Hydrogen Production & Delivery Program

- Plenary Presentation -

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Hydrogen Production & Delivery Roadmap

**Goal:** affordable H₂ from diverse renewable domestic resources

### Production Method

- **Natural Gas Reforming**
  - established industrial process
- **Biomass Gasification**
- **Electrolysis (wind)**
- **Electrolysis (solar)**
- **Coal Gasification (with CCUS)**
- **High-temp Electrolysis**
- **PEC, STCH, Photo-biological**

### Mid-scale

- **Distributed SMR**
- **Grid Electrolysis**
- **Bio-derived Liquids**
- **Microbial Conversion**

### Delivery Method

- **Tube Trailer Transport**
  - Mobile Re-fuelers
  - High Capacity Tube Trailers
  - Forecourt CSD
- **Liquid Tanker Transport**
  - Advanced Liquefaction
  - Distribution Pipelines
  - Advanced Forecourt CSD
- **Pipeline Transport (& alternatives)**
  - Fiber Reinforced Pipelines
  - Game-changing Compressors
  - Cold GH₂ Delivery

### Near-term, Mid-term, Long-term

**Biomass Pathways**
- Hybrid & Other

**Solar Pathways**
Mission

To enable the widespread commercialization of hydrogen and fuel cell technologies

2020 Targets by Application

- Fuel Cell Cost: $40/kW | $1,000/kW* | $1,500/kW**
- Durability: 5,000 hrs | 80,000 hrs
- H₂ Storage Cost: $10/kWh | 1.8 kWh/L, 1.3 kWh/kg
- H₂ Cost at Pump: <$4/gge | <$7/gge (early market)

*For Natural Gas  **For Biogas

Target-driven approach to accelerate H₂ & fuel cells market penetration
Hydrogen Cost Status and Targets

**Dispensed H₂ Cost Status**

- **Low-Volume**
  - Early markets using NG
  - **$16/kg to $13/kg**

- **High-Volume**
  - Renewable technologies
  - **$7.5/kg to $5/kg**

*High-volume projections assume economies of scale*

**Targets**

- **High-Volume Target**
  - $4/kg

- **Early Market Target**
  - $7/kg

**Notes**

- **LOW-VOLUME**, early market cost status is based on low-cost H₂ from NG (<$2/kg) plus >$11/kg for delivery & dispensing.

- **Developing delivery/dispensing infrastructure is immediate need**

- **HIGH-VOLUME** projected cost status is based on ~$2.5-5/kg H₂ (biomass gasification-water electrolysis) plus ~$2.50/kg delivery & dispensing.

- **RD&D of diverse renewable H₂ technology pathways is vital**

**Continued RD&D is needed for renewable H₂ production & delivery**
H₂ Delivery and Dispensing Cost Trajectories

Cost of Delivering and Dispensing Hydrogen from Central Production

projected to high volume with economies of scale

Key Assumptions:
1. City: 1.4M population, 10% market penetration FCEVs
2. Station: 750 kg/day
3. Production: Centralized location, 62 miles from city
4. Manufacturing: All equipment manufactured at economies of scale

Reducing cost of FCEV refueling stations is an immediate priority
Renewable H₂ Production Cost Trajectories

H₂A techno-economic analysis quantifies projected cost status and identifies key levers for reducing costs through RD&D

Advanced Electrolysis
- Capital Costs: 34%
  - Stack
  - BOP
  - Indirect
- Electrical Energy Costs: 47%
- Thermal Energy Costs: 11%
- O&M Cost: 8%

Advanced high-T solid oxide electrolysis offers cost benefits over PEM electrolysis, but energy and capital costs still dominate

Continued RD&D to reduce cost of renewable pathways is critical
Applied RD&D Portfolio Development

Techno-economic analyses & stakeholder input inform programmatic decisions & priorities for pre-competitive RD&D
Applied RD&D Strategies and Framework

Challenge
Reduce the cost of clean, sustainable hydrogen production & delivery while meeting safety and performance requirements

- Feedstock costs
- Capital costs
- O&M costs

Strategies

Near-term
Minimize cost of 700 bar hydrogen at refueling stations

Long-term
Improve performance and durability of materials & systems for production from renewable sources

RD&D Focus

- Techno-economic & life cycle analysis
- Reliability and cost of compression, storage and dispensing
- Renewable integration
- Advanced materials and systems for H₂ delivery
- Innovations in materials, devices and reactors for renewable H₂ production
- Improved balance of plant for P&D systems

