U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

H2-PACE: Power and Control Electronics for Hydrogen Technologies

2021 Experts Panel Summary Report

Hydrogen and Fuel Cell Technologies Office

U.S. Department of Energy

December 2021

ENERGY
earthshots
U.S. DEPARTMENT OF ENERGY
Hydrogen

A Hydrogen Energy Earthshot Event

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Acknowledgments

The Hydrogen and Fuel Cell Technologies Office would like to thank all of the invited expert speakers who presented and the team of organizers who planned and executed the virtual H2-PACE Experts Meeting.[1] The H2-PACE organizing team would also like to thank all of the meeting participants for engaging in valuable discussion and providing informative feedback.

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[1] H2-PACE Experts Meeting Organizers included: HFTO: Eric Miller, Will Gibbons, James Vickers, Dave Peterson, Greg Kleen, Colin Gore, Donna Ho, Dimitrios Papageorgopoulos, McKenzie Hubert, Marika Wieliczko, Cassie Osvatics, Eric Parker, Matt Villante; AMO: Al Hefner; VTO: Fernando Salcedo; FECM: Jai-Who Kim; ARPA-E: Ian Robinson; NREL: Rob Hovsapian, Barry Mather, Keith Wipke, Bridget Ford, Ryan Ingwersen

Nomenclature or List of Acronyms

A	Amperage (Electrical Current)
AC	Alternating Current
ARIES	Advanced Research on Integrated Energy Systems
BIL	Bipartisan Infrastructure Law
BOP	Balance of Plant
BTM	Behind The Meter
CHIL	Controller Hardware in the Loop
COTS	Commercial Off the Shelf
DC	Direct Current
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EPRI	Electric Power Research Institute
ESIF	Energy Systems Integration Facility
GaN	Gallium Nitride
GW	GigaWatt
H2-PACE	Power and Control Electronics for Hydrogen Technologies
HDV	Heavy-Duty Vehicles
HFTO	Hydrogen and Fuel Cell Technologies Office
HIL	Hardware in the Loop
HTE	High-Temperature Electrolyzer
Hz	Hertz
I	Electrical Current
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-Gate Bipolar Transistor
kW	KiloWatt

LCA	Life Cycle Assessment
LTE	Low-Temperature Electrolyzer
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MW	MegaWatt
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturers
O&M	Operation and Maintenance
PEGI	Power Electronic Grid Interference
PEM	Polymer Electrolyte Membrane
PGM	Platinum Group Metals
PHIL	Power Hardware in the Loop
PV	Photovoltaic Solar Cell
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RDD&D	Research, Development, Demonstration, and Deployment
SiC	Silicon Carbide
SOFC	Solid Oxide Fuel Cell
TCO	Total Cost of Ownership
TEA	Techno-Economic Analysis
UL	Underwriters' Laboratories (Standards)
V	Electrical Voltage
VAR	Volt-Amps Reactive
Vrms	Root-Mean-Square Voltage
WBG	Wide Bandgap Semiconductor

Executive Summary

The U.S. Department of Energy (DOE) Hydrogen Program, led by the Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE) conducts research and development in hydrogen production, delivery, infrastructure, storage, and fuel cells. Hydrogen demonstrates major promise towards reducing CO_2 emissions and increasing energy security through, for example, decarbonizing energy intensive industries and facilitating increased deployment of clean energy on the grid. To accelerate the production of clean hydrogen, the DOE announced the Hydrogen Energy Earthshot, the first of several Energy Earthshots.[2] The Hydrogen Shot sets an ambitious yet achievable cost target to accelerate innovations and spur demand of clean hydrogen by reducing its cost by 80% to $1/kg H2 by 2031.

In 2020, the DOE, National Renewable Energy Laboratory (NREL),[3] with support from its Advanced Research on Integrated Energy Systems (ARIES)[4] facility, held a Power Electronic Grid Interface (PEGI) Workshop, focused on the research challenges of operating power systems with ever-increasing levels of inverter-based generation and power-electronic-based load. In the past two years since the PEGI workshop, the prioritization of hydrogen-based technologies through H2@Scale[5] and the Hydrogen Shot has warranted an event specifically focused on addressing pressing challenges and exciting opportunities in advancing power and control electronics for hydrogen and fuel cell technologies. For this purpose, the H2-PACE (Power And Control Electronics) Experts Meeting was organized by HFTO in collaboration with other EERE Offices, with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) and Million Mile Fuel Cell Truck (M2FCT) consortia, and with NREL, with support from its ARIES facility.

To achieve the H2@Scale vision of widespread adoption of clean hydrogen technologies across sectors in support of decarbonization, economic growth, and environmental justice; continued technology improvements and cost reductions are still needed in electrolyzers and fuel cells. Detailed technoeconomic analyses have identified, for both electrolyzers and fuel cells, the capital costs of power and control electronics as a significant contributor to the overall balance of plant (BOP) costs. The limited lifetimes of these components also affect the operations and maintenance costs. Opportunities to develop cost-effective power and control electronics solutions at scales relevant to the H2@Scale vision will need to rely on experts in electrolysis and fuel cells, electronics original equipment manufacturers, systems integrators, and commercialization specialists. H2-PACE was organized to bring together such experts to explore these opportunities.

The two-day virtual H2-PACE Experts Meeting was structured with motivational plenary talks, panel discussions, and breakout sessions in four focus areas including grid/microgrid integrated systems, off-grid systems integrated with renewable power, fuel cell systems for transportation, and cross-cutting areas for power and control electronics in hydrogen and fuel cell technologies. The meeting also featured Q&A sessions to record additional stakeholder feedback.

Some key themes and topics emphasized during the H2-PACE panel, breakout, and Q&A sessions included: the need and opportunities for cost reductions in integrated electrolyzer and fuel cell systems through innovations and advances in power and control electronics; the importance of leveraging lessons learned from other industries and initiatives in the development of power and control electronics products for electrolyzers and fuel cell systems; the importance of standardization and modularity in such development, including establishment of meaningful metrics and targets for different scales and end-uses; the critical need for testing and validation facilities to accelerate the development, scale-up, and commercialization of efficient and durable integrated systems; and exploring opportunities to address policy and regulatory frameworks that

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[2] Hydrogen Shot | Department of Energy
[3] National Renewable Energy Laboratory (NREL) Home Page | NREL
[4] ARIES: Advanced Research on Integrated Energy Systems | NREL
[5] H2@Scale | Department of Energy

would facilitate such efforts. Participants expressed a sense of urgency in the need for affordable integrated systems for clean hydrogen production and utilization, specifically motivated by national and global priorities in addressing clean energy targets and the climate crisis.

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1 Introduction and Motivation

1.1 Introduction

As part of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), a primary objective of the Hydrogen and Fuel Cell Technologies Office (HFTO) is advancing a portfolio of technologies for hydrogen production, storage, delivery, and utilization. Stakeholder engagement is critical to the success of the Hydrogen Program. HFTO conducts experts meetings and workshops that bring together members of the research community from academia, industry, national laboratories, and government to identify challenges and discuss key opportunities for the research, development, and demonstration (RD&D) of materials, components, and integrated systems supporting the wide-scale adoption of clean hydrogen across sectors. Such activities support the goals of the DOE Hydrogen Energy Earthshot (also known as the Hydrogen Shot) to achieve $1 for 1 kg of clean hydrogen within 1 decade.[6] The Hydrogen Shot is0 aligned with the Department's H2@Scale initiative aiming to advance affordable clean hydrogen utilization to enable decarbonization and revenue opportunities across multiple sectors of the U.S. economy.[7] Cost reductions are needed to enable the adoption of hydrogen and fuel cell technologies at increasing scales relevant to the Hydrogen Shot and H2@Scale visions, requiring innovative RD&D. One area that HFTO has identified with the potential for substantial cost-reduction is in the use of advanced power and control electronics in hydrogen technology systems. In order to foster community development and collaboration between stakeholders and collectively identify RD&D needs and potential strategies for advancing power and control electronics, HFTO held the virtual H2-PACE (Power And Control Electronics for Hydrogen Technologies) Experts Meeting on December 2-3, 2021. The meeting was attended by over 150 experts and original equipment manufacturers (OEMs) from 77 organizations representing the electrolyzer, fuel cell, power and control electronics, and systems integration communities; and included 21 expert panelists invested in power and control electronics for hydrogen technologies.

1.2 Motivation

In October of 2020, the DOE National Renewable Energy Laboratory (NREL), with support from its Advanced Research on Integrated Energy Systems (ARIES) facility, held a Power Electronic Grid Interface (PEGI) Workshop, focused on the research challenges of operating power systems with ever-increasing levels of inverter-based generation and power-electronic-based load.[8] In the past two years, the prioritization of hydrogen-based technologies through H2@Scale and the Hydrogen Shot has warranted a follow-up event specifically focused on addressing pressing challenges and exciting opportunities in advancing power and control electronics for hydrogen and fuel cell technologies. For this purpose, the H2-PACE Experts Meeting was organized by HFTO in collaboration with other EERE Offices, the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) and Million Mile Fuel Cell Truck (M2FCT) consortia, and with NREL, with support from its ARIES facility.

Federal investments in hydrogen and fuel cell technologies over the past 20 years have resulted in significant advances in innovation and early market acceptance, as evidenced in the more than 1,100 U.S. patents and over 30 commercial technologies, along with more than 65 technologies that could be commercial in the next several years. Current commercial deployments include more than 50,000 fuel cell forklifts, over 50 open retail fueling stations, greater than 80 buses, more than 13,000 fuel cell vehicles, and over 550 MW of fuel cells for stationary and backup power (e.g., for telecommunications).

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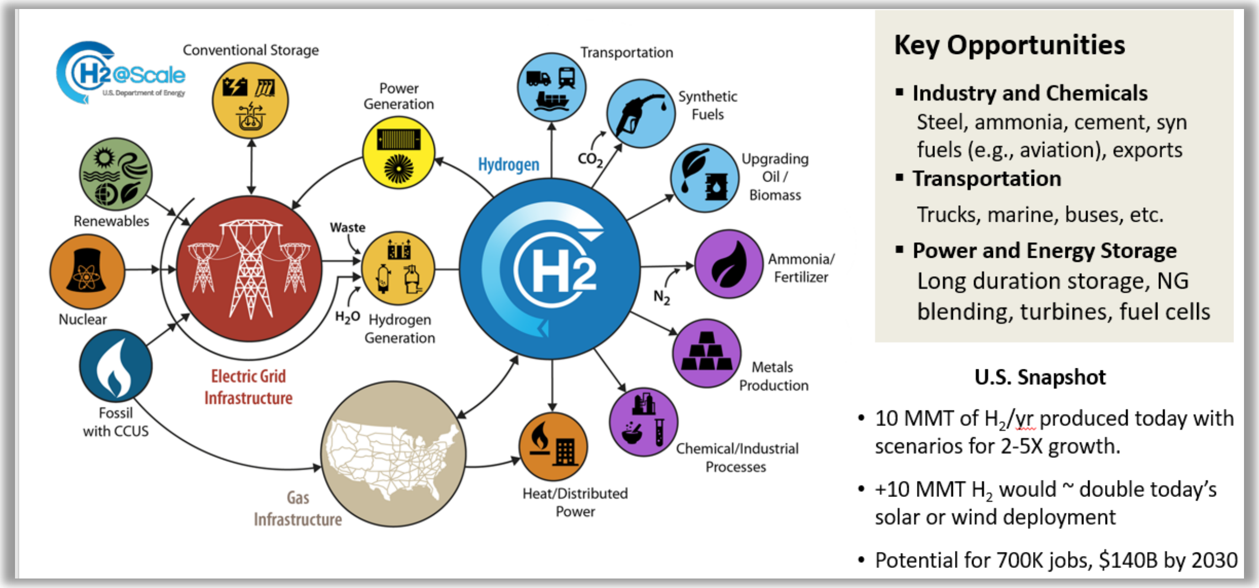
[6] DOE Hydrogen Energy Earthshot, also known as the Hydrogen Shot: Hydrogen Shot | Department of Energy
[7] DOE H2@Scale Initiative: H2@Scale | Department of Energy
[8] Power Electronic Grid Interface Platform Workshop | NREL

The Hydrogen Shot goal of $1 per 1 kg of clean hydrogen in 1 decade is a key enabler for DOE's H2@Scale Initiative. An illustration of the H2@Scale concept is shown in Figure 1, along with some key growth opportunities in sectors including industry and chemicals, transportation, and power and energy storage. The goal of H2@Scale is to advance affordable clean hydrogen production, transport, storage, and utilization to enable decarbonization and revenue opportunities across multiple sectors.

These growth opportunities have been confirmed through various analyses and stakeholder feedback which have projected significant increases in demand for affordable clean hydrogen across sectors. For example, DOE has assessed various scenarios that show a range from approximately 20 to more than 40 million tonnes per year of hydrogen demand by 2040 based on economic demand – two to four times the current demand. The Bipartisan Infrastructure Law (BIL) hydrogen provisions, which include $9.5 billion across research, development, demonstration, and deployment (RDD&D), in addition to the annual appropriations to support the Hydrogen Shot, H2@Scale, and enabling activities, are uniquely positioned to build on past successes and jumpstart a sustainable hydrogen market.



Key Opportunities

- **Industry and Chemicals**
  Steel, ammonia, cement, syn fuels (e.g., aviation), exports
- **Transportation**
  Trucks, marine, buses, etc.
- **Power and Energy Storage**
  Long duration storage, NG blending, turbines, fuel cells

U.S. Snapshot

- 10 MMT of H_2/yr produced today with scenarios for 2-5X growth.
- +10 MMT H_2 would ~ double today's solar or wind deployment
- Potential for 700K jobs, $140B by 2030

Figure 1. The DOE H2@Scale vision, including opportunities to address hard-to-decarbonize sectors.

To achieve widespread adoption across sectors, continued technology improvements and cost reductions will be needed in electrolyzers and fuel cells. Detailed technoeconomic analyses have identified, for both electrolyzers and fuel cells, the capital costs of power and control electronics as a significant contributor to the overall balance of plant (BOP) costs. The limited lifetimes of these components also affect the operations and maintenance costs.[9] Some examples of these analyses are included in Figure 2 below. Opportunities to develop cost-effective power and control electronics solutions at scales relevant to the H2@Scale vision will need to rely on technical experts in the fields of electrolysis and fuel cells, as well as electronics OEMs, systems integrators, and commercialization specialists. H2-PACE brought together such experts to explore these opportunities.

