H₂ FROM H₂O
A market assessment for a catalyst technology that produces hydrogen from water

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May 2011
THE HYDROGEN CATALYST TEAM

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- Brooks Kincaid
OBJECTIVE:
ANALYZE THE MARKET POTENTIAL FOR A HYDROGEN GENERATING CATALYST AND RECOMMEND A PATH TO MARKET
WHAT HAS LIMITED THE ADOPTION OF CLEAN HYDROGEN?

The hydrogen landscape

- Overview
- Production
- Use
- Distribution

Our technology

Path to market
HYDROGEN IS EVERYWHERE

– The most abundant chemical element on earth
– Requires transformation to isolate hydrogen gas

– Energy source and chemical constituent
– Clean burning, future of energy?
HYDROGEN IS MAINLY PRODUCED FROM FOSSIL SOURCES...

**U.S. PRODUCTION**
*(bil kg/year)*

- Electrolysis: 0.3 bil kg/year, ~$4/kg
- (SMR) Steam methane reforming: 6.9 bil kg/year, ~$1/kg

...AND MAINLY USED IN OIL AND CHEMICAL PRODUCTION

**U.S. PRODUCTION**

- Electrolysis 0.3
- (SMR) Steam methane reformation 6.9

**U.S. USE**

*(bil kg/year)*

- Other 0.2
- Chemicals 2.4
- Refining 4.6
- Metals
- Aerospace
- Electronics
- Other
- Light FCVs
- Heavy FCVs
- Utilities
- Stationary fuel cells
- Food
- Refining
- H2 reformation
- Steam methanation
- Chemicals
- Other

*Sources: 2008 National Hydrogen Association, US Department of Energy*
HYDROGEN IS EXPENSIVE TO DISTRIBUTE AT LOW VOLUMES

Sources: Air Products Diagram, EPRI Briefing to DOE, National Academies Press (assuming gas at 60 degrees F and 1 atmosphere)
CLEAN HYDROGEN HAS NOT MET EXPECTATIONS BUT CAN BE COMPETITIVE

Electrolysis has not replaced carbon-intensive SMR

High costs and limited infrastructure are barriers to adoption

Opportunity at small distributed scale where willingness to pay is high
LBNL CATALYST LOWERS ELECTROLYSIS COST

- Electrolysis
- A new catalyst
- Cost advantage
ELECTROLYSIS SPLITS WATER INTO HYDROGEN AND OXYGEN

\[ 4\text{H}_2\text{O} + 4\text{e}^- \rightarrow 2\text{H}_2 + 4\text{OH}^- \]

\[ 2\text{H}_2\text{O} - 4\text{e}^- \rightarrow \text{O}_2 + 4\text{H}^+ \]

Catalyst

Cathode

Anode

Power supply 1.23 V
CATALYST IS MAJORITY OF ELECTROLYZER CAPITAL COST

Electrolyzer capital cost breakdown

- Catalyst: 77%
- Membrane: 5%
- JDL: 5%
- Bipolar Plate: 3%
- Seal: 6%
- Balance of System: 2%
- Assembly: 2%

Sources: REVIEW OF SMALL STATIONARY REFORMERS FOR HYDROGEN PRODUCTION (Dr. Joan M. Ogden); NREL Electrolyzer Capital Cost study
LBNL CATALYST HAS SIGNIFICANT ADVANTAGES OVER PLATINUM

<table>
<thead>
<tr>
<th></th>
<th>MolyOxo catalyst</th>
<th>Standard catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material cost</td>
<td>$1/oz</td>
<td>$1800/oz</td>
</tr>
<tr>
<td>Water quality</td>
<td>No treatment</td>
<td>Treatment</td>
</tr>
<tr>
<td>Durability</td>
<td>Robust</td>
<td>Easily fouled</td>
</tr>
<tr>
<td>Energy Conversion</td>
<td>~50%</td>
<td>~65%</td>
</tr>
</tbody>
</table>

Source: Nature May 2010
IMPACT OF CAPITAL COST REDUCTION GREATEST AT SMALL SCALE

H2 production levelized cost ($/kg) using grid electrolysis

<table>
<thead>
<tr>
<th>Capital cost</th>
<th>66%</th>
<th>53%</th>
<th>35%</th>
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</thead>
<tbody>
<tr>
<td>$/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 kg/day</td>
<td>$18.43</td>
<td>$10.31</td>
<td>$6.83</td>
</tr>
<tr>
<td>100 kg/day</td>
<td></td>
<td></td>
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<tr>
<td>1000 kg/day</td>
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<td></td>
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</tbody>
</table>

Source: NREL Electrolyzer Capital Cost study

UC Berkeley: Cleantech to Market - Confidential
LBNL CATALYST MAKES ELECTROLYSIS COMPETITIVE AT SMALL SCALE

Capital Cost Comparison (SMR Vs Electrolyzer)

Sources: Review of Small Stationary Reformers for Hydrogen Production (Dr. Joan M. Ogden); NREL Electrolyzer Capital Cost study
REDUCTION IN CATALYST VOLTAGE INPUT HAS LARGEST IMPACT ON COST OF PRODUCED H2

Baseline Cost ($18.43)

Voltage input (0.5V to 1.5V)

Cost of electricity (+/- 30%)

Catalyst cost reduction (-90% to -25%)

Source: C2M Team Analysis based on electrolysis cell potential
HOW SHOULD THE LBNL CATALYST BE BROUGHT TO MARKET?

