen Solutions for Off-Road Equipment and Vehicles"

BayoTech markets distributed hydrogen hubs that produce 1–5 tons of hydrogen per day, providing customers with low-cost and low-/no-carbon hydrogen with less upfront investment. The hub can supply 5–10 hydrogen refueling stations operating at high utilization. The hydrogen generators can use biomethane as a feedstock and can be equipped with CO_2 capture technology.

Bayotech also markets mobile, modular compression and dispensing skids for fast deployment of hydrogen vehicle fueling. Mobile hydrogen dispensing skids are one solution for bringing hydrogen to the mining equipment since mining vehicles are filled at the site and "don't pull into stations." Providing power at the mine is critical.

BayoTech hydrogen generators provide backup power at more than 3,000 cell phone tower sites in the United States. Compared to diesel generators, hydrogen generators produce zero emissions and provide silent operation with no noise, vibration, heat signature, or smell. They also provide longer life, improved reliability, and lower annual maintenance.

Paul Dawson, President and CEO, OneH2, Inc. "Hydrogen Distribution: Lessons Learned"

OneH2 specializes in providing mobile onsite hydrogen generation, typically providing onsite generation as a service rather than selling the equipment.

For refueling light-duty FC vehicles, site space constraints and low demand volumes do not justify investment in onsite hydrogen generation. Hydrogen is produced at centralized locations and delivered as a liquid or gas to refueling stations in a state that is not ready for use or sale as a transportation fuel.

Mr. Dawson explained that additional onsite gas processing is required before it can be sold as a transportation fuel. The gas processing and storage infrastructure at the point of refueling is highly complex, resulting in both high capital cost and downtime rates—which makes investment in refueling stations unattractive to private investors.

In contrast, in the industrial hydrogen market, hydrogen is often delivered to the customer in a "ready to use" state, requiring no further processing at the point of use. Process complexity is centralized at the point of generation, allowing simplified delivery systems at the point of use, which leads to higher capital efficiency and reliability.

Hydrogen demand for even small Class 8 truck fleets can exceed the ability to deliver gaseous hydrogen to the fueling site, said Mr. Dawson. Onsite hydrogen generation is an important component of the future infrastructure needs for a growing Class 8 fleet. Decentralizing fuel generation is important to ensure a robust and redundant hydrogen fueling network.

The process equipment required to produce hydrogen by electrolysis or SMR accounts for more than 60% of the investment in onsite hydrogen generation. Thus, one can begin producing hydrogen using one technology and then recapitalize with a different technology without having to start over. Natural gas is more reliable and costs less than electricity in most U.S. markets. End users are increasingly mixing natural gas with renewable natural gas to achieve an increasing renewable feedstock as well as considering adding CO_2 capture or switching to electrolysis if it makes economic sense.

Mike Peters, Engineer, NREL, "Refueling Processes"

NREL's Innovating Hydrogen Stations Project is a research and industry partnership for an experimentally validated, high-flow-rate fueling model and near-term hydrogen station innovations. This DOE-funded multiyear project is a first-of-a-kind experimental research capability of fueling 60+ kg of hydrogen at a rate of 10 kg/min, which is the DOE Hydrogen Class 8 Long Haul Truck Ultimate Fill Rate Target. It enables comprehensive high flow rate fueling models to be validated with experimental data. Modeling is used to inform decisions with flexible, fast, easy-to-use models being developed to accommodate the different types of medium- and heavy-duty trucks and 3D modeling being used to avoid unsafe conditions, such as hot spots, stratification, etc., during the filling process.

In progress to date, all major equipment has been installed and commissioning is ongoing. Six computational fluid dynamic fills have been completed. H2FillS, the publicly available modeling tool, is being upgraded for heavy-duty applications including improvements in computational speed with multiple tank scenarios.

Conclusions

Attendees indicated that there are numerous opportunities for hydrogen and FC technologies in agriculture, construction, and mining. Hydrogen and FCs currently have several key advantages over batteries for use in agriculture, construction, and mining applications including increased range and payload, higher mission flexibility, shorter refueling times, and lower lifecycle costs.

The attendees also identified challenges for deploying hydrogen and FCs in agriculture, construction, and mining. A major challenge is storing enough hydrogen onboard the vehicles to meet the operating requirements. Although liquid hydrogen provides a higher volumetric energy storage density than gaseous hydrogen, there are concerns that even the higher volumetric energy storage density of liquid hydrogen may not be adequate for some applications.

There are also operational challenges transporting, handling, and storing, including bunkering, liquid hydrogen. Participants indicated that the hydrogen supply infrastructure including the number of liquefaction facilities needs to be increased to meet future demand.

FCs have their own set of challenges. The lower operating temperature of PEM FCs compared to ICEs causes thermal management issues. For example, in construction equipment where ram air is not available for cooling, more fan power and larger radiator sizes are needed for FC systems compared to diesel engine systems to maintain acceptable FC temperatures. Despite these challenges, hydrogen and FCs are some of the most promising routes to decarbonize these hard-to-decarbonize sectors.

Attendees and organizers agreed further discussion and sharing of information on requirements and lessons learned in equipment demonstration projects would further our understanding of the technology gaps, identify collaborative research and development opportunities, and advance the development of FCs and hydrogen in off-road applications.

An ongoing working group has been established by the HFTO to continue the discussion and address the challenges and issues identified in this workshop.

List of Abbreviations

ARPA-E	Advanced Research Projects Agency-Energy
BEV	battery electric vehicle
CAPEX	capital expenditure
CARB	California Air Resources Board
CNG	compressed natural gas
DERA	Diesel Emissions Reduction Act
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EU	European Union
FC	fuel cell
FCD	fuel cell dominant
FCH	fuel cell hybrid
FCS	fuel cell system
FCEV	fuel cell electric vehicle
ft	foot (feet)
gal	gallon(s)
GDP	gross domestic product
GHG	greenhouse gas
GW	gigawatt
h	hour(s)
HDV	heavy-duty vehicle
HFC	hydrogen fuel cell
HFTO	Hydrogen and Fuel Cell Technologies Office
hp	horsepower
ICE	internal combustion engine
kg	kilogram
kW	kilowatt
L	liter
LDV	light-duty vehicles
LNG	liquefied natural gas
MI	Mission Innovation
MMT	million metric tons
MOU	memorandum of understanding
mpg	miles per gallon
MW	megawatt

OEM	original equipment manufacturer
PEM	polymer electrolyte membrane
PEMFC	polymer electrolyte membrane fuel cell
R&D	research and development
RH_2	renewable hydrogen
SOFC	solid oxide fuel cell
SMR	steam methane reforming
TCO	total cost of ownership
tpd	tons per day
U.S.	United States
Wh	Watt-hour
WTW	well-to-wheel
ZEV	zero-emission vehicle

Appendix A: Breakout Group Questions

Breakout #1 (Equipment) Session: Potential Questions

1. What are the FC system performance characteristics that are priorities for agriculture equipment to be accepted by end-users?

   a. Durability
   b. Reliability
   c. Capital equipment cost (FC power system $/kW)
   d. Volumetric power density of the FC system (kW/ft^3 or kW/L)
   e. Thermal management under a wide range of ambient conditions (-20°F to 120°F)
   f. Other (specify in chat)

2. What technical challenges must be overcome to improve the top-priority FC system performance characteristics?

3. What performance characteristics are most important to end-user's FC applications?

   a. Export power capability to run accessories
   b. Towing large, heavy loads relative to vehicle weight
   c. Operation of vehicles over extreme and variable topographies, including operation while towing large, heavy loads
   d. Ability to be serviced locally
   e. Exhaust water usage
   f. Other (specify in chat)

4. How much onboard fuel is necessary for typical agricultural applications (gge or dge)?

5. What are the most attractive potential opportunities for deploying hydrogen FC equipment?

6. For both FC equipment and onboard hydrogen energy storage applications, what specific R&D should government agencies be funding, through industry-government agreements, or the private industry? What are the priority technical needs?

