

Hydrogen Station Economics and Business (HySEB) -- Preliminary Results

Principal Investigator(s):

Zhenhong Lin (Presenter)

Changzheng Liu



**2014 U.S. DOE Hydrogen Program and
Vehicle Technologies Program Annual
Merit Review and Peer Evaluation
Meeting**

June 16-20, 2014

Project: AN046

OVERVIEW

Timeline

- Project start date: Oct. 2013
- Project end date: Oct 2014

**Project continuation and direction determined annually by DOE*

Barriers (System Analysis)*

- A. Future Market Behavior
- B. Stove-piped/Siloed Analytical Capability
- D. Insufficient Suite of Models and Tools

**from 2011-2020 FCTO MYPP*

Budget (DOE share)

- FY14 funding: \$100k
- Total DOE Project Value: \$100k

Partners/Collaborators

- University of Tennessee
- University of California, Davis
- Ford
- Argonne National Laboratory
- National Renewable Energy Laboratory
- US Department of Transportation

Objective: develop a tool to analyze profitability, risk and public-private partnership in hydrogen station deployment.

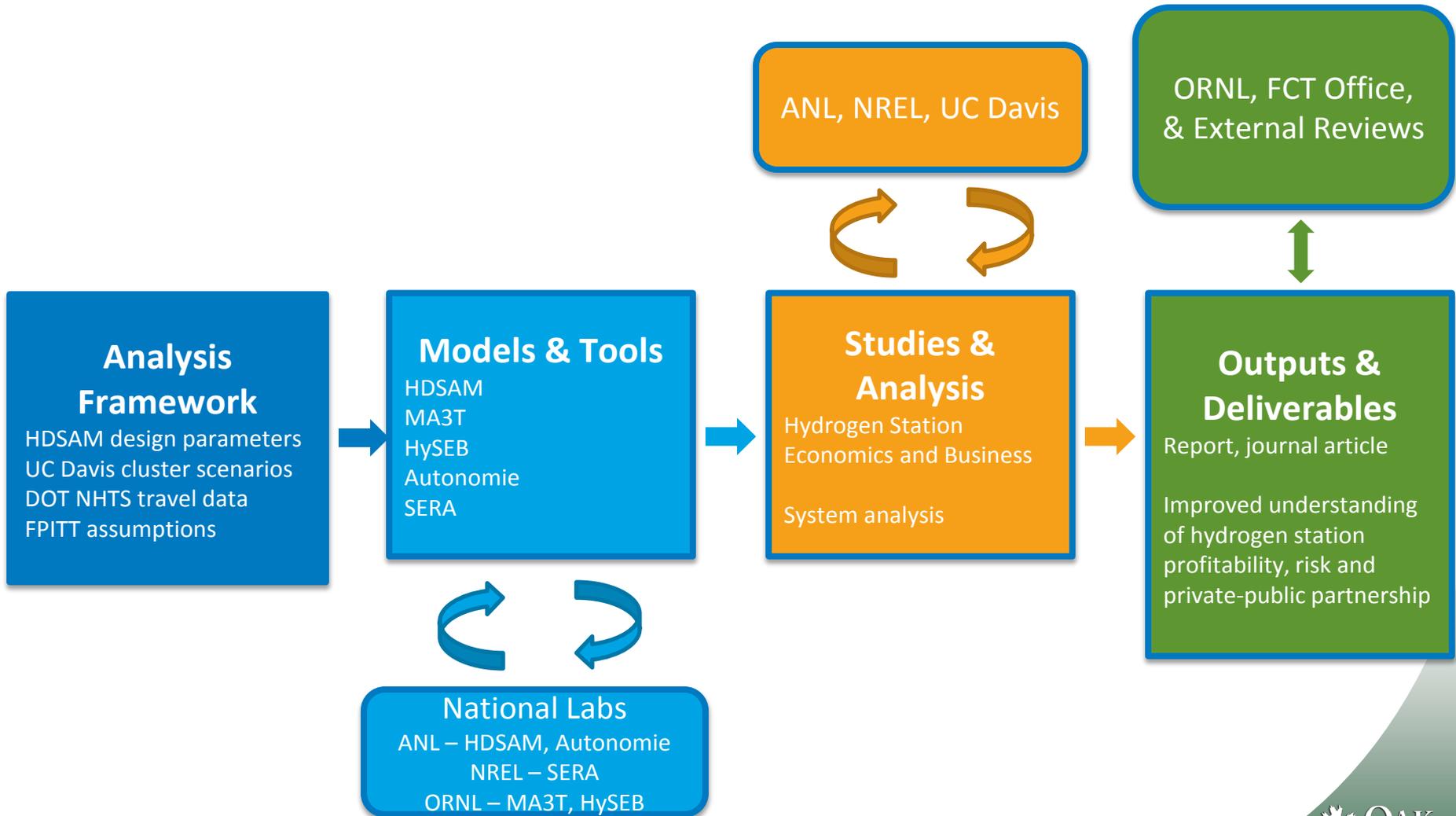
Barriers	Project Goals
Future market behavior	Develop more understanding to the supply of H2 infrastructure and the interplay between infrastructure and FCV* demand
Stove-piped/Siloed Analytical Capability	Integrate relevant outputs from UC Davis, ANL, NREL; Support H2USA activities; provide insights to designing public-private partnership policies that can motivate private investment with efficient use of government subsidy.
Insufficient suite of models and tools	Develop a model that optimizes H2 station deployment and provides insights on station economics and business models under public-private partnership

* acronyms are listed and defined in technical backup slides.

Analytical framework needed for analyzing private profitability and risk of hydrogen station deployment.

- Problem complexity
 - early adopters of FCVs requires sufficient fuel availability (% of stations), but increased number of stations reduces station utilization, or reduces economy of scale and thus inflates delivered H2 cost
 - Refueling inconvenience can be theoretically compensated, if the required compensation can be justified by station cost savings
 - Required government subsidy is related to industry perception of market prospect, investor patience, infrastructure cost, and transition optimality.
- Issues of interest
 - At what level and by how soon can government subsidy realize market-driven station deployment?
 - What are the uncertainties, barriers and opportunities in identifying early adopters with the cluster strategy?
 - What is the profitability and risk faced by investors?
 - How to design the public-private investment partnership?

Hydrogen Station Economics and Business (HySEB)



The Hydrogen Station Economics and Business (HySEB) model optimizes key deployment decisions to maximize profitability in consideration of investment risks.