The hydrogen landscape  Our technology  Path to market

- Application fit
- Competition
- Optimal business model
- Performance targets
SMALL SCALE APPLICATIONS OFFER GREATEST OPPORTUNITY

**Insight**

- Large decrease in capital cost
- SMR has strong cost advantages at large scale
- Feed stock electricity costs drive economics

**Market Criteria**

- Markets where capital cost is high percent of overall cost
- Niche markets where electrolysis has advantage
- Markets with access to cheap electricity
LBNL CATALYST ALIGNS BEST WITH FOUR APPLICATIONS

Framework Criteria
- Barriers to entry
- Switching costs
- Substitution/competition
- Volume usage
- Market size/potential

Best Fit Applications
- Distributed small scale energy generation
- Power generator coolant
- On-board ICE hydrogen booster
- Oxygen concentrator

Applications:
- Ammonia Production
- Oil Refining
- Semiconductors
- Metal Fabrication
- Hydrogen Peroxide
- Food & Bev
- Commercial Marine
- Yachting
- Float Glass
- Medical Drugs
- Fuel Cell Vehicles
- Grid Storage
CASE STUDY: POWER PLANT COOLING

Hydrogen gas circulates within thermal generators to remove heat from windings

**Strengths**

+ Access to low cost electricity
+ Volume output alignment
+ Exceeds payback criteria
+ Growth in Asia energy demand
+ Thermal conductivity properties

**Limitations**

– Switching costs
– Best with coal and natural gas
– Limited benefits of being ‘green’

**Market Details**

- **H₂ Market Size:** 2011: 25M 2020: $100M
- **Avg. H₂ Purchase Price:** $50/kg H₂
- **Key buyers:** Large utilities, Independent Power Producers
- **Potential partners:** GE, Siemens, ABB

*Sources: 1 – Cost Model (Assumed $200k per plant, 30% of plants, and 30% of electrolyzer), Google Images, GE Energy*
ADDRESSABLE MARKET SIZE TO GROW FROM $400M TODAY TO $32B IN 2020

- Energy Source: Fuel Cell Vehicles
- Energy Source: Telecom
- Energy Source: Mobile Military
- Energy Source: Materials Handling
- Hydrogen ICE booster
- Oxygen Concentrator
- Power Plant Cooling

Total addressable market size (in USD millions)

Source: C2M Team Analysis based on various market potentials
NEW CATALYSTS ARE STARTING TO TRANSFORM ELECTROLYSIS MARKET

Sources: Freedonia, Proton Energy Systems, Johnson Matthey, Google Images
## MOST ATTRACTIVE BUSINESS MODELS ARE TO LICENSE OR PRODUCE THE CATALYST

<table>
<thead>
<tr>
<th></th>
<th>Addressable market</th>
<th>Cost of entry</th>
<th>Value of technology</th>
<th>Expertise/ability to produce</th>
<th>Time to Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produce H2</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Produce electrolyzers</td>
<td>☻</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
</tr>
<tr>
<td>Produce catalyst</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
</tr>
<tr>
<td>License to electrolyzer manufacturer</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
<td>☾</td>
</tr>
<tr>
<td>License to catalyst producer</td>
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EMERGING FORCES WOULD RAPIDLY CHANGE THE ADOPTION OF ELECTROLYSIS

Low cost intermittent renewable sources

Large scale production of fuel cell vehicles

Global prices for GHG emissions

Sources: Google Images
FURTHER RESEARCH WILL IMPROVE COMMERCIAL POTENTIAL

• Basic research
  – Reduce thermodynamic over potential
  – Research impacts of direct solar energy

• Applied research
  – Develop a complete electrolysis cell
  – Research the use of the catalyst for fuel cells

• Prototype
  – Expand beyond lab scale

Sources: Google Images
LOW COST CATALYST CREATES VALUE FOR SMALL SCALE DISTRIBUTED HYDROGEN GENERATION

The hydrogen landscape
Cost & infrastructure barriers have limited electrolysis adoption

Our technology
Lower capital cost catalyst = small scale advantage

Path to market
License or produce catalyst for growing markets
QUESTIONS & ANSWERS
HOW DID YOU GET TO UC-BERKELEY TODAY?

- “'Hydrogen Highway' Plans Riding on Misconceptions” – 2003
- Governor Schwarzenegger signs executive order to construct hydrogen highway – Apr. 2004
- “Has Schwarzenegger's hydrogen highway gone bust?” – 2009

Sources: CNN, Scientific American, LA Times, EXECUTIVE ORDER 5-7-04
HOW DOES LBNL CATALYST FARE AGAINST PLATINUM ON A $/KG OF PRODUCED HYDROGEN BASIS?

