Two Audio Options: Streaming Audio and Dial-In.
- Streaming Audio/Computer Speakers (Default)
- Dial-In: Use the Audio Panel (right side of screen) to see dial-in instructions. Call-in separately with your telephone.

Question & Answers
- Ask questions using the Questions Panel on the right side of your screen.

Recording & Slides
- The recording of the webinar and the slides will be available after the event. Registrants will be notified by email.

Troubleshooting
- Contact Emanuel Wagner | ewagner@californiahydrogen.org

HOUSEKEEPING
FEATURED MODERATOR AND SPEAKER

William “Bill” Zobel  
Executive Director,  
California Hydrogen Business Council

Dr. Jack Brouwer  
Director, National Fuel Cell Research Center,  
UC Irvine  
Director, Advanced Power and Energy Program, UC Irvine  
Professor of Mechanical and Aerospace Engineering
Our Vision:
- CHBC is committed to advancing the commercialization of hydrogen in the energy and transportation sectors to achieve California’s climate, air quality, and decarbonization goals.

Our Mission:
- Provide clear value to our members and serve as an indispensable and leading voice in promoting the use of hydrogen in the utility and transportation sectors in California and beyond.

Our Principals:
- Leadership, Integrity, Teamwork and Inclusion.

Our Objectives:
- Enhance market commercialization through effective advocacy and education of policymakers and policy influencers
- Be “the” trusted “go to” resource on Hydrogen and Fuel Cell technology for policymakers and policy influencers
- Accelerate market growth via networking opportunities and information exchange for the industry and its customers
VALUE IN MEMBERSHIP

- Active representation in all relevant California policy making venues
- A trusted and knowledgeable industry resource
- Access to policymakers, policy influencers and industry
- Track record of success
- Platform for industry collaboration
- Learn more: www.californiahydrogen.org

BECOME A MEMBER AND MAKE A DIFFERENCE
TOGETHER WE CAN INFLUENCE PUBLIC POLICY AND GROW YOUR BOTTOM LINE
Dr. Jack Brouwer
Director, National Fuel Cell Research Center, UC Irvine
Director, Advanced Power and Energy Program, UC Irvine
Professor of Mechanical and Aerospace Engineering
Hydrogen 101 – Myths vs. Facts

Jack Brouwer

June 17, 2021

California Hydrogen Business Council
Webinar Series
Hydrogen Properties

Molecular Hydrogen Properties

- Gaseous specific gravity of 0.0695 at atmospheric pressure
  - $\text{H}_2$ molecular weight = 2
- Boiling point of -423°F (-252.8°C) at atmospheric pressure
- Colorless
- Odorless
- Tasteless
- Non-toxic
- Flammable gas
  - Higher heating value (HHV) = 60,958 BTU/lb (141,670 kJ/kg)
  - Lower heating value (LHV) = 51,571 BTU/lb (119,855 kJ/kg)
Some Hydrogen Myths

- Hydrogen is not safe
- Hydrogen is fossil
- Hydrogen will be more expensive than other zero emission options
- Hydrogen is less efficient than other zero emission options
- Hydrogen leaks too much
- Hydrogen is not compatible in current infrastructure
Hydrogen Safety

• Risk scenarios must consider: (1) flammability, (2) density, (3) diffusivity, (4) ignition energy, (5) total energy available

Density:
• Hydrogen is the lightest element and molecule.
• $\text{H}_2$ is 8 times lighter than natural gas. Per unit of energy contained, $\text{H}_2$ weighs 64% less than gasoline or 61% less than natural gas.
• Hydrogen is 14.4 times lighter than air. Natural gas is only 1.7 times lighter than air.

Diffusivity:
• Hydrogen is four time more diffusive than natural gas and 11 times more diffusive than gasoline fumes. $\text{H}_2$ is most diffusive fuel.