- Current status and assumptions

- All station costs based on Ogden 2013 AMR and H2A
- 1st station is 100kg/d mobile refueler; capacity and timing of subsequent stations are to be optimized
- FCV sales estimates based on ZEV mandate
- Clustering strategy based on Ogden and Nicholas (2010)
- Detailed modeling of station deployment at a city level
 - Scenarios: small stations first, uniform size, large stations first
 - Trade off between station cost and fuel accessibility cost
- Incorporate daily travel patterns to more accurately reflect fuel demand at home stations in the context of cluster strategy

- Mix and daily distance distributions of 6 driver types: Frequent Long Commute (FLC), Frequent Short commute (FSC), Average Long Commute (ALC), Average Short Commute (ASC), Modest Long Commute (MLC), Modest Short Commute (MSC)

- Capability of modeling fuel cell PHEVs
- Cash flow analysis of home stations
 - Capital, O&M, revenue, fuel accessibility
 - Hydrogen price subsidy, capital cost subsidy
 - System NPV, investor NPV, buy-down cost, next-N-years NPV

- On-going efforts

- implementing optimization algorithm
- more uncertainty analysis

Assumption—clustering strategy is our starting point and we focus on station network economics at one cluster (a small city)

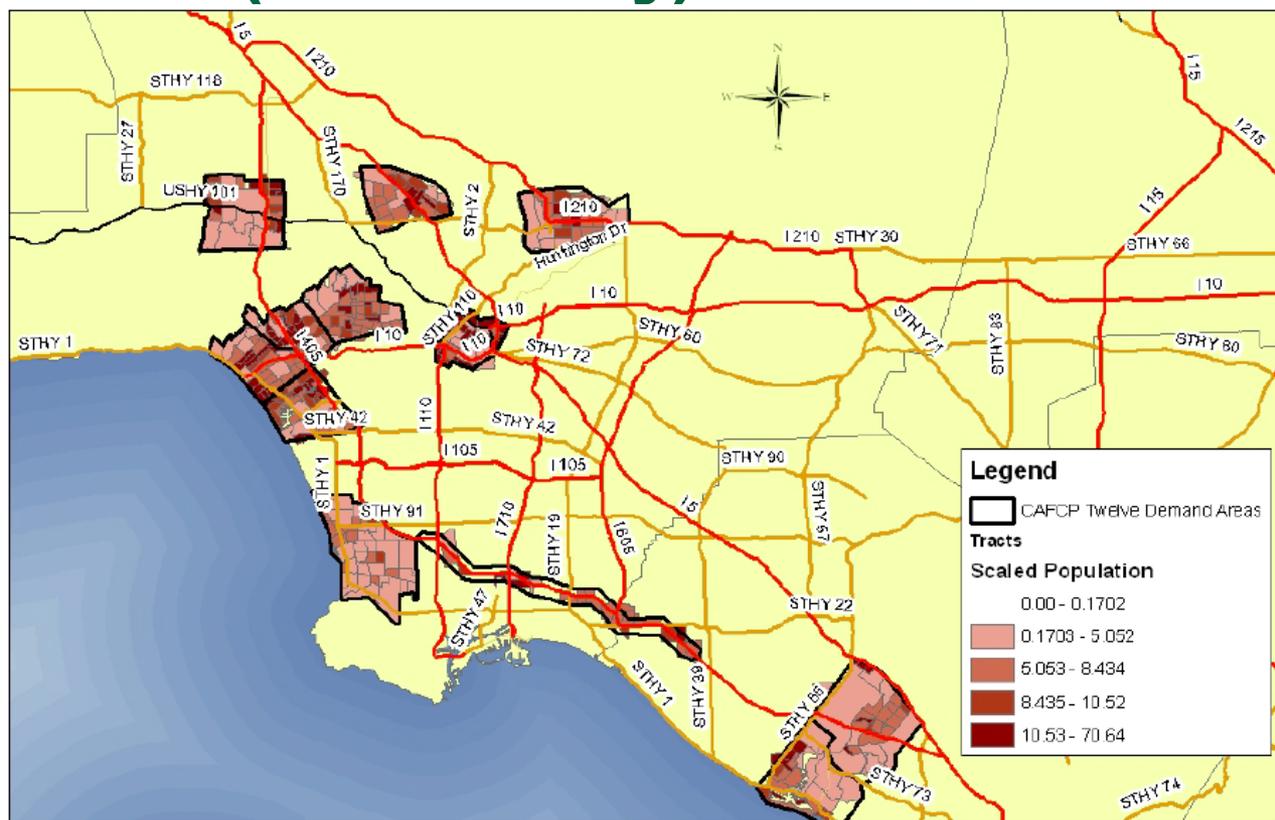


Figure 3 Scaled population distribution within the clusters so that each cluster represents the same number of people. Population is a proxy for attractiveness of vehicle placement. Having each cluster represent the same number of vehicles implies that each cluster is equally attractive.

Source: J. Ogden, M. Nicholas, 2010. Energy Policy, 39(4), Pg 1923-1938

Travel time to the nearest station for clustered consumers varies among clusters, but generally is lower than that for region-wide random consumers.

Home station fuel accessibility cost is a function of fuel availability (% of stations), FA curve that reflects city density, travel time value that reflects income level, and number of FCVs on road.

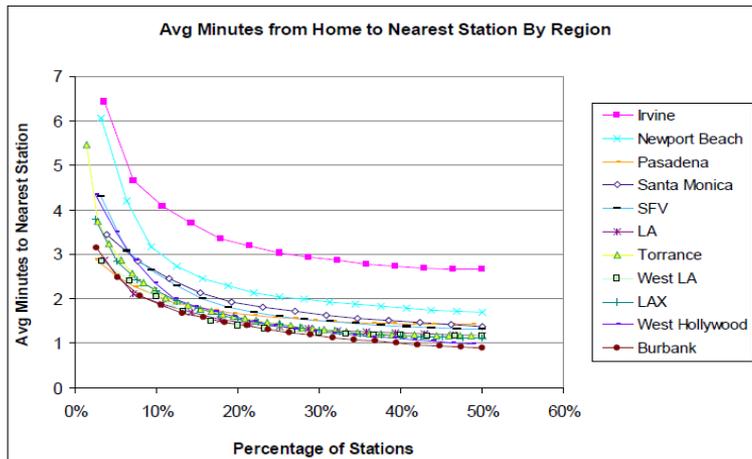
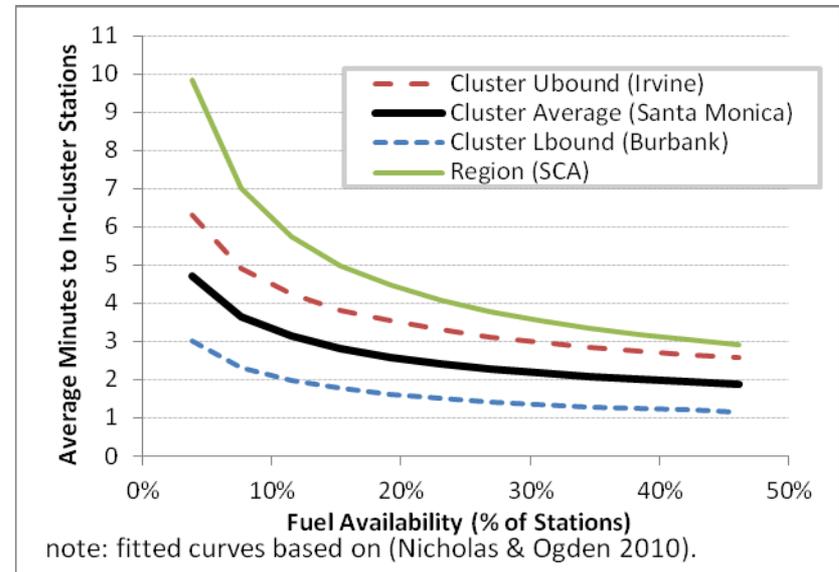


Figure 6 Due to the varying number of stations per cluster, the average minutes to the nearest station is plotted as a function of the percentage of gasoline stations that offer hydrogen. Each dot signifies a hydrogen station. One station is signified by the leftmost dot in each line. Subsequent dots signify additional stations. Irvine, as defined by the cluster boundary, shows poorer access to fuel than other clusters. If there were 50% as many hydrogen stations as gasoline stations, most clusters would average a little over a minute to the nearest station.