Breakout #2 (Hydrogen) Session: Potential Questions

1. What are the major technical and economic challenges to deploying hydrogen fueling infrastructures for agriculture end users?
2. Do you envision hydrogen being generated onsite or being delivered to end-use sites?
3. What are technical challenges to generating hydrogen on-site or delivering hydrogen to the end-use site?
4. How often is refueling necessary?
5. Is refueling typically conducted in the field or at the local farm station (barn)?
6. Do you envision that renewable hydrogen (RH_2) production could be an opportunity for new revenue for farmers as producers of feedstocks that can be converted into RH_2 fuel?
7. As cars and trucks in the US transition from ICE drivetrains to zero-emission electric drivetrains, can RH_{H2} produced from agriculture feedstocks be a potential revenue source?
8. What fueling infrastructure characteristics are most important to end-user's FC applications?
    a. Making fuel onsite or at nearby hub sites developed and operated by co-operatives
    b. Ability to use co-operatives to scale up hydrogen demand
    c. The ability to refuel where the equipment is used
    d. The amount of time to refuel
    e. Storing the volume of hydrogen required to meet the desired refueling interval
    f. The ability to park equipment without hydrogen loss
    g. Other (specify in chat)
9. What are the types of safety processes and standards needed to support an agricultural operation?
10. What specific R&D should government agencies be funding, through industry-government agreements, or the private industry? What are the priority technical needs?
11. What technical and performance characteristics will end users need to see before they consider trials or adoption of FC and hydrogen infrastructure technologies?

Appendix B: Breakout Sessions

The workshop had several breakout sessions, during which the participants provided their insights and expertise. The discussion was guided by the questions provided (see Appendix A) and the Workshop Agenda.

Breakout Session #1: Equipment Development

Agriculture

Q1. What are the FC system performance characteristics that are priorities for agricultural equipment to be accepted by end users?

a. Durability

b. Reliability

c. Capital equipment cost (FC power system \$/kW)

d. Volumetric power density of the FC system (kW/ft^3 or kW/L)

e. Thermal management under a wide range of ambient conditions (-20°F to 120°F)

f. Other

- The participants indicated that the priorities are cost, thermal management, hydrogen storage volumetric energy density, FC durability, cooling, and the availability of refueling infrastructure.
- At present, FC drivetrain costs are much greater than diesel drivetrain, mainly due to low FC production volumes.
- Hydrogen fuel costs are about 4–5 times that of diesel costs on a \$/kWh basis. If the DOE FC system and storage targets are reached, then cost for the FC system can achieve parity with diesel.
- Durability, reliability (i.e., mean time between failure), efficiency, and ease of use are main drivers for farmers. FC equipment needs to match or exceed diesel equipment in these areas.
- Agriculture equipment operates over a wide variety of topographies on unpaved surfaces that cause shock and vibration. The equipment must operate over extreme weather conditions and duty cycles (daily and seasonal). FC equipment must be durable enough to withstand operation in these conditions Target lifetimes of 10,000 hours (time to engine retrofit) for tractors and 20,000 hours for harvesters are appropriate. Development of durable materials capable of operating at higher temperatures is key to achieving the targets.
- Hydrogen storage and refueling are priorities. Agricultural equipment uses vary, so the onboard hydrogen storage needs vary from about 4 kg for an 80-kW tractor used 4 h/day to ~110 kg for a 300-kW tractor used 12 h/day. Agriculture equipment often operates 16–24 h/day under 85–100% load. Storing this much hydrogen on the vehicle is difficult, as packaging space is very limited and very defined in a tractor. A redesign of the vehicle may be necessary to increase packaging space.

Cheaper hydrogen storage technology may also be needed going forward – even if future DOE cost targets are achieved.

Q2. What technical challenges must be overcome to improve the top-priority FC system performance characteristics?

- Attendees indicated that the main challenges are hydrogen storage volumetric energy density, FC durability, and cooling. Replacing a 647-L diesel tank with hydrogen storage is a challenge, as even liquid hydrogen would be ~7 times larger volume than a diesel fuel storage system. Packaging space is very limited and very defined on a tractor. A redesign of the vehicle to increase packaging space may be needed. An increase in FC volumetric power density while increasing efficiency is key (rated at higher efficiency points, e.g., 0,7 V/cell).

- Thermal management is also a challenge. A 300-kW FC system would require a radiator with **5 times** greater heat rejection capacity than is currently available. Potential solutions include adding more radiators although packaging space is very limited, increasing fan power which comes at the expense of increasing the parasitic power load, and increasing the stack operating temperature from 80°C today to 105°C while maintaining lifetime targets. Some attendees indicated that using evaporative water for cooling may also be beneficial.

- Durability is another challenge. Participants indicated that a 10,000-hour lifetime (time to engine retrofit) is needed for tractors and a 20,000-hour lifetime is needed for harvesters. Durability needs to encompass a wide variation in duty cycles — both daily and seasonal. Lifetime estimates of FC systems in agriculture will be impacted by longer operation at higher temperatures. Lifetime can be engineered into the system, but with higher costs. Development of durable materials operating at higher temperatures is key to achieve the targets.

Q3. What performance characteristics are most important to end-users' FC applications?

a. Export power capability to run accessories

b. Towing large, heavy loads relative to vehicle weight

c. Operation of vehicles over extreme and variable topographies, including operation while towing large, heavy loads

d. Ability to be serviced locally

e. Exhaust water usage

f. Other (specify in chat)

- Participants indicated that it is important to be able to refuel the machine in the field so that you do not need to go back to a central depot to refuel.

- Durability and ruggedness of the machine was also an important characteristic, as the equipment needs to operate over variable topographies in potentially extreme weather conditions. In addition, shock and vibration from operating in the field on unpaved, debris-riddled surfaces can be extreme.

- Attendees expressed some concern about cooling and indicated that current fan power would not be sufficient for a FC drivetrain and that larger fans and/or radiators would be needed.

- Air quality was also mentioned as a concern. The potentially dusty, debris-laden air could impact both the cooling system and FC performance.
- Some participants indicated that emergency use of FCs as back-up power generator is important.
- Attendees indicated that service technician training would be important (at dealer or farm).

Q4. How much onboard fuel is necessary for typical agricultural applications (gallon of gasoline equivalent or diesel gallon equivalent)?

- Large diesel tractors are typically refueled twice per 16–24 hour day. Similar operation should be targeted for FC tractors.
- Onboard hydrogen storage for a FC tractor is expected to range from 4 kg for an 80-kW tractor operating ~4 hours/day to 110 kg for a 300-kW tractor operating ~12 hours/day.

Q5. What are the most attractive potential opportunities for deploying hydrogen FC equipment?

- Today's level of FC and onboard storage technology could support small tractors in the 50–100 kW size range. These tractors are typically used on small farms as utility tractors and have low energy use.
- Packaging challenges are expected to be lowest here due to the low daily energy use.
- Participants thought batteries would not be sufficient for midsize tractors in the 100–200 kW range typically used for dairy and livestock and on small to medium sized farms.
- Hydrogen was most interesting for the large tractors in the 200–450 kW and above range. These tractors have a high energy use and are typically used for crop farming on large farms.

Q6. For both FC equipment and onboard hydrogen energy storage applications, what specific R&D should government agencies be funding, through industry-government agreements, or the private industry? What are the priority technical needs?

Chat and Discussion Highlights

Agriculture Equipment OEM session:

- Governments should fund technology projects to reduce the cost and increase the energy density of hydrogen storage systems, reduce FC system cost, increase efficiency and volumetric power density, and to enable operation of FC systems at higher temperatures continuously. Governments should support the buildup of the infrastructure required to produce hydrogen at farms OR have a distribution network for other applications (e.g., hydrogen ICEs) that can be used for farms.
- More refined TCO analysis is needed, because there were substantial differences in cost assumptions between the preliminary TCO analysis presented in Session I and the data reported during the Agriculture Equipment OEM session.
- Modeling and simulation of hybrid battery – hydrogen FC electric drivetrains should be pursued for a selected range of tractors and duty cycles with a goal to optimize battery–FC–hydrogen storage for a range of duty cycles.