Total Available Energy:
• 1 kg of hydrogen has about the same energy as 1 gallon of gasoline which weighs 2.8 kg. Gasoline has 22 times the explosive power per unit of volume than gaseous hydrogen.
Hydrogen Safety

- Risk scenarios must consider: (1) flammability, (2) density, (3) diffusivity, (4) ignition energy, (5) total energy available

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Total Available Energy:
- 1 kg of hydrogen has about the same energy as 1 gallon of gasoline which weighs 2.8 kg. Gasoline has 22 times the explosive power per unit of volume than gaseous hydrogen. \( \text{H}_2 \) unequivocally safer than current fuels!
Hydrogen Safety – Flammability Limits

<table>
<thead>
<tr>
<th>Property</th>
<th>Hydrogen</th>
<th>Methane</th>
<th>Propane</th>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Flammability Limit</td>
<td>4%</td>
<td>5.3%</td>
<td>1.7%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Lower Detonation Limit</td>
<td>18.3%</td>
<td>6.3%</td>
<td>3.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Upper Detonation Limit</td>
<td>59%</td>
<td>13.5%</td>
<td>9.2%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Upper Flammability Limit</td>
<td>75%</td>
<td>17%</td>
<td>10.9%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Auto Ignition Temperature</td>
<td>585 C</td>
<td>537 C</td>
<td>450 C</td>
<td>228-471 C</td>
</tr>
<tr>
<td>Minimum Ignition Energy</td>
<td>0.017 mJ</td>
<td>0.274 mJ</td>
<td>0.240 mJ</td>
<td>0.240 mJ</td>
</tr>
</tbody>
</table>

- Upper Flammability Limit is of less practical consequence
- Radius of concern is defined by LFL
- Safety sensors design for % of LFL
- 4 times higher concentration than gasoline required to get flammability yet it disperses 11 times faster. It is only half as likely as gasoline to ignite in open air.
Hydrogen Safety – Ignition Energy

- Lowest ignition energy at stochiometric point.
- At 4-10% concentrations (at LFL, common leak scenario), ignition energy of H\(_2\) is comparable to natural gas.
- Tendency to ignite and burn before large energy accumulation occurs.
- Typical static shock is 10 mJ. It could ignite methane, propane, gasoline and hydrogen.

Figure from: Air Products via Jay Keller, ICHS, 2009
Hydrogen saved lives in the Hindenburg disaster

• 36 out of 97 died mostly trapped by the fire of fabric, diesel fuel, furniture, … or jumping (not hydrogen)

• The craft did not explode but burned & while burning stayed aloft (hydrogen still in the nose)

• The craft fell to the ground tail first – the nose was still full of hydrogen

• Radiation from the flame was red, orange and yellow – hydrogen flames emit in the near UV (mostly blue in color)

• Main Cause: The covering was coated with cellulose nitrate or cellulose acetate -- both flammable materials. Furthermore, the cellulose material was impregnated with aluminum flakes to reflect sunlight. -- Dr. Addison Bain

• A similar fire took place when an airship with an acetate-aluminum skin burned in Georgia & it used helium (not hydrogen)

From: Jay Keller, ICHS, 2009
Hydrogen is NOT Fossil – Energy Carrier
Many Important Renewable Pathways
Cost of Hydrogen for 100% Zero Emissions

Data Center Configurations/Locations Modeled

**Battery - Central Storage**

Data Center powered directly from renewable generators when available. Excess of electricity stored in batteries.

- Wyoming
- Iowa
- Virginia
- Texas

**Excess power to gas**

Data Center powered directly from renewable generators when available. Excess of electricity converted to hydrogen and used when required.

- Wyoming
- Iowa
- Virginia
- Texas

**Power to gas**

All renewable electricity generation converted to hydrogen. Data Center powered from hydrogen.