Source: J. Ogden, M. Nicholas, 2010. Energy Policy, 39(4), Pg 1923-1938



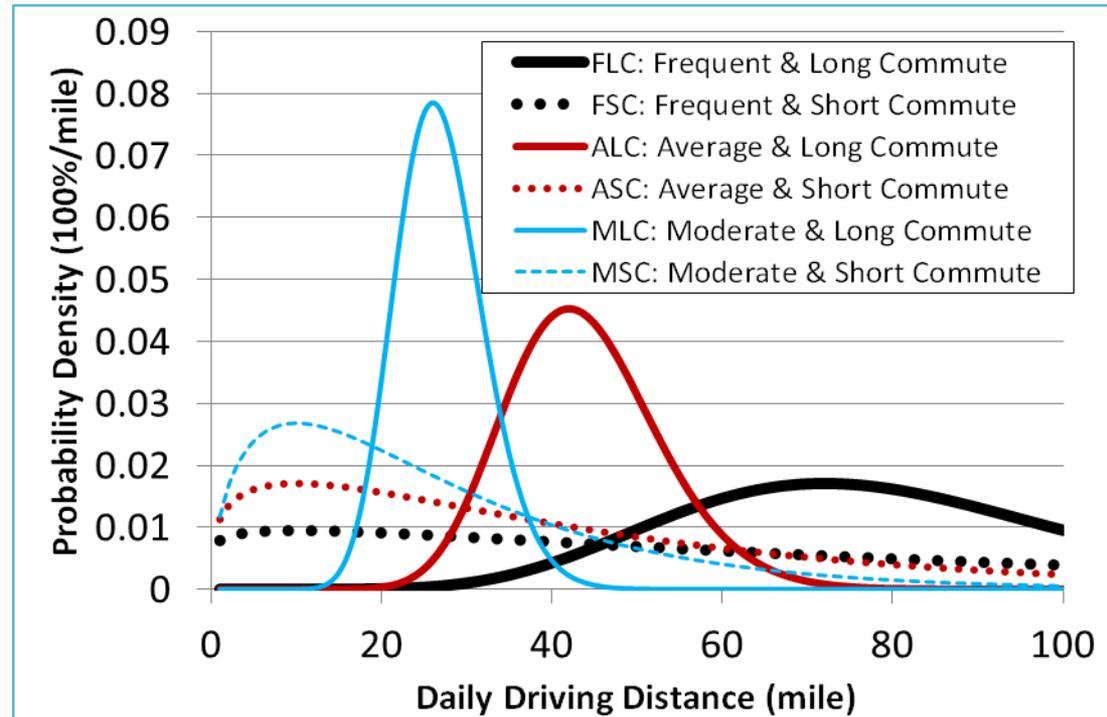
note: fitted curves based on (Nicholas & Ogden 2010).

Accomplishments and Progress -- Preliminary

Driving pattern heterogeneity affects home station business and is captured with a set of daily distance probability density curves.

- 6 California drivers were selected from NHTS 2009 as data source to capture driving pattern heterogeneity. Driver shares are calibrated for an average driving intensity of 13k miles/year based on California.
- A higher share of frequent drivers with long commute distance is expected to contribute more to home station business.
- For each driver group, fuel demand at home stations are calculated (refueling at connector stations if daily driving distance > a threshold value)
- The daily long distance threshold is assumed to be 100 miles.

	Miles /year	miles to work	% of miles on home stations	H2 demand from home stations (kg/d)	% of drivers
FLC	29250	36	72%	0.93	2%
FSC	31107	5	34%	0.49	2%
ALC	14263	21	100%	0.73	25%
ASC	12500	5	73%	0.53	25%
MLC:	9850	13	100%	0.45	23%
MSC	9849	5	96%	0.43	23%



Accomplishments and Progress -- Preliminary

We developed HySEB, an Excel/VBA model, to optimize clustering deployment decisions under a wide range of user-specified market and technological parameters, and to inform public-private investment decisions.

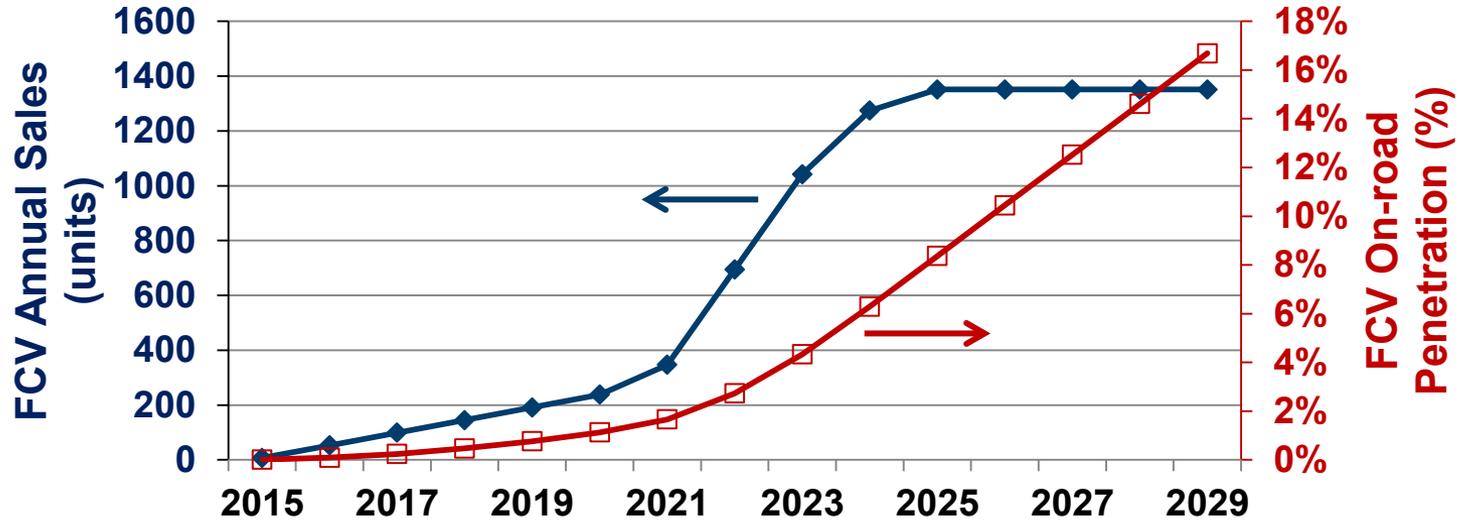
- 4 groups of inputs: City-Vehicle, Driver, Infrastructure, Market Scenario.
- Optimization algorithm is under development.
- Users can use the interface to examine in real-time how system NPV, next-N-years NPV, and cashflows respond to input changes.