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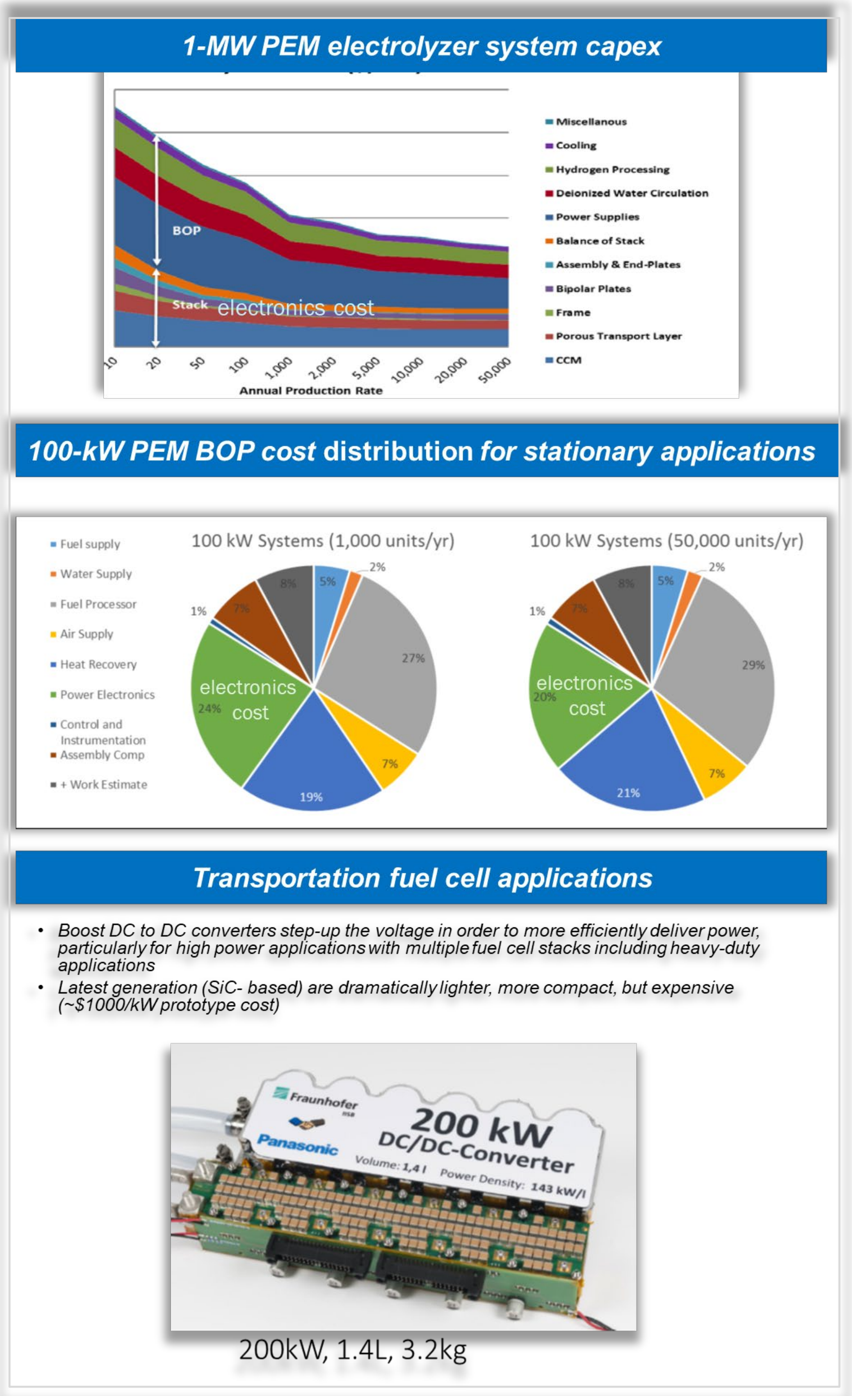
[9] For technoeconomic assessments of hydrogen and fuel cell technologies, refer to HFTO Program Records found at: [Program Records: DOE Hydrogen Program (energy.gov)](); See also additional references for electrolyzers such as: [Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers (nrel.gov)]()



1-MW PEM electrolyzer system capex

100-kW PEM BOP cost distribution *for stationary applications*

Transportation fuel cell applications

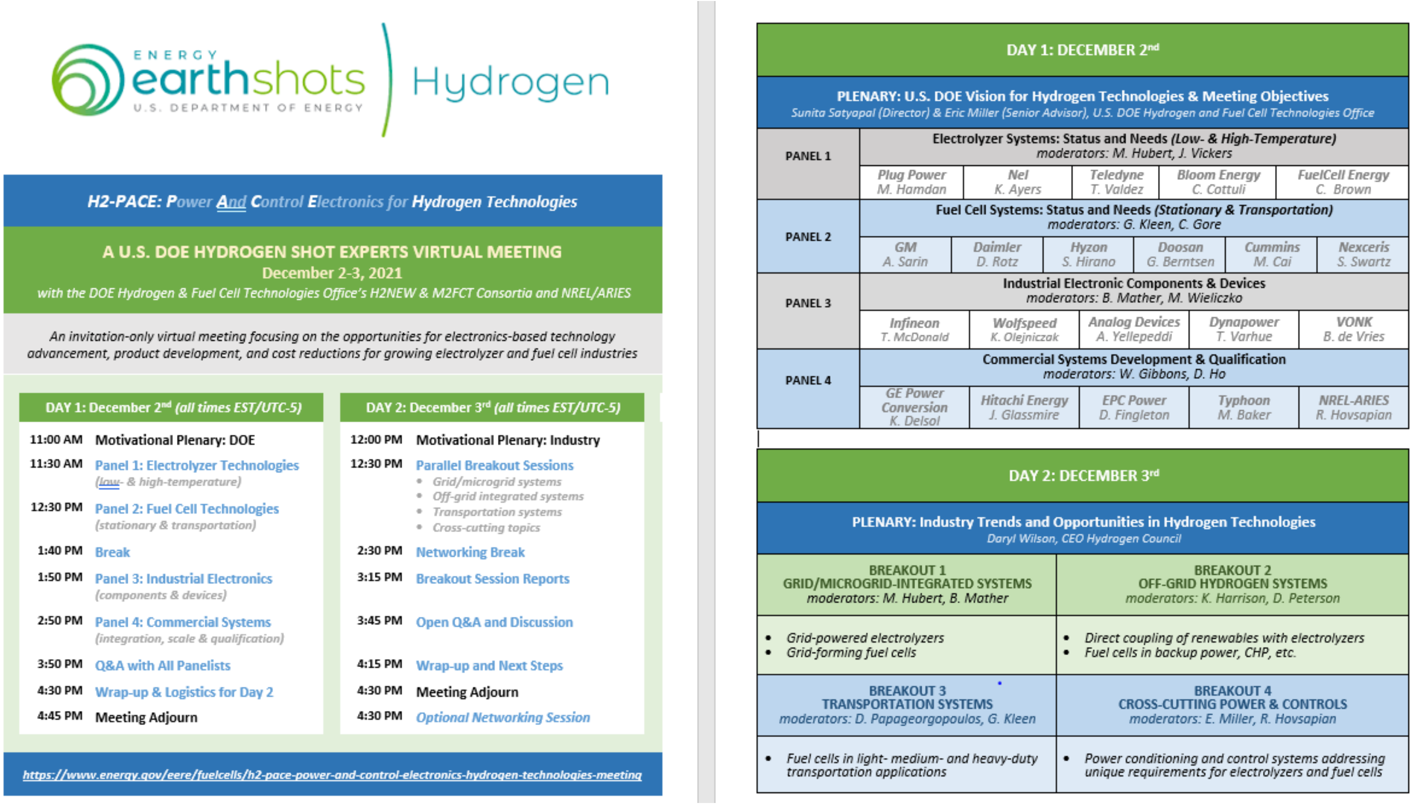
- *Boost DC to DC converters step-up the voltage in order to more efficiently deliver power, particularly for high power applications with multiple fuel cell stacks including heavy-duty applications*
- *Latest generation (SiC- based) are dramatically lighter, more compact, but expensive (~$1000/kW prototype cost)*

200kW, 1.4L, 3.2kg

Figure 2. Cost of power and control electronics remains important in hydrogen and fuel cell technologies, including in Proton Exchange Membrane (PEM) electrolyzer systems; fuel cell systems for stationary power applications; and fuel cells in transportation applications.

1.3 Meeting Agenda

The H2-PACE Experts Meeting opened with a welcome to participants and introductory remarks on the HFTO mission. These remarks highlighting the rapidly growing interest and support for continued development and deployment of clean hydrogen technologies, including the significant recent Federal funding opportunities through the hydrogen provisions in the 2022 BIL.[10] Day one of the meeting (December 2, 2021) continued with four panels featuring brief presentations and discussions from experts in areas of electrolysis, fuel cells, power and control electronics, and systems integration and qualification for commercialization. Day two (December 3, 2021) opened with a motivational introduction from the Hydrogen Council, followed by breakout sessions in four focus areas including grid/microgrid integrated systems, off-grid systems integrated with renewable power, fuel cell systems for transportation, and cross-cutting areas for power and control electronics in hydrogen and fuel cell technologies. Both days concluded with open Q&A sessions to record additional stakeholder feedback. The full agenda is summarized in Figure 3 below.



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H2-PACE: Power And Control Electronics for Hydrogen Technologies

A U.S. DOE HYDROGEN SHOT EXPERTS VIRTUAL MEETING
December 2-3, 2021
with the DOE Hydrogen & Fuel Cell Technologies Office's H2NEW & M2FCT Consortia and NREL/ARIES

An invitation-only virtual meeting focusing on the opportunities for electronics-based technology advancement, product development, and cost reductions for growing electrolyzer and fuel cell industries

DAY 1: December 2nd *(all times EST/UTC-5)*	
11:00 AM	Motivational Plenary: DOE
11:30 AM	Panel 1: Electrolyzer Technologies *(low- & high-temperature)*
12:30 PM	Panel 2: Fuel Cell Technologies *(stationary & transportation)*
1:40 PM	Break
1:50 PM	Panel 3: Industrial Electronics *(components & devices)*
2:50 PM	Panel 4: Commercial Systems *(integration, scale & qualification)*
3:50 PM	Q&A with All Panelists
4:30 PM	Wrap-up & Logistics for Day 2
4:45 PM	Meeting Adjourn

DAY 2: December 3rd *(all times EST/UTC-5)*	
12:00 PM	Motivational Plenary: Industry
12:30 PM	Parallel Breakout Sessions • *Grid/microgrid systems* • *Off-grid integrated systems* • *Transportation systems* • *Cross-cutting topics*
2:30 PM	Networking Break
3:15 PM	Breakout Session Reports
3:45 PM	Open Q&A and Discussion
4:15 PM	Wrap-up and Next Steps
4:30 PM	Meeting Adjourn
4:30 PM	*Optional Networking Session*

https://www.energy.gov/eere/fuelcells/h2-pace-power-and-control-electronics-hydrogen-technologies-meeting

DAY 1: DECEMBER 2nd

PLENARY: U.S. DOE Vision for Hydrogen Technologies & Meeting Objectives
Sunita Satyapal (Director) & Eric Miller (Senior Advisor), U.S. DOE Hydrogen and Fuel Cell Technologies Office

PANEL 1
Electrolyzer Systems: Status and Needs *(Low- & High-Temperature)*
moderators: M. Hubert, J. Vickers

Plug Power	*Nel*	*Teledyne*	*Bloom Energy*	*FuelCell Energy*
M. Hamdan	*K. Ayers*	*T. Valdez*	*C. Cottuli*	*C. Brown*

PANEL 2
Fuel Cell Systems: Status and Needs *(Stationary & Transportation)*
moderators: G. Kleen, C. Gore

GM	*Daimler*	*Hyzon*	*Doosan*	*Cummins*	*Nexceris*
A. Sarin	*D. Rotz*	*S. Hirano*	*G. Berntsen*	*M. Cai*	*S. Swartz*

PANEL 3
Industrial Electronic Components & Devices
moderators: B. Mather, M. Wieliczko

Infineon	*Wolfspeed*	*Analog Devices*	*Dynapower*	*VONK*
T. McDonald	*K. Olejniczak*	*A. Yellepeddi*	*T. Varhue*	*B. de Vries*

PANEL 4
Commercial Systems Development & Qualification
moderators: W. Gibbons, D. Ho

GE Power Conversion	*Hitachi Energy*	*EPC Power*	*Typhoon*	*NREL-ARIES*
K. Delsol	*J. Glassmire*	*D. Fingleton*	*M. Baker*	*R. Hovsapian*

DAY 2: DECEMBER 3rd

PLENARY: Industry Trends and Opportunities in Hydrogen Technologies
Daryl Wilson, CEO Hydrogen Council

BREAKOUT 1 GRID/MICROGRID-INTEGRATED SYSTEMS *moderators: M. Hubert, B. Mather*	BREAKOUT 2 OFF-GRID HYDROGEN SYSTEMS *moderators: K. Harrison, D. Peterson*
• *Grid-powered electrolyzers* • *Grid-forming fuel cells*	• *Direct coupling of renewables with electrolyzers* • *Fuel cells in backup power, CHP, etc.*
BREAKOUT 3 TRANSPORTATION SYSTEMS *moderators: D. Papageorgopoulos, G. Kleen*	**BREAKOUT 4 CROSS-CUTTING POWER & CONTROLS** *moderators: E. Miller, R. Hovsapian*
• *Fuel cells in light- medium- and heavy-duty transportation applications*	• *Power conditioning and control systems addressing unique requirements for electrolyzers and fuel cells*

Figure 3. Agenda of the H2-PACE Experts Meeting.

1.4 Meeting Participants and Interests

The meeting was attended by over 150 experts and OEMs from the electrolyzer, fuel cell, power and control electronics, and systems integration communities, representing 77 organizations with broad stakeholder interest in power and control electronics for hydrogen technologies. There was significant industrial

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[10] The U.S. Bipartisan Infrastructure Law: President Biden's Bipartisan Infrastructure Law | The White House

stakeholder participation, as shown in Figure 4 below, as well as participation from government, academia, and the national laboratories. As part of the registration process, participants were asked to indicate their priority areas of interest for discussion and breakout sessions. Figure 5 summarizes the distribution of registrant interest over six topics. The most popular topics were selected as focus areas for breakout sessions.

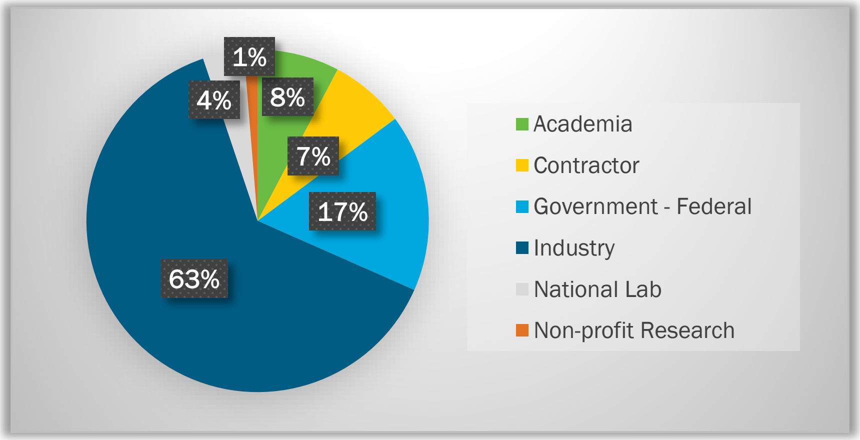


Figure 4. Sector breakdown of participating stakeholders at H2-PACE.

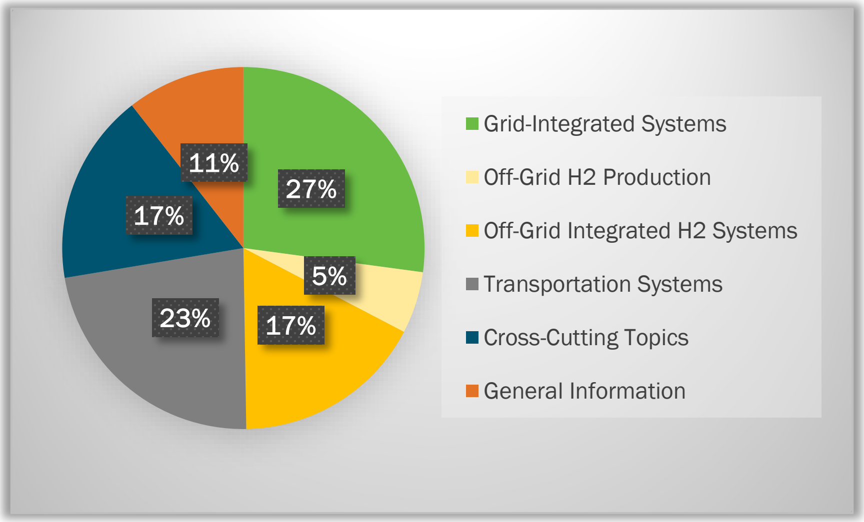


Figure 5. Priority breakout session topic areas based on registrant feedback.