Construction

Q1. What are the FC system performance characteristics that are priorities for construction equipment to be accepted by end users?

a. Durability

b. Reliability

c. Capital equipment cost (FC power system $/kW)

d. Volumetric power density of the FC system (kW/ft^3 or kW/L)

e. Thermal management under a wide range of ambient conditions (-20°F to 120°F)

f. Other

- Attendees indicated that all the mentioned characteristics, i.e., capital cost, durability, thermal management, and power density, are priorities.
- Some indicated that they thought capital cost has been replaced by TCO and that TCO is the most important metric. Others indicated TCO is strongly tied to durability and the duty cycle, and that the use cases for small equipment are different than for large equipment. In small and medium construction equipment, the durability requirement is not as high as for large equipment such as that used in mining. In addition, some companies sell equipment off after ~3 years to resale, and this should be considered in TCO calculations.
- Some indicated that they think everything other than hydrogen storage density can be solved, and that operators may have to rethink how they operate and refuel more often.
- Construction equipment needs to work in a wide range of climates, from the Middle East where 60°C ambient is common to Canada and other areas where -40°C is common.
- Some indicated that they were surprised by the amount of additional cooling needed for FC equipment and indicated added cooling could impact visibility for the machine. Others mentioned suppliers are increasing the operating temperature of their FCs, which will reduce the heat rejection and packaging issues.
- Attendees indicated that there is an order of magnitude more variability in duty cycles for off-road equipment than for on-road and that more work needs to be done between FC developers and off-road equipment developers.
- Attendees discussed the importance of reselling of equipment in the construction market.

Q2. What technical challenges must be overcome to improve the FC system performance?

- Degradation and thermal management were identified as areas that need improvement.
- FCs age and performance decreases substantially while performance from diesel engines over time is more constant.

- Thermal management is also a concern. Construction equipment operates with little or no ram-air, making this a greater problem than for on-road vehicles. Increasing the operating temperature can help, but the power density of current high temperature PEM is too low. Materials development is needed to enable higher temperature operation.

- Varied terrain.

- Very good diagnostics that inform maintenance and workforce development.

Q3. What performance characteristics are most important?

- Some respondents indicated that reduction in CO_2 emissions was the most important characteristic, especially in Europe, where there will be a carbon tax and penalties for CO_2 emissions in CO_2-free zones in some cities such as London, which has requirements for zero emissions by 2040.

- Others indicated that the driver/operator experience is important, and their feedback for low noise/silent operation and low vibrations is a positive.

- Some attendees indicated that the ability to operate over extreme and variable topographies with large amounts of dust, dirt, water, snow, and ice present is very important for construction equipment. Dust and dirt can be a problem for the FC and thermal management.

- Some attendees questioned the ability of FCs to meet the dynamic load and transient power demands and wondered about the hydraulic versus electric actuation of implements and tools on the machine.

- Discussion noted that counterbalance is an issue for specific machine types but is not an across the board issue.

Q4. How much onboard fuel is necessary for typical construction applications (gallon of gasoline equivalent or diesel gallon equivalent)?

- Attendees indicated that the run time for construction equipment varies from about 4 to 12 hours/day. Some suggested the target should be 12 hours of runtime, but that 8 hours would be acceptable. The threshold for operation of FC equipment would be 4 hours between refueling. Others thought that it would vary greatly between types of construction equipment and the range is too broad to make this a useful question.

- Participants indicated that how you refuel the equipment is important. Some machines can return to a central refueling location, but other machines cannot, and fuel will have to be brought to the machine to refuel it.

- Nozzle design for on-road applications may not be sufficient in the dirty/dusty construction environment.

Q5. What are the most attractive applications?

- Attendees indicated that applications such as a port or airport where equipment moves around a central location would be most attractive. An example provided was snow removal at an airport.

- City center operations where there are regulations against carbon emissions were also mentioned as attractive.

- Size was mentioned as a differentiator, with medium-sized equipment thought to be the most attractive. The smallest equipment may be able to be served by batteries, while the largest equipment may need technical breakthroughs.

Q6. What specific R&D should governments be funding?

- Attendees indicated that field demonstrations, R&D for energy storage, materials development to enable higher temperature operation, coolant systems, and thermal management should be areas for government funding.

- Other areas attendees thought governments should also fund development of regulations and codes and standards.

- User-friendly liquid hydrogen refueling systems were also identified as an area where government funding could be beneficial.

- Supply chain availability (DC-DC converters, motors, filling nozzles) was also mentioned.

Mining

Q1. What are the FC system performance characteristics that are priorities for mining equipment to be accepted by end-users?

a. Durability

b. Reliability

c. Capital equipment cost (FC power system $/kW)

d. Volumetric power density of the FC system (kW/ft3 or kW/L)

e. Thermal management under a wide range of ambient conditions (-20°F to 120°F)

f. Other (specify in chat)

- Durability at least through the warranty period and targeting 20,000 hours. Equivalent to the ICE with a mid-life maintenance overhaul for diesel at 20,000–30,000 hours, frame durability of 40,000–80,000 hours, and component durability of 8,000–15,000 hours.

- Reliability must address shock and vibrations experienced in normal operations. FC must be able to maintain 55% efficiency over lifetime.

- FC modules should be standardized for multiple applications to help lower capital equipment cost.

- Volumetric power density of the FC system must be similar to that of the diesel engine because of space and productivity constraints. May have to oversize the FC to address lifetime degradation.

- Must consider the hydrogen fuel load required to meet performance requirements. Issues associated with FC can be addressed but storing sufficient fuel onboard will be a challenge.

- There is a need for servie trained personnel and the ability to access spare parts.

Q2. What technical challenges must be overcome to improve the FC system performance characteristics?

- Mining environment is a challenge. Equipment must be able to operate in dusty environment. Fuel cell systems must have the ability to operate on constantly changing elevations and slopes.
- Developing air filters is a challenge. Must be able to remove not only dust particles from the air but also requires removing emissions associated with the operation of legacy diesel equipment.
- For underground mining, safety issues associated with the use of hydrogen in an enclosed environment must be addressed. A game changer would be a new fuel for use in underground applications that would result in less demanding ventilation requirements than are required for use of diesel fuel.
- No response time issues. Hybridization of the FC with a battery does not help.
- Need to oversize the FC to get higher efficiency.
- Large FC-powered trucks provide an opportunity for recovering regenerative braking energy, which can reduce the amount of hydrogen stored onboard to meet operation requirements.

Q3. What performance characteristics are most important to end users' FC applications?

- It is very disruptive for equipment to have to leave the mine for refueling. Fueling is currently done at the top of the mine.

Q4. How much onboard fuel is necessary for typical mining applications (gallon of gasoline equivalent or diesel gallon equivalent)?

- The equipment must have enough hydrogen to return to the fueling location and should not require more than one or two fuelings per day.

Q5. What are the most attractive potential equipment use cases for deploying hydrogen FC equipment?

- Depends on the individual mine and mining use, and will differ from mine to mine. For example, a coal mine will have different demands than a copper mine. Some mines can operate using a trolley system, while other mines cannot. Identify mines where using hydrogen FCs is a good fit.
- Capital cost is a concern with larger FC trucks demanding more hydrogen. Larger sizes decrease all costs.
- Must consider the cost and benefits for retrofitting diesel equipment with hydrogen and FCs compared to buying new hydrogen FC equipment. Whether or not to retrofit depends on the TCO, but at what cost retrofitting is unfavorable is unknown.

Q6. For both FC equipment and onboard hydrogen energy storage applications, what specific R&D should government agencies be funding, through industry-government agreements, or the private industry? What are the priority technical needs?