Hydrogen Station Economics and Business (HySEB)																																																																																																																																						
Contact: Zhenhong Lin, linz@ornl.gov, Oak Ridge National Laboratory																																																																																																																																						
City-Vehicle		Output		Market Scenario and Infrastructure Deployment																																																																																																																																		
units	FCV volume 15-17	159	System Cost NPV (\$/kg)	12.3	Year	2015	2022	2029																																																																																																																														
units	FCV volume 18-20	574	Infrastructure NPV (\$/kg)	9.1	Time Step	1	8	15																																																																																																																														
units	FCV volume 21-23	2083	Fuel Accessibility NPV (\$/kg)	3.2	FCV Sales	7	694	1351																																																																																																																														
%	Clustering Scale	100%																																																																																																																																				
units	City vehicle volume	65000																																																																																																																																				
persons	City population	90000																																																																																																																																				
mpkg	FCV CS Fuel Economy	60																																																																																																																																				
Wh/mi	FCV CD Electricity Rate	235																																																																																																																																				
miles	FCV CD Range	0																																																																																																																																				
kg	H2 On-board Capacity	5.0																																																																																																																																				
kg/day	Per-vehicle H2 Use	0.55																																																																																																																																				
Driver																																																																																																																																						
%	FLC Share	2%																																																																																																																																				
%	FSC Share	2%																																																																																																																																				
%	ALC Share	25%																																																																																																																																				
%	ASC Share	25%																																																																																																																																				
%	MLC Share	23%																																																																																																																																				
%	MSC Share	23%																																																																																																																																				
min	Value of travel time	20																																																																																																																																				
	anoyance multiplier	3																																																																																																																																				
	early adopter AM factor	5																																																																																																																																				
	Consumer discount rate	7%																																																																																																																																				
	Investor discount rate	12%																																																																																																																																				
Infrastructure			<table border="1"> <thead> <tr> <th>Station On Line</th> <th>2015</th> <th>2022</th> <th>2029</th> </tr> </thead> <tbody> <tr><td>1</td><td>#1</td><td>1</td><td>1</td><td>1</td></tr> <tr><td>2</td><td>#2</td><td>0</td><td>1</td><td>1</td></tr> <tr><td>3</td><td>#3</td><td>0</td><td>1</td><td>1</td></tr> <tr><td>4</td><td>#4</td><td>0</td><td>1</td><td>1</td></tr> <tr><td>5</td><td>#5</td><td>0</td><td>0</td><td>1</td></tr> <tr><td>6</td><td>#6</td><td>0</td><td>0</td><td>1</td></tr> <tr><td>7</td><td>#7</td><td>0</td><td>0</td><td>1</td></tr> <tr><td>8</td><td>#8</td><td>0</td><td>0</td><td>1</td></tr> <tr><td>9</td><td>#9</td><td>0</td><td>0</td><td>1</td></tr> <tr><td>10</td><td>#10</td><td>0</td><td>0</td><td>1</td></tr> </tbody> </table> <table border="1"> <thead> <tr> <th>Station Capacity (kg/day)</th> <th>2015</th> <th>2022</th> <th>2029</th> </tr> </thead> <tbody> <tr><td>#1</td><td>100</td><td>100</td><td>100</td></tr> <tr><td>#2</td><td>0</td><td>444</td><td>444</td></tr> <tr><td>#3</td><td>0</td><td>514</td><td>514</td></tr> <tr><td>#4</td><td>0</td><td>583</td><td>583</td></tr> <tr><td>#5</td><td>0</td><td>0</td><td>653</td></tr> <tr><td>#6</td><td>0</td><td>0</td><td>722</td></tr> <tr><td>#7</td><td>0</td><td>0</td><td>792</td></tr> <tr><td>#8</td><td>0</td><td>0</td><td>861</td></tr> <tr><td>#9</td><td>0</td><td>0</td><td>931</td></tr> <tr><td>#10</td><td>0</td><td>0</td><td>1000</td></tr> </tbody> </table> <table border="1"> <thead> <tr> <th>City H2 Supply Capacity (kg/d)</th> <th>2015</th> <th>2022</th> <th>2029</th> </tr> </thead> <tbody> <tr><td>City H2 Supply Capacity (kg/d)</td><td>100</td><td>1641</td><td>6600</td></tr> <tr><td>City H2 Demand (kg/day)</td><td>4</td><td>972</td><td>5940</td></tr> <tr><td>City H2 Station Utilization</td><td>0.04</td><td>1</td><td>1</td></tr> </tbody> </table> <table border="1"> <thead> <tr> <th>Station Output (kg/day)</th> <th>2015</th> <th>2022</th> <th>2029</th> </tr> </thead> <tbody> <tr><td>#1</td><td>4</td><td>59</td><td>90</td></tr> <tr><td>#2</td><td>-</td><td>263</td><td>400</td></tr> </tbody> </table>						Station On Line	2015	2022	2029	1	#1	1	1	1	2	#2	0	1	1	3	#3	0	1	1	4	#4	0	1	1	5	#5	0	0	1	6	#6	0	0	1	7	#7	0	0	1	8	#8	0	0	1	9	#9	0	0	1	10	#10	0	0	1	Station Capacity (kg/day)	2015	2022	2029	#1	100	100	100	#2	0	444	444	#3	0	514	514	#4	0	583	583	#5	0	0	653	#6	0	0	722	#7	0	0	792	#8	0	0	861	#9	0	0	931	#10	0	0	1000	City H2 Supply Capacity (kg/d)	2015	2022	2029	City H2 Supply Capacity (kg/d)	100	1641	6600	City H2 Demand (kg/day)	4	972	5940	City H2 Station Utilization	0.04	1	1	Station Output (kg/day)	2015	2022	2029	#1	4	59	90	#2	-	263	400
Station On Line	2015	2022							2029																																																																																																																													
1	#1	1							1	1																																																																																																																												
2	#2	0							1	1																																																																																																																												
3	#3	0							1	1																																																																																																																												
4	#4	0							1	1																																																																																																																												
5	#5	0							0	1																																																																																																																												
6	#6	0							0	1																																																																																																																												
7	#7	0							0	1																																																																																																																												
8	#8	0							0	1																																																																																																																												
9	#9	0	0	1																																																																																																																																		
10	#10	0	0	1																																																																																																																																		
Station Capacity (kg/day)	2015	2022	2029																																																																																																																																			
#1	100	100	100																																																																																																																																			
#2	0	444	444																																																																																																																																			
#3	0	514	514																																																																																																																																			
#4	0	583	583																																																																																																																																			
#5	0	0	653																																																																																																																																			
#6	0	0	722																																																																																																																																			
#7	0	0	792																																																																																																																																			
#8	0	0	861																																																																																																																																			
#9	0	0	931																																																																																																																																			
#10	0	0	1000																																																																																																																																			
City H2 Supply Capacity (kg/d)	2015	2022	2029																																																																																																																																			
City H2 Supply Capacity (kg/d)	100	1641	6600																																																																																																																																			
City H2 Demand (kg/day)	4	972	5940																																																																																																																																			
City H2 Station Utilization	0.04	1	1																																																																																																																																			
Station Output (kg/day)	2015	2022	2029																																																																																																																																			
#1	4	59	90																																																																																																																																			
#2	-	263	400																																																																																																																																			
kg/day	Min H2 Supply Capacity	6,600																																																																																																																																				
	Minimum Sta No.	7																																																																																																																																				
	DV--Station No.	10																																																																																																																																				
kg/day	Avg Station Size	722																																																																																																																																				
kg/day	Smallest Station Size	444																																																																																																																																				
kg/day	2nd Station Size	444																																																																																																																																				
kg/day	Incre Size	69																																																																																																																																				
	Roll-out Scenario	SmallFirst																																																																																																																																				
year	Station Lifetime	15																																																																																																																																				

Accomplishments and Progress -- Preliminary

To estimate H2 use, clustered FCV volume is assumed to grow rapidly during 3 ZEV-compliance periods and then stabilize.

