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**Mission:** NREL advances the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provides the knowledge to integrate and optimize energy systems.

**Example Technology Areas:**

- Approximately 2,200 employees, postdoctoral researchers, interns, visiting professionals, and subcontractors
- 327-acre campus in Golden & 305-acre National Wind Technology Center 13 miles north
- 63 R&D 100 awards. More than 1000 scientific and technical materials published annually

[www.nrel.gov/about](http://www.nrel.gov/about)
Partnering with Business for Competitive Advantage

Nearly 820 active partnerships with industry, academia, and government

In 2018 NREL had:

- 272 new partnership agreements
- $70.0 million value of new partnership agreements
- 69 unique new partners
- 528 unique active partners
NREL Overview

Energy System Challenges & H2@Scale

Demand and Resource Technical Potential

Why Electrolytic Hydrogen?

Economic Potential

Concluding Thoughts
Select (Relevant) Megatrends

- Increased global focus on emissions, increased policy regulations (market impact)
- Low, cost intermittent renewable electrons
- Increased electrification

When the Planet Looks Like a Climate-Change Ad (9/12/17)

Downtown Denver from NREL’s Energy System Integration Facility

The Great Barrier Reef’s catastrophic coral bleaching, in one map
Air Quality – Downtown Denver

27 September 2016 / GENEVA - A new WHO air quality model confirms that 92% of the world’s population lives in places where air quality levels exceed WHO limits.

WHO: Air pollution caused one in eight deaths / March 25, 2014

http://www.cnn.com/2014/03/25/health/who-air-pollution-deaths/
Changing Energy System – Policy

Renewable Portfolio Standards (RPS)
Senate Bill 100, signed by Gov. Edmund G. Brown, Jr. codifies 60% by 2030 & 100% by 2045 RPS (2018)
http://www.energy.ca.gov/renewables/

Zero Emission Vehicles (ZEV)
2016 ZEV Action Plan toward 1.5 million ZEVs
by 2025.

Renewable Gas Standard
SB-687 Renewable gas standard
http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=20152016058687
Renewable electricity price trends

Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1’15 Report, 2. DOE EERE Wind Report, 2015
How much power does an investor get for a dollar?

Lazard LCOE analysis from https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-100/
Variable Renewable Electricity Challenges

Denholm et al. 2008

[Graph showing PV penetration and hour with various energy sources including PV, Gas, Turbine, Pumped Storage, Hydro, Combined Cycle, Imports, Coal, Nuclear, Wind, Geo, and Exports.]
Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands.
Curtailment and Electricity Prices

Curtailment is increasing

Lower average electricity prices and hours with negative prices

Impacts of Curtailment Renewable Investment

- Reduced revenue would likely limit penetration of VRE generation outside of policy factors (RPS)
- If a purchaser could accept a low utilization factor, they could get low-price electricity and extend the VRE penetration limit

Options for Storing Electrical Energy

Long-term (e.g., seasonal) storage is challenging

Challenges Reaching High Renewable Electricity Penetrations

Note: % VRE in 2015

Actual Operating System
Modeled System

Deep Decarbonization
1400 GW wind
900 GW Solar

Credit: B. Kroposki, NREL

Alaska Village
Lanai
Mau
I
Denmark*
Ireland
CA 50%
WWSIS
ERGIS
REF
Cont. USA
CA*

DOE 2050 Goals
35% Wind (404 GW)
19% PV (632 GW)

Relatively Easy
Much harder
Extremely Difficult

* Part of a larger synchronous AC power system

WWSIS = Western Wind and Solar Integration Study
ERGIS = Eastern Renewable Generation Integration Study
REF = Renewable Electricity Futures Study
Electricity is Not the Only Energy Challenge

- Electrification is increasing in utilization sectors
- But they have limited electricity options
- Reducing emissions will need a combination of efficiency and reduced carbon sources

Source: https://www.nrel.gov/analysis/electrification-futures.html
"If you can't solve a problem, enlarge it"

Source: https://www.whitehouse.gov/sites/whitehouse.gov/files/images/first-family/34_dwight_d_eisenhower%5B1%5D.jpg
H2@Scale Concept


*Illustrative example, not comprehensive
Demand and Resource Technical Potential
H₂ is different and changing fast

H₂ Council*

- Launched in January 2017 its members include leading companies with over $10 billion in investments along the hydrogen value chain, including transportation, industry, and energy exploration, production, and distribution.

13 members (Jan 2017).