Key Areas

Delivery
- Polymers & composites for delivery technologies
- Liquefaction technologies
- Nonmechanical compression
- Novel pressure vessel designs

Production
- Advanced electrolysis
- Biomass conversion
- Hybrid approaches
- Solar water splitting: PEC & STCH

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RD&D Support Framework:

- FCTO FOA & Lab Calls
- SBIR/STTR
- DOE MOUs: NSF & NIST
- Incubator/Seedlings
- Crosscuts: Grid, EMN...
- Prizes and Other

Leveraging resources to address near- to longer-term challenges
Hydrogen RD&D Portfolio Distribution

FCTO funding distribution in FOA, LAB, SBIR/STTR & joint NSF projects

**H₂ Production**
- Electrolysis: 36%
- PEC: 17%
- Biogas: 11%
- Microbial: 10%

**H₂ Delivery**
- Liquefaction: 20%
- Pipelines: 20%
- Compressors: 18%
- Storage: 18%
- Dispenser: 10%
- Other forecourt: 15%

Balanced portfolio addressing near- to longer-term challenges
Stabilized budgets are needed to sustain critical RD&D; Continued leveraging of broader research resources is needed

EMPHASIS

- Expand TE & LCA analysis, and refine near- and long-term targets
- Expand portfolio of near-, mid- and long-term P&D technologies
  - *advanced high-T electrolysis*
  - *advanced compression*
- Continue cross-office/agency and international coordination/collaboration
- Support H2@Scale Lab Big Idea
- Initiate HydroGen Advanced Water Splitting Materials consortium within Energy Materials Network

FCTO H₂ Production & Delivery Budget

FY 2017 Request = $21.4M
FY 2016 Appropriation = $25.4M

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FY 2016 Appropriation | FY2017 Request
H₂ Production & Delivery Collaborations

DOE/EERE FCTO

Hydrogen P&D Applied RD&D
- FOA/Lab projects
- SBIR projects
- Joint NSF projects
- Incubator projects

INTERNATIONAL ACTIVITIES
- IEA HIA Tasks
- Infrastructure Workshops
- IPHE

EXAMPLES:
- IEA HIA Tasks
- Infrastructure Workshops
- IPHE

INDUSTRY
- USDRIVE Tech Teams
  - H₂ Production
  - H₂ Delivery
  - Analysis
- H₂USA – H₂First
- Codes & Standards Organizations

DOE CROSS-CUTS
- Grid cross-cut
- EMN cross-cut

TECHNOLOGY VALIDATION
Grid Integration/Energy Storage

INTRA- AND INTER-AGENCY COLLABORATIONS

DOE: BES
Including JCAP

DOE: NE and FE

BETO & SETO

ARPA-E

NSF

NIST

H₂@Scale
H2First Accomplishment— HyStEP

Hydrogen Station Equipment Performance (HyStEP) testing device

- The mobile HyStEP device:
  - Enables rapid hydrogen station commissioning by collecting the data needed to validate station fueling protocols

- The HyStEP has been testing stations in CA since December 2015

Mercedes, Honda, Hyundai, and Toyota have all tested and validated the device and have accepted it as deployment ready!
H2 Refuel H-Prize Finalist Announced!

Finalist must meet all technical and cost criteria simultaneously to win!

$1 M competition for on-site H₂ fueling

Finalist team: simple.fuel.™

• Innovative packaging for reduced footprint
• H₂ produced by electrolysis, stored at 350 bar
• Boost fill for 700 bar fueling

For more information about the H-Prize, visit http://hydrogenprize.org/
Advanced Electrolysis Accomplishments

**Activity and stability optimized through tuning composition and support of non-PGM catalysts.**

- Metrics achieved:
  - Cell: 6 A/cm² at ~1.65 V (78% LHV efficiency)
  - 20 cell stack: 3 A/cm² at ~1.5 V (84% LHV efficiency)

**First demo of ultra-high current, high-T SOEC cell and stack with potential for reversible operation**

**Full non-PGM Operational Test**
- 25 cm² | 80°C | 500 mA/cm²
- Testing conducted with water feed to the anode (OER electrode)
- Addition of 1%wt of K₂CO₃ to buffer feed water