A list of the registered participants who have consented to share this information is shown below in Table 1.

Table 1. H2-PACE Registered Participants *(presented with consent).*

For more detailed contact information, please contact H2PE@ee.doe.gov

Name	**Organization**
Abhinav, Shankar	MathWorks
Adams, Jesse	U.S. Department of Energy
Afridi, Khurram	Cornell University
Andersen, Shuang	University of Southern Denmark
Ayers, Katherine	Nel Hydrogen U.S.
Baker, Matt	Typhoon HIL, INC
Baranwal, Rohit	Eaton Corporation
Batten, William	Energetics
Bayham, Sam	U.S. Department of Energy/NETL
Berntsen, George	Doosan
Bethune, Keith	Hawaii Natural Energy Institute, U. of HI
Bishop, Sean	Sandia National Laboratory
Blackburn, Bryan	Redox Power Systems
Blom, Rogier	GE Research
Bolohan, Daniel	Bursa HyPower AG
Brown, Casey	FuelCell Energy
Cai, Minyu	Cummins Inc.
Chakulski, Brian	Doosan Fuel Cell America
Collins, Keri	Phillips 66
Cortes, Tim	Plug Power
Cottuli, Carl	Bloomenergy
Miller, Eric	U.S. Department of Energy - HFTO
Mills-Price, Michael	Bloom Energy
Montalvo, Tony	Analog Devices
Moran, Matthew	NEL Hydrogen
Moses, Poul Georg	Haldor Topsoe
Mukerjee, Subhasish	Ceres power
Muljadi, Eduard	Auburn University
Murthi, Vivek	Nikola Motor Company
Nagasawa, Kazunori	National Renewable Energy Laboratory
Ohodnicki, Paul	University of Pittsburgh
Olejniczak, Kraig	Wolfspeed
Omole, Imona	Phillips 66
Ordonez, Juan	FAMU-FSU College of Engineering
Osvatics, Cassie	U.S. Department of Energy - HFTO
Ozpineci, Burak	ORNL
Padmavathy, Pragalath	Detroit Diesel Corp.
Pant, Siddharth	GE Renewable Energy
Pant, Siddharth	GE Renewable Energy
Papageorgopoulos, Dimitrios	Department of Energy
Parker, Eric	Keylogic
Pastula, Michael	FuelCell Energy, Inc.

da Cruz, Flavio	SoCalGas
Dahmani, Ouahid	Lhyfe
Daniels, Jessica	U.S. EPA
Das, Debrup	Hitachi Energy
Dass, Sasha	Analog Devices
Davies, Rich	Oak Ridge National Laboratory
Davis, Keith	FuelCell Energy
de Vries, Bart	VONK
Delsol, Kevin	GE
Duggan, Conor	First Mode
Elgowainy, Amgad	Argonne National Laboratory
Ewan, Mitch	HNEI
Fingleton, Daniel	EPC
Freyermuth, Vincent	Argonne National Laboratory
Fu, Jian	U.S. Department of Energy
Garabedian, Raffi	Electric Hydrogen Co.
Gardner, Tim	Tim
Gertler, Noah	AES Clean Energy
Ghezel-Ayagh, Hossein	FuelCell Energy
Gibbons, William	U.S. Department of Energy - HFTO
Glassmire, John	Hitachi Energy
Gore, Colin	U.S. Department of Energy - HFTO
Gupta, Anish Kumar	Garrett Motion
Hamdan, Monjid	Plug Power, Inc.

Pekař, Jaroslav	Garrett Motion
Peters, Michael	National Renewable Energy Laboratory
Peterson, David	U.S. Department of Energy - HFTO
Pilawa, Robert	University of California, Berkeley
Pivovar, Bryan	National Renewable Energy Lab
PMSVVSV, Prasad	Bloomenergy
Procter, Michael	cellcentric
Prosser, Jacob	Strategic Analysis, Inc.
Ramanan, Ram	Bloom Energy Corporation
Robinson, Ian	U.S. Department of Energy/ARPA-E
Rotz, Derek	Daimler Trucks
Ruiz, Antonio	Nikola Motor Company
Sahu, Bhagawan	Plug Power Inc.
Salcedo, Fernando	ORISE/OARU
Sarin, Ashkay	GM
Schmidt, Jens Ejbye	University of Southern Denmark
Seaba, James	Phillips 66
Singh, Brij	John Deere
Small, Terrence	GE
Soloveichik, Grigorii	U.S. Department of Energy
Somani, Apurva	Dynapower
Song-Manguelle, Joseph	Oak Ridge National Lab
Stekli, Joseph	EPRI
Stetson, Ned	U.S. Department of Energy - HFTO

Harrington, Brian	Analog Devices, Inc.
Harrison, Kevin	National Renewable Energy Laboratory
Hart, Richard	GE Research
Hasenfuss, Joe	Teledyne Energy Systems
Hefner, Al	U.S. Department of Energy
Hirano, Shinichi	Hyzon Motors
Ho, Donna	U.S. Department of Energy - HFTO
Horowitz, Kelsey	AES Clean Energy LLC
Hovsapian, Rob	National Renewable Energy Laboratory
Hubert, McKenzie	U.S. Department of Energy - HFTO
Hultqvist, Michael	Haldor Topsoe
Hunter, Brian	U.S. Department of Energy
Huya-Kouadio, Jennie	Strategic Analysis
Ingram, David	Phillips 66
Isani, Taimoor	Taimoor
Ishimura, Darren	Hawaiian Electric Company
Ivanco, Andrej	Allison Transmission
Jain, Rishabh	National Renewable Energy Lab
James, Brian	Strategic Analysis Inc.
Kent, Ronald	Southern California Gas Company
Kim, Jai-Who	U.S. Department of Energy
Klapp, Dave	Power to Hydrogen
Kleen, Greg	U.S. Department of Energy
Liaw, Boryann	Idaho National Laboratory
Liu, Ying	Phillips 66

Su, Gui-Jia	Oak Ridge National Laboratory
Sujan, Vivek	Oak Ridge National Laboratory
Svendsen, Kjetil	Nel Hydrogen
Swartz, Scott	Nexceris, LLC
Swider-Lyons, Karen	Plug Power Inc
Tao, Meng	Arizona State University
Thibault, Murcia	Plug Power
Thorington, Matthew	Robert BOSCH LLC
Tiwari, Arvind	GE Research
Uchanski, Michael	Garrett Motion
Utz, Robert	Teledyne Energy Systems
Valdez, Thomas	Teledyne
Van Beek, Troy	Ideal Energy LLC
Varhue, Timothy	Dynapower
Venkataraman, Venkat	Bloom Energy
Vickers, James	U.S. Department of Energy
Vijayagopal, Ram	Argonne National Laboratory
Villeneuve, Darek	Daimler Trucks NA
Vs, Abhijith	Garrett Motion
Walters, Dennis	STARS Technology
Wang, Alex	U.S. Environmental Protection Agency
Wang, Zhang	Plug Power
Weaver, Matt	Nel Hydrogen
Wegeng, Robert	STARS Technology Corporation
Wentlent, Luke	Plug Power

Lu, Xiaonan	Temple University
Luessen, Peter	Peter
Masten, David	General Motors
Mather, Barry	National Renewable Energy Laboratory
Mathuraiveeran, Thangaraj	Cummins Inc
McDonald, Tim	Infineon Technologies
Mehta, Darius	Garrett
Miller, David	National Energy Technology Laboratory

Westlake, Brittany	EPRI
Wheeler, Douglas	DJW TECHNOLOGY, LLC
White, Nan	Nan
Wieliczko, Marika	U.S. Department of Energy - HFTO
Wipke, Keith	National Renewable Energy Laboratory
Xu , Hui	Giner Inc.
Yellepeddi, Atulya	Analog Devices
Yuan, Guohui	U.S. Department of Energy - EERE

2 Panel Sessions

After the introductory remarks on the first day, the meeting continued with four panel sessions focused on different aspects of development, integration, and qualification of power and control electronics for electrolyzer and fuel cell technologies. The topic areas, panelists (with affiliations), and panel moderators are listed in Table 2. Panel members gave presentations on their activities, strategies, vision, and challenges of power electronics for hydrogen and fuel cell technologies in their respective areas of expertise. Following each panel session was a brief question and answer (Q&A) session. Participants were also able to submit questions through the virtual platform Q&A function. The main highlights, questions, and responses are summarized for each panel in the following sections.

Table 2. Summary of Panel Topics, Panelists, and Panel Moderators

Panel	Panelists	Moderators
Electrolyzer Technologies **(low- and high-temperature)**	• Monjid Hamden, *Plug Power* • Kathy Ayers, *Nel Hydrogen* • Thomas Valdez (on behalf of Joe Poindexter), *Teledyne* • Carl Cottuli, *Bloom Energy* • Casey Brown, *FuelCell Energy*	• McKenzie Hubert (HFTO) • James Vickers (HFTO)
Fuel Cell Technologies **(stationary and transportation)**	• Akshay Sarin, *General Motors* • Derek Rotz, *Daimler* • Shinichi Hirano, *Hyzon* • George Berntsen, *Doosan* • Minyu Cai, *Cummins* • Scott Swartz, *Nexceris*	• Greg Kleen (HFTO) • Collin Gore (HFTO)
Industrial Electronics **(components and devices)**	• Tim McDonald, *Infineon* • Kraig Olejniczak, *Wolfspeed* • Atulya Yellepeddi, *Analog Devices* • Tim Varhue, *Dynapower* • Bart de Vries, *Vonk*	• Barry Mather (NREL) • Marika Wieliczko (HFTO)
Systems Commercialization **(scale, integration, and qualification)**	• Kevin Delsol, *GE Power Conversion* • John Glassmire, *Hitachi Energy* • Daniel Fingleton, *EPC Power*	• Will Gibbons (HFTO) • Donna Ho (HFTO)

	• Matt Baker, *Typhoon* • Rob Hovsapian, *NREL-ARIES*	

2.1 Panel 1: Electrolyzer Technologies

The ***Electrolyzer Technologies Panel*** focused on the specific power electronics needs for electrolyzer technologies. The panel featured five representatives from electrolyzer OEMs of both low-temperature electrolyzer (LTE) and high-temperature electrolyzer (HTE) technologies: Plug Power, Nel Hydrogen, Bloom Energy, FuelCell Energy, and Teledyne. Each panelist gave an overview presentation of their respective electrolyzer technologies with an emphasis on the current and future operating strategies and power electronics needs, such as current/voltage requirements, operating ranges, efficiency, and thermal management. In particular, panelists addressed the current challenges they face with power and control electronic systems and shared their perspective on the potential pathways to overcome those challenges. Common power electronics opportunities described by both LTE and HTE panelists include capital cost reduction, stack voltage monitoring and controls to optimize performance, reduced size and weight, higher efficiency at all operating points, and alleviating harmonic feedback concerns.

The presentations were followed by a brief discussion with input from all panelists. Topics included:

Power electronics costs are known to be a high-cost item for the overall electrolyzer system. What are your thoughts on ways to bring these costs down, and what are the hurdles to doing so?

There are trade-offs in power electronics between capital cost, power quality, harmonic feedback, and efficiency that need to be further explored and quantified. Confirming that electrolyzer stacks and systems can operate on dirty power will result in simplification of the power electronics requirements leading to cost reductions. The operating strategy of electrolyzers must be considered in cost trade-offs as well. Electrolyzers that operate in a load-following mode, such as when directly coupled to renewable energy sources, as opposed to a constant power mode require power electronics with high efficiency over a much wider range of operating points. As electrolyzer system power requirements continue to grow to ~10s and ~100s of MW, private substations for electrolyzers could prove cost effective. However, further discussions with utilities and research on harmonic feedback and other regulations are needed. While considering the cost reduction strategies mentioned here, reducing the size and weight of power electronics can also help to reduce delivery and land costs.

What value do you see in standardizing power and control electronics across electrolyzer technologies (and sizes)? How do you envision the industry pursuing that goal?

While today’s power electronics are custom designed for each electrolyzer system, standardizing a modular “off-the-shelf” power electronics unit could help to reduce costs. Standardizing power electronics requirements across the electrolyzer OEMs could be difficult given the different designs and power requirements that each are independently optimizing. Today, OEMs select power electronics to fit their stack requirements, but designing stacks to fit a low-cost, standard power electronics unit could be the subject of future system analysis and optimization research. Beyond standardizing hardware, standardizing regulations, and codes both domestically and internationally would also be of value. Regulations and codes could simplify design requirements, and future discussions should include organizations such as IEEE, UL, and other relevant entities.

2.2 Panel 2: Fuel Cell Technologies

The ***Fuel Cell Technologies Panel*** was centered around both stationary and transportation applications. Six panelists represented key high- and low-temperature fuel cell companies with technologies for both applications: General Motors (GM), Daimler, Hyzon, Doosan, Cummins, and Nexceris. Panelists presented an overview of their companies as well as the unique power electronics needs for stationary and transportation applications. Transportation applications at GM, Daimler, and Hyzon focused on electronics that support the powertrain, while stationary applications at Cummins, Nexceris, and Doosan focused more on inverters and other electronics components needed for delivery to grids, microgrids, etc.

General Motors: Fuel cells are needed for heavy duty vehicles – both trucks and trains were mentioned. Fast filling/charging of the electrified vehicle and enhanced cold weather performance make fuel cell powertrains a vital opportunity for these vehicles. Power Electronics (PEs) are needed for high power DC-DC converters to stabilize voltage for the motors, and PEs are needed for the low power DC-DC conversion for BOP equipment. PEs need to be efficient, small, and cheap, but these are competing demands for PE designers/suppliers. Fuel cell vehicles are always going to be augmented by a battery system for handling peak power needs (up hills, etc.). Especially for peak demand operation, extensive cooling is required for the PEs, not just for the fuel cell stacks. Currently water-glycol mixtures are used to cool both the PE loop and the fuel cell loop. Even 5000 hours of lifetime may be difficult for wide bandgap high power density components to achieve in realistic systems. There is a need both for cooling improvements and for improving wide bandgap lifetimes. Coolants are also needed for high temperature applications, 75°C and above. Managing transient loads and the associated heat rejection remains a major concern.

Daimler: The company has been focused on heavy duty vehicle electrification for 5-6 years but have only focused on fuel cell power systems for heavy duty vehicles (HDVs) for 5-6 months. Increased range is driving their interest in fuel cells. Battery electric vehicles have ~200-mile range per charge at present, with the potential to reach a 300–500-mile range. Fuel cells enable a range of 600-700 miles per day. Fuel cells are more efficient than diesel engines, but they require greater heat rejection loads through the radiator and associated cooling loop. Diesel engines typically reject over half of the heat load via the tailpipe, and the remaining heat is rejected via the radiator and cooling loop. Much less heat from fuel cell systems is rejected through the tailpipe due to lower temperature operation/lower quality waste heat (lower difference between operating temp and ambient conditions) to reject. Lower quality waste heat needs a larger cooling system to reject it. Diesel systems are rejecting at ~105°C vs. only 70-80°C for fuel cell system cooling loops.

Hyzon: Hyzon has existed for 2 years, but is connected to Horizon in Singapore that has a much longer history. They are developing 42-ton trucks for the EU and coach buses. In relation to power electronics, Hyzon has developed patent-pending eAxle multi-traction motors. These motors deliver 97% motor to wheel efficiency, which is ~40% increase as compared to typical equipment. Total cost of ownership (TCO) is a main concern for further development, with hydrogen as a significant cost driver as opposed to HDV lifetimes.

There are two categories of PEs in their systems. Traction controls operate on the 250-350 kW scale. The fuel cell system output goes through a DC-DC boost converter to supply the traction system at the appropriate voltage and must be capable of high currents to support the high-power needs of the traction system. An inverter is needed for the air compressor to deliver oxidant to the fuel cell stacks. For PEs, high efficiency is the most important factor. Integration is also a major challenge, as there are multiple inverters and DC-DC components. Hyzon is focused on developing common components based on the design of an 800 V bus. New functions relating to measurement and control are enabled by these systems and are being developed.