- R&D efforts should focus on hybridization of the FC system with a battery. However, running the battery at high discharge rates will reduce battery lifetime leading to more battery replacement, maintenance, and disposal costs.

- Hydrogen production at the mine is going to drive deployment of FC technology. FC mining equipment will quickly follow if hydrogen is available at the mine.
- Hydrogen storage options for large equipment. You cannot stop a haulage truck every 2 hours to refuel.
- Identify 3–4 mines located close to liquid hydrogen supplies in the United States and do demonstration projects at those mines.

Breakout Session #2: Hydrogen Production and Refueling

Agriculture

Q1. What are the types of safety processes and standards needed to support an agricultural operation?

- DOE HFTO plans to conduct a webinar or virtual workshop that will focus on hydrogen safety codes and standards for the heavy-duty off road market sectors.

Q2. What are the major technical and economic challenges to deploying hydrogen fueling infrastructures for agriculture end-users?

- The economics are a major challenge. Hydrogen fuel systems a have higher capital cost than liquid fossil fuel systems. Deploying hydrogen at a farm has a very high investment cost, with capital costs on the order of $1,200–$3,000 US per kg of hydrogen dispensed daily, which is likely too expensive for small to medium farms. Renewable electricity infrastructure may add additional investment requirements if renewable electricity cannot be supplied by the grid. Making the business case is difficult in the absence of incentives. Cost reduction is key.

- The availability of a hydrogen refueling infrastructure is also a challenge. For a 9.0-L diesel engine (~300 kW) tractor operating at 35% load over a 10-hour duty cycle, some have estimated that you would need to refuel a hydrogen tractor 10 times as often as a diesel tractor and at fuel cost for hydrogen that is 4–5 times higher than diesel on a $/kWh basis.

- Vehicle standards for hydrogen-fueled agricultural equipment are absent (e.g., hydrogen storage pressure, fueling interface). Agriculture may benefit from smaller production/compression solutions with larger storage capacity than on-road hydrogen FC vehicle applications (cascade fueling pathways).

Q3. Do you envision hydrogen being generated on-site or being delivered to end-use sites? What are technical challenges to generating hydrogen on-site or delivering hydrogen to the end-use site?

- Depending on size and location, the hydrogen may be generated onsite or delivered.

Q4. How often is refueling necessary? Is refueling typically conducted in the field or at the local farm station (barn)?

- Tractors are typically refueled in the field.

Q5. Do you envision that renewable hydrogen (RH_2) production could be an opportunity for new revenue for farmers as producers of feedstocks that can be converted into RH_2 fuel? As cars and trucks in the United States transition from ICE drivetrains to zero-emission electric drivetrains, can RH_2 produced from agriculture feedstocks be a potential revenue source?

- The zero-emission vehicle legislative policies and related global climate change policies in many global markets are ramping up the adoption of zero-emission electric vehicle technologies to replace fossil fuels. The transition to electric drivetrains represents a risk to corn crop revenues in the United States associated with the 10–15% blending of corn-derived ethanol into gasoline fuel for light-duty cars and trucks.

- Small “hydrogen hubs” are available today that could be a potential solution for the agriculture market with hydrogen produced at your site or delivered on demand. They should be able to supply

5–10 hydrogen refueling stations operating at high utilization. A distributed network would allow for capacity coverage. Low- to zero-carbon hydrogen generators can use biomethane derived from biogas as a feedstock. This could be a potential opportunity for the agriculture market at $6/kg delivered cost.

Q6. What fueling infrastructure characteristics are most important to end-user's FC applications?

a. Making fuel on-site or at nearby hub sites developed and operated by agriculture co-operatives

b. Ability to use co-operatives to scale up hydrogen demand

c. The ability to refuel where the equipment is used

d. The amount of time to refuel

e. Storing the volume of hydrogen required to meet the desired refueling interval

f. The ability to park equipment without hydrogen loss

g. Other (specify in chat)

- High refueling rates are important to the agricultural sector. It is not clear if the DOE heavy-duty FC truck hydrogen fill rate 2030 target of 8 kg H_2/min by 2030 and the ultimate target of 10 kg H_2/min is relevant to agriculture equipment.

- Small hydrogen hubs able to supply 5–10 hydrogen refueling stations operating at high utilization are available today that could offer potential for the agriculture market. Hydrogen could be produced at the agricultural site or delivered on demand. A distributed network allows for capacity coverage.

- Low- to zero-carbon hydrogen generators can use biomethane, derived from biogas, as feedstock. This provides a potential opportunity for the agriculture market at $6/kg delivered cost.

Q7. What specific R&D should government agencies be funding, through industry-government agreements, or the private industry? What are the priority technical needs? What technical and performance characteristics will end users need to see before they consider trials or adoption of FC and hydrogen infrastructure technologies?

- Participants recommended funding technology projects to support the buildup of the infrastructure required to produce hydrogen at farms or the development of a hydrogen distribution network for other applications such as hydrogen ICEs that can be deployed at farms.

Construction

Q1. What are the major technical and economic challenges to deploying hydrogen fueling infrastructures for construction end users?

- Attendees replied that high-rate fueling and mobile refueling are major challenges.

- Refueling at a construction site appears difficult with current permitting and certification requirements for grounding systems, setback distances, leak detection, etc.

- Dirt and dust tolerance were also mentioned as technical challenges.
- Delivery and storage of the large quantities of hydrogen that may be required onsite is a challenge.
- There are a lot of small operators in construction and democratizing access to this technology and ensuring small operators have access is a challenge.

Q2. Do you envision hydrogen being generated onsite or being delivered to end-use sites?

- Hydrogen delivery onsite may be the best option, except for very large sites. A boost compressor may be needed onsite to get high pressures and adequate storage on the vehicles if gaseous hydrogen is used.

Q3. What are the technical challenges for generating hydrogen onsite?

- Finding the footprint needed for onsite generation at a construction site is a challenge, and construction sites are temporary, so the hydrogen generation equipment would likely need to be mobile. It is possible to use the grid; however, the electrical infrastructure needs to be able to handle what may be a high demand to generate sufficient hydrogen onsite, and a clean water supply is needed.

Q4. How often is refueling necessary?

- Attendees indicated fueling is usually done once a shift (8–12 hours).

Q5. What fueling infrastructure characteristics are most important to end users' FC applications (for both gaseous and liquid hydrogen)?

- Attendees stated that for construction, the fuel almost needs to be liquid hydrogen.
- Refueling where the equipment is used, rather than taking the equipment to a central refueling location, is important.
- Currently, fuel is delivered from a central location to the equipment by a fuel bowser. Liquid hydrogen may make this mode of refueling easier.
- Storing the amount of fuel needed both at the construction site and on the vehicle is a challenge. Liquid hydrogen would reduce this somewhat and allow for faster refueling times than gaseous hydrogen.
- Refueling time is important and a refueling time of 8–10 minutes is desired. Some expressed concerns about boil-off losses if onboard liquid hydrogen storage is used, while others believed boil-off losses will be manageable and dormancy of several days could be achieved with current technology. Active cooling may be possible to limit or prevent losses.
- To refuel with hydrogen on-site, companies will need to work with local fire departments.

Q6. What are the types of safety processes and standards needed to support a construction operation?

- Standards and regulations for hydrogen in construction currently do not exist, which is a real barrier to entry.
- It is difficult to determine what codes and standards apply and need to be met.

- A streamlined method or tool to identify the applicable codes and standards would be helpful.
- Without national codes and standards, local permitting is more difficult.
- Educating local authorities would be beneficial.

Q7. What specific R&D should government agencies be funding, through industry-government cost-shared agreements, or the private industry? What are the priority technical needs?

