UCDAVIS

SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

An Institute of Transportation Studies Program

Overview of Hydrogen Systems Analysis Research at UC Davis

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University of California, Davis

November 15, 2012

HTAC Meeting

UC DAVIS
H_2 SYSTEMS ANALYSIS RESEARCH

- **Fuel Cell Vehicle Modeling Program (1999-2002)**
- **Hydrogen Pathways Program (2003-2006)**
- **Sustainable Transportation Energy Pathways (STEPS & NextSTEPS) (2007-present)**

NextSTEPS research focuses on: *Scenarios & Transition Strategies* *(2011-2014)*

Hydrogen	**Biofuels**	**Electricity**	**Fossil Fuels**
Fuel Cell Vehicles H2-ICE Vehicles	Bio-ICE Vehicles 2nd Gen Biofuels	Battery-electric Plug-in hybrids	Bus. as usual ***Natural Gas*** Low-carbon fuels (incl. ***CCS***)

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 United States Environmental Protection Agency

California Air Resources Board

Caltrans

SOUTH COAST AQMD

BMW

DAIMLER

Ford

GM

HONDA

NISSAN

RENAULT

TOYOTA

أرامكو السعودية Saudi Aramco

bp

Chevron

इंडियनऑयल IndianOil

Sempra Energy

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 H_2 ANALYSIS RESEARCH

- Proposal to study H2 households with GPS (Data Acquisition or DAQ project)
- FCV/H_2 Rollout strategies in California
- H_2 Infrastructure Build out Comparison US regions, other countries
- Green H_2 studies (California, US)
- Tri-generation strategies for early H_2 infrastructure (residential & commercial bldg.)
- Social costs, materials, land, water issues for H_2, other fuel/vehicle pathways
- Implications of low cost, plentiful natural gas for H_2 production
- Potential role of H_2 in low-C energy future

UC Davis Data Acquisition (DAQ) Project for PEVs, add FCs?

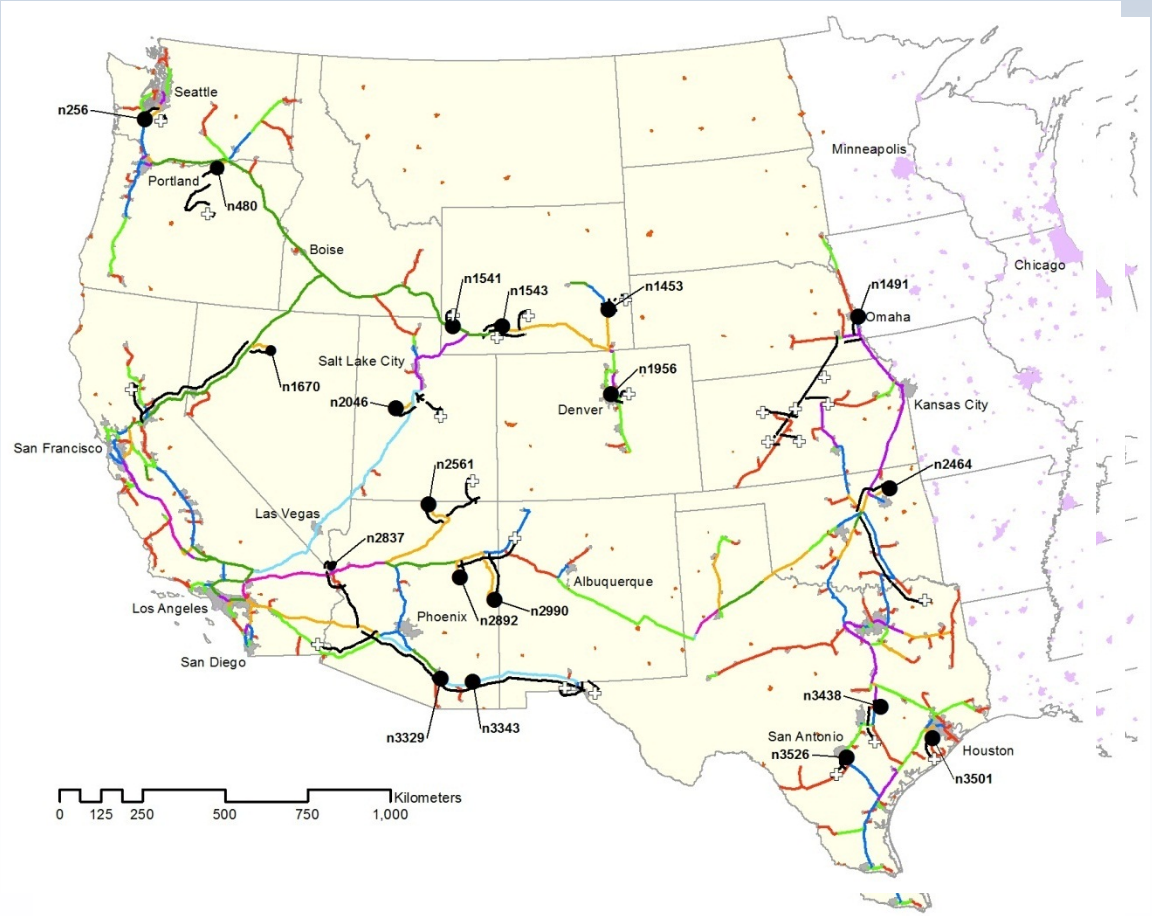
- UC Davis was selected to develop a full proposal to ARB. Project starts mid-2013.
- Monitor all vehicles in PEV households. PEVs: Leaf, Volt, Prius Plug-in

- 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,

Green H_2 Study
(Christopher Yang, Joan Ogden)

- 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

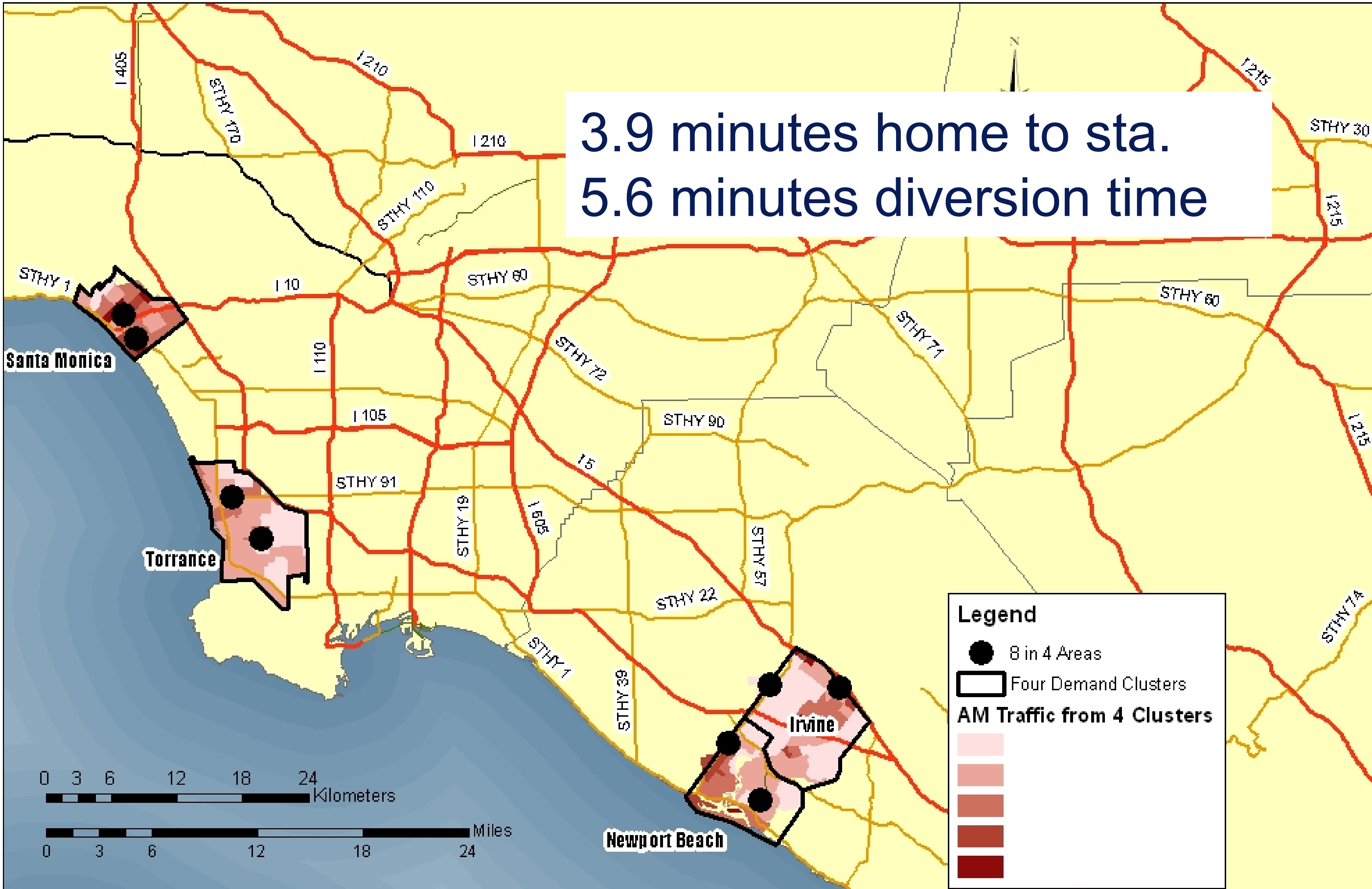
Two Ways to Measure Consumer Convenience