Doosan: Doosan has deployed 50 MW of stacks based on their phosphoric-acid fuel cell technology with fuel flexibility (e.g., natural gas, hydrogen, or liquid petroleum gas). Their technology aims to provide multi-MW grid support, combined heat and power systems, as well as critical power for microgrids and critical backup (e.g., for data centers). Unit specifications included a 48% efficiency when running on hydrogen, with electrical output at 460 kW (net) and 480 V AC, with dispatchability of 10 kW/sec. They emphasized the importance of addressing grid needs, in support of IEEE-1547/UL-1741 standards; and highlighted where power and control electronics play a critical role in meeting those standards including, voltage regulation; response to abnormal conditions (e.g., voltage ride-through, frequency ride-through, and anti-islanding); power quality (e.g., harmonics); and interoperability. They also coupled the roles of power and control electronics with relevant fuel cell requirements for grid-connected and grid-independent operations (e.g., supporting plant parasitic loads on grid disturbances to shorten return-to-service); and backup/microgrid operations (e.g., multi-unit load sharing, rapid load transients, transformer pickup, etc.)

Cummins: Cummins described the air-cooled electronics sub-systems for their 20 kW solid oxide fuel cell (SOFC) units, including a three-phase inverter with output of 20 kW at 208 V_{rms} and 60 Hz; 20 kW fuel cell DC-DC boost charger; battery DC-DC buck (6 kW) – boost (20 kW) charger; operating with a common DC bus voltage of 450 V. Power electronics remain an important factor in system performance and durability. They also discussed general electronics considerations and priorities related to fuel cell modules, controls, and system-specific architectures. For example, they discussed the specific operational considerations in data center power systems running at a continuous load of 30-40% of the rated load, where transient loads can be significant. Today, fuel cells from different manufactures have different output characteristics, and need customized DC-DC converters. An important but often overlooked consideration is the system grounding convention which could impact isolation requirements. Necessary controls must consider application-related deployment; centralized versus distributed systems for grid-tied, microgrid, and islanded systems. The development of application-specific targets is needed for cost, lifetime, power density, efficiency, reliability, and serviceability.

Nexceris: Nexceris discussed their design and build under an ARPA-E project of a hybrid power system that integrates a SOFC with a gas turbine, including the importance of power and control electronics. The system will generate 100 kW of power at 70% LHV efficiency with natural gas as fuel. Specific power and control requirements include: 160 A per stack with 8 stacks for a 100 kW scale system; 40-72 volts per stack; steady state operations of the SOFC stack and turbine, with batteries for load following; DC-DC converters needed to step up voltage prior to efficient DC-to-AC conversion; and highly efficient DC-to-AC inverters. Optimizing efficiency, lifetime, and cost of the power and control electronics components and sub-systems remains a priority for meeting aggressive project targets.

The presentations were followed by a brief discussion with input from all panelists. One question that was addressed in included below (additional questions were more thoroughly address in the Transportation breakout session on Day two):

What are the most overlooked aspects of fuel cell power electronics and controls for your application?

Thermal management is a critical factor in performance and lifetimes of electronics sub-systems across applications. Cooling systems costs versus acceptable operating temperatures for electronics over an expected range of environmental and operational conditions still present challenges. A better understanding of the electronics failure modes (including thermally-related failures) is needed to develop cost-effective solutions that would extend service and replacement intervals. Over-engineering and building in redundancy are common but costly approaches that could be reduced through continued RD&D. The emergence of affordable wide bandgap semiconductor components and modules offers new opportunities for enhanced performance and lifetimes in next-generation sub-systems specifically designed for fuel cell operations.

2.3 Panel 3: Industrial Electronics

The ***Industrial Electronics Panel*** focused primarily on electronics components and devices that have been or could be integrated into optimized electrolyzer and fuel cell systems for power and/or control functionality. The panelists represented vendors of electronics components and power supplies: Infineon, Wolfspeed, Analog Devices, Dynapower, and VONK. Each panelist gave a presentation to highlight the company activities to improve options for integrated power and controls systems and describe their specific applications in the industrial electronics space.

Infineon presented on a range of silicon (Si), silicon carbide (SiC), and gallium nitride (GaN) options for power and control electronics covering a wide range of power/voltage/frequency with relevance to hydrogen-based conversion and generation technologies. Wolfspeed presented on its medium- and high-voltage silicon carbide power products, specifically in context of power electronics for hydrogen-based technologies. Analog Devices presented on its innovative silicon-based control methodology for electrolyzer cells and stacks that incorporates artificial intelligence in predictive analytics and self-healing algorithms to enhance lifetime. Dynapower presented on its approach to hydrogen power supplies addressing important factors such as harmonics, power factor correction, ripple current, ramp rate, and control response. VONK presented on its experience in developing customized power and control electronics for large-scale electrolyzer installations addressing voltage, current, and harmonic requirements.

The presentations were followed by a brief discussion with input from all panelists. Topics included:

How do you approach optimizing power and control electronics solutions for integration with electrolyzers?

A components- and systems-level point-of-view is needed that considers the specific voltage, current, and harmonic requirements for electrolyzer stacks and systems. Power and control electronic choices will be impacted by electrolyzer cell, stack, and system design and the tradeoff between current and voltage; technical coordination between electrolyzer and electronics developers and suppliers is critical. As one example, design of electrolyzer stacks that operate at high voltages to minimize current at rated power could offer operational and cost advantages from an electronics perspective. Though silicon-based architectures could be designed today for such application, mid- to longer-term options to maximize the benefits of high-voltage operations would include the use of wide bandgap semiconductors such as silicon carbide which are inherently better suited to such voltages, and which continue to decrease in cost through technology development and market adoption.

How important is the development of standardization in the design of electronic components and integrated circuits for hydrogen-based technologies, and what scales of deployment would motivate the development of such standards?

It would be difficult to standardize power and control systems for use across all electrolyzer and fuel cell technology applications, however, standardization of specific sub-components and modules would greatly facilitate development of new product lines specifically optimized for these technologies at needed scales. Such products could use standardized sub-components in a building block approach, meeting specific operational requirements of a given application, including voltage, current, and harmonics, as well as thermal management, durability, and lifetime. Incentives for scale-up of electronics products and supply chains for electrolyzer and fuel cells are expected to be provided in specific application areas such as energy storage and heavy-duty vehicles. Achieving scale not only has the benefits of economies of scale but will also increase sub-component availability and supply chains. Power and control electronics have been implemented at the MW and GW scales for different applications, and best-practices and lessons learned should be leveraged in the deployment of electrolyzers and fuel cells.

Do supply chain issues, such as with critical minerals needed for semiconductor electronics components, pose a challenge for progress in developing power and control systems for electrolyzers and fuel cells at relevant scales?

This can be a challenge that impedes progress. Supply chain issues already exist in power modules and communications electronics for many different end-uses with some significant back orders for major projects and deployments. As one example, the international dominance of silicon-based fabrication presents potential risks. Critical minerals and supply chain insecurity are expected to pose some challenges, not only to the electronics sub-systems, but also to some of the core electrolyzer and fuel cell technologies (e.g., PGM catalysts and perflourinated polymers in PEM based systems). Future mitigation of the issue can be addressed through continued technology development (including development of some replacement materials where appropriate), and through innovations in manufacturing as well as recycling processes.

2.4 Panel 4: Systems Commercialization

The ***Systems Commercialization Panel*** focused on issues including scale, integration, and qualification for commercial systems. The panelists were comprised of representatives from large scale commercial system manufacturers (GE Power Conversion, Hitachi Energy), a controls solutions provider (Typhoon), the ARIES program at NREL, and a mid-level PV power converter manufacturer (EPC Power). The discussion focused broadly on the advantages and opportunities made available through coupling of system controls, electronics, and hardware. Each panelist provided specific insight into the approach that their company or organization is currently taking to improve overall system control, response, and efficiency, and offered outlook related to system performance when coupled with electrolyzers. It was emphasized that the standardization and modularization of the design to scale-up to various sizes of electrolyzers can support cross-technology integration between storage, renewables, and grid assets, while leveraging power conversion interfaces between different technology platforms.

GE Power Conversion began the conversation with an overview of their electrolyzer power supplies based on Thyristor, insulated-gate bipolar transistor (IGBT), and metal-oxide-semiconductor field-effect transistor (MOSFET) architectures. These electronics, with a long history in the chlor-alkali industry, were discussed in terms of their history and future relevant to hydrogen production technologies, which is expected to rely heavily on IGBT and MOSFET architectures. Adjustments to the MOSFET architectures through the incorporation of SiC could improve reliability and maintainability. Hitachi Energy introduced their hydrogen-related power electronics and systems product line and discussed grid edge solutions, particularly for renewable and storage technologies in light of the company's future carbon neutral goals. The discussion emphasized the importance of the electronic components and need for broader electrification given that electricity conversion is conducted at least once during the process of generating, storing, and transporting renewable hydrogen.

Typhoon presented an overview of their controller hardware for grid modernization, along with software solutions for model based systems engineering design. These tools improve grid stability and offer control/prediction opportunities that reduce risk, enabling additional optimization and improvement without destabilizing the grid or leading to unexpected component failure. An example of deployment of their tools with Duke Energy was presented, which consisted of a distribution management system that included grid controllers and automation devices, protection relays, capacitor bank controls, reclosers, and an energy storage power converter. This project leveraged their Real Time platform for CHIL (controller hardware in the loop) and PHIL (power hardware in the loop). This platform and approach of CHIL & PHIL is relevant for at-scale validation of emerging technologies for hydrogen generation that could ultimately reduce the cost of integration and deployment. This platform could also become a facilitator to better integrate various other distributed energy resources technologies.

EPC provided a company overview and discussed their power converter portfolio for solar PV and energy storage, focusing on the modular nature of their commercial and utility scale systems and their ability to customize hardware to meet customer needs. EPC has incorporated Typhoon hardware in the loop (HIL) approaches to optimize operation and de-risk the integration of new and legacy hardware.

NREL and ARIES are focused on their at-scale validation environment to integrate power systems, power electronics, communication systems, and enable characterization of MW-level devices from a whole system perspective. Currently, ARIES capabilities are being leveraged for several hydrogen projects with focus on clean hydrogen, standardization, modularization, and HIL validation in collaboration with EPC, Typhoon, and Nel. CHIL and PHIL validation of grid-integrated hydrogen technologies will support standardization, renewable integration, and storage as part of hybrid energy systems integration at MW-scale.

The presentations were followed by a brief discussion with input from all panelists. Topics included:

What are the lessons learned from other industries regarding standardization? In particular, are there useful examples from PV, wind, battery, and/or other technologies from which the hydrogen community can benefit?

Beyond safety and lower manufacturing costs, standardization enables construction and deployment of modular systems. The PV industry has demonstrated the substantial value of modular standard components (panels, inverters, etc.), enabling high volume manufacturing and rapid replacement of any failed components. The software and controls required to optimize the overall system performance are a crucial element required to achieve high system efficiency and reliability. The primary lesson for the hydrogen community is that standard communications protocols and standard modular components (power supplies, electrolyzers, etc.) will simultaneously maximize overall system efficiency while minimizing risk of component failure.

Where do the challenges lie in integration or hybridization of hydrogen production with renewable energy production and storage technologies?

The system components for the hybrid systems consisting of PV, wind, battery (or supercapacitor) storage, electrolyzers, and hydrogen storage are available independently, and several examples of such systems were discussed explicitly at small (1MW) and large (100 MW) scales. The standardized components and communications protocols are essential to low-cost build-out of such systems, specific to the local needs, and the real time simulation tools and controls are required to ensure stable and efficient operation, particularly under grid-tied operation. Notably, these same simulation tools substantially de-risk full scale system construction by providing targeted economic assessments.

3 Breakout Sessions

The second day of the meeting began with an opening plenary from Darryl Wilson, CEO of the Hydrogen Council on *Industry Trends and Opportunities in Hydrogen Technologies*. This was followed by four parallel interactive breakout sessions designed to foster maximum stakeholder feedback.

The focus areas of each breakout session are listed in Table 3 and the discussions and key findings for each session are summarized in the following sessions.

Table 3. Breakout session topics and moderators

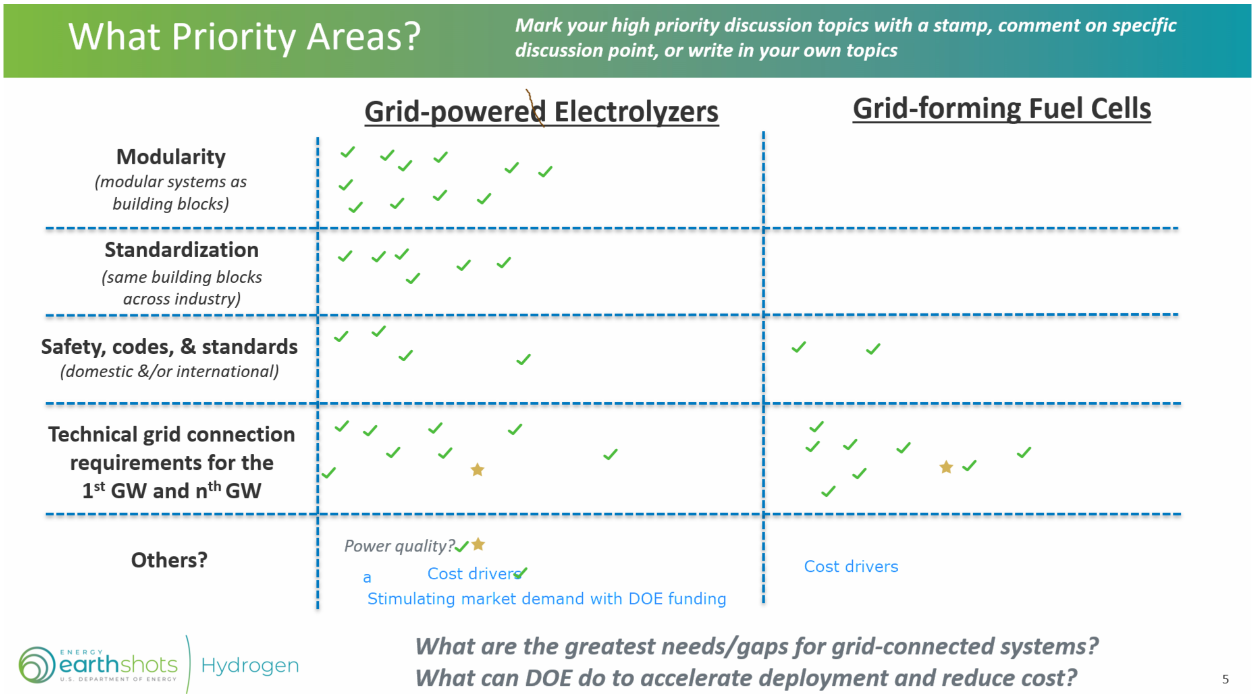
Breakout Session	Moderator(s)
Grid- and Microgrid-Integrated Systems	• Barry Mather (NREL) • Keith Wipke (NREL) • McKenzie Hubert (HFTO)
Off-grid Integrated Systems	• David Peterson (HFTO) • Kevin Harrison (NREL) • James Vickers (HFTO)
Transportation Systems	• Dimitrios Papageorgopoulos (HFTO) • Greg Kleen (HFTO) • Colin Gore (HFTO)
Cross-cutting Topics	• Eric Miller (HFTO) • Rob Hovsapian (NREL) • Will Gibbons (HFTO) • Marika Wieliczko (HFTO)

3.1 Breakout Session 1: Grid- and Microgrid-Integrated Systems

The GW-scale deployment of electrolyzer and fuel cell technologies will impact the electricity systems they draw power from and supply power to. These electricity systems may range in size from national-scale electricity grids to community-scale microgrids. The objectives of this breakout session were to (1) identify the greatest needs and gaps for grid- and microgrid-integrated electrolyzer and fuel cell systems, and (2) identify RD&D opportunities to accelerate deployment and reduce system costs.

