UC DAVIS
H₂ SYSTEMS ANALYSIS RESEARCH

• Hydrogen Pathways Program (2003-2006)
• Sustainable Transportation Energy Pathways (STEPS & NextSTEPS) (2007-present)
**NextSTEPS research focuses on:**

*Scenarios & Transition Strategies (2011-2014)*

<table>
<thead>
<tr>
<th>Hydrogen</th>
<th>Biofuels</th>
<th>Electricity</th>
<th>Fossil Fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Vehicles</td>
<td>Bio-ICE Vehicles</td>
<td>Battery-electric Plug-in hybrids</td>
<td>Bus. as usual <em>Natural Gas</em> Low-carbon fuels (incl. <em>CCS</em>)</td>
</tr>
</tbody>
</table>

**Transition Dynamics**
(Consumer Demand & Behavior, Innovation & Business Strategy)

**Models & Analyses**
(Infrastructure, Env./Econ./Energy Cost Analyses, Vehicle Tech. Eval., VMT/Travel Behavior)

**Policy Analysis**
(market instruments, fuel requirements, sustainability standards)

**Integrative Scenarios & Transition Strategies**
NextSTEPS Consortium Sponsors

U.S. Department of Energy
U.S. Department of Transportation
EPA
California Air Resources Board
Caltrans
South Coast AQMD
BMW
DAIMLER
Ford
GM
HONDA
NISSAN
TOYOTA
Renault
Volkswagen
bp
Chevron
IndianOil
Sempra Energy
Saudia Aramco
SELECTED H$_2$ SYSTEMS ANALYSIS PROJECTS (2003-2011)

- Contributor to H2A
- Supply chain analysis for different H2 pathways, delivery modes
- Transition analysis for NRC study (2008)
- Regional infrastructure case studies: biomass-to-H2, fossil H2 w/CCS.
- Social costs for H2 FCVs vs. other fuel/vehicle pathways
- Air quality impacts of H2 FCVs
ONGOING H₂ ANALYSIS RESEARCH

- Proposal to study H₂ households with GPS (Data Acquisition or DAQ project)
- FCV/H₂ Rollout strategies in California
- H₂ Infrastructure Build out Comparison US regions, other countries
- Green H₂ studies (California, US)
- Tri-generation strategies for early H₂ infrastructure (residential & commercial bldg.)
- Social costs, materials, land, water issues for H₂, other fuel/vehicle pathways
- Implications of low cost, plentiful natural gas for H₂ production
- Potential role of H₂ in low-C energy future
UC Davis Data Acquisition (DAQ)  
Project for PEVs, add FCs?

- UC Davis was selected to develop a full proposal to ARB. Project starts mid-2013.
- Monitor all vehicles in PEV households. PEVs: Leaf, Volt, Prius Plug-in
- 115-135 households
- Monitor OBD and charging parameters along with location
- Determine PEV household travel dynamics. How is the PEV used compared to other cars?
- Determine charging frequency and location. L1, L2, QC location.
- Want to add fuel cells to this study, but need OEM participation. Monitor fueling location and driving.
Regional strategies for H2 in the US
(Nils Johnson, Joan Ogden, Chris Yang)
Regional scope enables aggregated demand, lower infrastructure costs

Source: N. Johnson,
To realize its full potential for reducing GHG emissions, H2 must be produced from low-carbon primary resources.

Develop comprehensive supply scenario for H2 transportation fuel in California, building toward a large scale system based on low carbon sources, serving 25 million vehicles in 2050.