- Wyoming
- Iowa
- Virginia
- Texas
## Cost of Hydrogen for 100% Zero Emissions

### Excess P2G & Battery Cases – Wyoming (optimal mix of solar/wind)

<table>
<thead>
<tr>
<th>Hydrogen Case</th>
<th>Wind Onshore</th>
<th>Solar PV</th>
<th>Electrolyzer</th>
<th>Fuel Cell</th>
<th>LH2 Storage + Liquefaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, MW (MWh)</td>
<td>48</td>
<td>271</td>
<td>100</td>
<td>55</td>
<td>520.6</td>
</tr>
<tr>
<td>Dewar, ton</td>
<td>0.43</td>
<td>1.19</td>
<td>0.31</td>
<td>0.18</td>
<td>0.335</td>
</tr>
<tr>
<td>Liquefier, kg/s</td>
<td>-</td>
<td>39.14</td>
<td>154.7</td>
<td>-</td>
<td>23.6</td>
</tr>
<tr>
<td>OM fixed, M$/yr</td>
<td>0.43</td>
<td>0.31</td>
<td>0.18</td>
<td>0.335</td>
<td>0.28</td>
</tr>
<tr>
<td>OM var, $/MWh</td>
<td>0.57</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.78</td>
</tr>
<tr>
<td>Cooling cost, $/h</td>
<td>23.6</td>
<td>799.2</td>
<td>39</td>
<td>154.7</td>
<td>28.43</td>
</tr>
<tr>
<td>Energy cost, $/h</td>
<td>43.40</td>
<td>196.01</td>
<td>62.25</td>
<td>35.35</td>
<td>67.0</td>
</tr>
<tr>
<td>Capital, M$</td>
<td>43.40</td>
<td>196.01</td>
<td>62.25</td>
<td>35.35</td>
<td>67.0</td>
</tr>
<tr>
<td>Cell capex, M$</td>
<td>3396.5</td>
<td>2823.4</td>
<td>2.12</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Power conversion capex, M$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BOS capex, M$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<tr>
<td>LCOH(E), $/MWh</td>
<td>29.57</td>
<td>67.05</td>
<td>131.5</td>
<td>371.2</td>
<td>7.06E-2</td>
</tr>
<tr>
<td>LCOH, $/kg (EZ+stor)</td>
<td>29.57</td>
<td>67.05</td>
<td>131.5</td>
<td>371.2</td>
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<tr>
<td>LCOE, $/MWh_e</td>
<td>119.82</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4,798.20</td>
</tr>
</tbody>
</table>

### Battery Case

<table>
<thead>
<tr>
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<th>Wind onshore</th>
<th>Solar PV</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, MW (MWh)</td>
<td>31</td>
<td>177</td>
<td>21,781</td>
</tr>
<tr>
<td>Dewar, ton</td>
<td>0.28</td>
<td>0.78</td>
<td>306.5</td>
</tr>
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<tr>
<td>WACC_{inf}</td>
<td>6.86E-2</td>
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# Cost of Hydrogen for 100% Zero Emissions

**Excess P2G & Battery Cases – Wyoming (optimal mix of solar/wind)**

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Every H2 case for 100% renewable w/ all storage is significantly cheaper!
Efficiency of Emerging Electrolysis Systems

- Can achieve much higher round-trip efficiency

![Graph showing Efficiency of Emerging Electrolysis Systems](image-url)
H₂ leakage from NG Infrastructure

H₂ injection into existing natural gas infrastructure (low pressure)
• NG, H₂/NG mixtures, H₂ leak at same rate

![Graph showing pressure in inH₂O over day of test for NG, 10% H₂, and H₂.](image-url)
H₂ leakage mitigation technologies

H₂ injection into existing natural gas infrastructure (low pressure)

- Copper epoxy applied (Ace Duraflow®) to mitigate H₂ leaks

![Graph showing pressure vs. day of test]
H₂ Leakage Rates

• Results from a previous study (1992) support our recent findings!

<table>
<thead>
<tr>
<th>Leakage Flow Regime</th>
<th>Ratio of flow between H₂ and CH₄</th>
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<tr>
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<td>3.15</td>
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Entrance effects? Compressibility?

Hydrogen Steel Pipeline Embrittlement

Simulation of H2 embrittlement and fatigue crack growth with UIUC

- Fatigue crack growth in 6” SoCalGas pipeline

0.188” wall thickness: \( h = 0.188'' = 4.8 \text{ mm} \)

\[
\frac{a_0^{cr}}{h} = 0.53
\]


Perhaps not a Show Stopper - Manageable

Large International Effort Underway
SNL, UIUC, Kyushu Univ., MPA Stuttgart, CEA, and others
Hydrogen Massive Storage Facility Transformation

Salt Caverns already widely used and proven
- Air Liquide & Praxair operating H₂ salt cavern storage in Texas since 2016
  - Very low leakage rate
  - Massive energy storage
  - Safe & Low-cost storage
- Similar success in Europe
- Magnum working with LADWP to adopt similar salt cavern H₂ storage in Utah

Current CA depleted oil and gas fields not yet used or proven for H₂ use
- Several research and development needs
  - H₂ leakage
  - H₂ reaction with petroleum remnants
  - H₂ biological interactions
  - H₂ storage capacity
  - H₂ safety
Some Hydrogen Subtle Untruths – Popular Thinking

Zero Emissions Strategy:

- 100% renewable (solar, wind, geothermal, ...) power generation
- Electrify all end-uses
- Use batteries to handle intermittency on grid & for end-uses

Arguments against hydrogen & fuel cells:

- Most hydrogen today is made from fossil fuels (natural gas)
- Making hydrogen from water & electricity is less efficient than charging a battery
- Making electricity from hydrogen in a fuel cell is less efficient than a battery (i.e., round-trip efficiency is lower than a battery except for long duration storage!)
- Hydrogen is difficult to store and move around in society compared to fossil fuels!