- Pt Catalyst: $19.64
- LNBL Catalyst: $18.43

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Pt Catalyst</th>
<th>LNBL Catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed O&amp;M</td>
<td>$4.00</td>
<td>$2.00</td>
</tr>
<tr>
<td>Electricity Costs</td>
<td>$6.00</td>
<td>$4.00</td>
</tr>
<tr>
<td>Capital Costs</td>
<td>$9.00</td>
<td>$12.00</td>
</tr>
</tbody>
</table>
**PRIORITY APPLICATIONS**

<table>
<thead>
<tr>
<th>Application</th>
<th>Benefits/Sub-steps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Plant Cooling</strong></td>
<td>- Access to low cost electricity</td>
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<tr>
<td></td>
<td>- Low volume demands</td>
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<tr>
<td></td>
<td>- Currently customers pay &gt; $40/kg for delivered H2</td>
</tr>
<tr>
<td><strong>Hydrogen booster for diesel engines</strong></td>
<td>- Increased mileage by 15-20%</td>
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<tr>
<td></td>
<td>- No substitute technology</td>
</tr>
<tr>
<td></td>
<td>- Relatively inexpensive retrofits required</td>
</tr>
<tr>
<td><strong>Materials Handling (Forklifts)</strong></td>
<td>- Large addressable market (&gt;1 billion)</td>
</tr>
<tr>
<td></td>
<td>- Adoption of Fuel cell powered forklifts has increased in last 2 years</td>
</tr>
<tr>
<td><strong>Military (Mobile)</strong></td>
<td>- Large market open to trying new technologies</td>
</tr>
<tr>
<td></td>
<td>- Unique needs unmet by other technologies (Weight of battery pack, noise factor)</td>
</tr>
<tr>
<td><strong>Telecom</strong></td>
<td>- Very large market that has severe power disruption issues in developing regions (70% of towers have diesel gensets)</td>
</tr>
<tr>
<td></td>
<td>- Fuel Cells and other renewables starting to become more pervasive</td>
</tr>
<tr>
<td></td>
<td>- Easier to transport water than fossil fuels</td>
</tr>
<tr>
<td><strong>Refueling stations for Fuel Cell Vehicles</strong></td>
<td>- Need for H2 refueling infrastructure to support penetration of FCVs</td>
</tr>
<tr>
<td></td>
<td>- Lack of competition in small scale home refueling systems</td>
</tr>
</tbody>
</table>
CASE STUDY: FCV HOME REFUELING

Hydrogen gas produced to refuel personal fuel cell vehicle

**Strengths**

+ Large potential market
+ EV stations priming market
+ Expansion in home PV systems
+ Limited set of buyers

**Limitations**

– No market today
– Could increase cost of ownership
– Buyers have lots of leverage

**Market Details**

- **H₂ Market Size**: 2011: 0M 2020: $XM
- **Avg. H₂ Purchase Price**: $50/kg H₂
- **Key buyers**: Auto Manufacturers
- **Potential partners**: Utilities, Smart Grid technology companies

Source> Google Images
CASE STUDY: OXYGEN CONCENTRATOR

Oxygen is used for medical support and hydrogen is used to power distribution

**Strengths**

+ High growth market  
+ Uses both H₂ and O₂ output  
+ Low-cost catalyst needed to change dynamics  
+ Size (produce 5-10 Liters of O₂)

**Limitations**

– Must compete with PSA on cost  
– Limited electrolysis solutions  
– Must receive FDA approval

**Market Details**

- **Market Size:** 2011: $380M 2020: $2,000M  
- **Avg. Equipment Price:** $800  
- **Key buyers:** Medical supply; Equipment  
- **Potential partners:** Hospitals, Insurance

Source> Google Images, Oxygen Concentrator market WinterGreen Research
# EQUIPMENT MANUFACTURERS AND CATALYST PRODUCERS SHARE COMMON MARKET ENTRY

## Factors of Competition

<table>
<thead>
<tr>
<th>Factors of Competition</th>
<th>Hydrogen Gas</th>
<th>Electrolyzer Equipment</th>
<th>Catalyst Producer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Size</td>
<td>Positive</td>
<td>Neutral</td>
<td>Negative</td>
</tr>
<tr>
<td>Lifecycle Stage</td>
<td>Neutral</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>Market share concentration</td>
<td>Positive</td>
<td>Neutral</td>
<td>Positive</td>
</tr>
<tr>
<td>Capital Intensity</td>
<td>Negative</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
<tr>
<td>Cost Structure</td>
<td>Neutral</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>Neutral</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
</tbody>
</table>

## Attractiveness

- **Positive**
- **Neutral**
- **Negative**
EXTERNAL FORCES MAINTAIN INDUSTRY STATUS QUO

High impact

- Low natural gas prices
- US Shifts Focus Away From Hydrogen
- Japan Nuclear Explosion
- Clean Energy Investment
- Carbon Markets
- Climate Change Support
- BP Gulf Oil Spill

Low Impact

- Petroleum Price Volatility
- International Government Support

Negative Influence

Neutral Influence

Positive Influence