- 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

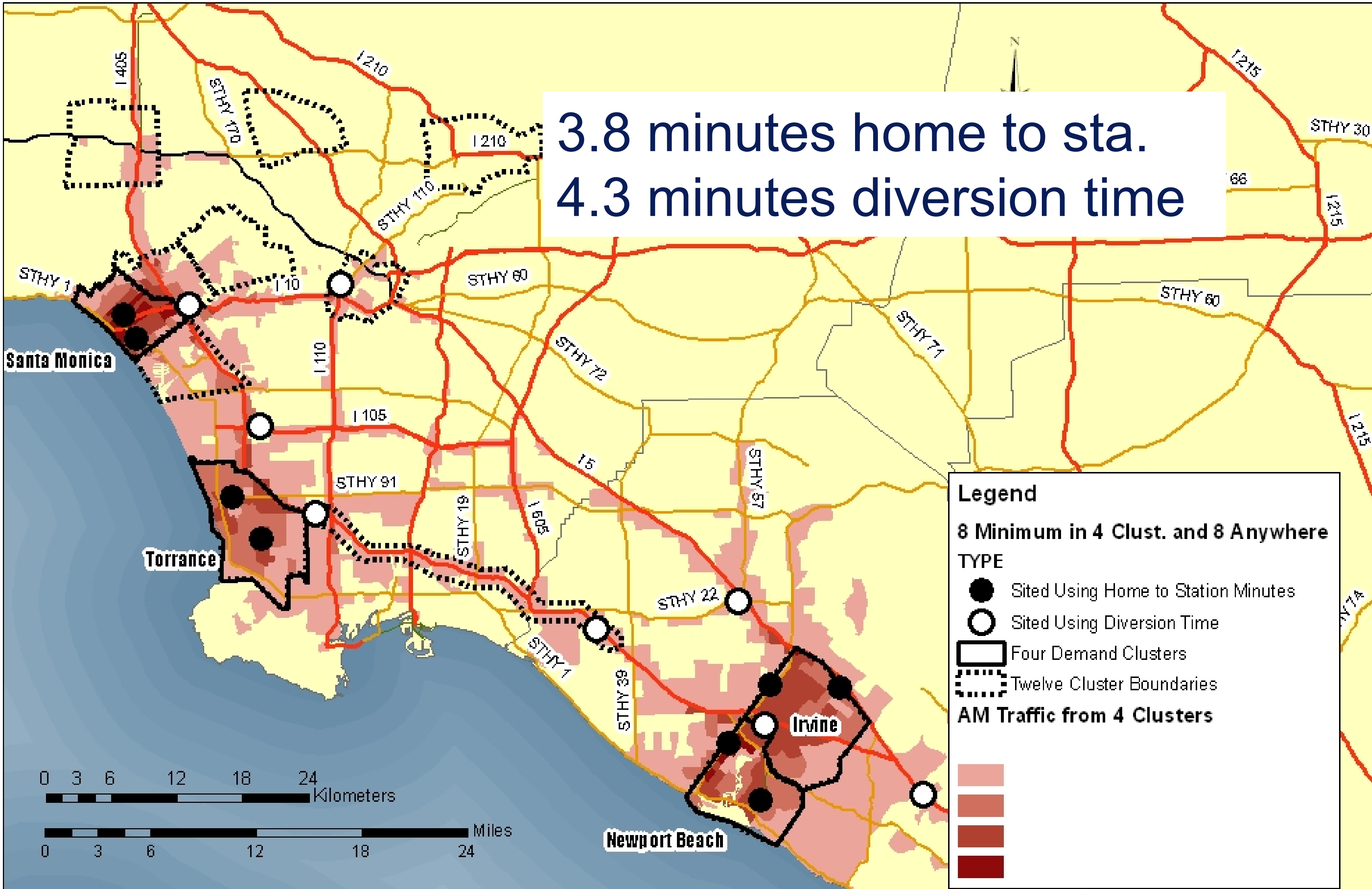
3.9 minutes home to sta.
5.6 minutes diversion time



16 Station Example

Add 8 Connector Stations => lower diversion time

3.8 minutes home to sta.
4.3 minutes diversion time

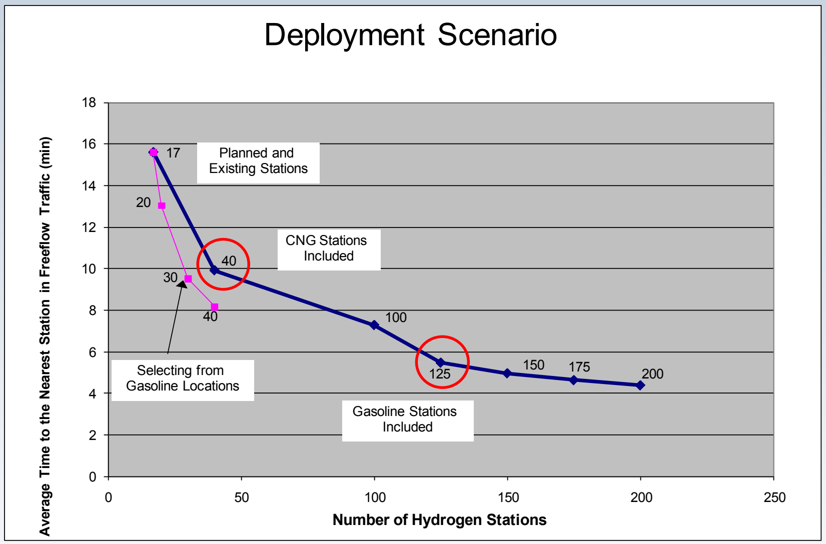


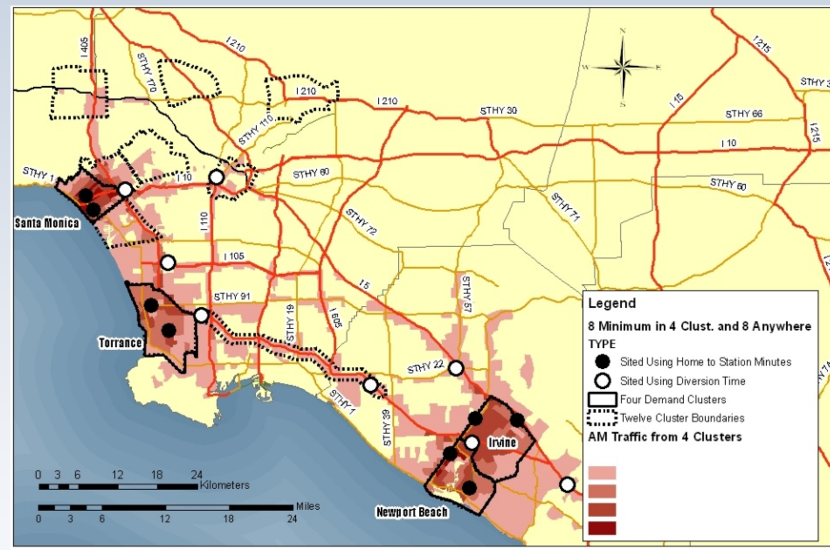
Cluster Strategy => GOOD FUELING CONVENIENCE W/ SPARSE EARLY NETWORK (<1% OF GASOLINE STATIONS)