Estimate H2 demand, H2 supply mix, H2 costs, infrastructure costs, GHG emissions at different levels of H2 demand.
Trigeneration: Home, Neighborhood or Commercial Bldg. Refueling (Dr. Xuping Li)

*Tri-generation system produces electricity and heat for residences or commercial buildings (e.g. big box or grocery stores), and H2 for vehicles*

- High value co-products (electricity and heat) to improve economics of H2 production; better utilize H2 production equipment
- Early adopter convenience/security of home refueling

CA Case study shows competitive economics for single family system w/policy support and for neighborhood or commercial systems over wide range of conditions.
Analysis of Rollout Strategies for Fuel Cell Vehicles and H2 Infrastructure in California

Dr. Michael Nicholas, Prof. Joan Ogden,
Institute of Transportation Studies
University of California, Davis
H2 Fuel Cell Vehicle Introduction

FCVs Approaching technical and cost targets
Major automakers plan commercial introduction c. 2015
H2 Infrastructure needed to support early vehicles
Plans for rollout must coordinate

FCV placement + H2 infrastructure build-out, geographically and over time
H2 Infrastructure Should Offer

**COVERAGE:** enough stations, located to provide fuel accessibility for early vehicles

**CAPACITY** meet H2 demand as FCV fleet grows

**CASH FLOW:** positive cash flow for individual station owners and network-wide supply

**COMPETITIVENESS:** H2 fuel cost to consumers
Rollout Strategies for H2 Fuel Cell Vehicles

Analyze “cluster” strategy for introducing Fuel Cell vehicles and H2 refueling infrastructure in California over the next decade, to satisfy ZEV regulation.

- Station placement
- Convenience of the refueling network
- Economics – consider perspectives of
  - Fuel Supply Network
  - Individual Station owner
  - Consumer (cost of H2)
FCVs in LA Basin

Use projected FCV numbers based on California Fuel Cell Partnership surveys

Vehicles and stations placed in 4 to 12 “clusters” identified by stakeholders as early market sites.

Some connector stations are added to facilitate travel throughout the LA Basin.
12 Clusters Identified by the CAFCP Survey
Two Ways to Measure Consumer Convenience

- Average travel time: Home to the nearest station
- “Diversion” time: ave. time to nearest station while driving throughout LA Basin
8 Station Example
4 Clusters – 2 Local Stations Per Cluster

3.9 minutes home to sta.
5.6 minutes diversion time
16 Station Example
Add 8 Connector Stations => lower diversion time

3.8 minutes home to sta.
4.3 minutes diversion time
Cluster Strategy => GOOD FUELING CONVENIENCE W/ SPARSE EARLY NETWORK (<1% OF GASOLINE STATIONS)

Cluster strategy:

Vehicles placed by population

Co-locate early FCVs & H2 sta. in a few cities in region

Deployment Scenario

H2 Pathways CA H2 Highway Network Study 2005:
Ave. travel time to 17 optimally placed stations in LA Basin

= 16 minutes

UCD H2 Rollout Study 2010:
Ave. travel time to 16 optimally placed stations in LA Basin

= 4 minutes

Further Work: Demand for Hydrogen Vehicles
Based on H2 Station Location

Who wants to Buy?
- People with higher education
- Hybrid owners
- Looking for a new vehicle

Who can buy?
- Higher income
- 2nd car in the HH
- Travel patterns

Who can refuel easily?
- Station close to home
- Stations close to frequent routes
- Stations close to desired destinations
Demand for Hydrogen Vehicles

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- People with higher education
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## Demand for Hydrogen Vehicles

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### Who can buy?
- Higher income
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- Travel patterns

### Who can refuel easily?
- Station close to home
- Stations close to frequent routes
- Stations close to desired destinations
New Car Buyers? Same Places.

Who Can Buy?

Legend
Density Veh Sales/yr
Veh/SqKm
0.00 - 62.10
62.11 - 136.8
136.9 - 222.0
222.1 - 337.1
337.2 - 526.3
526.4 - 846.2
846.3 - 1368
1369 - 2900
Los Angeles New Car Buyers