- A requirements analysis with construction operators and FC and hydrogen producers should be funded.
- A demonstration on a construction site using liquid hydrogen should be a priority. There was a discussion about the different scales of construction sites and equipment and whether smaller or larger equipment would be better for a demonstration. A medium 7–9 ton excavator, 75–175 hp, is an interesting break point in equipment. A 10–24 ton excavator is more common.
- A demonstration at an urban construction site where noise and diesel emissions are most problematic, particularly a site in a city considering banning internal combustion engines within the city limits.
- It was pointed out that there is a big gap between component development and vehicle level and infrastructure development and that the implementation of hydrogen equipment and infrastructure is lagging the technology. Governments need to continue to express their interest in developing hydrogen infrastructure. Workforce development and training for equipment operators was also identified as a gap.

Q8. What technical and performance information will users need to see before they consider trials or adoption of FC and hydrogen technologies?

- Participants indicated that a full project TCO analysis would be needed for users to consider adopting FCs and hydrogen for construction equipment. An analysis of a full construction project or site using hydrogen is also needed. We need to understand the infrastructure for the whole site, not just one piece of equipment, and how it compares to the infrastructure required for BEVs on the site and understand the limits of battery and FCs.

Mining

Q1. What are the major technical and economic challenges to deploying hydrogen fueling infrastructures for mining end users?

- Infrastructure and fueling costs are challenging.
- Chile is an example of a location that has favorable solar conditions and large spaces are available at the mine that justify co-locating a hydrogen plant at a mine, or one centrally located to service three or four mines. However, these conditions are not uniform across the world.
- Technical challenges are well known, but until we do it, we do not know how to meet the economic needs of the end user.
- Challenges and problems that are common to most, if not all, mining operations should be addressed by collaborative R&D followed by demonstrations. Perhaps an international agreement

to do a demonstration. Suggest an approach similar to what the U.S. semiconductor industry established for collaborative R&D in the 1990s.

- Standardization is needed in many sectors of the hydrogen value chain to replicate equipment and systems from mine to mine.

- In large, open-pit mines, such as in operation in Chile, the concern is how to supply hydrogen to fuel large mining trucks. In the early stages of deployment, the hydrogen fueling must coexist with petroleum fueling. The hydrogen fueling system must be able to relocate as the mine site layout evolves over time. Differences in the safety culture between fueling with petroleum and fueling with hydrogen must be addressed.

- Cost of electricity across the globe. NEL's target is $20/MWh. U.S. residential price is roughly $110/MWh. How will NEL meet its target? Large power purchase price agreements need to address the differences.

- Mines are mini-cities, for example, nickel mines in western Australia. The choice between electrolysis or SMR depends on the mine lifetime. If the mine lifetime is 15–20 years, then the operation is permanently sited; however, it the lifetime is 5–10 years, the operation must be mobile to be cost-effective.

- Fueling locations are generally located near the crusher and away from the mine pit. Mobile refueling capable of delivering 500 kg of gaseous hydrogen per day is needed. Fueling rates need to increase, if not, multiple fueling locations would be needed to be cost-effective.

- Hydrogen would move faster in the mining industry if they had a hydrogen solution and the ability to do refueling similar in all aspects to how diesel refueling is done today.

Q2. Do you envision hydrogen being generated on-site or being delivered to end-use sites? For onsite generation what are the challenges regarding:

   a. Adequate power production

   b. Water availability

- This question was not addressed due to time limitations.

Q3. What are technical challenges to generating hydrogen on-site or delivering hydrogen to the end-use site?

- Technical challenges are known but until we do it, we will not know how to meet the economic needs of the end user.

- Finding skilled labor especially at remote mines will be a major challenge.

- Try to leverage lessons learned from companies that have already made investments in hydrogen and FC technology.

Q4. How much bulk hydrogen fuel needs to be stored on site for typical operations?

- This question was not addressed due to time limitations.

Q5. How often is refueling necessary?

- Time required for refueling is critical for production machinery.

Q6. What fueling infrastructure characteristics are most important to end user's FC applications?

a. The ability to refuel where the equipment is used

b. The amount of time to refuel

c. The ability to park equipment without hydrogen loss

d. Other (specify in Chat)

- Hydrogen and FC technology would be deployed faster in the mining industry if there was a solution to the hydrogen fueling infrastructure and the ability to do refueling similar in all aspects as diesel is done today.

Q7. What are the types of safety processes and standards needed to support a surface mining operation?

- This question was not addressed due to time limitations.

Q8. What specific R&D should government agencies be funding, through industry-government cost-shared agreements, or the private industry? What are the priority technical needs?

- This question was not addressed due to time limitations.

Q9. What technical and performance information will users need to see before they consider trials or adoption of FC and hydrogen technologies?

- Safety – Need to assess and understand all hazards associated with the use of hydrogen.
- De-risking the entire hydrogen value chain. There are open issues all along the hydrogen value chain. There is a lot of nervousness. Need to make sure all aspects of the hydrogen value chain would work, not just one aspect.
- Success in heavy-duty trucking would bring a degree of confidence to other heavy-duty applications.

Appendix C: Workshop Agenda

Mission Innovation Hydrogen Fuel Cell

Off-Road Equipment and Vehicles

Virtual Workshop Agenda

September 22–24, 2021

Virtual Workshop powered by Zoom – All times are given in Eastern Time

Workshop Introduction and Objectives

Government and industry technology developers world-wide are realizing the potential for hydrogen heavy-duty, off road applications including fuel cells for agriculture, construction, and mining equipment. This workshop will help identify needed research to accelerate technology development and address barriers to industry commercialization.

This workshop is being hosted by the U.S. Department of Energy. We welcome workshop participants and look forward to exploring opportunities for cooperation and collaboration on agriculture, construction, and mining equipment areas of interest.

The objectives of this workshop are to:

- Assess the state of the art for heavy-duty applications specifically using hydrogen fuel cells for agriculture, construction, and mining equipment
- Discuss operational requirements and lessons learned on early equipment demonstration projects for agriculture, construction, and mining
- Understand current technology gaps and identify collaborative R&D opportunities
- Identify refueling infrastructure challenges

Wednesday, September 22 | Day 1

Session I – Perspectives on Hydrogen for Mining, Construction and Agriculture Applications

(Session Moderator – Pete Devlin)

1:00 PM Mission Innovation: Clean Hydrogen Mission Opening Remarks

Matthijs Soede, MI 2.0 Clean Hydrogen Mission Director, European Commission

1:05 PM U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office

Sunita Satyapal, Director

Pete Devlin, Technology Acceleration, Development Manager

1:15 PM Ministry of Energy of Chile

Max Correa, Head for Fuels and New Energy Carriers Division

1:30 PM Australian Renewable Energy Agency

Matt Walden, Investment Director

1:45 PM U.S. Department of Agriculture

Mark Brodziski, Deputy Administrator for Rural Business-Cooperative Service

2:00 PM U.S. Environmental Protection Agency

Britney J. McCoy, Center Director, Climate Analysis and Strategies Center, Office of Transportation and Air Quality

2:15 PM California Air Resources Board

William Robertson, Vehicle Program Specialist

2:30 PM Association of Equipment Manufacturers

Curt Blades, Senior Vice President

2:45 PM ANL – Preliminary Equipment TCOs

Rajesh Ahluwalia, Group Leader for Engineering and Systems Analysis

3:15 PM **Break**

Session II – Agriculture Equipment

(Session Moderator – Greg Moreland)

3:30 PM John Deere

Mike Duffield, Module Lead - Energy Storage

3:45 PM CNH Industrial

William Resende, Manager Electrified PWT Fuel Cell Engineering

4:00 PM **AGCO**

Ismo Hamalainen, R&D Manager of AGCO Power, Finland

4:15 PM Schmuecker Renewable Energy System

Jay Schmuecker, President

4:30 PM Day 1 Feedback & Adjourn

Thursday, September 23 | Day 2

Session III – Construction Equipment

(Session Moderator – Ben Gould)

10:00 AM Caterpillar

Brian Lowry, Engineering Manager

10:15 AM Komatsu

Michael Lewis, Technical Director – Technology

10:30 AM **Prinoth**

Martin Kirchmair, Technical Director

10:45 AM **Break**

Session IV – Mining and Loader Equipment

(Session Moderator – Fernanda Stegmaier Fernandez)

12:30 PM Komatsu

Michael Lewis, Technical Director – Technology

12:45 PM **Volvo**

Ray Gallant, Vice President Product Management and Productivity

1:00 PM Anglo American

Julian Soles, Head of Technology Development Mining & Sustainability at Anglo American

1:15 PM McKinsey & Company – TCO Analysis for Hydrogen FCs in Mining Applications

Clemens Müller-Falcke, Partner

1:30 PM **Break**

Session V – Fuel Cell Developers

(Session Moderator – Greg Moreland)

1:45 PM Cummins

Ryan Sookhoo, Director New Initiatives

2:00 PM **Ballard**

Tim Sasseen, Market Development Manager, US

2:15 PM **Nuvera**

Gus Block, Director of Marketing and Corporate Development

2:30 PM Plug Power

Rick Mason, Vice President of Business Development and Product Management

2:45 PM PowerCell

Johan Burgren, Business Manager

3:00 PM Breakout Sessions, Equipment Development

- Integrated equipment and power system development.
- Shock/vibration, air filtration, heat management.