FCV Sales and On-Road Penetration



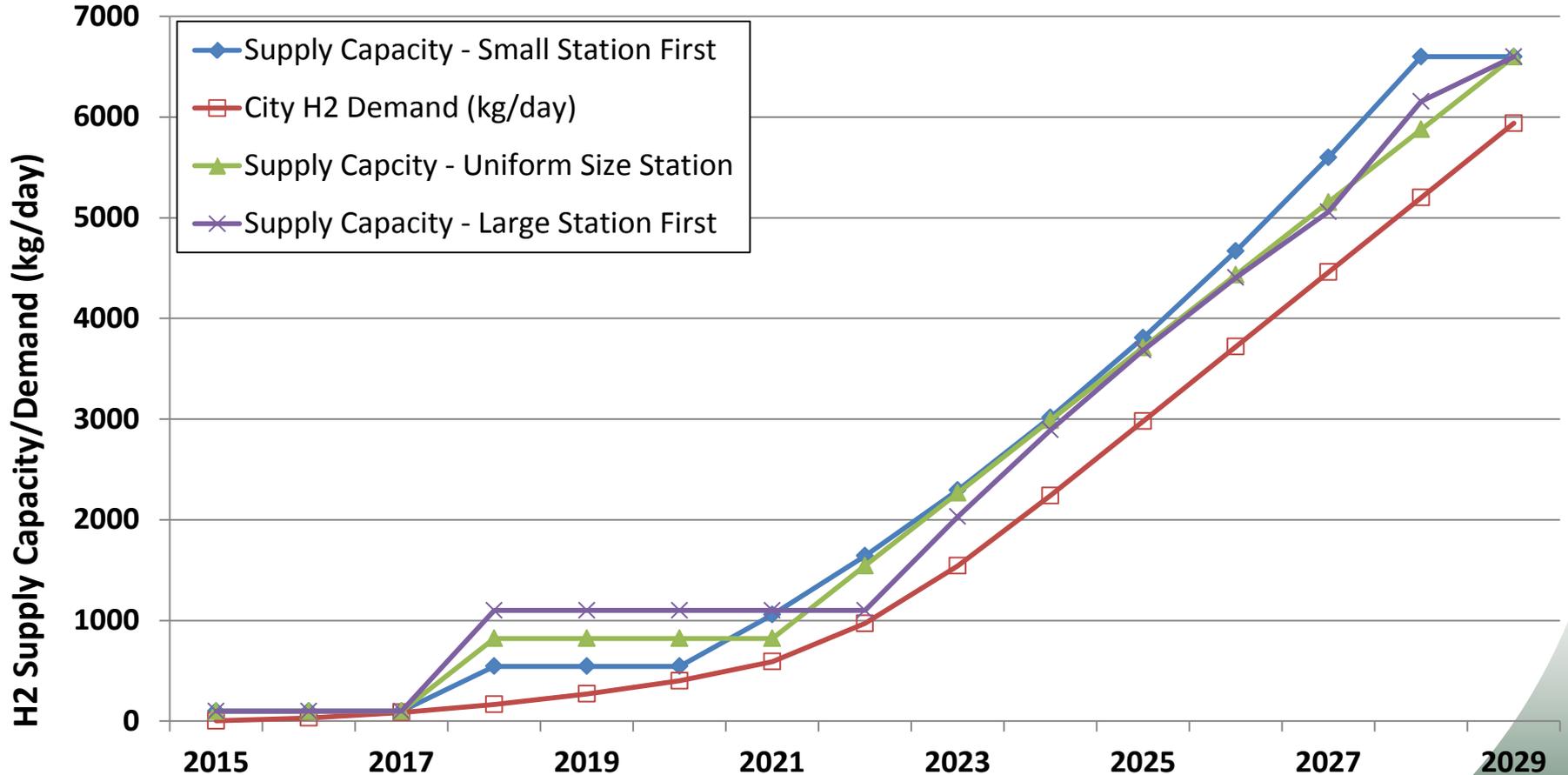
Assumptions

- Use Santa Monica as the clustering context. In 2007, city vehicle volume about 65000, city population about 90000, a total of 159 FCVs sold during 2015-2017, 574 during 2018-2020, and 2083 during 2021-2023, consistent with ZEV-compliance scenarios in (Ogden, Nicholas, 2010); 3 years to stabilize the annual sales.
- A 100 kg/day mobile refueler is assumed as the 1st station; all subsequent stations are onsite SMR with varied sizes.
- All station capital, O&M costs and efficiency data are consistent with (Ogden 2013 AMR) and H2A.

Accomplishments and Progress -- Preliminary

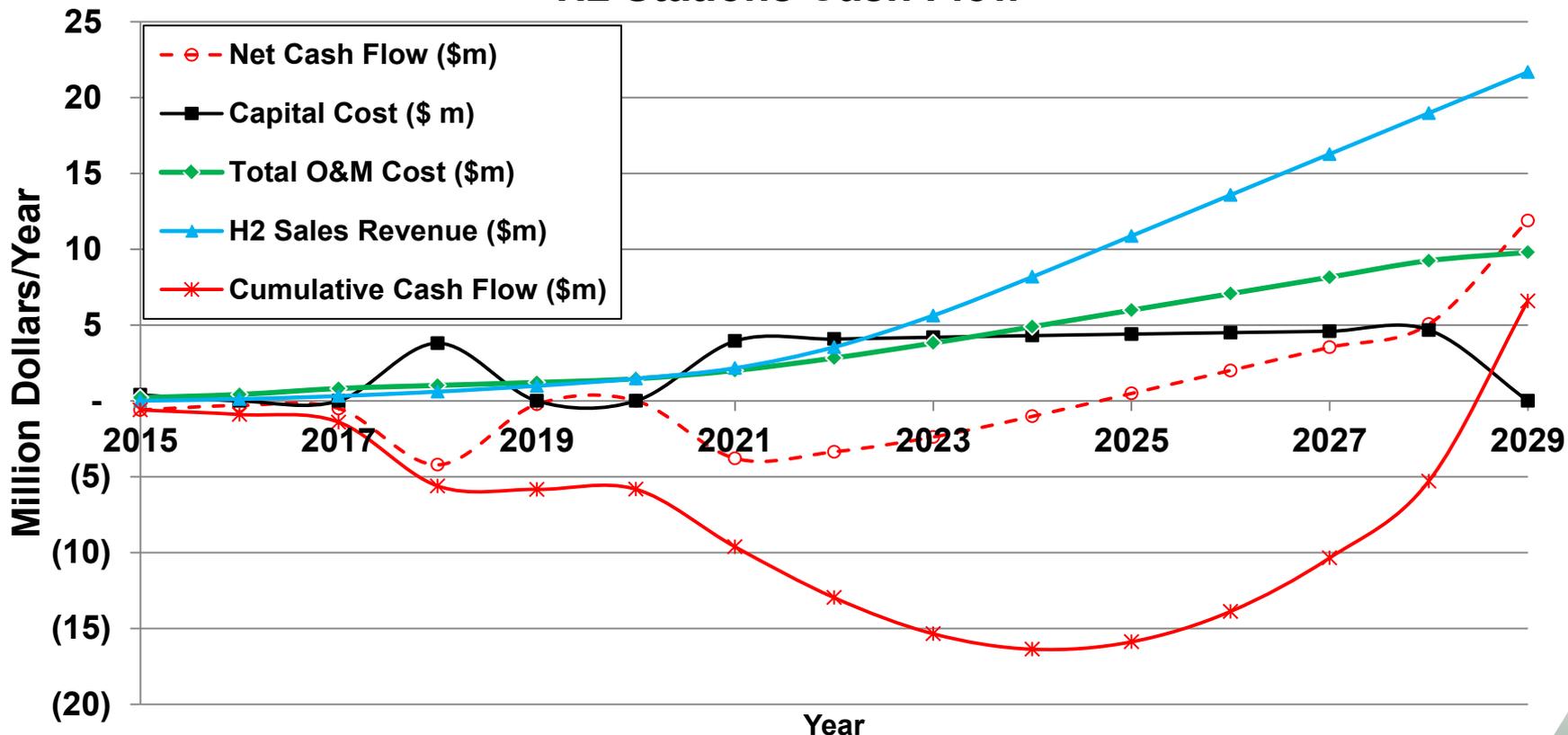
Three H2 station roll-out scenarios are considered to examine the significance of station economy of scale and timing.