I agree with most of this!
Subtly untruthful - Not the whole story
Hydrogen Facts – Unique Zero Emissions Features

Hydrogen: 11 features required for 100% zero carbon & pollutant emissions

- Massive energy storage potential
- Rapid vehicle fueling
- Long vehicle range
- Heavy vehicle/ship/train payload
- Seasonal (long duration) storage potential
- Sufficient raw materials on earth
- Water naturally recycled in short time on earth
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g., ammonia)
- Pre-cursor for high energy density renewable liquid fuels
- Re-use of existing infrastructure (lower cost)

Hydrogen Facts – Unique Zero Emissions Features

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Massive Storage Required for 100% Renewable – CA

Wind Dominant Case

Deficit
Surplus

Pumped Hydro
Current H₂ Storage
21 million EVs*

Time (Jan to Dec)

* Nissan Leaf Equiv. – 62 kWh

Saeedmanesh, A. Mac Kinnon, M. Brouwer, J., Current Opinion in Electrochemistry, Vol. 12, pp. 166-181, 2018
Massive Storage Required for 100% Renewable – CA

21 million EVs*

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Saeedmanesh, A. Mac Kinnon, M. Brouwer, J., Current Opinion in Electrochemistry, Vol. 12, pp. 166-181, 2018
## Energy Storage Need - World

Simulate meeting of total world energy demand w/ Solar & Wind

<table>
<thead>
<tr>
<th></th>
<th>Solar contribution</th>
<th>Wind contribution</th>
<th>Consumption and storage ratio</th>
<th>Consumption (TWh)</th>
<th>Storage (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>0.70</td>
<td>0.30</td>
<td>8.39</td>
<td>9,123</td>
<td>1,088</td>
</tr>
<tr>
<td>America</td>
<td>0.45</td>
<td>0.55</td>
<td>7.83</td>
<td>38,541</td>
<td>4,919</td>
</tr>
<tr>
<td>Asia</td>
<td>0.50</td>
<td>0.50</td>
<td>7.95</td>
<td>80,866</td>
<td>10,178</td>
</tr>
<tr>
<td>Europe</td>
<td>0.30</td>
<td>0.70</td>
<td>7.50</td>
<td>26,951</td>
<td>3,592</td>
</tr>
<tr>
<td>Oceania</td>
<td>0.50</td>
<td>0.50</td>
<td>7.95</td>
<td>1,625</td>
<td>205</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>157,106</td>
<td>19,981 TWh</td>
<td></td>
</tr>
</tbody>
</table>

[Nuria Tirado, M.S. Thesis, 2018]

- To build one Li-ion battery requires: Li: 3,144 Mt  Co: 25,815 Mt
- World Li resources: 53 Mt
- World Co resources: 25 Mt (terrestrial), 120 Mt (ocean floor)
- > 60% of Co comes from the Democratic Republic of Congo

Source: U.S. Geological Survey, 2018
Energy Storage Need - World

Simulate meeting of total world energy demand with Solar & Wind

<table>
<thead>
<tr>
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<th>Solar contribution</th>
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<td>205</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19,981 TWh</td>
</tr>
</tbody>
</table>

- To build one Li-ion battery requires: Li: 3,144 Mt, Co: 25,815 Mt
- World Li resources: 53 Mt (terrestrial), 120 Mt (ocean floor)
- World Co resources: 25 Mt (terrestrial), 120 Mt (ocean floor)
- > 60% of Co comes from the Democratic Republic of Congo

There is not enough lithium or cobalt in the world.

Source: U.S. Geological Survey, 2018
Efficiency for Long Duration Storage
Round-Trip Efficiency (>90% in Laboratory Testing)
• Measured battery system performance in Utility Applications

- Self-Discharge (the main culprit), plus cooling, transforming, inverting/converting, ...

From: 2017 SGIP Advanced Energy Storage Impacts, Itron, E3

Average RTE ~60%

Batteries not EFFICIENT enough & suffer SELF-DISCHARGE
Hydrogen Energy Storage Dynamics

- Hydrogen Storage complements Texas Wind & Power Dynamics

- Load shifting from high wind days to low wind days
- Hydrogen stored in adjacent salt cavern

Hydrogen Energy Storage Dynamics

- Weekly and seasonal storage w/ $H_2$, fuel cells, electrolyzers
  - Weekly
  - Seasonal

But what can we do if we don’t have a salt cavern?