Vehicles placed by population

Cluster strategy:

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





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

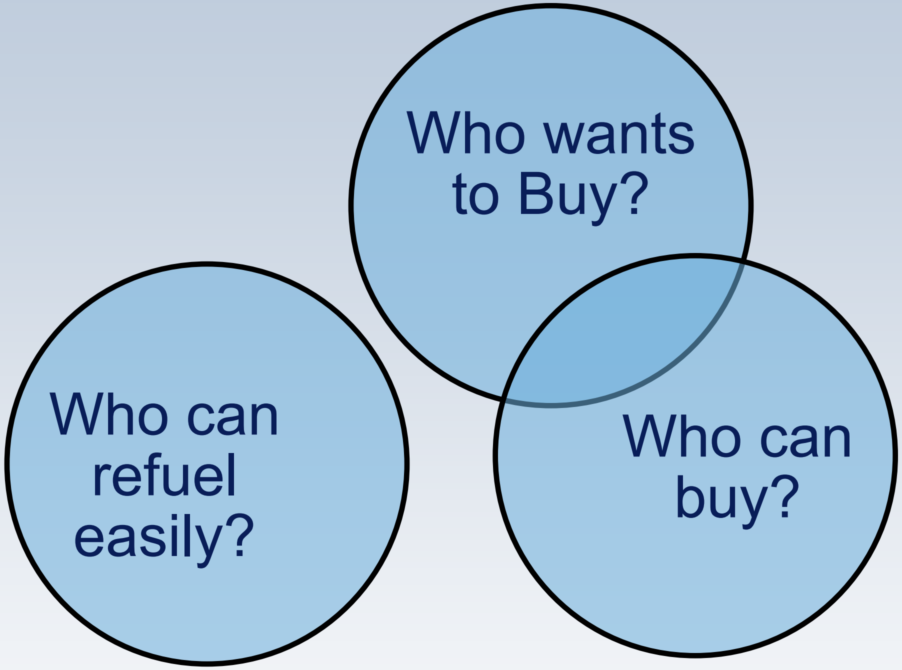
= 16 minutes

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

= 4 minutes

Nicholas, Michael A. and Joan M. Ogden (2010) An Analysis of Near-Term Hydrogen Vehicle Rollout Scenarios for Southern California. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-10-03.

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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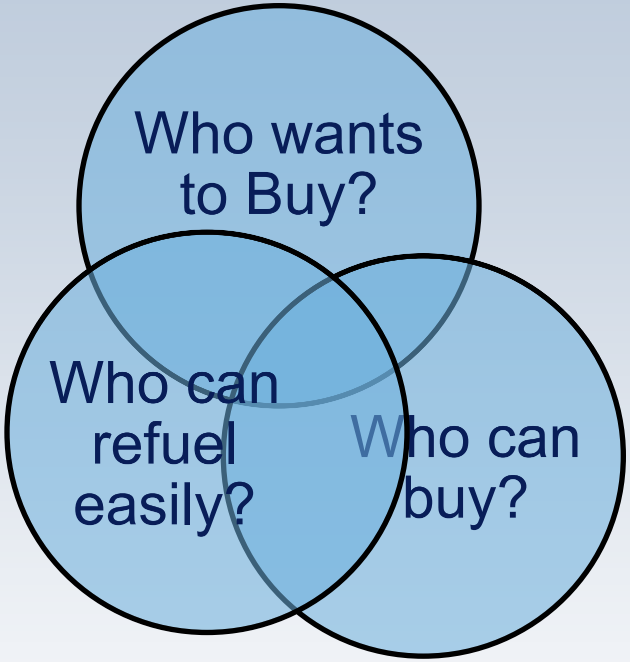
Demand for Hydrogen Vehicles



Who wants to Buy?	People with higher education	Hybrid owners	Looking for a new vehicle
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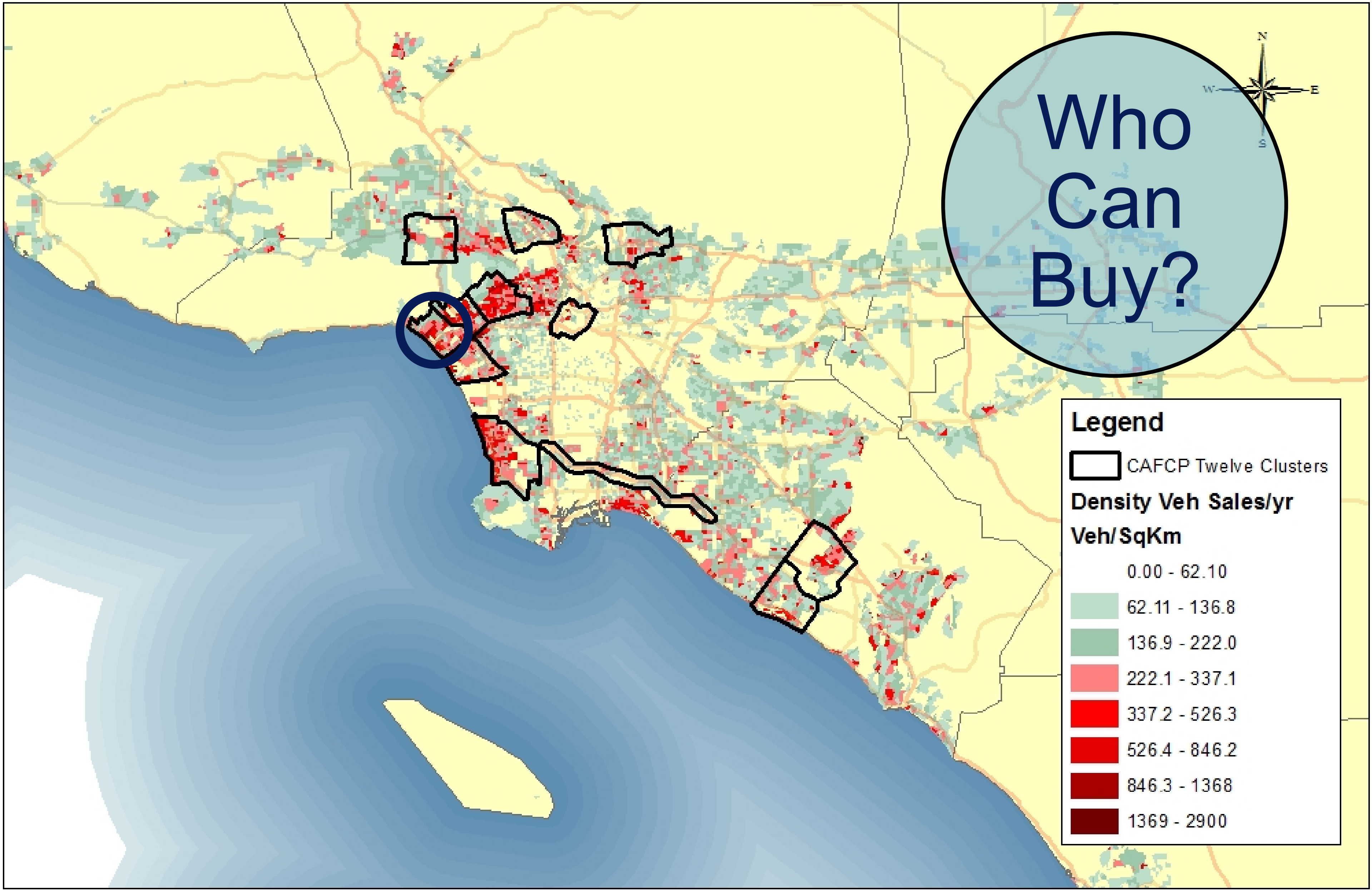
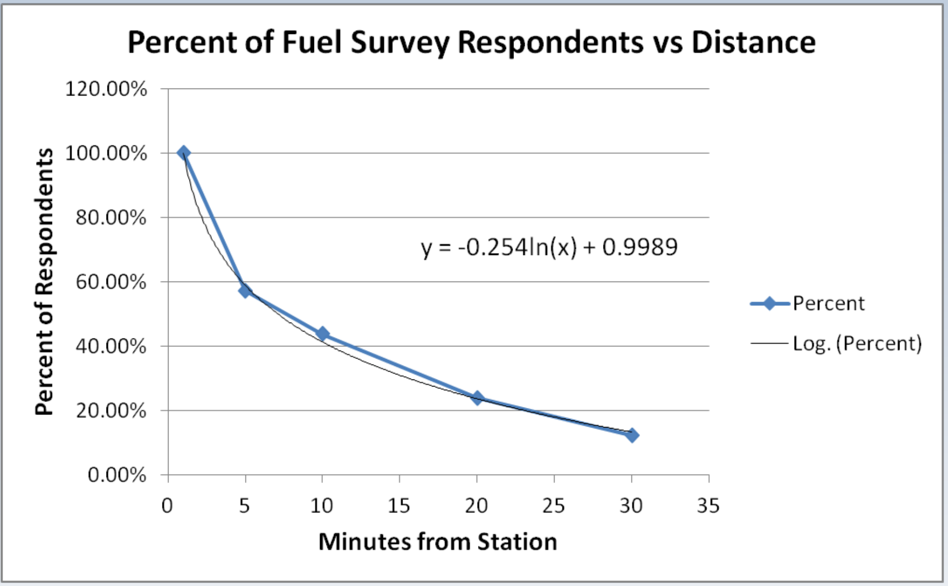
New Car Buyers? Same Places.