4:00 PM Breakout sessions report out

4:30 PM Adjourn

Friday, September 24| Day 3

Session VI – Hydrogen Onsite Production and Refueling

(Session Moderator – Greg Moreland)

10:00 AM Air Liquide

Dave Edwards, Director and Advocate for Hydrogen Energy

10:15 AM Linde

Al Burgunder, Director Clean Hydrogen

10:30 AM **Nel**

Kyle McKeown, Application Engineering Manager

10:45 AM BayoTech

Michael Koonce, President

11:00 AM OneH2 (biogas)

Paul Dawson, CEO

11:15 PM NREL – Refueling Processes

Mike Peters, Engineer

11:30 AM	**Break**
12:00 PM	Breakout Sessions Hydrogen Production and Refueling - Refueling logistics, processes - Hydrogen production
1:00 PM	Breakout Sessions Report Out
1:30 PM	Concluding Remarks
1:45 PM	**Adjourn**

Appendix D: Speaker Bios

Dr. Rajesh Ahluwalia – Group Leader for Engineering and Systems Analysis, Argonne National Laboratory

Dr. Rajesh Ahluwalia manages the Fuel Cell and Hydrogen group in Argonne National Laboratory's Energy Systems division. He is a co-developer of GCTool (General Computational Toolkit), a software package that helps design, analyze, and optimize automotive and stationary distributed FC power generation systems, as well as other power-plant configurations.

Curt Blades – Association of Equipment Manufacturers

Curt Blades is the Senior Vice President at the Association of Equipment Manufacturers. In this role he leads the non-road equipment associations efforts in sustainability, regulatory affairs, safety, and global product leadership. In addition, he oversees the organizations' effort to support the North American agriculture equipment manufacturers and the agriculture industry. Curt is a farm kid from Missouri with a passion for agriculture and the innovation that continues to transform the world.

Gus Block – Director of Marketing and Corporate Development, Nuvera

Gus Block is a founding member of Nuvera Fuel Cells, a company established in 2000 to provide hydrogen and FC solutions for on- and off-road vehicles. His focus at Nuvera is on developing FC markets for medium- and heavy-duty transport applications.

Mark Brodziski – Deputy Administrator for Fural Business-Cooperative Service, U.S. Department of Agriculture

Mark Brodziski is serving as Deputy Administrator at USDA Rural Development's Rural Business-Cooperative Service. In this role, Mr. Brodziski oversees a portfolio of grant, loan, and loan guarantee programs that spur economic development, support creation of rural jobs, and improve the quality of life throughout rural America.

Johan Burgren – Powercell

Johan has over 20 years' experience in marine sales and development of maritime technology and possesses a high level of experience in service solution development. Throughout the years he has developed a broad network in the marine industry and industrial OEM marketplace.

Al Burgunder – Director of Clean Hydrogen, Linde

Al Burgunder is the Director of Clean Hydrogen Markets in the United States and a contributing member of Linde's Global Clean Hydrogen organization. Al has had a variety of management responsibilities in the Industrial Gas Industry during the past 25 years. His primary interests have been new market developments, plant operations, and growing Linde's Merchant Hydrogen Business. Al started his career with BOC Gases, transitioned to Praxair, Inc., and now works for Linde PLC, the result of the Linde AG and Praxair, Inc., merger in 2019. Al's current mission is to help drive the transition of mobility markets, stationary power generation, and technology markets to deploying zero-emission propulsion and power generation. Al possesses a BS in Aerospace Engineering and an MBA from Carnegie Mellon University.

Max Correa – Head for Fuels and New Energy Carriers Division, Ministry of Energy of Chile

Max is currently the Head of the Fuels and New Energy Division at the Ministry of Energy, Chile. His division is comprised of three units: Hydrocarbons, Wood Fuels, and New Energy, the latter responsible for promoting the development of a green hydrogen industry in the country. Before joining the Ministry of Energy, Max served as the Executive Director of the Solar and Energy Innovation Committee at the Chilean Economic Development Agency, Corfo. During his tenure, the Committee's work has been largely focused on increasing international collaboration and on the promotion of green hydrogen and other energy innovations as critical elements of Chile's energy transition.

Max previously worked at Corfo as Deputy Director of Strategy and Sustainability, supporting the Executive Vice President in defining and implementing the institutional strategy, and providing prospective and exploratory information to identify upcoming trends. During this period, Max led a team to draft and promote the creation of the largest technological institute ever created in Chile—the Clean Technologies Institute—which will have a strong industrial focus on development, scaling, and adoption of technological solutions in solar energy, low-emissions mining, and advanced materials derived from lithium and other minerals. The Institute will receive a public subsidy of up to US$190 million with an additional 30% of the total budget to be financed by the private sector. Prior to Corfo, Max worked as General Counsel and Chief Compliance Officer at Andes Iron, an iron ore mining company that owns two world-class IOCG Ore Deposits along the Andes Coastal Range. His experience also includes working as an associate to the Energy and Corporate Group of Chile's largest full-service law firm, Carey & Co.

Max is on the Board of Directors of the Chilean Natural Resources Information Centre, CIREN (part of the Ministry of Agriculture) and as City Councilor for the Municipality of Zapallar; a well preserved seaside area in central Chile. He also contributes to several conservation initiatives, most notably to Corporación Bosques de Zapallar (http://bosquesdezapallar.cl/), Chile's first Land Trust devoted to preserve a unique Mediterranean forest located in the country's central coast. Max graduated from Universidad de Chile, Faculty of Law and holds an MPhil in Environmental Policy, Department of Land Economy, from Cambridge University in the UK and undertook a Certificate Program in Innovation and Entrepreneurship at Stanford University Graduate School of Business. He was awarded with a joint full scholarship by the UK Government's Chevening scheme, the Cambridge Overseas Trust and British Gas Group.

Paul Dawson – CEO, OneH2

Paul Dawson is the President and Chief Executive Officer of OneH2, Inc., based in Longview, North Carolina, USA. He is an experienced global executive known in the North American, UK, and Australasian industrial equipment and automotive industries. His experience is based on a track record of growing technology-based start-up enterprises through to maturity and exit, and he has proven skill in strategic marketing. OneH2, Inc., founded by Paul in September 2015, is his current venture. Paul is the recipient of National risk solution awards in the UK and Australia and is also an International Design Award recipient.

Mike Duffield – Module Lead – Energy Storage, John Deere

Michael is the energy storage development team lead at John Deere. Michael joined John Deere in 2019 and has more than 25 years of experience in product development, including 10 years at Hydrogenics and General Motors, where he worked on hydrogen FC and lithium-ion battery development and integration. Michael also spent 6 years at Saft Batteries, where he held various positions including Battery Engineering Manager.