32 steering members and 20 supporting members (Nov 2018). *Steering members shown, additional supporting members www.hydrogencouncil.com

Potential Impacts from Hydrogen Council Roadmap Study. By 2050:
- $2.5 trillion in global revenues
- 30 million jobs
- 400 million cars, 15-20 million trucks
- 18% of total global energy demand
Agencies should invest in early-stage, innovative technologies that show promise in harnessing American energy resources safely and efficiently.

Source: Hydrogen Council

“Hydrogen Scaling Up”

“Roadmap to a US Hydrogen Economy” (2019)
Demand potential of hydrogen market by 2050 is >9X.

Other applications are possible based on technology and policy growth as well as smaller applications.

### Demand Potential

<table>
<thead>
<tr>
<th>Application</th>
<th>Demand Potential (MMT/yr)</th>
<th>2015 Market for On-Purpose H2 (MMT/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refineries and the chemical processing industry (CPI) a</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Metals</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Ammonia</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Biofuels</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Synthetic fuels and chemicals</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>Natural gas supplementation</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Seasonal energy storage for the electricity grid</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Industry and Storage Subtotal</td>
<td>67</td>
<td>10</td>
</tr>
<tr>
<td>Light-duty fuel cell electric vehicles (FCEVs)</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>Medium- &amp; Heavy-Duty FCEVs</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Transportation Fuel Subtotal</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>99</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>

Definition: The demand potential is the estimated market size constrained by the services for which society currently uses energy, real-world geography, system performance, and by optimistic market shares but not by economic calculations.
## Technical Potential Supply from Renewable Resources

<table>
<thead>
<tr>
<th>Solid Biomass</th>
<th>EIA 2015 current consumption (quads/yr)</th>
<th>Required to meet demand of 99 MMT / yr (quads/yr)</th>
<th>Technical Potential (quads/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.7</td>
<td>24</td>
<td>19</td>
</tr>
<tr>
<td>Wind Electrolysis</td>
<td>0.68</td>
<td>16</td>
<td>170</td>
</tr>
<tr>
<td>Solar Electrolysis</td>
<td>0.17</td>
<td>16</td>
<td>1,000</td>
</tr>
</tbody>
</table>

Total demand including hydrogen is satisfied by ≈10% of wind, 2% of solar, and ≈150% of biomass technical potential.

### Wind Technical Potential

- Current consumption 2015
- Residual Technical Potential

### Solar Technical Potential

- Required to meet demand of 99 MMT of H2
- Preliminary Results
Hydrogen can be produced from diverse domestic resources to meet aggressive growth in demand.

![Graph showing resource consumption by type (Quads per year) and years to depletion.](Image)

- Natural Gas: Required to meet demand of 99 MMT of H2 in 2040
- Natural Gas: 16 years
- Natural Gas: Current consumption 2015
- Natural Gas: ≈ 60 years
- Coal: 22 years
- Coal: ≈ 180 years
- Coal: ≈ 250 years
- Nuclear: 27 years
- Nuclear: ≈ 250 years
- Nuclear: ≈ 180 years
- Nuclear: 8 years

Resource Consumption by Type (Quads per year)

Current consumption 2015

- Years to depletion based on proven and unproven reserves
- Years to depletion based on reasonably assured reserves at <$260/kg and both once-through and breeder reactors

Preliminary Results

Hydrogen consumption and depletion based on type of resource.
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Electricity Prices Vary Across the Year

- Hours with energy at very low and very high prices are increasing
- Other revenue streams (e.g., capacity, services) are becoming more critical
- Wind and solar power purchase agreements (PPAs) are key opportunities

Figure created using data from publicly available CA-ISO and SPP datasets
Potential Opportunity: Low Temperature Electrolysis

Electrolytic H₂ has the potential to be cost competitive.

Availability of low-cost electricity can help enable low-cost H₂ production, even at low capacity factors.

Potential Levelized Costs of H₂ Production

Source: Bryan Pivovar & Josh Eichman
Opportunity for Electrolytic Hydrogen Generation

Palo Verde 2017

- Electrolytic hydrogen could be cost-competitive if flexible, low-temperature electrolyzers can be purchased at $400/kW and markets are available

$400/kW electrolyzer purchase cost. Operating during lowest cost hours of the year
A Dispatchable Load Could Utilize Low-Cost, Dispatch-Constrained Electricity (LDE)

A controllable, dispatchable load could remove the cap on penetration of variable renewable generation.