Many industrial sectors were represented by the participants in the Grid- and Microgrid-Integrated Systems Breakout Session: electrolyzer OEMs, fuel cell OEMs, electricity research organizations, electric utilities, control electronics developers, academia, national laboratories, and government. At the start of the session, participants identified topics of highest interest or priority to pursue further in-depth discussion. The top discussion topics were (1) modularity of power electronics for electrolyzers, and (2) technical grid connection requirements for the 1st and nth GW of electrolyzers and fuel cells installed (Figure 6 below).

For the top priority topics, participants provided input on the current status, challenges, and both the near-term (1-5 yr) and long-term (5-10 yr) opportunities to overcome those challenges (shown in Figure 7 and Figure 8 below).



What Priority Areas?

Mark your high priority discussion topics with a stamp, comment on specific discussion point, or write in your own topics

	Grid-powered Electrolyzers	Grid-forming Fuel Cells
Modularity *(modular systems as building blocks)*	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	
Standardization *(same building blocks across industry)*	✓ ✓ ✓ ✓ ✓ ✓	
Safety, codes, & standards *(domestic &/or international)*	✓ ✓ ✓ ✓	✓ ✓
Technical grid connection requirements for the 1st GW and nth GW	✓ ✓ ✓ ✓ ✓ ✓ ✓ ★ ✓	✓ ✓ ✓ ✓ ✓ ✓ ★ ✓ ✓
Others?	*Power quality?*✓★ a Cost drivers✓ Stimulating market demand with DOE funding	Cost drivers

What are the greatest needs/gaps for grid-connected systems?
What can DOE do to accelerate deployment and reduce cost?

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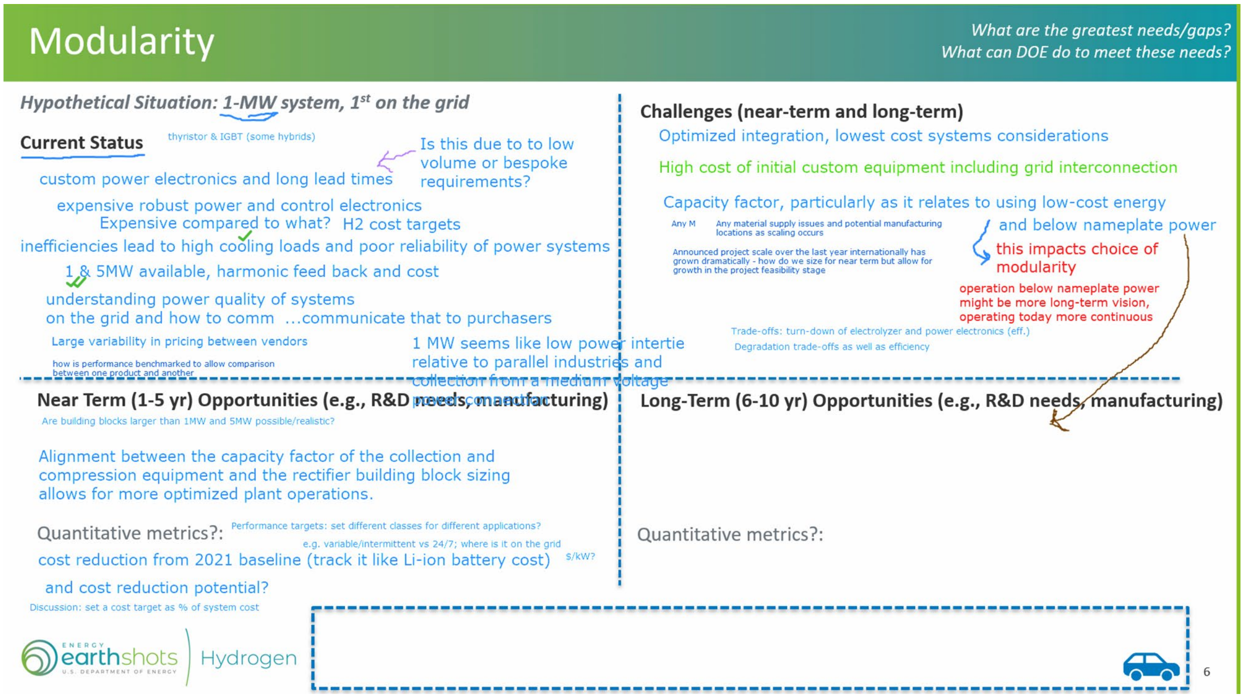
Figure 6. Prioritization of discussion topics in the Grid- and Microgrid-Integrated Breakout Session.



Modularity

What are the greatest needs/gaps?
What can DOE do to meet these needs?

Hypothetical Situation: 1-MW system, 1st on the grid

Current Status

thyristor & IGBT (some hybrids)

custom power electronics and long lead times

Is this due to to low volume or bespoke requirements?

expensive robust power and control electronics

Expensive compared to what? H2 cost targets

inefficiencies lead to high cooling loads and poor reliability of power systems ✓

1 & 5MW available, harmonic feed back and cost ✓✓

understanding power quality of systems on the grid and how to comm ...communicate that to purchasers

Large variability in pricing between vendors

how is performance benchmarked to allow comparison between one product and another

1 MW seems like low power intertie relative to parallel industries and collection from a medium voltage power connection

Challenges (near-term and long-term)

Optimized integration, lowest cost systems considerations

High cost of initial custom equipment including grid interconnection

Capacity factor, particularly as it relates to using low-cost energy

Any M Any material supply issues and potential manufacturing locations as scaling occurs

Announced project scale over the last year internationally has grown dramatically - how do we size for near term but allow for growth in the project feasibility stage

and below nameplate power

this impacts choice of modularity

operation below nameplate power might be more long-term vision, operating today more continuous

Trade-offs: turn-down of electrolyzer and power electronics (eff.)

Degradation trade-offs as well as efficiency

Near Term (1-5 yr) Opportunities (e.g., R&D needs, manufacturing)

Are building blocks larger than 1MW and 5MW possible/realistic?

Alignment between the capacity factor of the collection and compression equipment and the rectifier building block sizing allows for more optimized plant operations.

Quantitative metrics?: Performance targets: set different classes for different applications?

e.g. variable/intermittent vs 24/7; where is it on the grid

cost reduction from 2021 baseline (track it like Li-ion battery cost) $/kW?

and cost reduction potential?

Discussion: set a cost target as % of system cost

Long-Term (6-10 yr) Opportunities (e.g., R&D needs, manufacturing)

Quantitative metrics?:

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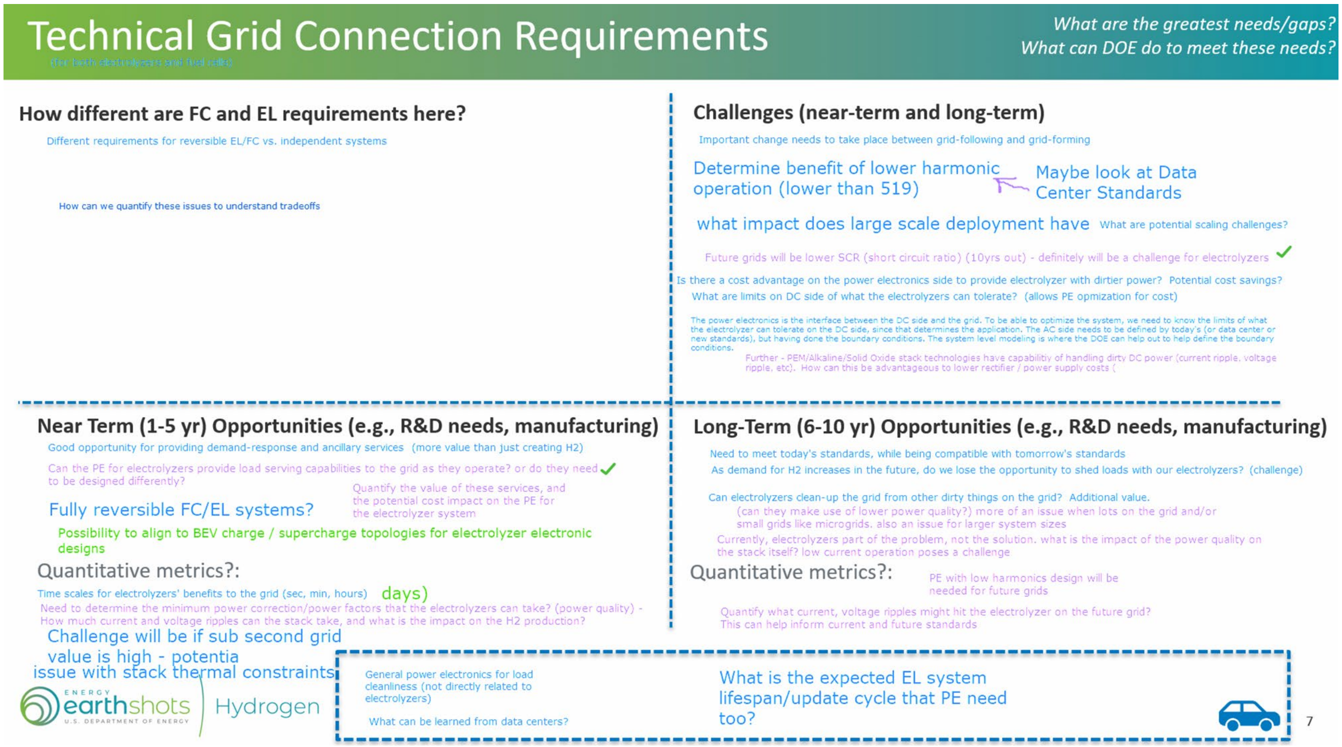
Figure 7. Mapping of status and challenges related to the topic of Modularity.



Technical Grid Connection Requirements

(for both electrolyzers and fuel cells)

What are the greatest needs/gaps?
What can DOE do to meet these needs?

How different are FC and EL requirements here?

Different requirements for reversible EL/FC vs. independent systems

How can we quantify these issues to understand tradeoffs

Challenges (near-term and long-term)

Important change needs to take place between grid-following and grid-forming

Determine benefit of lower harmonic operation (lower than 519)

Maybe look at Data Center Standards

what impact does large scale deployment have

What are potential scaling challenges?

Future grids will be lower SCR (short circuit ratio) (10yrs out) - definitely will be a challenge for electrolyzers ✓

Is there a cost advantage on the power electronics side to provide electrolyzer with dirtier power? Potential cost savings?

What are limits on DC side of what the electrolyzers can tolerate? (allows PE opmization for cost)

The power electronics is the interface between the DC side and the grid. To be able to optimize the system, we need to know the limits of what the electrolyzer can tolerate on the DC side, since that determines the application. The AC side needs to be defined by today's (or data center or new standards), but having done the boundary conditions. The system level modeling is where the DOE can help out to help define the boundary conditions.

Further - PEM/Alkaline/Solid Oxide stack technologies have capabilitiy of handling dirty DC power (current ripple, voltage ripple, etc). How can this be advantageous to lower rectifier / power supply costs (

Near Term (1-5 yr) Opportunities (e.g., R&D needs, manufacturing)

Good opportunity for providing demand-response and ancillary services (more value than just creating H2)

Can the PE for electrolyzers provide load serving capabilities to the grid as they operate? or do they need to be designed differently? ✓

Fully reversible FC/EL systems?

Quantify the value of these services, and the potential cost impact on the PE for the electrolyzer system

Possibility to align to BEV charge / supercharge topologies for electrolyzer electronic designs

Quantitative metrics?:

Time scales for electrolyzers' benefits to the grid (sec, min, hours) days)

Need to determine the minimum power correction/power factors that the electrolyzers can take? (power quality) - How much current and voltage ripples can the stack take, and what is the impact on the H2 production?

Challenge will be if sub second grid value is high - potentia issue with stack thermal constraints

Long-Term (6-10 yr) Opportunities (e.g., R&D needs, manufacturing)

Need to meet today's standards, while being compatible with tomorrow's standards

As demand for H2 increases in the future, do we lose the opportunity to shed loads with our electrolyzers? (challenge)

Can electrolyzers clean-up the grid from other dirty things on the grid? Additional value.

(can they make use of lower power quality?) more of an issue when lots on the grid and/or small grids like microgrids. also an issue for larger system sizes

Currently, electrolyzers part of the problem, not the solution. what is the impact of the power quality on the stack itself? low current operation poses a challenge

Quantitative metrics?:

PE with low harmonics design will be needed for future grids

Quantify what current, voltage ripples might hit the electrolyzer on the future grid? This can help inform current and future standards

General power electronics for load cleanliness (not directly related to electrolyzers)

What can be learned from data centers?

What is the expected EL system lifespan/update cycle that PE need too?

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Figure 8. Mapping of status and challenges related to the topic of Grid Connection Requirements.

3.1.1 Modularity and Standardization

Status

1 MW and 5 MW power electronic systems are available today, but they are custom-made with long lead times. There is large variability in the quoted power electronics prices between different suppliers.

Challenges

As hydrogen system designs evolve and each OEM chooses different size modules, it is likely that standardized module sizes could take years to establish for commercial products. There may be a greater opportunity for standardization of new electrolyzer and fuel cell systems, or by startup companies that are eager to share BOP with competitors to reduce their initial market-entry cost. Another challenge for standardization is how manufacturers size and rate their systems to handle the different capacity factors that their equipment might experience in use to either follow renewable power profiles or operate at a constant power setting.

Needs & Opportunities

Whole-system optimization R&D, including broad system boundaries to include hydrogen compression and storage, should be conducted to identify the cost reduction opportunities of different modular system sizes/configurations, and how the optimal system size may change with different capacity factors and operating ranges employed. There is also a need to identify power electronics performance and cost metrics/targets for electrolyzer and fuel cell systems. Performance targets should consider intermittent vs. continuous operation. Performance metrics could include balancing power quality, efficiency, and harmonics. Cost metrics could be described as a percentage of system cost or on a $/kW basis. No specific values were discussed, but it was agreed that metrics should be developed.

3.1.2 Technical Grid Connection Requirements

Status

Utilities have not considered the potential impacts of electrolyzers and fuel cells connected to the grid, beyond following IEEE 519 standards. This is akin to the early days of solar technology when the market penetration was very low and the overall grid was driven by traditional rotating power production assets.

Challenges

Harmonic feedback from the electrolyzer or fuel cell system to the grid could be a challenge, especially for microgrids. The impact of large-scale deployment of electrolyzers on the grid is not yet known. But if this challenge is overcome, it could result in power electronics cost reductions through reducing the number of components.