Dave Edwards – Director and Advocate for Hydrogen Energy, Air Liquide

Dave Edwards is a Director and Advocate for Hydrogen Energy for Air Liquide in the United States. Dave is responsible for establishing and maintaining internal and external partnerships with industry, academia, and government entities to advance the technology and business opportunities in hydrogen energy. Dave has been with Air Liquide for more than 20 years in a wide range of energy-related roles.

Ray Gallant – Vice President Product Management and Productivity, Volvo

Ray is the Vice-President for Product Management and Productivity for Volvo Construction Equipment, part of the Volvo group of companies. Ray is a forest engineer with over 30 years' experience working in product development, product planning, and sales and marketing with a variety of equipment products. His responsibilities include sales and application engineering; product, sales and operator training; customer center operations; and product strategy and development for Region Americas. He received his Bachelor of Science in Chemistry from Dalhousie University, a Bachelor of Science in Forest Engineering from University of New Brunswick (UNB), and a Master of Science in Management from Boston University and a Doctor of Business Administration.

Ismo Hamalainen – R&D Manager, AGCO Power

Ismo has worked at AGCO Power for 13 years, starting as a design engineer. In his current position as R&D Manager, Ismo is responsible for engine performance development and research and advanced engineering. Ismo's career also features work at AVL, one of the world's largest independent companies involved in the development and testing of motive technologies, creating innovative, affordable, and clean motive technologies. Ismo has a master's degree in mechanical engineering from Helsinki University of Technology.

Martin Kirchmair – Technical Director, Prinoth

Martin Kirchmair studied at the FH Vorarlberg where he earned his Dipl.-Ing. (FH), followed by a MSc study program at the Napier University in Edinburgh (Scotland). He began his career at Connex Verkehr in Austria, where next to railway projects he was involved in gas engine and respective test bench development. In 2005, Martin Kirchmair started to work for the Prinoth AG in Vipiteno, where he became engaged in different departments—Research & Development, Prototyping & Testing, and Project Management—and in parallel studied at MCI Innsbruck to gain an MBA degree. As Technical Director for Prinoth Snow Groomers he is responsible for new products as well as existing ones: from the first idea, prototyping and testing up to series introduction and maintenance, thereby, as per Prinoth's mentality, maintaining the role of innovation leader inside the business.

Michael Koonce – President, Bayotech

No biographical information received.

Michael Lewis – Technical Director – Technology, Komatsu

Michael Lewis is Technical Director for Komatsu based in Tucson, Arizona, USA, where he works on setting the technology strategy to support Komatsu's work in sustainability, automation, safety, and digitization. Prior to his current role, he was General Manager at the Technology Interoperability Center of Excellence. Prior to joining Komatsu in 2019, he worked for Modular Mining Systems, a Komatsu subsidiary as Vice President of Product Innovation as well as leadership roles in sales, marketing, and consulting. Prior to joining Modular, Mr. Lewis worked at Barrick Goldstrike in Nevada and at Inco Mines

Research in Sudbury. Mr. Lewis holds a B.Sc. in Mechanical Engineering, and a M.Sc. in Mining Engineering, both from Queen's University.

Brian Lowry – Engineering Manager, Caterpillar

Brian has over 21 years of professional experience at Caterpillar in engineering, strategy, and finance. He is currently an Engineering Manager for Systems and Applications within Caterpillar's Advanced Power Products group. In this role, Brian leads a team that develops advanced power systems based on technologies such as lithium-ion batteries and FCs that are incorporated into Caterpillar products and systems in construction, mining, and energy and transportation.

Rick Mason – Vice President of Business Development and Product Management, Plug Power

Rick Mason is currently the Vice President of Business Development and Product Management for the New Markets Division for Plug Power, which covers On-Road and Off-Road Road Mobility and Power applications. With 21 years at Plug Power and the last 10+ years as Vice President of Operations, Rick has helped to build the supply chain for this industry and drive down overall costs for materials and manufacturing for FC and hydrogen components. Rick has an Electrical Engineering degree from Clarkson University and an MBA from Syracuse University.

Britney McCoy – Center Director, Climate Analysis and Strategies Center, Office of Transportation and Air Quality, U.S. Environmental Protection Agency

Britney McCoy is the Director of the Climate Analysis and Strategies Center within for the U.S. Environmental Protection Agency's Office of Transportation and Air Quality (OTAQ). In this role she is responsible for leading OTAQ's future-focused thinking regarding climate pollutants and advanced clean transportation technology options to achieve significant greenhouse gas reductions from transportation sources in the medium and long term. Britney specializes in advanced clean technology opportunities in transportation, diesel engine after-treatment retrofits, EPA's Clean School Bus Program, and black carbon emissions in the Arctic. As the Director of Educational Experiences for STEMLY, a nonprofit advocacy organization, she works to create bridges to STEM fields for underrepresented student populations in Washington, D.C. Her life's motto is, "I'm simply trying to create some meaning out of life while improving the environment and changing lives at the same time." She holds a Ph.D. in Engineering & Public Policy and a M.S. in Environmental Management and Science from Carnegie Mellon University, and a B.A. in Engineering and Government & Law from Lafayette College.

Kyle McKeown – Application Engineering Manager, Nel

Kyle's focus in hydrogen began in 2011 with reliability engineering and improvement efforts on Linde's early Ionic compressor hydrogen fueling stations. Kyle served as Project Manager for Linde's Advanced Technology Center's deployment of 900 bar ionic compressors in some of the first 4 Public H70 Fueling stations in California in 2015. Kyle is currently with NEL hydrogen, having commissioned six public fueling facilities for Shell Hydrogen in 2018–2019, and now leading an engineering department in the Bay Area, California. In 2017, Kyle was a panel member at a green hydrogen conference in Santiago, Chile, hosted by the Ministry of Energy (CORFO) focused on decarbonizing the mining sector.

Clemens Müller-Falcke – Partner, McKinsey & Company

Clemens is a partner of McKinsey & Company in the Santiago office, where he has been working for the last 10 years on helping mining companies achieve excellence in operations along the entire value chain. He is leading our sustainability work in the region and leading our mining sustainability service line globally.

Mike Peters – Engineer, Refueling Processes, National Renewable Energy Laboratory

Mike Peters has been working at NREL for over 10 years, specializing in renewable electrolysis, hydrogen infrastructure research, and business development. He is the PI for the Innovating Hydrogen Stations project, which aims to collect first-of-its-kind experimental data and validate models for fast fill medium- and heavy-duty hydrogen applications. In addition, he is the PI on the recently awarded HyBlend project, which focuses on materials compatibility R&D, technoeconomic analysis, and lifecycle assessment of blending hydrogen into the U.S. natural gas pipeline infrastructure. Mike is the business development lead for the Energy Conversion and Storage Systems Center within NREL. He has a B.S. in Mechanical Engineering from the University of Colorado at Boulder.

William Resende – Manager Electrified PWT Fuel Cell Engineering, CNH Industrial

William Resende is the FC systems engineering leader of FPT Industrial and joined the company in July of 2020. He has worked over 15 years with FCs mostly in in the automotive sector, holding senior engineering and managerial positions previously at AFCC (a joint venture of Daimler/Ford for FC development), BMW, and AVL. He holds a B.A.Sc. in chemical engineering from the State University of Campinas, Brazil.

Bill Robertson – Vehicle Program Specialist, California Air Resources Board

Bill Robertson is CARB's Vehicle Program Specialist for heavy-duty working across lower emission combustion and zero-emission regulation and incentives. He has been with CARB for 16 years, including projects evaluating alternative fuels, heavy-duty hybrids, aftertreatment retrofits and measurement techniques before taking his current position.