Los Angeles New Car Buyers



Where People Refueled ≠ Willingness to Buy But…

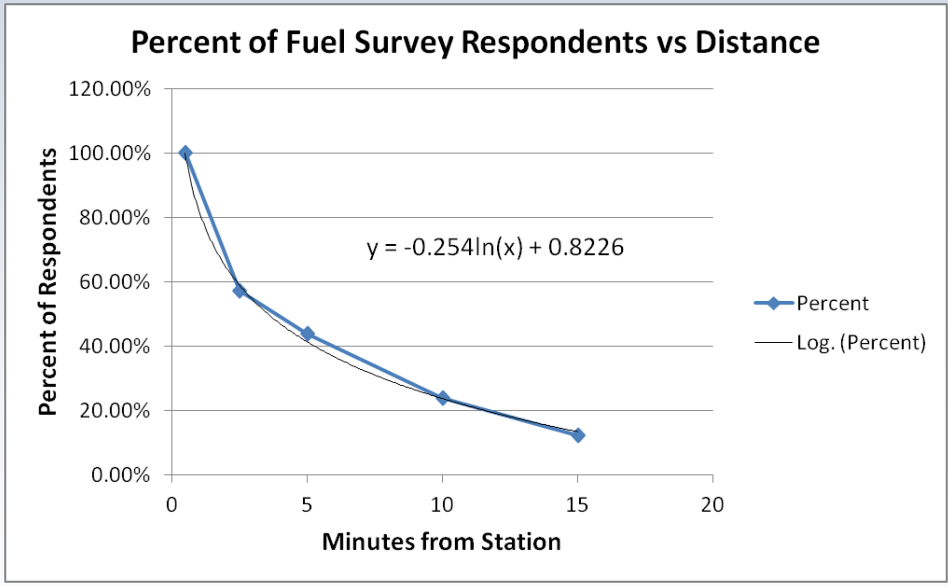
Kitamura, Ryuchi. and Dan Sperling. 1987. Refueling Behavior of Automobile Drivers. *Transportation Research* 21A, no. No. 3: 235-245



Trip time from work	Trip time from home (min) 0-5	6-10	11-20	21-30	>30	Total
0-5	238 (18.7)	53 (4.2)	92 (7.2)	52 (4.1)	33 (2.6)	468 (36.8)
6-10	95 (7.5)	51 (4.0)	37 (2.9)	11 (.9)	10 (.9)	204 (16.0)
11-20	103 (8.1)	33 (2.6)	72 (5.7)	25 (2.0)	14 (1.1)	247 (19.4)
21-30	55 (4.3)	17 (1.3)	24 (1.9)	50 (3.9)	8 (.6)	154 (12.1)
>30	54 (4.2)	16 (1.3)	28 (2.2)	9 (.7)	93 (7.3)	200 (15.7)
Total	545 (42.8)	170 (13.4)	253 (19.9)	147 (11.5)	158 (12.4)	1273 (100.0)

( ) = Percent of grand total

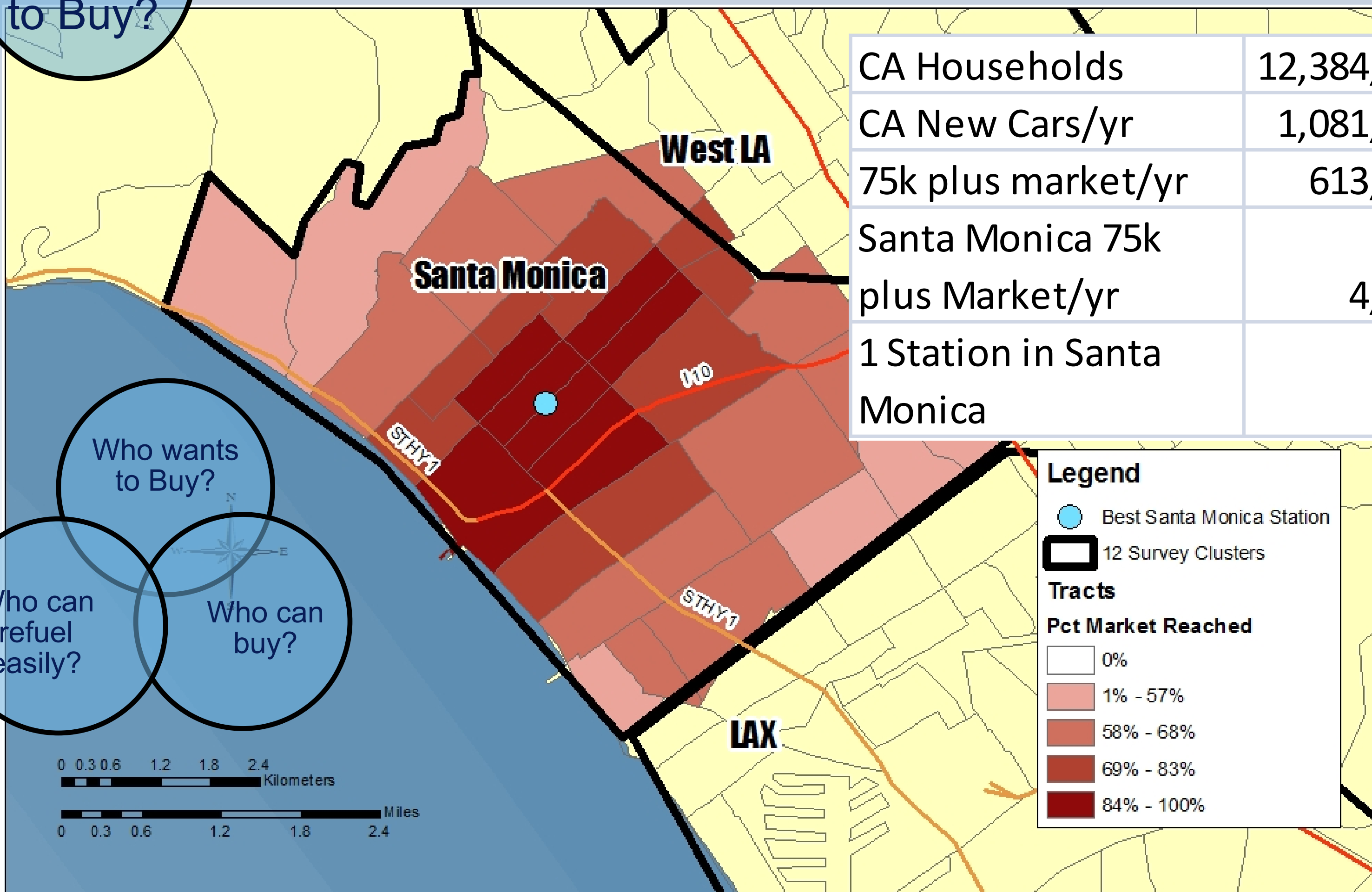
Equation can be adjusted. ½?