Needs & Opportunities

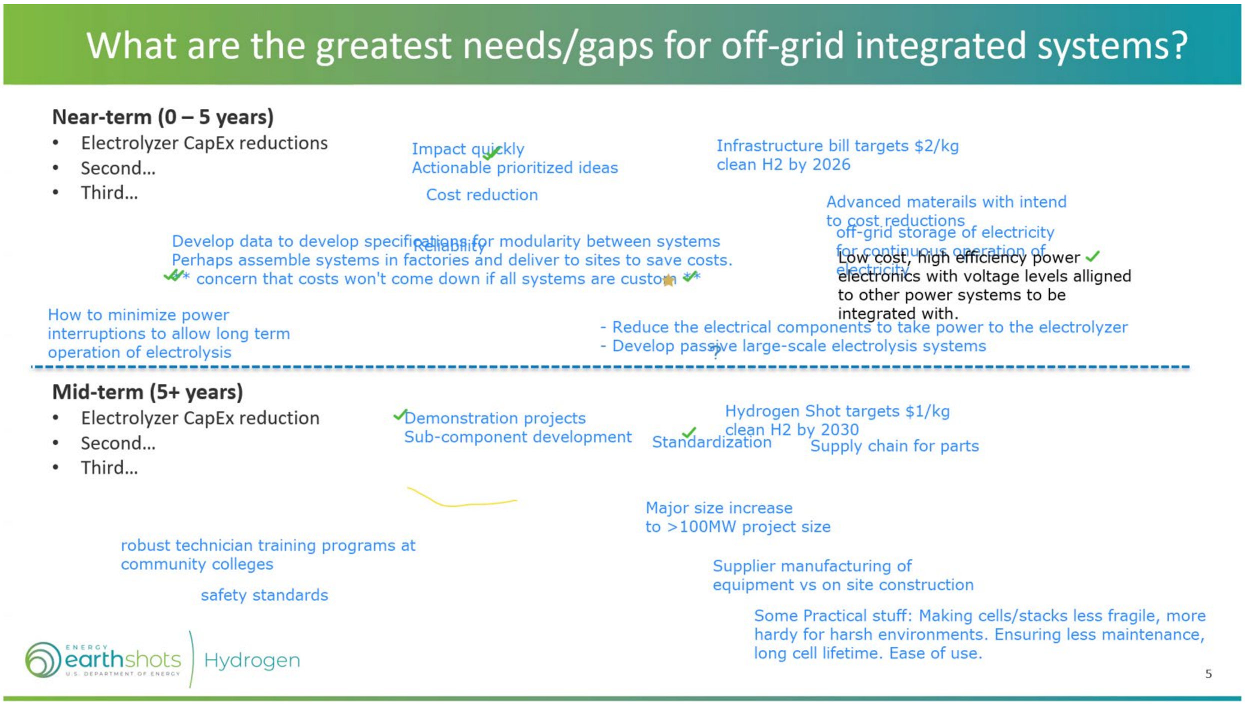
The limits and impacts of incoming power quality on the electrolyzer stack performance and degradation rate should be further investigated. The future power quality of the electricity grid and the role electrolyzers may play in providing demand/response services must be better understood to enable large scale deployment. Reversible fuel cells have the potential to provide grid services. The economic value of this service should be quantified as well as the technical potential of reversible fuel cell technology to do so.

3.2 Breakout Session 2: Off-grid Integrated Systems

This breakout session discussed the opportunities and challenges associated with coupling renewable electricity production technology directly to water electrolyzers without using grid electricity. It is anticipated that coupling electrolyzer operation directly to low-cost renewable electricity sources will be an effective approach for minimizing clean hydrogen production costs in support of the Hydrogen Shot target of $1/kg hydrogen in one decade. There have been very limited demonstrations of direct- or close-coupling of renewable electricity sources and electrolyzers. There are concerns about dynamic operation of electrolyzers when coupled to these inherently variable power sources and the impact on electrolyzer operation, gas purity, and stack lifetime.

Workshop participants were also asked to discuss existing avenues that can be leverages to accelerate development of these systems. Responses suggested leveraging local strengths, public/private partnerships, and outreach to engage the community in this effort. Community engagement will be especially important for integration of off-grid electrolyzer installations to remote communities. There was also interest in engaging; college/university involvement including diversity, equity, and inclusion efforts; the Office of Electricity on microgrids and DC power systems; the Advanced Manufacturing Office on SiC activities along with PowerAmerica for wide bandgap (WBG) power conditioning to inform modular/block-level devices; and Solar and Wind Energy Technology Offices for integrated system development.

Participants in the Off-Grid Integrated Systems breakout session included electrolyzer OEMs, fuel cell OEMs, power electronics developers, power conversion and controls solutions providers, national laboratories, and government. Early in the breakout session, participants provided input on greatest needs and gaps for off-grid integrated systems in both the near-term (1-5 yr) and mid-term (5-10 yr) as shown in Figure 9. The key discussion topics for the breakout session coalesced around DC power systems for electrolyzer stacks, especially for direct coupling with renewables, and cost reduction opportunities from development of modular and standardized power conversion solutions.



What are the greatest needs/gaps for off-grid integrated systems?

Near-term (0 – 5 years)

- Electrolyzer CapEx reductions
- Second…
- Third…

Impact quickly
Actionable prioritized ideas

Cost reduction

Infrastructure bill targets $2/kg
clean H2 by 2026

Advanced materails with intend
to cost reductions

off-grid storage of electricity
for continuous operation of
electricity

Low cost, high efficiency power
electronics with voltage levels alligned
to other power systems to be
integrated with.

Develop data to develop specifications for modularity between systems
Perhaps assemble systems in factories and deliver to sites to save costs.
** concern that costs won't come down if all systems are custom **

Reliability

How to minimize power
interruptions to allow long term
operation of electrolysis

- Reduce the electrical components to take power to the electrolyzer
- Develop passive large-scale electrolysis systems

?

Mid-term (5+ years)

- Electrolyzer CapEx reduction
- Second…
- Third…

Demonstration projects
Sub-component development

Standardization

Hydrogen Shot targets $1/kg
clean H2 by 2030

Supply chain for parts

Major size increase
to >100MW project size

robust technician training programs at
community colleges

safety standards

Supplier manufacturing of
equipment vs on site construction

Some Practical stuff: Making cells/stacks less fragile, more
hardy for harsh environments. Ensuring less maintenance,
long cell lifetime. Ease of use.

Figure 9. Mapping of greatest needs/gaps for off-grid integrated systems in near-term (1-5 yr) and mid-term (5-10 yr).

3.2.1 Direct Coupling DC Renewable Electricity Sources with Water Electrolyzers

Given the limited demonstration, as well as research & development, to date on directly coupling DC renewable electricity generation sources to electrolyzer stacks and systems, there is a significant need for work in this area to realize the potential and determine the limitations. There were discussions on the power requirements for remote applications and on power electronic design for effective, reliable, and efficient input of highly variable renewable power. There was also a discussion on whether electrolyzers can operate on direct electricity from variable renewable power or to what degree does it need to be cleaned up. From a cost and efficiency perspective, the ideal solution is to minimize the number of power conversion components/steps and operate directly on the direct DC power output of the electricity generator; however, this needs to be balanced by the electrolyzer system and stack tolerances to avoid reduction in lifetime of the stack and balance of plant components. For example, how much DC ripple current can the electrolyzer stack tolerate? The answer is likely to vary depending on the electrolyzer technology being utilized. There is a need for RD&D efforts focused on direct DC coupling of dynamic renewable energy sources to electrolyzer stacks and systems to answer these questions for both electrolyzer and PE manufacturers. Facilities such as national laboratories that have capabilities to test in real-world conditions and relevant analysis methods, would be valuable. Also additional technoeconomic analyses (TEA) and emissions life-cycle-assessments (LCA) focused on a solely DC integrated renewable energy-electrolyzer system are needed. TEAs should look at the DC power system sizing, coupling, hybridization, power quality, and turn down capability.

The electrical regulations and standards that off-grid systems must operate under are not clear and may be different from regulations for grid- and micro-grid systems. It is possible that the regulations and standards may be less strict given that the impact on the larger electrical grid does not need to be considered; however, it is unclear if there would be new system requirements to ensure safe stand-alone operations. This information would be useful for designing power electronics and electrolyzer systems for off-grid applications.

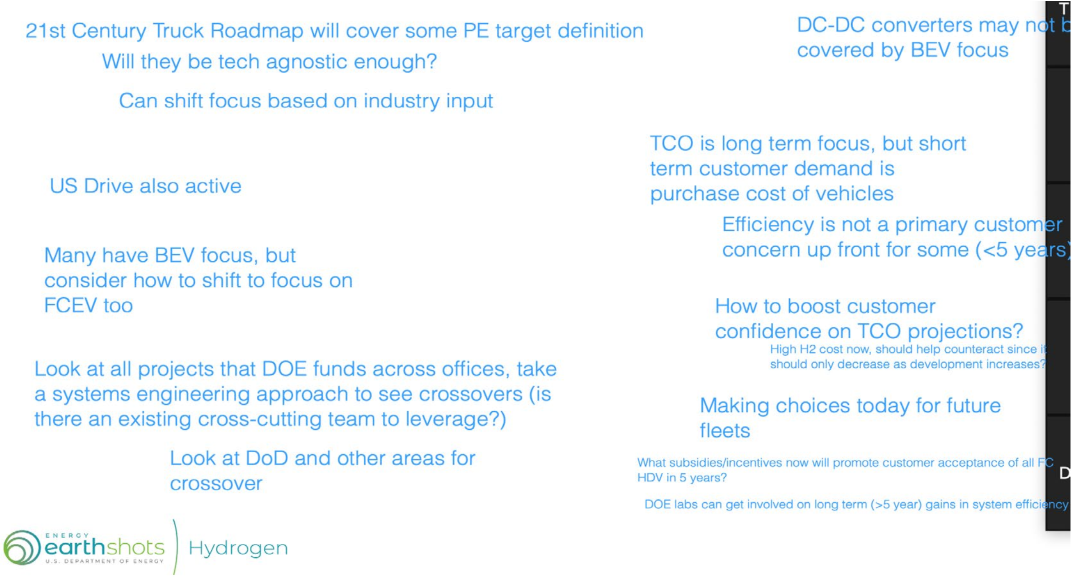
3.2.2 Power Electronics Standardization and Modularity for Low Cost

The need for standardized and modular power electronics was discussed in detail. Designing custom power electronics considering the requirements of the electrolyzer stack for each end-use case needs to be avoided to reduce costs. It would be ideal to align commercial off-the-shelf power conversion solutions for hydrogen technologies with, for example, those used in the wind and solar industries. It would also be useful to determine any unique needs for electrolyzer power electronics as compared to what is commercially available. Coordination between electrolyzer stack, especially, system manufacturers, and power electronics developers will be important. Developing data to specify system requirements/parameters for modularity with an aim towards low-cost power electronics and part minimization should lead to increased manufacturing of standard, low-cost integrated systems. One key consideration is the stack's operating voltage and current requirements and their impacts on power electronics decision-making (e.g., conventional IGBT, advanced WBG architectures based on SiC or GaN, or otherwise). There are tradeoffs between designing stacks with higher cell counts (i.e., higher DC voltage) with smaller cell active areas (i.e., lower DC current) and vice versa. Optimizing multi-stack system operations and whether to electrically wire stacks in series or parallel are other considerations.

3.3 Breakout Session 3: Transportation Applications

Fuel cells have the potential to provide an energy efficient, environmentally friendly solution for HDVs with greater range and lighter weight than current battery electric options. Shorter fueling times and greater driving range compared to internal combustion engine (ICE) trucks make hydrogen fuel cells ideal for the trucking industry and commercial HDV fleets. This breakout session intended to gather feedback from participants on the most critical technological challenges, gaps, and opportunities for successful implementation and acceleration of adoption of fuel cells for transportation applications. The participants of the discussion were also asked to consider technological gaps and performance targets for hydrogen FCEV systems in both the near term (<5 years) and long term (≥5years).

A number of key stakeholders participated in the breakout session including fuel cell OEMs, power semiconductor manufacturers, power electronics experts, truck fleet owners/operators, and university researchers. The session provided a constructive discussion on how to best leverage fuel cells and power electronics for transportation applications. Based on an initial round of brainstorming (results shown in Figure 10) the three topics however that showed to have the greatest interest by participants included (1) standardization of the power electronics systems, (2) improvements in thermal management systems for power



21st Century Truck Roadmap will cover some PE target definition

Will they be tech agnostic enough?

Can shift focus based on industry input

US Drive also active

Many have BEV focus, but consider how to shift to focus on FCEV too

Look at all projects that DOE funds across offices, take a systems engineering approach to see crossovers (is there an existing cross-cutting team to leverage?)

Look at DoD and other areas for crossover

DC-DC converters may not b covered by BEV focus

TCO is long term focus, but short term customer demand is purchase cost of vehicles

Efficiency is not a primary customer concern up front for some (<5 years

How to boost customer confidence on TCO projections?

High H2 cost now, should help counteract since i should only decrease as development increases?

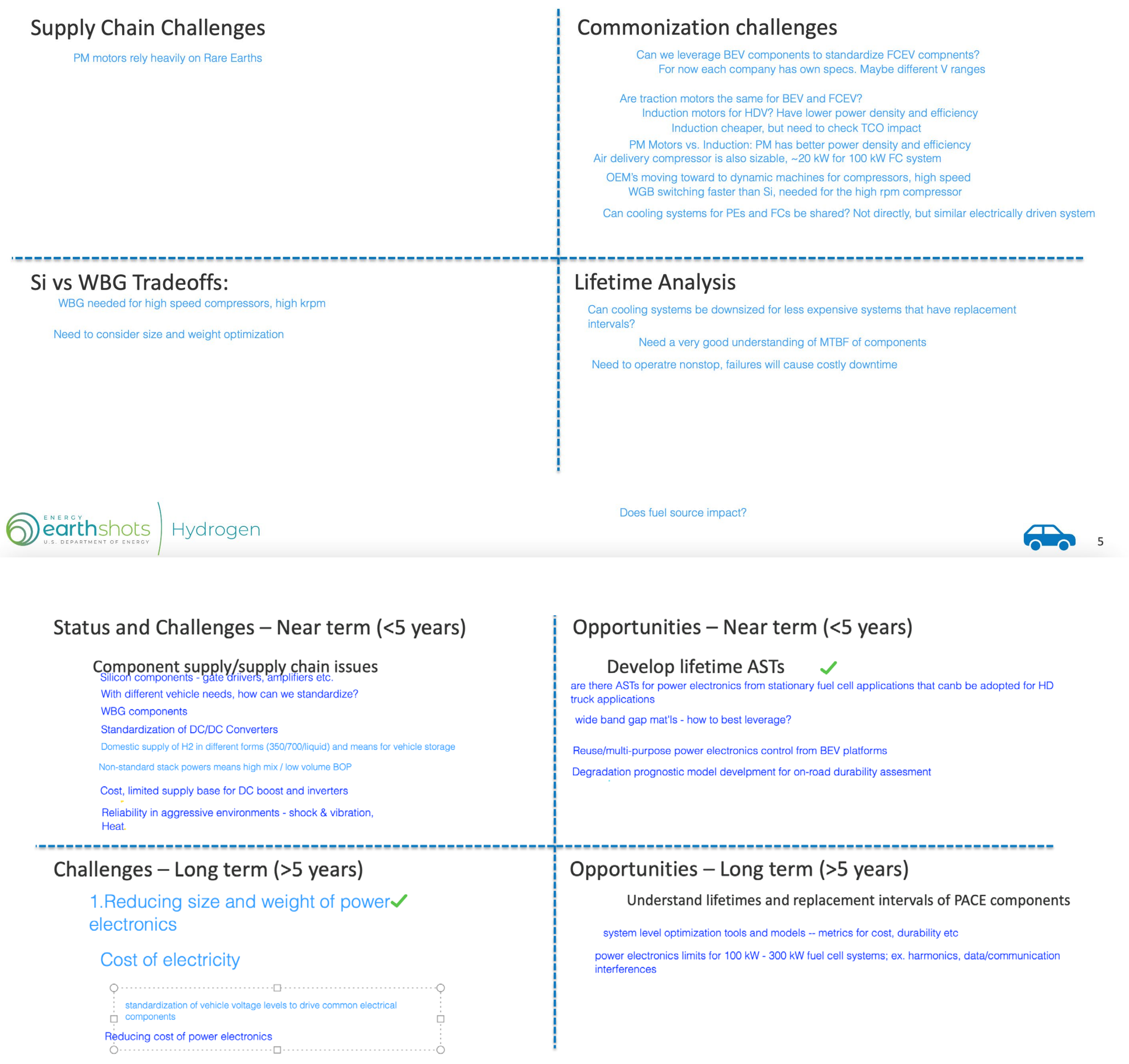
Making choices today for future fleets

What subsidies/incentives now will promote customer acceptance of all FC HDV in 5 years?