**Stack performance**
- Voltage vs. Current Density
- Elapsed time (hours) vs. Cell Voltage (V)

**First demonstration of stable, PGM-free AEM electrolysis!**
Bio-Derived H₂ Accomplishments

Advances in low carbon H₂ production from bio-feedstocks

Commercial fuel cell technology operated in electrolysis mode for:

- **Higher (~98%) purity H₂**
- **Lower CO₂ emissions**

NREL and Penn State: improved fermentation and MEC production while reducing costs

Double-mutant’s H₂ rate: >85% increase over last year’s strains

First prototype demo of Reformer/Electrolyzer/Purifier
H₂ Liquefaction Accomplishment

Magnetocalorics could be a game-changer in H₂ liquefaction

New 25 kg/day system with by-pass loop enabled:

- World record breaking 100°C temperature span, and liquefying a gas from room temperature
- 88% reduction in kilograms of magnetocalorical material used from 184 kg to 22.3 kg
- 87% increase in the figure of merit from 0.4 to >0.75

World’s first demonstration of gas liquefaction from room temperature using innovative magnetocaloric materials!
Solar H₂ Applied RD&D Accomplishments

**Exciting photoelectrochemical & solar thermochemical progress**

**Inverted metamorphic multijunctions (IMM)**
- Grown by organometallic vapor phase epitaxy
- Incorporates buried p/n junction
- Achieved 16% STH using solar simulator
- Achieved 14.3% STH under outdoor testing

**Cascading Pressure Receiver-Reactor (CPR2)**

**New PEC conversion efficiency world records!**

**STCH innovative reactor: concept to demo in 1 year!**
Protecting the surface of GaInP$_2$

- MoS$_2$ was used to protect GaInP$_2$ in acid
- MoS$_2$ further functions as a catalyst for the Hydrogen Evolution Reaction improving onset potential

Advanced computational materials discovery

Breaking new ground in PEC surface engineering

Accelerating discovery of new STCH Redox materials

Innovative materials research to advance PEC and STCH pathways
New Path Forward: HydroGen Consortium

New DOE Energy Materials Network consortium to accelerate the discovery and development on innovative materials critical to advanced water splitting technologies for renewable hydrogen:

- Advanced Electrolysis
- Photoelectrochemical
- Solar Thermochemical

Energy Materials Network
U.S. Department of Energy

Recent Activities and Upcoming Milestones

- DOE QTR *Hydrogen Fuel Sub-Chapter* and *Technology Assessment* published
- NRC evaluation of Hydrogen Production and Delivery Programs under US Drive Partnership
- New projects in fermentation, liquefaction, advanced electrolysis and advanced compression
- Continued projects under H2First (including HyStEP) in support of the H2USA mission
- Cross-office collaborations with EMN/MGI, CEMI, WBS, Grid Integration, Solar Fuels
- Webinars on topics including *Infrastructure, Solar Hydrogen, and H-Prize*
- Workshops, including *Advanced Water Splitting Materials* and *International Infrastructure*
- Initiation of the *HydroGen Advanced Water Splitting Materials* EMN consortium

### Timeline

- **2Q 2015**
  - FCTO/BETO joint Wastewater Workshop
- **2Q 2016**
  - FOA Topics released in Hi-T electrolysis, analysis advanced compression
  - International Infrastructure Workshop
- **3Q 2016**
  - Anticipated announcement of H2 Refuel Contest outcome
- **4Q 2016**
  - FY17 FOA topics released, including HydroGen topics
  - HydroGen EMN Consortium laboratory core
- **1Q 2017**
  - Negotiate and award FY16 Office Wide FOA Selections
  - Complete ASME certification of wire-wrapped pressure vessel design for hydrogen storage.
- **2Q 2017**
  - Establish HydroGen EMN Consortium
  - Design a reactor/receiver system for solar-based central production of > 50,000 kgH₂/day.
  - FCTO/WBS workshop on power electronics for electrolysis
- **3Q 2017**
  - 1Q 2018
  - Negotiate and award FY17 Office Wide FOA Selections
  - 4Q 2017
  - Successfully negotiated and awarded FY 15 P&D projects
  - 1Q 2016
  - SBIR topic for magnetocaloric materials discovery released
  - 3Q 2016
  - Advanced Water Splitting Materials Workshop
  - 4Q 2016
  - FCTO/BETO joint Wastewater Workshop
  - 1Q 2017
  - 3Q 2017
  - FCTO/BETO joint Wastewater Workshop
Thank you for your kind attention!

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http://energy.gov/eere/fuelcells/fuel-cell-technologies-office