City H2 Supply Capacity Scenarios and Demand



Base Case: build small stations first. System NPV is \$12.4/kg (33.5 \$m), including \$9.2/kg for infrastructure cost and \$3.2/kg for fuel accessibility cost.

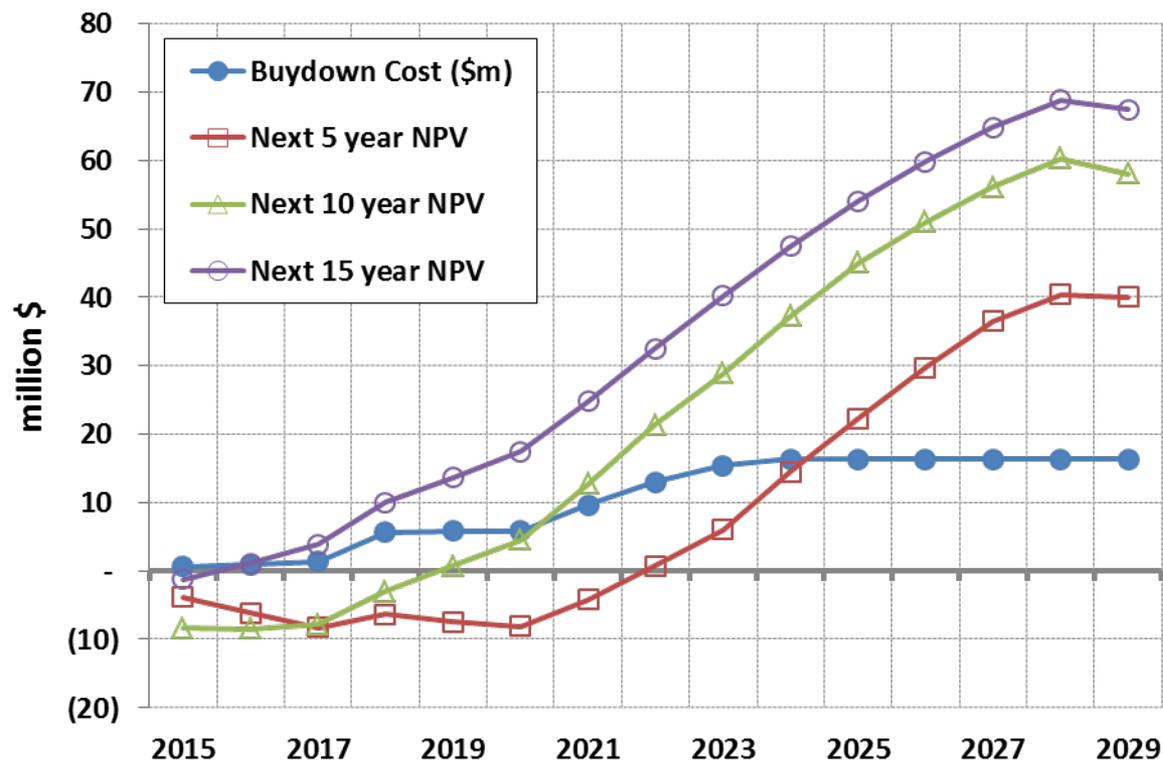
H2 Stations Cash Flow



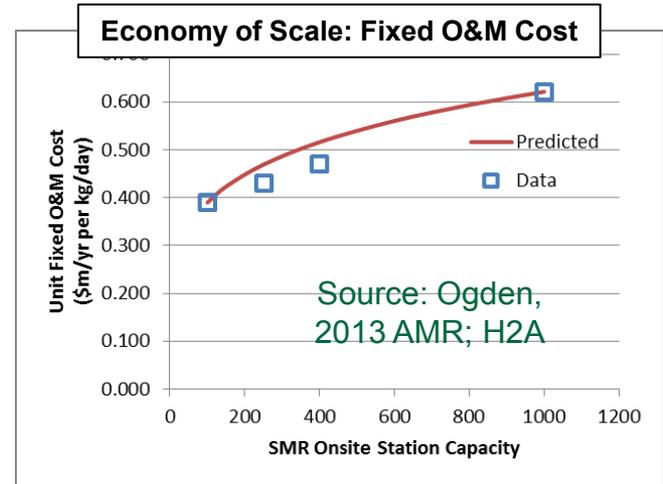
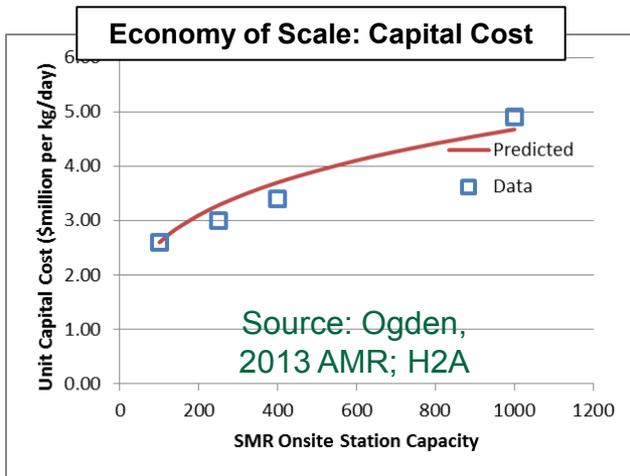
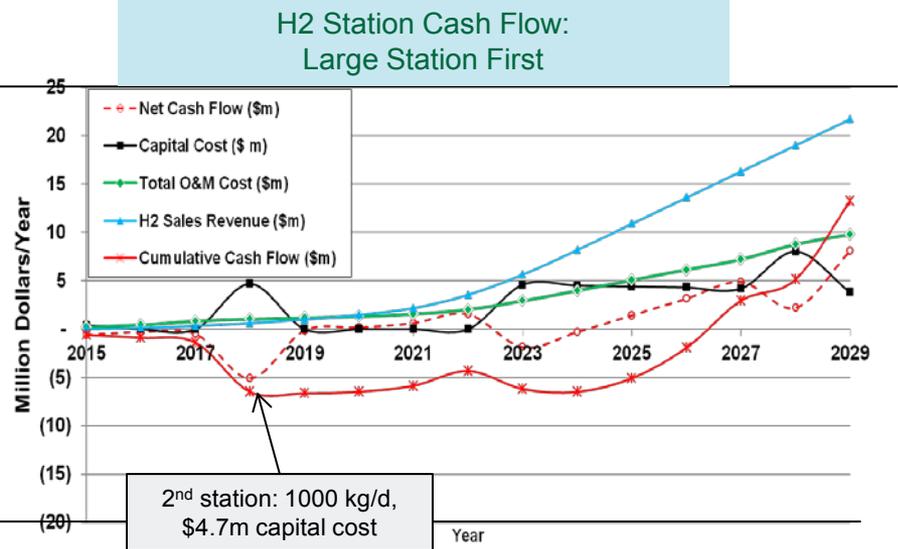
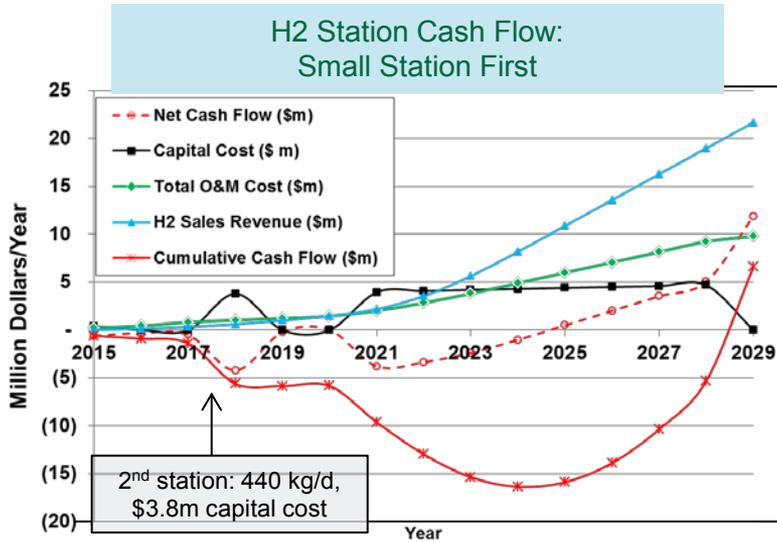
H2 price is assumed to be \$10/kg.