Who Can Buy?
Where People Refueled ≠ Willingness to Buy But…


### Table: Trip time from home

<table>
<thead>
<tr>
<th>Trip time from work</th>
<th>Trip time (min)</th>
<th>0-5</th>
<th>6-10</th>
<th>11-20</th>
<th>21-30</th>
<th>&gt;30</th>
<th>Total</th>
<th>() = Percent of grand total</th>
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</thead>
<tbody>
<tr>
<td>0-5</td>
<td>(18.7)</td>
<td>238</td>
<td>53</td>
<td>92</td>
<td>52</td>
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<td>468</td>
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<tr>
<td>6-10</td>
<td>(7.5)</td>
<td>95</td>
<td>51</td>
<td>37</td>
<td>11</td>
<td>10</td>
<td>204</td>
<td>(13.4)</td>
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<tr>
<td>11-20</td>
<td>(8.1)</td>
<td>103</td>
<td>33</td>
<td>72</td>
<td>25</td>
<td>14</td>
<td>247</td>
<td>(19.4)</td>
</tr>
<tr>
<td>21-30</td>
<td>(4.3)</td>
<td>55</td>
<td>17</td>
<td>24</td>
<td>50</td>
<td>8</td>
<td>154</td>
<td>(12.1)</td>
</tr>
<tr>
<td>&gt;30</td>
<td>(4.2)</td>
<td>54</td>
<td>16</td>
<td>28</td>
<td>9</td>
<td>93</td>
<td>200</td>
<td>(100.0)</td>
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<tr>
<td>Total</td>
<td></td>
<td>545</td>
<td>170</td>
<td>253</td>
<td>147</td>
<td>158</td>
<td>1273</td>
<td></td>
</tr>
</tbody>
</table>

Equation can be adjusted. ½?
How Much Might One Station Do?

If 5% of Market is interested: 148 cars per year in Santa Monica (Preliminary Only)

- CA Households: 12,384,351
- CA New Cars/yr: 1,081,526.97
- 75k plus market/yr: 613,215.90
- Santa Monica 75k plus Market/yr: 4,235.79

1 Station in Santa Monica: 70%

- 75k in 2000 = 100K in 2012

Who wants to buy?

Who can buy?

Who can refuel easily?
• Fuel Cell sales will be similar to hybrid sales (but that took 10 years and many models)
• There is a relationship between home-station distance and purchase decision
• 150 cars per year per station (in an area densely packed with new car buyers)
• 50 stations will garner 7500 cars per year
• Over 5 years, 37,500 cars
How Many Stations Are Necessary Depends on How Many People are “Just Waiting For Infrastructure”

To sell 20,000 vehicles: If 40% of the market is interested, you need 12 anchor stations in LA.

To sell 20,000 vehicles: If 20% of the market is interested, you need 72 anchor stations in LA.
Setting Sales Expectations

- Sales won’t be immediate,
- Stations will need lead time to start running at full capacity if they are large
- There will be some pent up demand that will make the first year better than might otherwise be expected
- At some point sales will taper off and you will over-saturate an area
- New areas have to be developed to reach pent up demand. I.e develop an area with minimum 2 stations then move on to other areas
Infrastructure Economic Analysis

• Estimate station capital and operating costs between 2012-2017
• Consider different infrastructure build-out scenarios through 2017
• Analyze economics from several perspectives
  • Network
  • Single station owner
• Find Cash flow and Break-even year (when can the station produce H2 competitively?)
• Estimate subsidies that might be needed to support early infrastructure
Station Capital Cost Assumptions

Station costs based on interviews with energy and industrial gas company experts reflecting current and future costs.

Onsite Reformer 100-1000 kg/d
Onsite electrolyzer 100-1000 kg/d
LH2 truck delivery 100-1000 kg/d
Compressed gas truck delivery 100-500 kg/d

For onsite future stations, assume $0.5-2 million for site prep, permitting, engineering, utility installation, for green-field site before any fuel equipment goes in. H2 equipment costs are added to this.