How Much Might One Station Do?
If 5% of Market is interested: 148 cars per year in Santa Monica (Preliminary Only)

Who Wants to Buy?

CA Households	12,384,351.00
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%



Who wants to Buy?

Who can refuel easily?

Who can buy?

Who Can Buy?

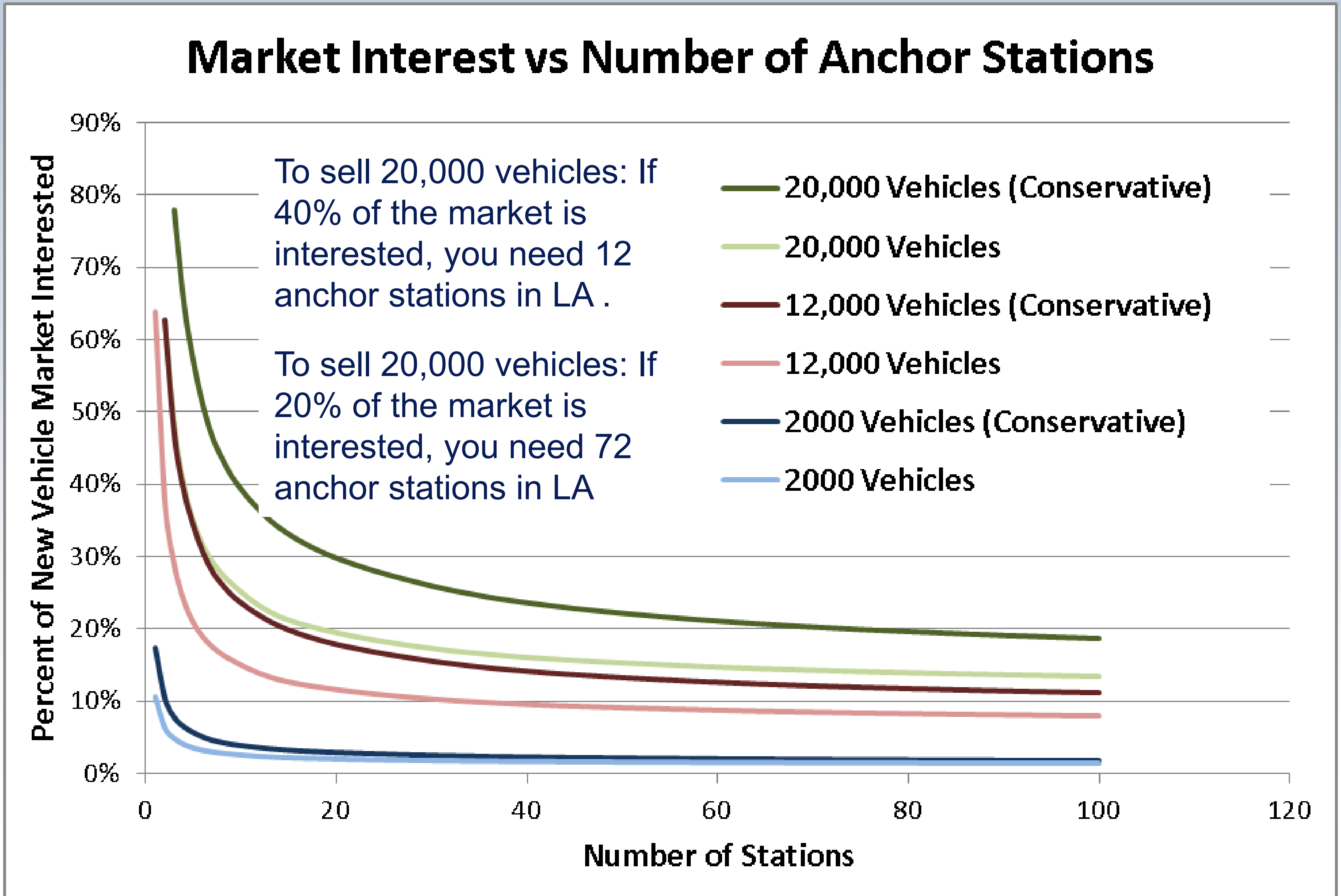
Who Can Refuel?

75k in 2000= 100K in 2012

Back of the Envelope

- 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 Nessecary Depends on How Many People are "Just Waiting For Infrastructure"



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. Ie 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.

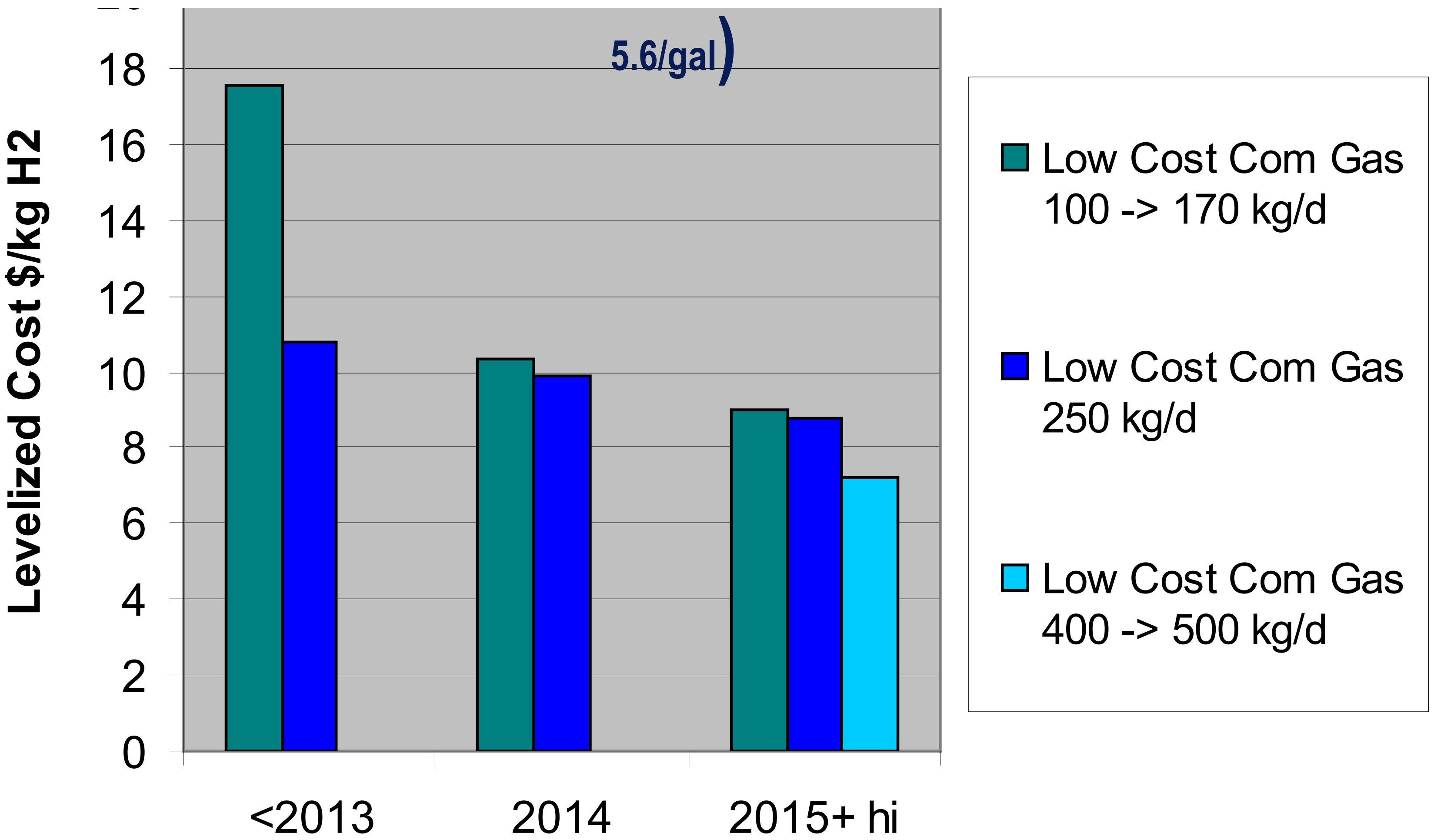
For 2012-2014, equipment costs = 2 X H2A "current tech"

For 2015-2017, equipment costs = H2A "current tech"