DOE labs can get involved on long term (>5 year) gains in system efficiency

Figure 10. Snapshots of initial discussions in the Transportation Applications Breakout Session.

conditioning, and (3) alleviating the concerns of TCO for HDV fleet owners due to the significant immediate cost (< 5years) for acquiring FCEV fleets. Participant discussions about these three topic areas are summarized in separate sub-sections below.



Supply Chain Challenges

PM motors rely heavily on Rare Earths

Commonization challenges

Can we leverage BEV components to standardize FCEV compnents?
For now each company has own specs. Maybe different V ranges

Are traction motors the same for BEV and FCEV?
Induction motors for HDV? Have lower power density and efficiency
Induction cheaper, but need to check TCO impact
PM Motors vs. Induction: PM has better power density and efficiency
Air delivery compressor is also sizable, ~20 kW for 100 kW FC system
OEM's moving toward to dynamic machines for compressors, high speed
WGB switching faster than Si, needed for the high rpm compressor

Can cooling systems for PEs and FCs be shared? Not directly, but similar electrically driven system

Si vs WBG Tradeoffs:

WBG needed for high speed compressors, high krpm

Need to consider size and weight optimization

Lifetime Analysis

Can cooling systems be downsized for less expensive systems that have replacement intervals?
Need a very good understanding of MTBF of components

Need to operatre nonstop, failures will cause costly downtime

Does fuel source impact?

Hydrogen

5

Status and Challenges – Near term (<5 years)

Component supply/supply chain issues
Silicon components - gate driivers, amplifiers etc.
With different vehicle needs, how can we standardize?
WBG components
Standardization of DC/DC Converters
Domestic supply of H2 in different forms (350/700/liquid) and means for vehicle storage
Non-standard stack powers means high mix / low volume BOP
Cost, limited supply base for DC boost and inverters
Reliability in aggressive environments - shock & vibration, Heat

Opportunities – Near term (<5 years)

Develop lifetime ASTs ✓
are there ASTs for power electronics from stationary fuel cell applications that canb be adopted for HD truck applications
wide band gap mat'ls - how to best leverage?

Reuse/multi-purpose power electronics control from BEV platforms

Degradation prognostic model develpment for on-road durability assesment

Challenges – Long term (>5 years)

1.Reducing size and weight of power✓ electronics

Cost of electricity

standardization of vehicle voltage levels to drive common electrical components
Reducing cost of power electronics

Opportunities – Long term (>5 years)

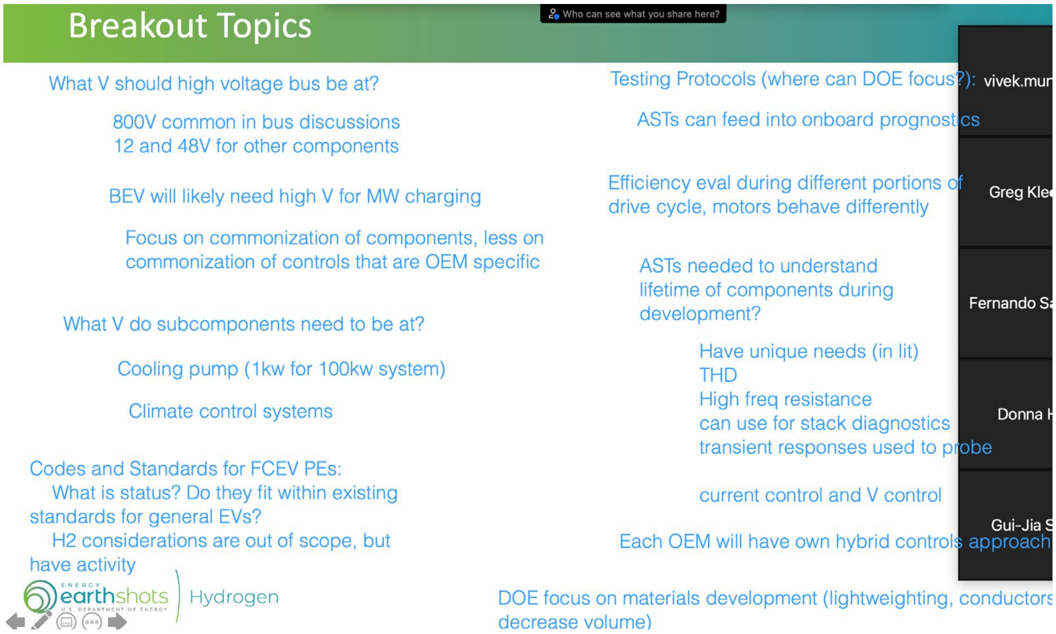
Understand lifetimes and replacement intervals of PACE components

system level optimization tools and models -- metrics for cost, durability etc

power electronics limits for 100 kW - 300 kW fuel cell systems; ex. harmonics, data/communication interferences

Figure 11. Mapping of status, challenges, and opportunities for fuel cells in transportation applications

Figure 11 shows the active discussion between the participants regarding the short-term and long-term challenges and opportunities for transportation applications of hydrogen fuel cells. The breakout conversation additionally focused on how to maximize innovation and commercial adoption by prioritizing specific sub-system and component RD&D for HDVs. Participants were asked to identify major components in fuel cell power conditioning systems which have the greatest impact on cost, efficiency, weight, and power density. Figure 12 below shows the active discussion between the participants regarding the targets needed by OEMs.



Breakout Topics

What V should high voltage bus be at?

800V common in bus discussions
12 and 48V for other components

BEV will likely need high V for MW charging

Focus on commonization of components, less on commonization of controls that are OEM specific

What V do subcomponents need to be at?

Cooling pump (1kw for 100kw system)

Climate control systems

Codes and Standards for FCEV PEs:
What is status? Do they fit within existing standards for general EVs?
H2 considerations are out of scope, but have activity

Testing Protocols (where can DOE focus?):

ASTs can feed into onboard prognostics

Efficiency eval during different portions of drive cycle, motors behave differently

ASTs needed to understand lifetime of components during development?

Have unique needs (in lit)
THD
High freq resistance
can use for stack diagnostics
transient responses used to probe

current control and V control

Each OEM will have own hybrid controls approach

DOE focus on materials development (lightweighting, conductors
decrease volume)

Figure 12. Participant discussion points on status and OEM needs in fuel cells for transportation applications.

3.3.1 Standardization of Power Electronics Systems

According to respondents, standardization of power electronics components and operating voltage levels would reduce the complexity of designs, simplify maintenance, and reduce costs. The current state of power electronics systems utilized in transportation applications are designed uniquely for the vehicle manufacturers electric motor power rating and the fuel cell pack voltage. Setting a standardized fuel cell pack size or voltage level would allow for FCEV manufacturers to reduce the total cost of production by shortening the design process. Standardization could also allow for device commonality in the power electronics sub-systems in transportation applications. Setting a shared operating voltage range would reduce the variance of application specific components, such as capacitors and power switches. Manufacturers could then purchase components in greater quantities, lowering the total cost per component, and total cost of the system.

It will be difficult to standardize power electronics for vehicle systems because vehicle manufacturers and OEMs are responsible for their power control designs, many of which utilize unique system designs geared for the specific vehicle models. The DOE is currently supporting partnerships with truck manufacturers, major suppliers, and interagency partners to determine opportunities to accelerate adoption, optimize power electronics, improve efficiencies, cost-competitiveness, and safety of FCEVs. Partnerships such as the 21st Century Truck Partnership, SuperTruck 3 program, and the M2FCT consortium are considering how power electronics standardization and optimization may accelerate electrification and advance the next generation fuel cell technology for medium- and heavy-duty (MD/HD) long haul trucks.

3.3.2 Improvements in Thermal Management System

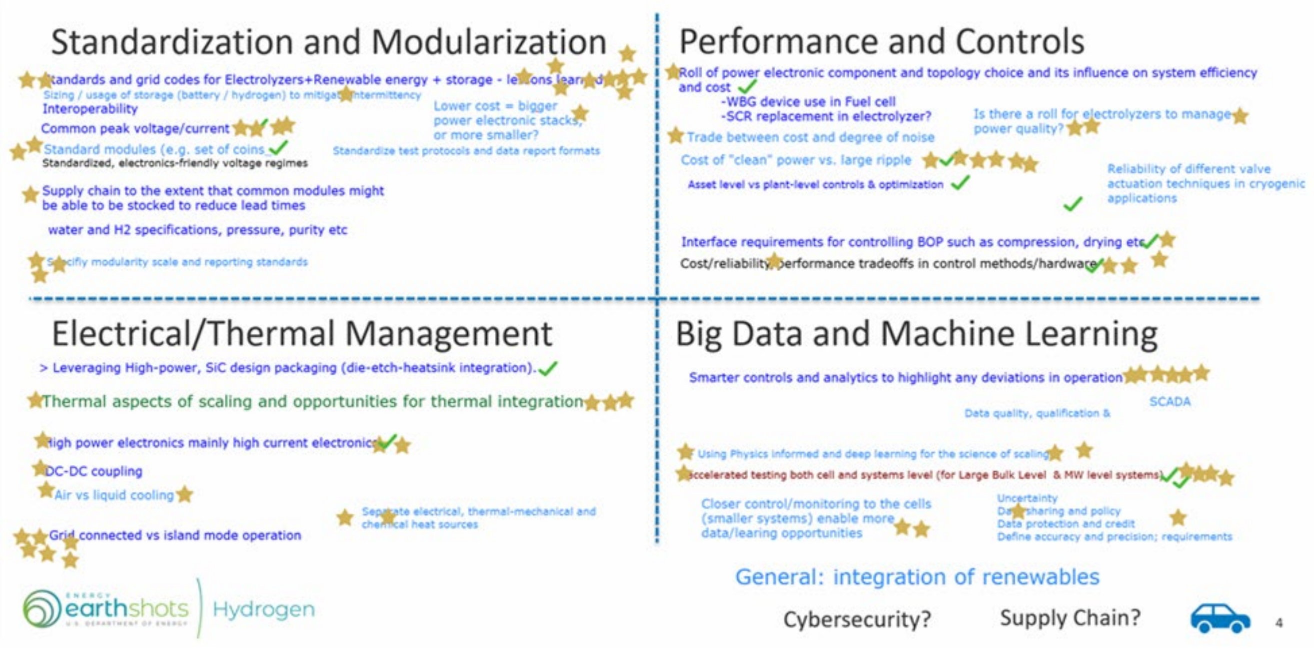
MD/HD vehicles require greater power requirements for the fuel cells, electric motor, and traction powertrain due to the size and weight of the vehicle as well as the greater required driving range. These higher power systems require custom, compact, demanding, and reliable thermal management systems to maintain component temperatures within the operating range. These systems are typically costly and add substantially to the total weight and volume of the power system. There is a need for more cost effective and power dense thermal management systems for FCEVs, including novel, cost-effective thermal interface materials for power modules, greater supply chain resiliency, and superior liquid cooling solutions. The current thermal management solutions utilized in power electronics were discussed and contrasted to determine the benefits and disadvantages of each cooling method. From a performance aspect, liquid cooling with a cold plate and radiator allows for greater cooling and therefore more efficient system.

3.3.3 Fuel Cell Cost of Acquisition

The total cost of ownership for MD/HD fuel cell truck fleet owners/operators was discussed. Fleet owners mentioned there are concerns for the adoption of FCEV trucks due to the substantial acquisition cost per vehicle. Many respondents stated that even though FCEV trucks have the potential for superior long-term returns compared to ICE trucks, the uncertainty of the technology direction and customer demand made short-term investments more of a priority for fleet owners. According to many in the discussion, improving the efficiency of FCEV trucks was also not as important as the need to significantly reduce the upfront investment for fleets. It is necessary to determine technological pathways to reduce the cost of the traction drive systems for FCEVs to reduce the acquisition cost of trucks for fleet owners/operators.

3.4 Breakout Session 4: Cross-cutting Topics

The cross-cutting breakout session began with participants using the annotation tools of the virtual meeting platform to add their suggestions for specific discussion topics under four broad categories of Standardization and Modularization, Electrical/Thermal Management, Performance and Controls, and Big Data and Machine Learning (which were identified by the organizers in advance). Participants were encouraged to add their own specific ideas as well as use indicators to highlight their agreement with or support of the suggestions for discussion from others, as shown in Figure 13. This initial brainstorming was used to further direct the discussion as participants identified common areas of interest, concern, and opportunity.



Standardization and Modularization

Standards and grid codes for Electrolyzers+Renewable energy + storage - lessons learned
Sizing / usage of storage (battery / hydrogen) to mitigate intermittency
Interoperability
Common peak voltage/current
Standard modules (e.g. set of coins
Standardized, electronics-friendly voltage regimes
Lower cost = bigger power electronic stacks, or more smaller?
Standardize test protocols and data report formats
Supply chain to the extent that common modules might be able to be stocked to reduce lead times
water and H2 specifications, pressure, purity etc
Specifiy modularity scale and reporting standards

Performance and Controls

Roll of power electronic component and topology choice and its influence on system efficiency and cost
-WBG device use in Fuel cell
-SCR replacement in electrolyzer?
Is there a roll for electrolyzers to manage power quality?
Trade between cost and degree of noise
Cost of "clean" power vs. large ripple
Asset level vs plant-level controls & optimization
Reliability of different valve actuation techniques in cryogenic applications
Interface requirements for controlling BOP such as compression, drying etc
Cost/reliability/performance tradeoffs in control methods/hardware

Electrical/Thermal Management

> Leveraging High-power, SiC design packaging (die-etch-heatsink integration).
Thermal aspects of scaling and opportunities for thermal integration
High power electronics mainly high current electronics
DC-DC coupling
Air vs liquid cooling
Separate electrical, thermal-mechanical and chemical heat sources
Grid connected vs island mode operation

Big Data and Machine Learning

Smarter controls and analytics to highlight any deviations in operation
SCADA
Data quality, qualification &
Using Physics informed and deep learning for the science of scaling
Accelerated testing both cell and systems level (for Large Bulk Level & MW level systems)
Closer control/monitoring to the cells (smaller systems) enable more data/learing opportunities
Uncertainty
Data sharing and policy
Data protection and credit
Define accuracy and precision; requirements

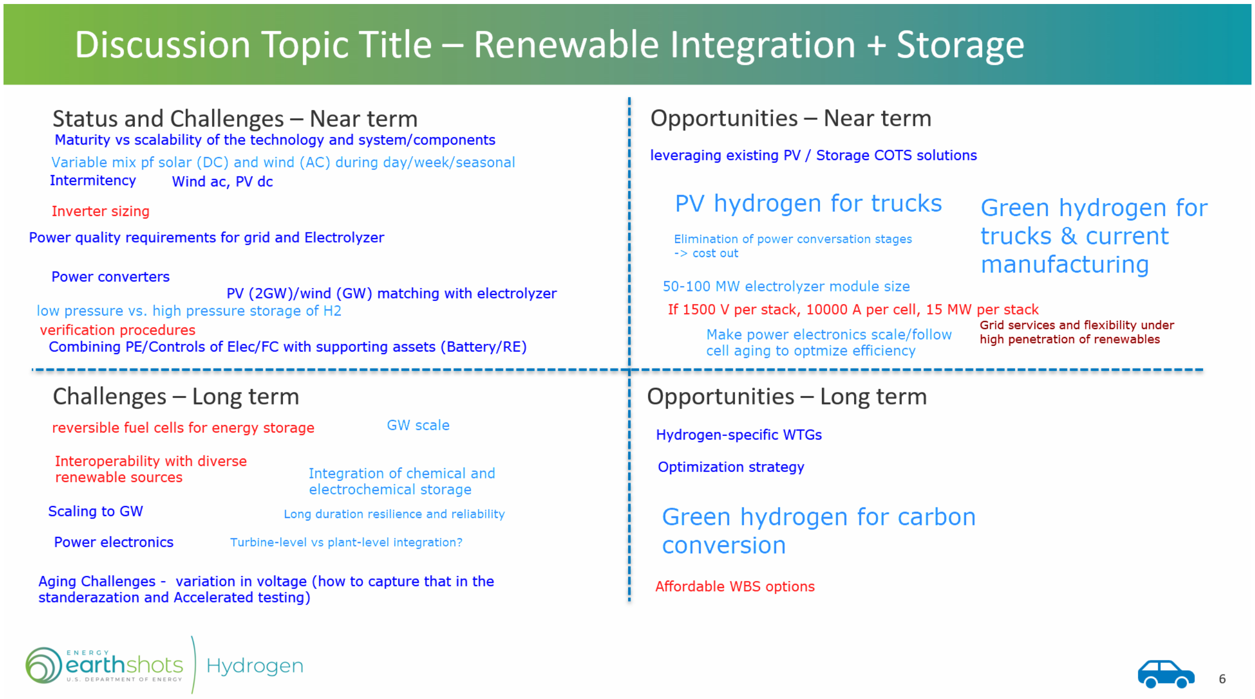
General: integration of renewables

Cybersecurity?
Supply Chain?