We developed a method to estimate LDE availability providing a flexible load will pay for it.
LDE Generation

Used ReEDS to estimate generator fleet and generation mix at multiple LDE values

Buildout with $0/MWh LDE

2050 Results at Various LDE Values

High Curtailment Scenario
Future Opportunities for LDE Utilization at Palo Verde

Under parameters that lead to high variable renewable generation and with a $20/MWh price floor,

- Additional LDE is available
- Electrolytic hydrogen can be cost competitive at Palo Verde
A Dispatchable Load Could Utilize Low-Cost, Dispatch-Constrained Electricity (LDE)

A controllable, dispatchable load could remove the cap on penetration of variable renewable generation.

We developed a method to estimate LDE availability providing a flexible load will pay for it.

- Set willingness to pay for LDE
- Run ReEDS to estimate optimal generator fleet
- Transfer fleet results to PLEXOS
- Run PLEXOS to estimate quantity and availability of LDE
- Develop LDE supply curve
Used PLEXOS Unit Commitment Model to create supply / availability curves for LDE
Developed supply curves for LTE-generated hydrogen based on each price / availability factor combination

Low Temperature Electrolysis of Low-Cost, Dispatch-Constrained Electricity:

- **Calculated hydrogen levelized costs** using H2A Future Central Hydrogen Production from PEM Electrolysis model at each price / availability factor combination
- **Added $20/MWh for transaction fees** for “Retail” prices and $10/MWh for “Retail w/ Services”
- Assume storage and delivery costs ~$0.40/kg\(H_2\) (cost for pipeline transport of 200,000 MT/yr 250 miles with geologic storage)
NREL Overview

Energy System Challenges & H2@Scale

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Concluding Thoughts
Economic Potential Methodology: Market Equilibrium

**Demand Curve**: how much are consumers willing and able to pay for a good?

**Supply Curve**: threshold prices showing how much are producers willing and able to produce at each?

**Economic Equilibrium**: Quantity where demand price is equal to the supply price.
- No excess supply or demand.
- Market pushes price and quantity to equilibrium.

### Economic Potential: Five National Scenarios

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Reference</th>
<th>Low NG Resource</th>
<th>Improved Electrolysis</th>
<th>Available Biomass Resource</th>
<th>Lowest-Cost Electrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas price assumption</td>
<td>Reference</td>
<td></td>
<td>Higher</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-Temperature Electrolysis (LTE) capital costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-cost, Dispatch-constrained Electricity purchase assumption</td>
<td>Current Trajectory</td>
<td>Improvements</td>
<td>Aggressive Assumptions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td></td>
<td>Not available</td>
<td>Available</td>
<td>Not Available</td>
</tr>
<tr>
<td>Metals demand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key differences in scenarios: 1) natural gas price assumption, 2) electrolyzer cost assumption, 3) electrolyzers’ access to grid service markets, 4) increased threshold price in metals industry, & 5) competition for biomass resource
The economic potential of hydrogen demand in the U.S. is 1.4-4X current annual consumption.
• Lowest natural gas prices; thus, higher penetrations of FCEVs
• About 10% of U.S. nuclear generation to H₂
• Refineries and ammonia demands based on growing markets
• Biofuels demand limited to Renewable Fuels Standard
Higher natural gas prices than reference scenario

Thus, negligible growth in hydrogen demand

Only economic demands: refining, ammonia, biofuels
• Low-Temperature electrolyzer (LTE) purchase cost reduced to $200/kW & reduced electricity price adder
• Supply growth due to electrolytic hydrogen
• Increased willingness to pay for H2 for metals refining
• Leads to demand for growing domestic metals refining industry
Only scenario with biomass available for hydrogen production
Lowest cost biomass resource assumed available
Lower cost hydrogen allows demand growth
Low-Temperature electrolyzer (LTE) purchase cost reduced to $100/kW & no electricity price adder

- Electrolytic hydrogen less costly than steam methane reforming
- Larger ammonia and chemicals opportunities than other scenarios
Potential Impact of H2@Scale on Wind and Solar PV Markets

Hydrogen is a potential dispatchable load that can increase economic demand for variable electricity.

- Estimates are based on national scenarios with minimal resolution into regional constraints.
- Lowest-Cost Electrolysis assumes aggressive electrolyzer costs ($100/kW)
Concluding Thoughts

• Energy requirements are getting more complex and H2@Scale is a potential opportunity
• The potential demand of hydrogen demand in the U.S. is >9X current annual consumption.
• The economic potential of hydrogen demand in the U.S. is 1.4-4X current annual consumption.
• Up to 20% of current nuclear power plants could improve their profitability by producing hydrogen.
• At high penetrations, the H2@Scale concept could increase PV penetration by about 30% and almost double wind generation
Thank You
Mark.Ruth@nrel.gov

Additional information on H2@Scale can be found at:
http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

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