Ind. Gas Co. Estimates for low-cost gas truck delivery options

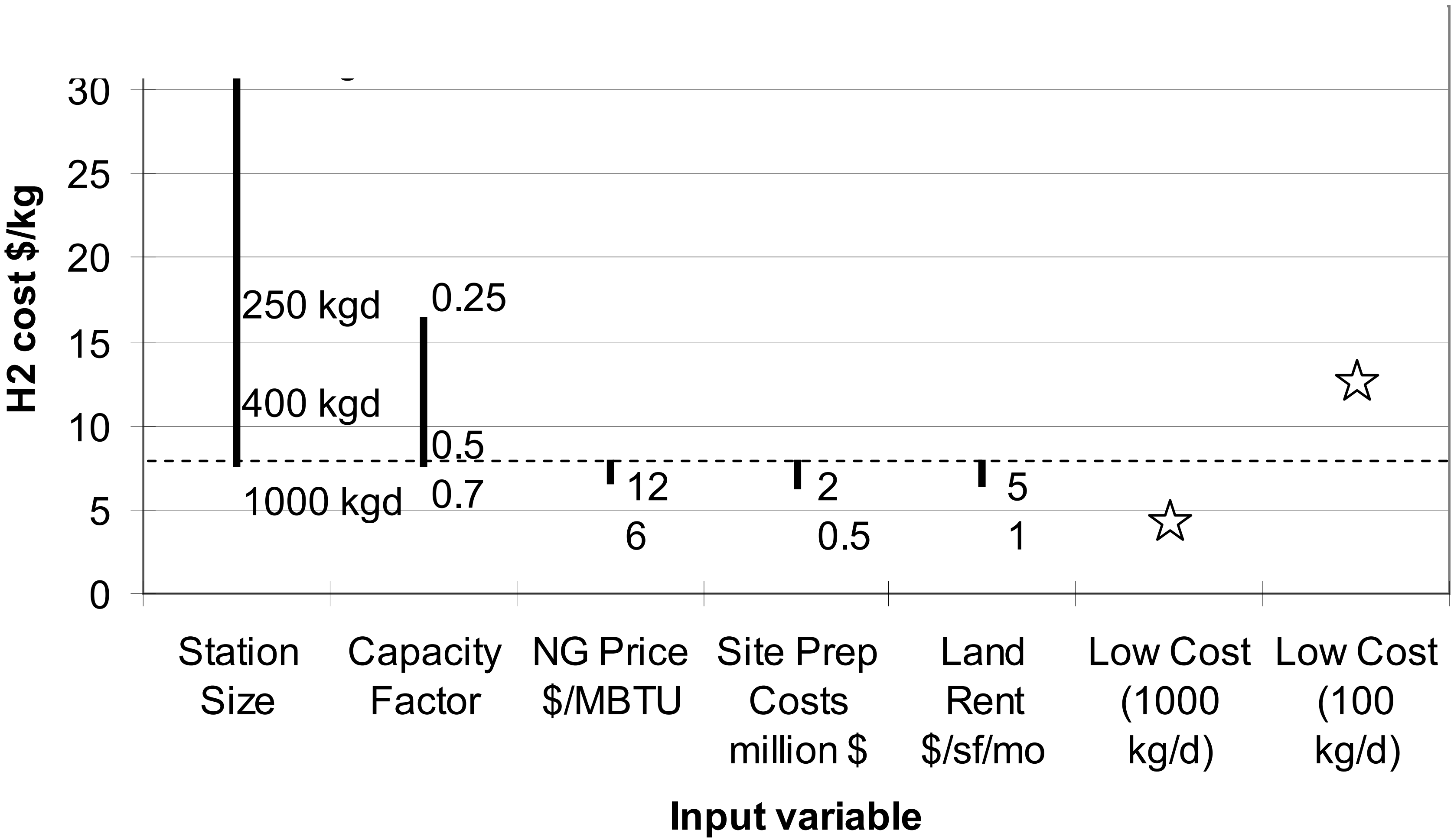
Delivered H_2 Cost Compressed Gas Truck

$/kg (2015+, H2~$7-9/kg ~ cent/mi~Gasoline HEV @ $4.3-5.6/gal)



Delivered H_2 cost Onsite SMR $/kg (2015+)

(2015+, H2~$5-8/kg, ~ cent/mi ~ Gasoline @ $3-5/gal)



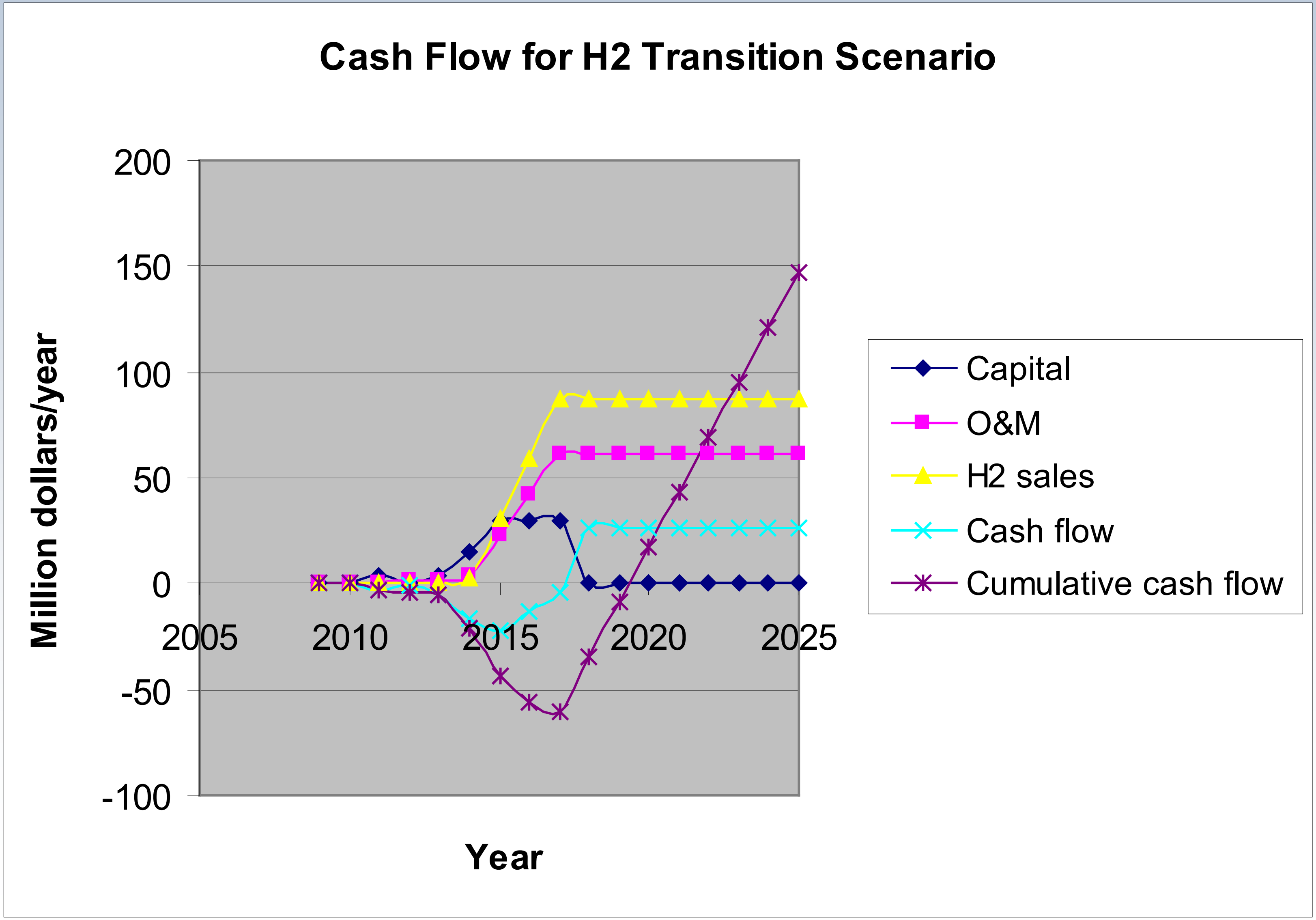
Transition Study:Use 2010 CAFCP estimates for FCVs in fleet in Southern California