Tim Sasseen – Market Development Manager, United States, Ballard

Tim started work with Ballard over 20 years ago, leading the engine control software development team for the first Mercedes FC buses that were deployed in public service across seven European cities. Tim has served in Ballard's Field Service team in Europe, coordinating field operations when these buses were delivered and deployed, and leads the Electrical Engineering design team for Ballard's 6th generation of FC module. Outside of Ballard, Tim has worked extensively in the wind energy, where his teams designed mid-sized wind turbines, megawatt-scale power systems, and advanced power converters. Tim earned his MBA at University of California San Diego (UCSD) while working in microgrid design and renewable generation project development, before returning to Ballard in 2018 for his present position, where he leads Ballard's market development for North America. In addition to the MBA, Tim has earned Bachelor and Master of Science degrees in electrical engineering from Michigan Technological University.

Dr. Sunita Satyapal – Office Director, U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office

Dr. Sunita Satyapal is the Director for the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy and is responsible for $150 million per year in hydrogen and FC R&D. She has two and a half decades of experience across industry, academia, and government, including at United Technologies managing research and business development, and as a visiting professor. She is also the current Chair of the International Partnership for hydrogen and FCs in the Economy, a partnership among over 18 countries to accelerate progress in hydrogen. She received her Ph.D. from Columbia University and did postdoctoral work in applied and engineering physics at Cornell University.

She has numerous publications, including in *Scientific American*, 10 patents, and a number of recognitions including a Presidential Rank Award.

Jay Schmuecker – President, Schmuecker Renewable Energy System

Jay Schmuecker spent his career at Caltech's Jet Propulsion Laboratory, where he worked on the mechanical portions of spacecraft. After retirement in 2009, he started work on his Iowa demonstration Solar Hydrogen System. It now makes carbon emission–free hydrogen, nitrogen, and ammonia from water, air, and solar power. He will discuss the use of hydrogen and ammonia as fuels in his farm tractor.

Matthijs Soede – MI 2.0 Clean Hydrogen Mission Director, European Commission

Matthijs Soede is the Clean Hydrogen Mission Director and is a Research Programme Officer in the Energy Directorate of DG Research and Innovation at the European Commission. Previously he served as Vice-Chairman of the Ocean Energy Systems Executive Committee.

Julian Soles – Head of Technology Development Mining & Sustainability, Anglo American

Julian Soles joined Anglo American in 2018 as Head of Technology Development, Sustainability, and is currently leading Anglo American's hydrogen development efforts. Prior to joining Anglo American, Julian worked in the oil and gas services sector for over 17 years with Transocean, the world's largest offshore drilling contractor.

Julian has received his bachelor's and master's degrees in naval architecture and ocean engineering from University College London. He earned his MBA from the University of Houston and has completed the Advanced Management Program at Harvard Business School.

Ryan Sookhoo – Director of New Initiatives, Cummins

Ryan is the Director New Initiatives at Cummins, Fuel Cell and Hydrogen Technologies. Since joining Hydrogenics, now Cummins, in 2006 as Project Manager for PEM FC development and commercialization, he has been a dedicated member of the research and development program. In his current role, Ryan is fortunate to be involved in the early stages of new technology adaptation. As a leader in hydrogen generation and FC industries, Cummins has given Ryan the opportunity to work with various industries and help to define many of tomorrow's energy and power solutions.

Matt Walden – Investment Director, Australian Renewable Energy Agency

No biographical information received.

Appendix E: List of Attendees

Name	Company/Organization
Jesse Adams	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Rajesh Ahluwalia	Argonne National Laboratory
Darren Almond	John Deere
Sebastián Álvarez	TRA-Busso Group
Johan Beyer	PowerCell Sweden AB
Reginald Bindl	John Deere
Curt Blades	Association of Equipment Manufacturers (AEM)
Matthew Blieske	LIFTE H2
Gus Block	Nuvera Fuel Cells
Andreas Boden	PowerCell Sweden AB
Nico Bouwkamp	California Fuel Cell Partnership
Mark Brodziski	U.S. Department of Agriculture, Rural Business-Cooperative Service
Johan Burgren	PowerCell Sweden AB
Albert (Al) Burgunder	Linde, Inc.
Felipe Cabrera	Mitsui Chile
Asha-Dee Celestine	U.S. Department of Energy, ORISE Fellow
Peter Chen	California Energy Commission
Dan Christenson	Air Liquide
Tyler Clements	Multiquip, Inc.
Chuck Crowell	Caterpillar, Inc.
Jessica Daniels	U.S. Environmental Protection Agency
Pete Devlin	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Michael Diderich	Hydrogen Europe
Matthew Diener	CARB
Victor Dörner	Codelco El Teniente
Danan Dou	John Deere Power Systems
Michael Duffield	John Deere
David Edwards	Air Liquide
Brian Ehrhart	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Torsten Erbel	Multiquip, Inc.
Mitch Ewan	Hawaii Natural Energy Institute
Sara Feuling	Association of Equipment Manufacturers (AEM)
Carter Fose	Cummins, Inc.
Juan Carlos Galdamez	Plug Power
Ray Gallant	Volvo Construction Equipment

Monterey Gardiner	Nikola Motor Company
Joan Geary	Linde, Inc.
Richard Gomez	Centro Nacional de Pilotaje
Leslie Goodbody	California Air Resources Board
Benjamin Gould	U.S. Naval Research Laboratory
David Gregor	CNH
Pedro Guedes de Campos	FCHJU — Fuel Cells and Hydrogen Joint Undertaking
Ismo Hamalainen	AGCO Power Inc.
Mike Hart	Sierra Energy
Jamie Holladay	Pacific Northwest National Laboratory
Helen Horner	Association of Equipment Manufacturers (AEM)
Todd Howatt	AGCO Corporation
Chris Jenks	California Energy Commission
Jeff Jurgens	Association of Equipment Manufacturers
Gary Kassen	CNH Industrial
Adam King	General Motors
Martin Kirchmair	PRINOTH SPA
Michael Koonce	IGX Group/BayoTech
John Kopasz	Argonne National Laboratory
Theodore Krause	Argonne National Laboratory
DeLisa Leighton	IGX
Michael Lewis	Komatsu
Brian Lowry	Caterpillar, Inc.
George Luxbacher	NIOSH
Nicolas Machuca	Centro Nacional de Pilotaje
Richard Mason	Plug Power
Loreto Maturana	Anglo American
Britney McCoy	U.S. Environmental Protection Agency
Kirk McDaniel	Department of Energy, Carlsbad Area Field Office
Kyle McKeown	NEL Hydrogen, Inc.
Joseph Mercurio	General Motors
David Montgomery	Caterpillar, Inc.
Gregory Moreland	GDIT contract with Oak Ridge National Laboratory
Clemens Müller-Falcke	McKinsey & Company
Charles Myers	GDIT
Rajalakshmi Natarajan	Deakin University
Michael Pankonin	AEM

Dionissios Papadias	Argonne National Laboratory
Richard Payne	Cummins, Inc.
Michael Peters	National Renewable Energy Laboratory
William Resende	FPT/CNH Industrial
Larry Rillera	California Energy Commission
William Robertson	California Air Resources Board
Antonio Ruiz	Nikola Motor Company
Riley Saito	County of Hawaii
Roberto Santiago	Centro Nacional de Pilotajes
Sunita Satyapal	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Robert Schaefer	Cummins
Jay Schmuecker	Schmuecker Renewable Energy System Charity
Anita Sennett	Association of Equipment Manufacturers (AEM)
John Shepler	CNH Industrial
Matthijs Soede	European Commission
Julian Soles	Anglo American
Grigorii Soloveichik	U.S. Department of Energy, Advanced Research Projects Agency-Energy/Hydrogen and Fuel Cell Technologies Office
John Somers	AEM
Ryan Sookhoo	Cummins
Andrew Star	Argonne National Laboratory
Fernanda Stegmaier	Ministry of Energy
Zac Taie	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Pablo Tello	GIZ Chile
Nick Tindall	AEM
Paul Turner	CMB Revolve Technologies, Ltd.
Zach Uppole	Komatsu America Corporation
Jorge Vargas	Sernageomin
Christine Watson	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Travis Webb	Association of Equipment Manufacturers (AEM)
Ben Wender	California Energy Commission
Marika Wieliczko	KeyLogic Systems

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