Resilient Storage & Transmission/Distribution Resource

- Natural Gas Transmission, Distribution & Storage System

> 99.999% available

Gas Technology Institute, Assessment of Natural Gas ... Service Reliability, 2018.

Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.
Resilient Storage & Transmission/Distribution Resource

- Natural Gas Transmission, Distribution & Storage System

> 99.999% available

650 GWh if stored at 5% H2 in natural gas

$130 billion battery (DOE future cost)

Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.

Gas Technology Institute, Assessment of Natural Gas ... Service Reliability, 2018.
Resilient Storage & Transmission/Distribution Resource

- Natural Gas Transmission, Distribution & Storage System
  - > 99.999% available

<table>
<thead>
<tr>
<th></th>
<th>Annual Tuition &amp; Fees</th>
<th>Total OC</th>
<th>4 years for entire population</th>
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<td>U.C. Irvine</td>
<td>$17,331</td>
<td>2,246,000</td>
<td>$39 billion</td>
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<table>
<thead>
<tr>
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<th>Average Annual Tuition &amp; Fees</th>
<th>Total Student Population</th>
<th>4 years for entire population</th>
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</thead>
<tbody>
<tr>
<td>All University of California Schools</td>
<td>$17,800</td>
<td>265,000</td>
<td>$4.7 billion</td>
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</tbody>
</table>

650 GWh in natural gas (DC value cost)

$130 billion needed annually

Gas Technology Institute, Assessment of Natural Gas ... Service Reliability, 2018.

Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.
Demonstrated Resilience of Fuel Cells and Gas System

San Diego Blackout, 9/28/11

Winter Storm Alfred, 10/29/11

Hurricane Sandy, 10/29/12

CA Earthquake, 8/24/14

Data Center Utility Outage, 4/16/15

Hurricane Joaquin, 10/15/15

Napa Fire, 10/9/17

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Why Hydrogen? Required for completely zero emissions

REVIEW SUMMARY

ENERGY

Net-zero emissions energy systems

Steven J. Davis*, Nathan S. Lewis*, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin I. Hoffert, Eric Ingersoll, Paulina Jaramillo, Klaus S. Lackner, Katharine J. Mach, Michael Mastrandrea, Joan Ogden, Per F. Peterson, Daniel L. Sanchez, Daniel Sperling, Joseph Stagner, Jessika E. Trancik, Chi-Jen Yang, Ken Caldeira*

Davis et al., Science 360, 1419 (2018)  29 June 2018
Why Hydrogen? Zero Emission Fuels Required

- Provide zero emissions fuel to difficult end-uses

Anything that requires (1) rapid fueling, (2) long range, (3) large payload
Why Hydrogen? Industry Requirements for Heat, Feedstock,
- Many examples of applications that cannot be electrified

Steel Manufacturing & Processing
(Cement Production)
(Plastics)
Ammonia & Fertilizer Production
Computer Chip Fabrication
Pharmaceuticals

(Photos: Galveston County Economic Development, ABB Cement, DowDuPont Inc., American Chemical Society, Geosyntec Consultants)
Summary

- We must and will inevitably increasingly depend upon solar power and its more direct derivatives (e.g., wind)
  - Air quality
  - Greenhouse gas emissions & climate
  - Energy, environment, & geopolitical sustainability
  - Environmental Justice

- The DYNAMICS of such a future are challenging – require complementary dispatch, massive storage, and seasonal storage
  - Batteries, hydro, power-to-gas (P2G), hydrogen energy storage (HES)

- HYDROGEN will become the indispensable zero emissions fuel and energy storage medium to enable this future – unique features
  - Long duration energy storage
  - Massive energy storage amount
  - Hydrogen & its derivative fuels
  - Will be lower cost (separate power/energy scaling)
  - High round-trip efficiency possible
  - Reliability & resilience (underground infrastructure)
Hydrogen 101 – Myths vs. Facts

Jack Brouwer

June 17, 2021

California Hydrogen Business Council Webinar Series
Q&A

- Submit your question in the Q&A Panel on your right.

Dr. Jack Brouwer
Director, National Fuel Cell Research Center, UC Irvine
Director, Advanced Power and Energy Program, UC Irvine
Professor of Mechanical and Aerospace Engineering
CONTACT

William Zobel
Executive Director
California Hydrogen Business Council
wzobel@californiahydrogen.org

Emanuel Wagner
Deputy Director
California Hydrogen Business Council
ewagner@californiahydrogen.org

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