For 2012-2014, equipment costs = 2 X H2A "current tech"
For 2015-2017, equipment costs = H2A "current tech"

Ind. Gas Co. Estimates for low-cost gas truck delivery options
Delivered H$_2$ Cost Compressed Gas Truck
$/kg (2015+, H2~$7-9/kg ~ cent/mi~Gasoline HEV @ $4.3-5.6/gal)

- Low Cost Com Gas
  - 100 -> 170 kg/d
  - 250 kg/d
  - 400 -> 500 kg/d

Delivered H$_2$ cost Onsite SMR $/kg (2015+)

(2015+, H$_2$~$5-8$/kg, ~ cent/mi ~ Gasoline @ $3-5/gal)
Transition Study: Use 2010 CAFCP estimates for FCVs in fleet in Southern California

<table>
<thead>
<tr>
<th>YEAR</th>
<th>#FCVs in fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>197</td>
</tr>
<tr>
<td>2012</td>
<td>240</td>
</tr>
<tr>
<td>2013</td>
<td>347</td>
</tr>
<tr>
<td>2014</td>
<td>1161</td>
</tr>
<tr>
<td>2015-2017</td>
<td>34,320</td>
</tr>
</tbody>
</table>
NETWORK PERSPECTIVE
2 Station Rollout Scenarios
Serving 34,000 FCVs in LA area in 2017

- Compressed Gas Truck Delivery: 78 stations in 2017
- Compressed Gas Truck Delivery + 1000 kg/d Onsite SMRs in 2016-2017: 58 stations in 2017
NETWORK Cash Flow: Delivered compressed H2 @$6/kg, H2 sell price $10/kg. 78 Sta. in 2017
Network Capital invest. = $113 million

Cash Flow for H2 Transition Scenario

Year

Million dollars/year

Capital
O&M
H2 sales
Cash flow
Cumulative cash flow
NETWORK Cash Flow: Delivered compressed H2 @$6/kg, H2 selling price $10/kg. 58 Sta. in 2017
Network Capital invest.=$160M

Cash Flow for H2 Transition Scenario

-150 -100 -50 0 50 100 150 200
2005 2010 2015 2020 2025
Million dollars/year
Year

-150 -100 -50 0 50 100 150 200
Capital
O&M
H2 sales
Cash flow
Cumulative cash flow
Economics: Station Owner Perspective

Base Case:

- 500 kg/d station. Station capital cost is $1.5 million
- H2 demand ramps up to full 500 kg/d over 4 years
- H2 costs $6/kg truck-delivered to the station
- H2 sold for $10/kg
- Station owner takes out a 5.5% 10-year loan for equipment

Sensitivity: H2 sell price, constr. time, loan terms

Subsidy: Make the station owner “whole” (pay loan payment until cash flow goes positive)
CASH FLOW: SINGLE 500 KG/D STATION.
Base Case.
Support needed until cash flow >0, ~$400K
CASH FLOW: SINGLE 500 KG/D STATION.
Base Case w/H2 selling price $9/kg.
Support needed until cash flow >0, ~$600K

Cash Flow for H2 Transition Scenario

Year: 2005 2010 2015 2020 2025
Million dollars/year:
-0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4
Capital
O&M
H2 sales
Cash flow
Cumulative cash flow
CASH FLOW: SINGLE 500 KG/D STATION.
Base Case $10/kg with 2 year construction time lag. Support needed til cash flow >0, ~$700K
Conclusions (1)

Early strategy w/ many small low cost stations using gas truck delivery yields H2 costs of <$10/kg. Levelized H2 cost decreases at larger sta.size. Cap.l investment for 58-78 sta. serving ~34,000 cars is $113-160 million ($3000-5000/car).

If (H2 selling price) – (truck delivered H2 cost) > $4/kg, the network breaks even in <8 years.

A single 500 kg/d station costing $1.5 million has a positive cash flow within a few years (once demand ramps up). Support to compensate for negative cash flow in early years ~$400-700K

Adding 1000 kg/d Onsite SMRs > 2016 =>lower ave. H2 cost (network wide), but in first decade has higher capital cost

Subsidy: Capital+O&M for 18 small stations (100-250 kg/d) & support for 60 500 kg/d stations until cash flow>0 costs $50-$70 million
Conclusions (2)

Coverage: sparse initial network of 8-20 small (100 kg/d) stations will suffice for first few 100-1000s vehicles in region.