The “term-limited buydown” public-private partnership

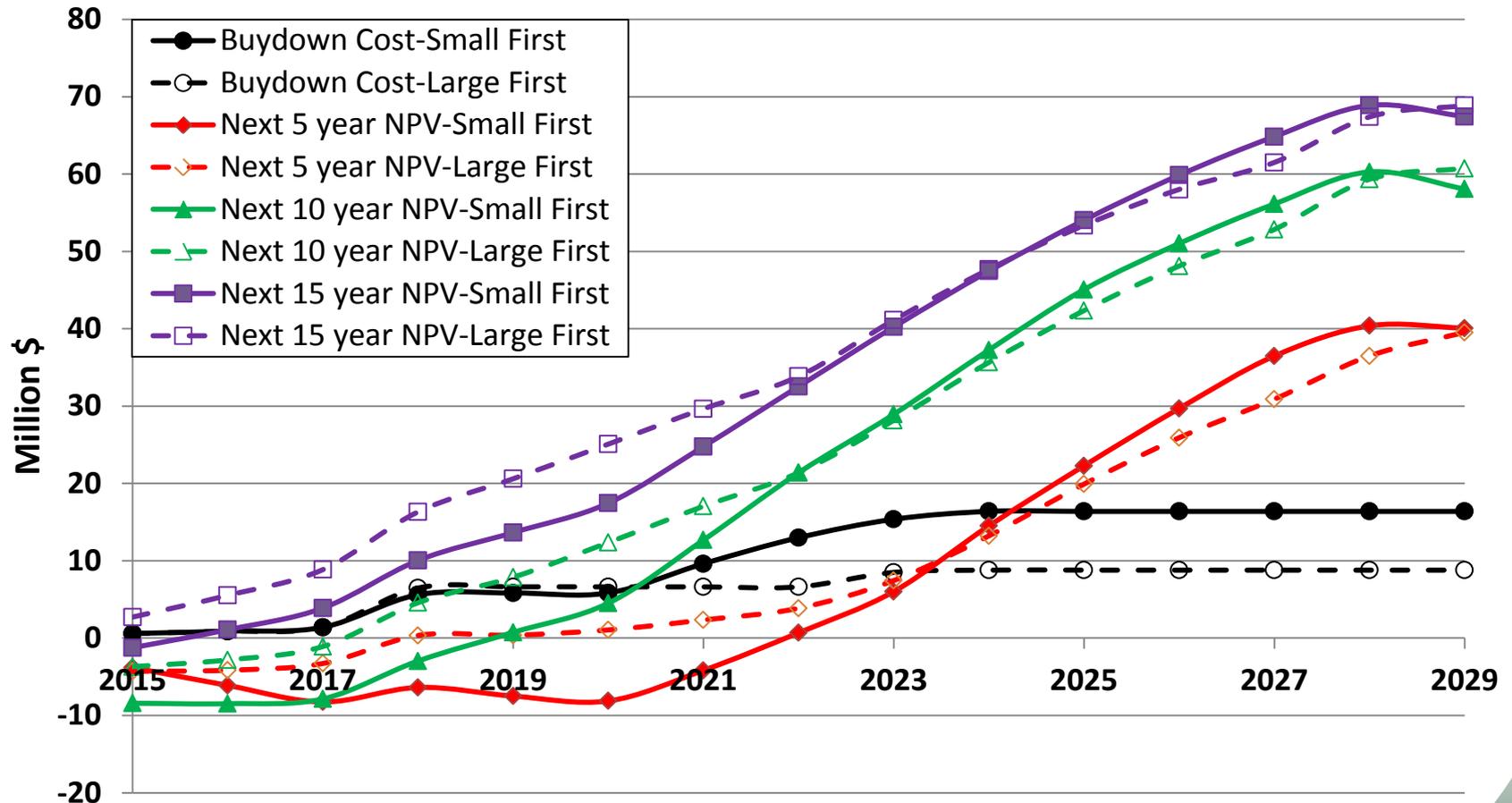
- buydown cost of year i = the cumulative sum of negative cash flows in year 1, 2... i .
- The next- N -years NPV of year i = NPV of the cash flows during the next N years starting from year $i+1$, discounted to the end of year i .
- E.g, in year 2020, the return to a \$5.5 million of 2015-2020 buydown (public investment) is a local hydrogen station business that is worth \$6.6 million for the next 10 years.
- But is 10-year investor patience too much to ask? Should we use 5 years, 15 years or something else?



Building large stations first could reduce system cost NPV due to near-term economy of scale.



Balancing station economy of scale with fuel availability can be important for private-public partnership.



Caution: how accurate is the estimated economy of scale?

Combining cluster strategy with station scale economy and favorable travel patterns can significantly lower system cost.

The table shows scenario system NPV in \$/kg and the number within the parenthesis shows the infrastructure cost component.

	Small Station First	Large Station First
Ref. Case (2/25/23% mix)	12.4 (9.2) \$/kg	11.4 (7.8) \$/kg
100% FLC	9.4 (5.9) \$/kg	9.7 (6.4) \$/kg
100% MSC	14.7 (11.7) \$/kg	12.3 (8.5) \$/kg

- System cost NPV = infrastructure cost NPV + fuel accessibility cost NPV. System cost is independent of hydrogen price, which only affects wealth transfer between consumers and fuel providers.
- On the other hand, frequent outside-network travelers with high time value would be a challenge for business viability of cluster strategy.
- Limiting public subsidy would require more investor patience, Investors may be more patient if they perceive less technological and policy risk.