Figure 13. Initial brainstorming and discussion outcomes from the Cross-cutting Breakout Session.

3.4.1 Cross-cutting challenges, and opportunities

As a result of the initial brainstorming, the group prioritized the topic of renewable integration and storage, each having relevance for both electrolyzers and fuel cells, and each touching on all four of the broader categories of Standardization and Modularization, Electrical/Thermal Management, Performance and Controls, and Big Data and Machine Learning. A more in-depth brainstorming session continued with participants focusing on challenges and opportunities in both the near and long term in the context of these specific topic areas, as illustrated in Figure 14.



Discussion Topic Title – Renewable Integration + Storage

Status and Challenges – Near term

Maturity vs scalability of the technology and system/components

Variable mix pf solar (DC) and wind (AC) during day/week/seasonal

Intermitency

Wind ac, PV dc

Inverter sizing

Power quality requirements for grid and Electrolyzer

Power converters

PV (2GW)/wind (GW) matching with electrolyzer

low pressure vs. high pressure storage of H2

verification procedures

Combining PE/Controls of Elec/FC with supporting assets (Battery/RE)

Opportunities – Near term

leveraging existing PV / Storage COTS solutions

PV hydrogen for trucks

Elimination of power conversation stages
-> cost out

Green hydrogen for trucks & current manufacturing

50-100 MW electrolyzer module size

If 1500 V per stack, 10000 A per cell, 15 MW per stack

Make power electronics scale/follow cell aging to optmize efficiency

Grid services and flexibility under high penetration of renewables

Challenges – Long term

reversible fuel cells for energy storage

GW scale

Interoperability with diverse renewable sources

Integration of chemical and electrochemical storage

Scaling to GW

Long duration resilience and reliability

Power electronics

Turbine-level vs plant-level integration?

Aging Challenges - variation in voltage (how to capture that in the standerazation and Accelerated testing)

Opportunities – Long term

Hydrogen-specific WTGs

Optimization strategy

Green hydrogen for carbon conversion

Affordable WBS options

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

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Figure 14. More in-depth brainstorming on prioritized topics of renewable integration and storage.

After the second round of brainstorming, the group embarked on more detailed discussions and prioritization of the various challenges and opportunities that had been identified. Key points from these discussions are summarized below:

3.4.2 Near-term priorities and opportunities

Immediate challenges that need to be addressed:

- Standardizing power quality requirements for grid and off-grid installations of electrolyzers and fuel cells
- Matching variable mix of solar (DC) and wind (AC) to electrolyzers at the multi-MW and GW scales
- Optimized integration of power electronics/controls of electrolyzer/fuel cell with supporting assets, e.g., batteries
- Addressing maturity vs scalability of technology and system/components, including the core electrolyzer and fuel cell technologies as well as the BOP electronics for stack power and controls and for auxiliary system functions such as water and gas management

- Development of new standards for power and control of electrolyzers and fuel cells that take into account unique electrochemical response characteristics of these technologies
- Developing accelerated testing protocols for both electrolyzers and fuel cells that relate voltage perturbations to aging mechanisms and can help in the design of electronics-based mitigation strategies for prolonging life.
- Developing accelerated qualification processes for integrated electrolyzer and fuel cell systems including power and control electronics sub-systems at scales relevant to anticipated commercial deployment

Some specific high-priority opportunities:

- Implementation of applications-driven designs for power and control electronics for hydrogen technologies at current scales (e.g., up to 1-2 MW) to develop lessons learned and best practices
- Demonstration of integrated systems at scales on the order of 10 MW or greater to start addressing specific issues relevant to these scales
- Design and optimization of power and control electronics sub-systems for planned electrolyzer installations at the 10-100 MW scale; specifically able to accommodate 1500 V/stack, 10000 A/cell, 15 MW/stack
- Development of innovative power and control electronics that follow cell aging to optimize efficiency and prolong electrolyzer and/or fuel cell life
- Applying data-drive machine learning to elucidate aging effects and develop mitigation strategies
- Demonstration and qualification of grid services and flexibility offered by electrolyzers and reversible fuel cells under high penetration of renewables (e.g., through research facilities such as NREL-ESIF/ARIES, as well as data collection at different demonstration and deployment sites)
- Leveraging interagency groups (including DOE, DOD, DOT, EPRI, among others) to focus on power electronics and thermal management RDD&D efforts in an integrated *Power Electronics Building Blocks* approach
- Leveraging existing PV/storage commercial off-the-shelf (COTS) solutions for integrated energy systems

3.4.3 Ongoing needs

Broad challenges and opportunities:

- Interoperability with diverse renewable resources
- Achieving GW-scale integrated systems that are affordable, including through implementation of scaling that include nonlinearity definitions
- Long duration resilience and reliability of electrolyzers and fuel cell, as well as electronics BOP
- Integration and controls of chemical and electrochemical storage
- Fundamental understanding of the relationship between voltage variations and degradation processes in electrolyzers and fuel cells to assist in development of accelerated testing and electronics-based mitigation strategies

- Fully-integrated systems specifically designed to directly couple wind turbines with electrolyzers for optimal hydrogen production
- Affordable and efficient unitized reversible fuel cells with appropriate power and control systems for energy storage applications
- Power and controls of integrated systems for carbon conversion to fuels and chemicals leveraging clean hydrogen
- Affordable wide bandgap semiconductor materials, devices and modules with voltage and thermal properties that could directly benefit integration with electrolyzers and fuel cells

Specific needs in renewable integration with storage:

- Matching energy source with hydrogen generation for optimizing capacity factor
- Establishing voltage, current, and harmonic standards to facilitate coupling of power generation and hydrogen production across scales
- Electronics solutions to both off-grid and grid-tied installations
- Electronics solutions to both bulk power and distributed systems (MW and GW scale)
- Modularization of electronics sub-systems as a means of achieving different scales
- Important considerations specifically related to power quality
- Need to establish unique power quality requirements across all relevant operational power levels
- Need to develop better understanding related to the rate of change for perturbations (current vs time and voltage vs time)
- Need to develop a better understanding of how voltage and current perturbations are distributed through the stack
- Need to establish clear power cleanliness requirements for grid-tied vs microgrid applications
- Need to develop a better understanding of time scale of power quality of electrical/thermal/chemical and coupling of processes
- Need to consider wide bandgap devices for power quality as an emerging option
- Need to address codes and standards relevant to grid installations, for example, IEEE 519, UL1741, CA rule 21, HI rule 14, etc.

3.4.4 Cross-cutting recommendations

Who needs to come to the table?

- Electrolyzer and fuel cell manufacturers
- Wind and PV system installers
- Industrial system integrators experienced in wind, PV, and storage systems
- Clean hydrogen users across sectors (including transportation, industry, chemicals, power utilities, major energy users, etc.)

- Electrochemical and electronic community experts (electrochemists and electrical engineers need to collaborate to develop practical innovative electronics-based solutions)
- Codes and standards experts – including, but not limited to IEEE 519, UL1741, CA rule 21, HI rule 14, etc.
- OEMs of electronics components, devices, modules, and integrated systems interested in leveraging the growing opportunities for hydrogen and fuel cell technologies (such as GE Power, ABB, Hitachi, among numerous others)
- Interagency groups (e.g., DOE, DOD, DOT, EPRI, among others)

Some key takeaways:

- Integration of electrolyzer and fuel cell technologies with renewables in both on- and off-grid installations offers substantial opportunities to provide 24/7 services, and optimization of power and control electronics interfaces will be important to this integration
- Microgrid demonstrations can provide valuable lessons-learned in scalability, performance, durability, safety, soft-costs, etc. that can be applied to a broad range of hybrid energy systems incorporating hydrogen and fuel cell technologies
- Standardization and modularization across technologies will be important for scale up and commercialization, and will help optimize necessary supply chains
- Large companies may not be ready to commit at this point without major incentives, e.g., tax credits
- Continued technoeconomic and life cycle cost analysis is still needed to identify key opportunities for cost reduction in integrated electrolyzer and fuel cell systems incorporating optimized power and control electronics sub-systems.

4 Common Themes from Open Discussion

All H2-PACE participants were welcomed to join in open discussion sessions at the end of both Day one and Day two of the H2-PACE Experts Meeting. In addition, open discussions were encouraged during the Wonder Room networking session on Day two. These discussions reiterated many of the key common themes and topics highlighted during the course of the panel and breakout sessions. Discussion themes and topics are summarized below.

Need for Cost Reductions Across Electrolyzer and Fuel Cell Technologies

Cost is a major driver in the implementation of integrated power and control systems for electrolyzer and fuel cell technologies for diverse end-use applications. Cost reductions through technology development and manufacturing economies of scale need to continue in electrolyzers, fuel cells, and in advanced power and control electronics. Specific cost-reduction potential opportunities exist in the co-design of systems, leveraging physical, electrical, and thermal integration strategies guided by performance, durability, and safety requirements. Power and control electronics sub-systems are a potential area for cost reduction through design flexibility in the optimization of stack hardware configurations and sizing. Advanced control approaches can also mitigate cell and stack failure modes, thus reducing replacement and operations and maintenance (O&M) costs. The design parameter space targeting cost reductions needs to account for delivered cost of the electrolyzer and/or fuel cell system, including shipping and installation, in addition to capital expense, O&M costs, etc. Electrical regulatory constraints on voltage and current (including safety concerns), frequency and harmonics, etc., need to be considered in the development of cost-effective strategies and designs covering a broad range of hydrogen and fuel cell applications.

Importance of Leveraging Lessons Learned for Other Industries and Initiatives

There are several important opportunities to leverage power and control electronics products developed for the renewable power and energy storage industries in developing similar products specifically geared for electrolyzers and fuel cells. This includes adapting inverter and DC-DC converter technologies and products developed for solar and wind power applications and behind-the-meter-storage technologies. The lessons learned should include mitigation strategies developed for real-world operational conditions such as temperature, elevation, coastal and marine environments, etc., that can impact the performance and durability of integrated systems comprising electrolyzers and fuel cells with power and control electronics. Leveraging related initiatives and activities (e.g., through the HFTO Consortia, DOE PowerAmerica Institute, the 21st Century Truck Partnership, projects with the NREL-ARIES Power Electronic Grid Interface platform, etc.) will be crucial.

Importance of Standardization and Modularity

An important takeaway from the meeting is the need for standardization and modularity to facilitate the development of power and control product serving a wide range of applications and scales for electrolyzers and fuel cells. Voltage, current, frequency, and harmonic standards need to be more firmly established relevant to grid, micro-grid, and direct renewable-coupling hardware (beyond current standards such as IEEE 519, UL1741, CA rule 21, HI rule 14, etc.). In the near-term, large-scale electrolyzer and fuel cell installations for grid connections pose unique challenges that need to be addressed; and standards need to evolve. Beyond defining and standardizing specific hardware metrics for power and control equipment in electrolyzers and fuel cells, it will be important to continue standardization of regulations and codes that addresses performance and durability as well as operations, maintenance, and safety, both domestically and internationally.

Opportunities to Address Policy and Regulatory Frameworks

There is an urgency for the development of integrated systems for clean hydrogen generation and utilization, and legislators and policy makers should help pave the way for smoother and more nimble process in support of public-private partnerships. Regulatory speed bumps and policy barriers have slowed progress in the development and scale-up of integrated electrolyzer and fuel cell systems (including the power and control electronics balance of plant). Specific regulatory constraints concerning voltage and current (including standards and safety concerns at high voltage and/or high current operations) as well as frequency and harmonics need to be considered and addressed when developing cost-effective power and control electronics solutions for electrolyzers and fuel cells.

Importance Testing and Validation Facilities

There is an important need for testing and validation facilities to inform public-private partnerships in technology development and commercial qualification, as well as informing priorities for policy makers and funding agencies. It is important to leverage interagency collaboration/consortia between existing testing and characterization facilities in laboratories, universities, and industry at MW-scales, including power electronics, hydrogen electrolyzer and fuel cell vendors, and system integrators. To help accelerate scale-up of commercialization, ready, plug-and-play test-beds with advanced capabilities such as hardware-in-the-loop and digital-twins are needed. These can build upon current capabilities (e.g., at NREL ESIF/ARIES, INL, PNNL, and NETL, with virtual interconnection for federated testing through the ESnet network) for demonstration of power and control electronics in low- and high-temperature electrolyzer and fuel cell systems. The Power Electronic Grid Interface (PEGI) platform at NREL-ARIES is a good example of a resource that could be leveraged. A distributed network of dedicate testing and validation facilities comprising national laboratories, universities, and industrial research entities should be developed to cover the range of applications and scales relevant to emerging electrolyzer and fuel cell markets. It is important to consider electronics requirements of the full electrolyzer and/or fuel cell system (including components such as compressors, dryers, water and thermal management sub-systems, etc., in addition to stack operations) in the development, testing, and validation efforts.

The Time is Now!

Given national and global priorities in clean energy and in addressing the climate challenge, there is urgency to muster all stakeholders in an ‘all-hands-on-deck’ effort to achieve the ambitious goals of the Hydrogen Energy Earthshot, including through innovation and advances in affordable integrated power and control systems for electrolyzer and fuel cell systems at different scales, and for diverse clean-energy end uses. Researchers, technology developers, testing and validation experts at universities and national laboratories with expertise in electronic and electrochemical systems need to work in conjunction with commercialization partners and with funding, policy, and regulatory agencies.

5 Next Steps

Materials from the H2-PACE Experts Meeting. including panelist presentations and this report will be published to the website:

H2-PACE: Power And Control Electronics for Hydrogen Technologies Meeting | Department of Energy

Additional Experts Meetings and Workshops under the Hydrogen Shot are being held in related topics, such as: advanced liquid alkaline electrolysis; high-temperature electrolyzer manufacturing; proton exchange membrane electrolyzers; fuel cell manufacturing and recycling; among others. Materials from these meetings and workshops will be made available at the website:

Workshop and Meeting Proceedings | Department of Energy

Feedback obtained from all these events will be used in conjunction with responses from requests for information and feedback from multiple listening sessions with stakeholders to help determine priority areas for RD&D investments through the U.S. Department of Energy’s Hydrogen Program, in support of the Hydrogen Energy Earthshot and the National Clean Hydrogen Strategy.

For additional information about the H2-PACE Experts Meeting, or to request additional contact information about its participants, please send an email to: H2PE@ee.doe.gov.

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