Capacity: Once the number of vehicles in region reaches 10,000s, add capacity in larger station size (500-1000 kg/d stations). These larger stations offer scale economies, lower H2 costs.

Cash Flow: A 500 kg/d station has cash flow >0 after 2-4 years (subsidy/station ~$400-700K). Network has positive cash flow after 5-7 years.

Competitiveness (deliv. H2): Early 100 kg/d truck-delivery sta. H2 <$10/kg, later 500 kg/d truck (H2 ~$7-9/kg) or 1000 kg/d onsite SMR ($5-8/kg).
extras
NextSTEPS research focuses on: *Scenarios & Transition Strategies (2011-2014)*

- Four-year (2011-2014) multidisciplinary research consortium

- Generating scenarios and transition strategies toward a sustainable transportation future

- Disseminating knowledge to decision-makers in the private sector and governmental agencies, so they may make informed technology, investment, and policy choices
## Compressed gas truck delivery

**H2 Station Cost Assumptions: 700 bar dispensing.**

<table>
<thead>
<tr>
<th>Time frame</th>
<th>Capital Cost</th>
<th>Annual O&amp;M cost $/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase 1 (&lt;2013)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 kg/d -&gt; 170 kg/d</td>
<td>$1 million</td>
<td>$100 K (fixed O&amp;M) + 1 kWh/kgH2 x kg H2/yr x $/kWh (compression elec cost) + H2 price $/kg x kg H2/y (H2 cost delivered by truck)</td>
</tr>
<tr>
<td>250 kg/d (has more ground storage)</td>
<td>$1.5 million</td>
<td></td>
</tr>
<tr>
<td><strong>Phase 2 (2014)</strong></td>
<td></td>
<td>Same as above</td>
</tr>
<tr>
<td>100 -&gt; 170 kg/d</td>
<td>$0.9 million</td>
<td></td>
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<tr>
<td>250 kg/d</td>
<td>$1.4 million</td>
<td></td>
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<tr>
<td><strong>Phase 3 (2015+)</strong></td>
<td></td>
<td>Same as above</td>
</tr>
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<td>250 kg/d</td>
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<tr>
<td>400 -&gt; 500 kg/d</td>
<td>$1.5-2 million</td>
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</table>
### New stations added vs. year (78 total in 2017)

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>Mobile Refueler</td>
<td>4</td>
<td>0</td>
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<td>Compressed Gas Truck Delivery</td>
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</tr>
<tr>
<td>170 kg/d</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
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<tr>
<td>250 kg/d</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0</td>
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<tr>
<td>500 kg/d</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>20</td>
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<tr>
<td>Total sta. capacity (kg/y)</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>400</td>
<td>400</td>
<td>1080</td>
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<td>23213</td>
<td>34320</td>
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<tr>
<td>H2 demand (kg/d)</td>
<td>137</td>
<td>168</td>
<td>250</td>
<td>800</td>
<td>8500</td>
<td>16000</td>
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New stations added vs. year (58 total in 2017)

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<td>0</td>
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<td>4</td>
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<td>10</td>
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<tr>
<td>500 kg/d</td>
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<td>0</td>
<td>20</td>
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<td>SMR 1000 kg/d</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Total sta. cap.(kg/y)</td>
<td>400</td>
<td>400</td>
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<td>3580</td>
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</tbody>
</table>
Other Future Work

• Social costs for H2 pathways
• Materials, water, land issues for H2
• H2 has complex interactions with electric sector, better understand H2 role within energy system
NextSTEPS H2/FCV Research team

Prof. Joan Ogden, track lead

Dr. Andrew Burke
Dr. Mark Delucchi
Anthony Eggert
Prof. Yueyue Fan
Nils Johnson
Matt Jones
Dr. Xuping Li
Dr. Marshall Miller

Dr. Michael Nicholas
Dr. Nathan Parker
Kalai Ramea
Prof. Dan Sperling
Dr. Yongling Sun
Dr. Christopher Yang
Dr. Sonia Yeh
Dr. Hengbing Zhao