- **The project is new and has not been reviewed before.**
- **We look forward to your comments, recommendations and advice.**

Collaborations/Contributions

Institution	Role
<u>Oak Ridge National Laboratory (ORNL)</u> Zhenhong Lin (PI), Changzheng Liu	Prime, oversee the project, model formulation and implementation, data collection, analysis
<u>University of Tennessee</u> David Greene	Comments on methods and issues of interest
<u>University of California, Davis</u> Joan Ogden, Michael Nicholas	Provide station costs, generate cluster roll-out scenarios, fuel accessibility analysis
<u>Ford</u> Mike Tamor	Travel pattern analysis; daily distance distribution
<u>Argonne National Laboratory</u> Amgad Elgowainy	Execute the H2A model and provide delivered H2 costs for various station sizes and pressures
<u>National Renewable Energy Laboratory</u> Marc Melaina, Brian Bush, Yongling Sun, Jennifer Melius	Generate hydrogen station roll-out scenarios at various spatial levels
<u>US Department of Transportation</u> Danielle Gray, Rick Goeltz (ornl), Tim Reuscher (contr)	Provide and explain household travel survey data

Future work will focus on model upgrade, uncertainty, and public-private cost share mechanisms

- Develop an optimization algorithm that finds station placing and sizing strategy to minimize system cost.
- Uncertainties, especially of demand and station cost
- Integrate with consumer choice model and analyze the interplay between infrastructure and vehicle penetration by representing investor patience, risk, and hydrogen pricing.
- Business viability for connector stations
- More analysis of public-private cost share mechanisms

Summary

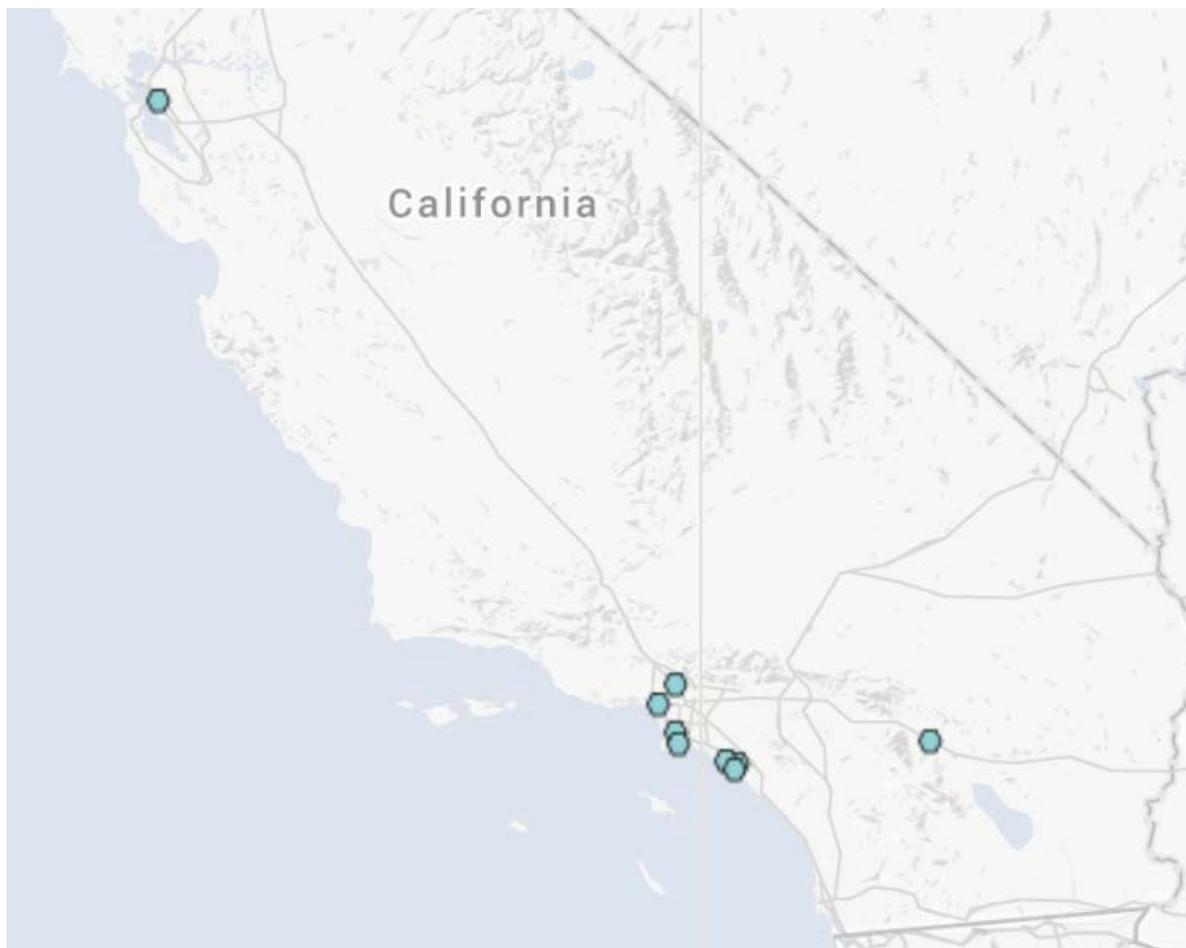
- The project aims at analyze profitability, risk and public-private partnership in hydrogen station deployment.
- Toward this goal, we developed HySEB to analyze business viability and risk of home stations under cluster strategy, with some unique features:
 - Optimal roll-out decisions (expected); minimize sum of infrastructure cost and fuel accessibility cost
 - Travel pattern heterogeneity (daily variation and driver mix)
 - “Term-limited buydown + next-N-year NPV” allows public-private cost share analysis
- Preliminary results suggest the importance of station economy of scale and travel patterns.
- Future work will focus on model upgrade, uncertainty, and public-private cost share mechanisms.

THANK YOU

Acronyms

ALC	Average Long Commute
AOP	Annual Operating Plan
ASC	Average Short Commute
FA	Fuel availability
FCV	Fuel cell vehicle
FLC	Frequent Long Commute
FPITT	Fuel Pathway Integration Tech Team
FSC	Frequent Short commute
H2A	Hydrogen Analysis
HySEB	Hydrogen Station Economics and Business
MA3T	Market Acceptance of Advanced Automotive Technologies
MLC	Modest Long Commute
MSC	Modest Short Commute
MYPP	Multi-year Program Plan
NHTS	National Household Travel Survey
NPV	Net present value
O&M	Operation and Maintenance
OP	Optimal pressure
ZEV	Zero-emission vehicle

A total of 9 hydrogen stations exist in California, most in SCA



Source: afdc.energy.gov, accessed on April 2, 2014

Driving pattern heterogeneity is found to be significant, which affects the business viability and risk of hydrogen stations.

- NHTS 2009 Filtering criteria: State=CA, vehicle age<5, household per-driver vehicle >1, detached home, full-time worker (N=2512)
- NHTS 2009 is used to obtain California driving pattern with the validated ORNL Gamma method. 6 sampled drivers were selected from the 2512 drivers to represent a wide range of driving intensity and pattern. Their shares are calibrated to the average driving intensity of California drivers.

	Annual distance driven (miles)	Distance to work (miles)
Mean	13,739	14
Median	12,501	11
Mode	15,000	5
St. Deviation	7,031	11
Std/Mean	0.51	0.75
Count	2,512	2,512