YEAR	#FCVs in fleet
2011	197
2012	240
2013	347
2014	1161
2015-2017	34,320

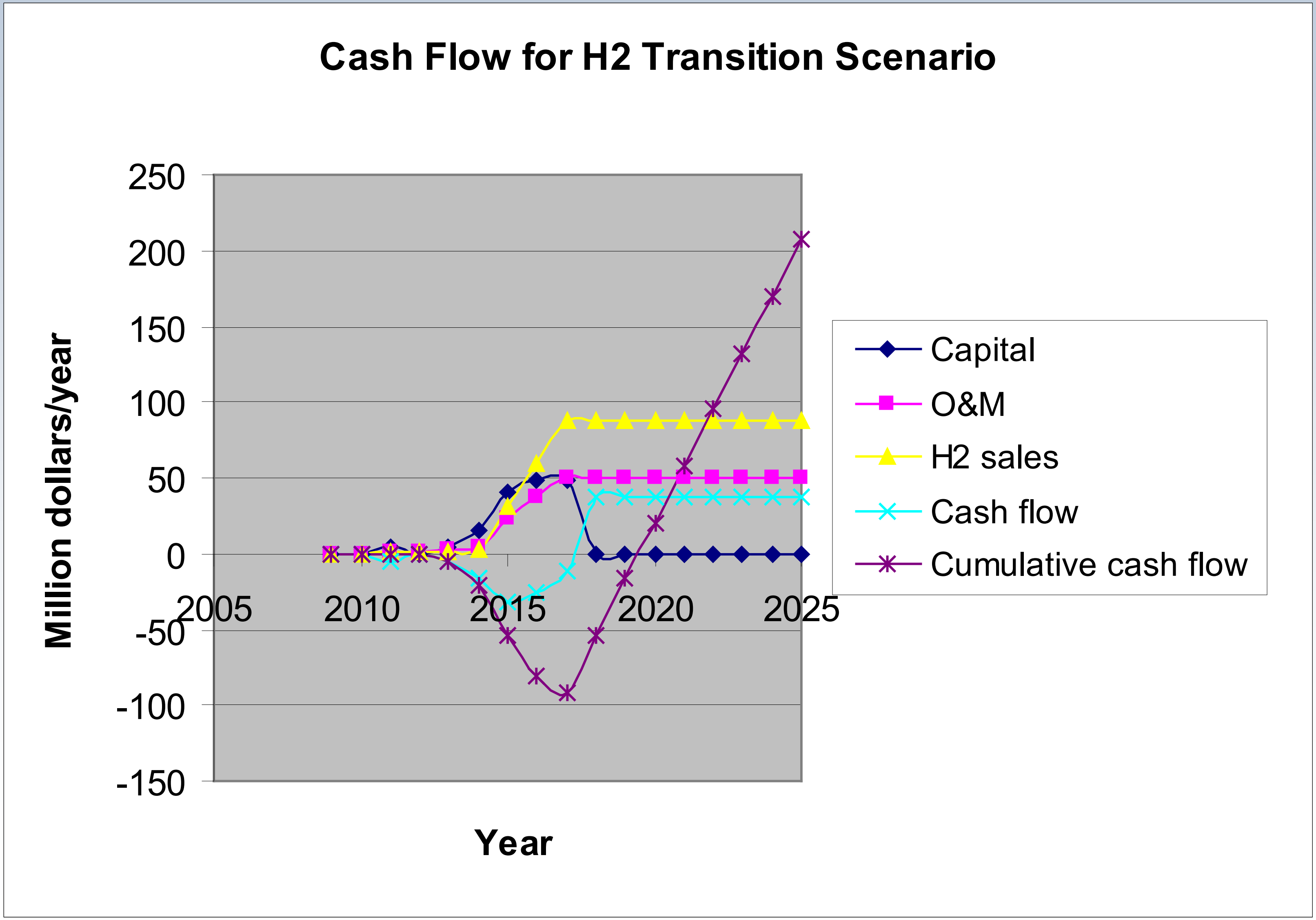
NETWORK PERSPECTIVE
2 Station Rollout Scenarios
Serving 34,000 FCVs in LA area in 2017

- 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



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



Economics: Station Owner Perspective

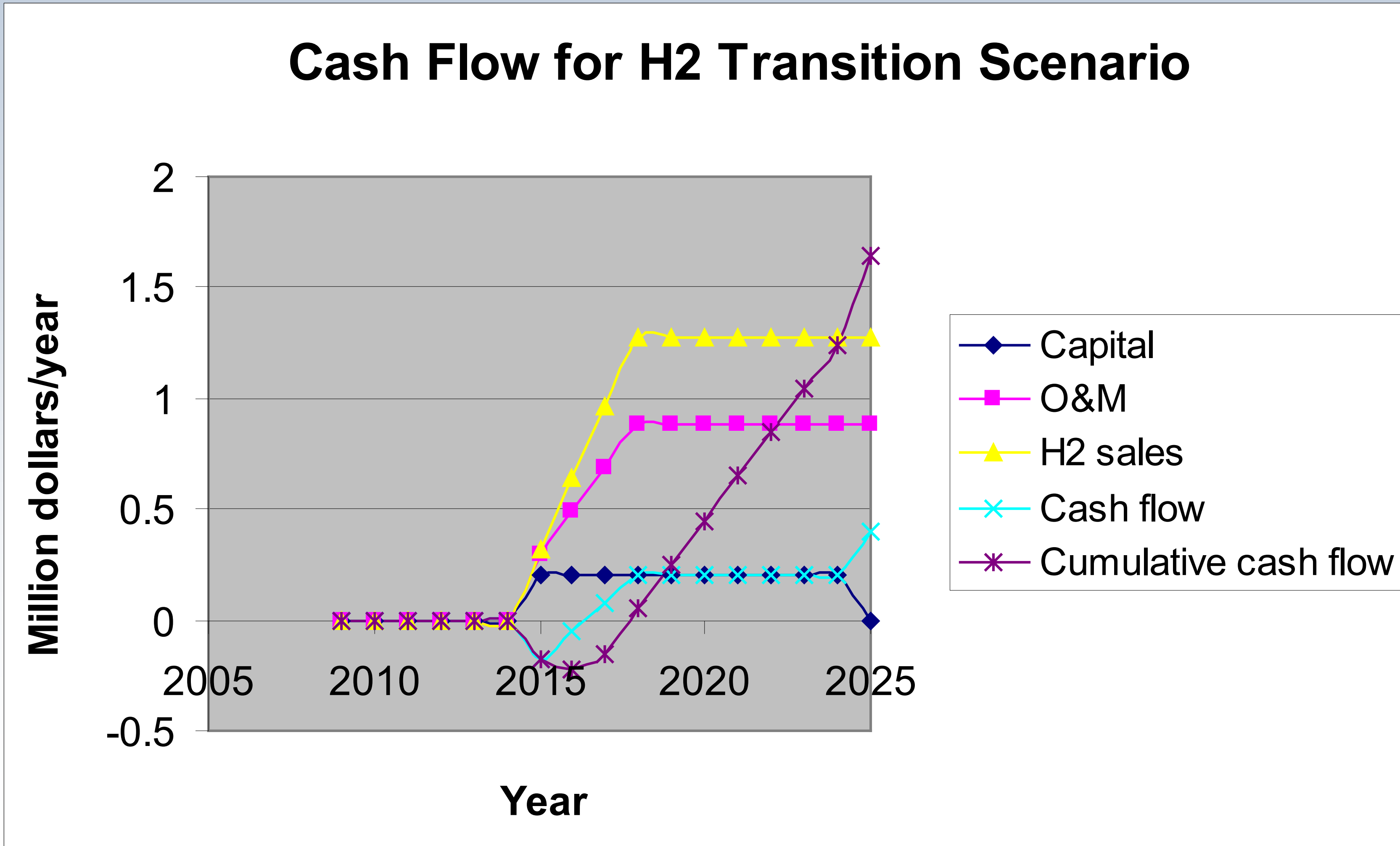
Base Case:

- 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

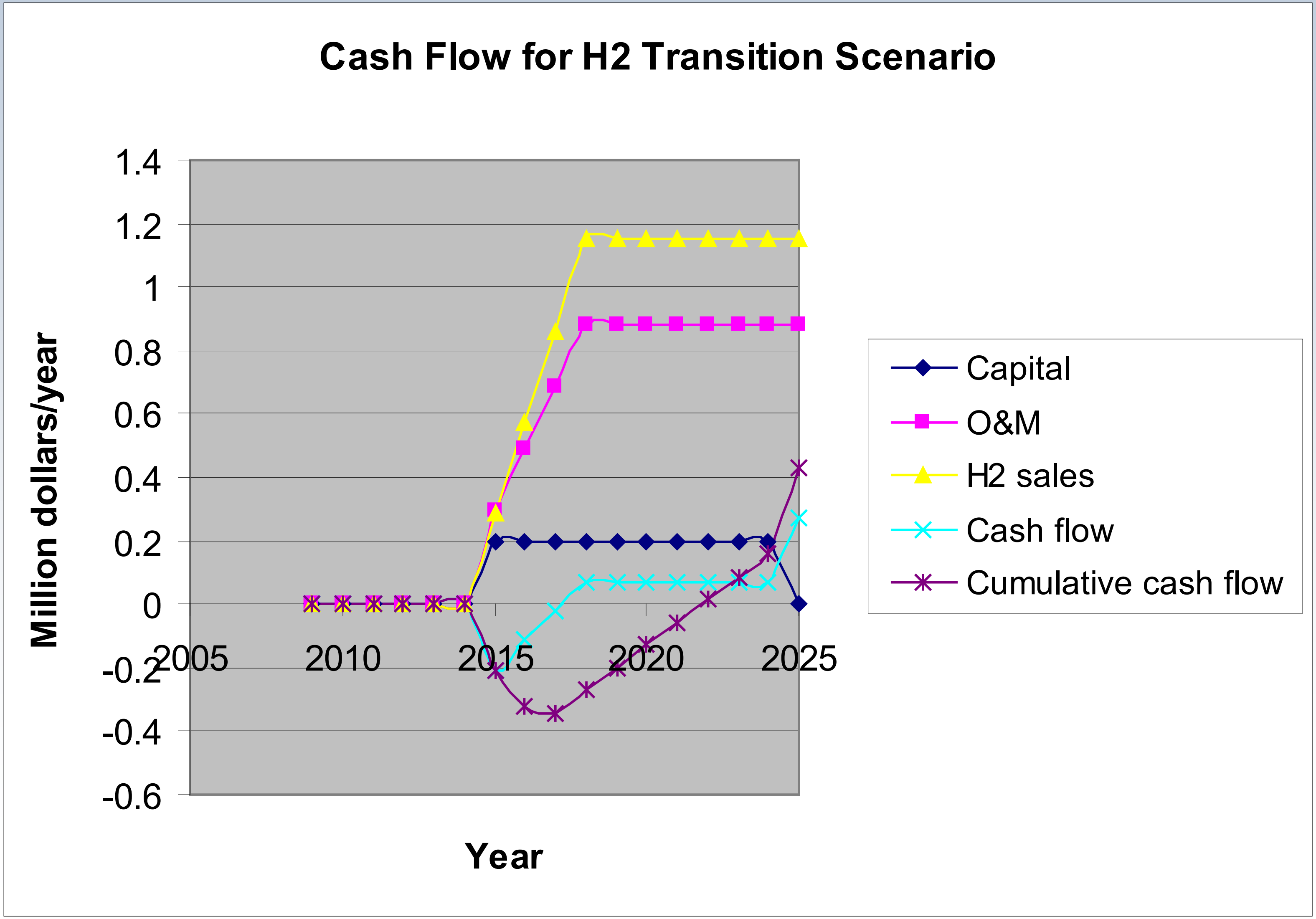
Sensitivity : H2 sell price, constr. time, loan terms

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

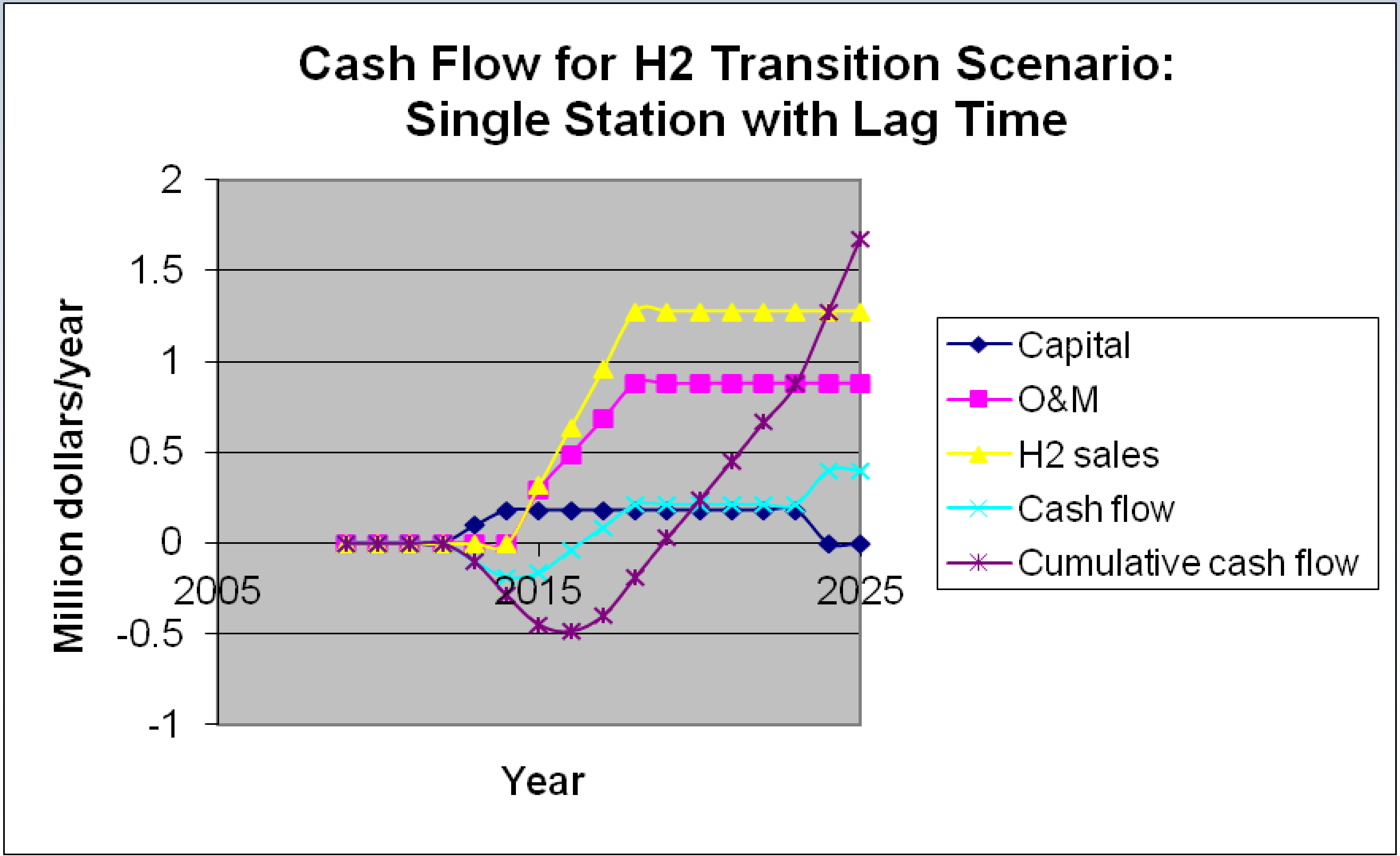


CASH FLOW: SINGLE 500 KG/D STATION. Base Case w/H2 selling price $9/kg. <u>Support needed until cash flow >0, ~$600K</u>



CASH FLOW: SINGLE 500 KG/D STATION.

Base Case $10/kg w/ 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) $\geq$ $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.

Time frame	Capital Cost	Annual O&M cost $/yr
<u>Phase I (<2013)</u> 100 kg/d -> 170 kg/d 250 kg/d (has more ground storage)	$1 million $1.5 million	$100 K (fixed O&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)
<u>Phase 2 (2014)</u> 100 -> 170 kg/d 250 kg/d	$0.9 million $1.4 million	Same as above
<u>Phase 3 (2015+)</u> 100 -> 170 kg/d 250 kg/d 400 -> 500 kg/d	$0.5 million $0.9 million $1.5-2 million	Same as above

New stations added vs. year (78 total in 2017)

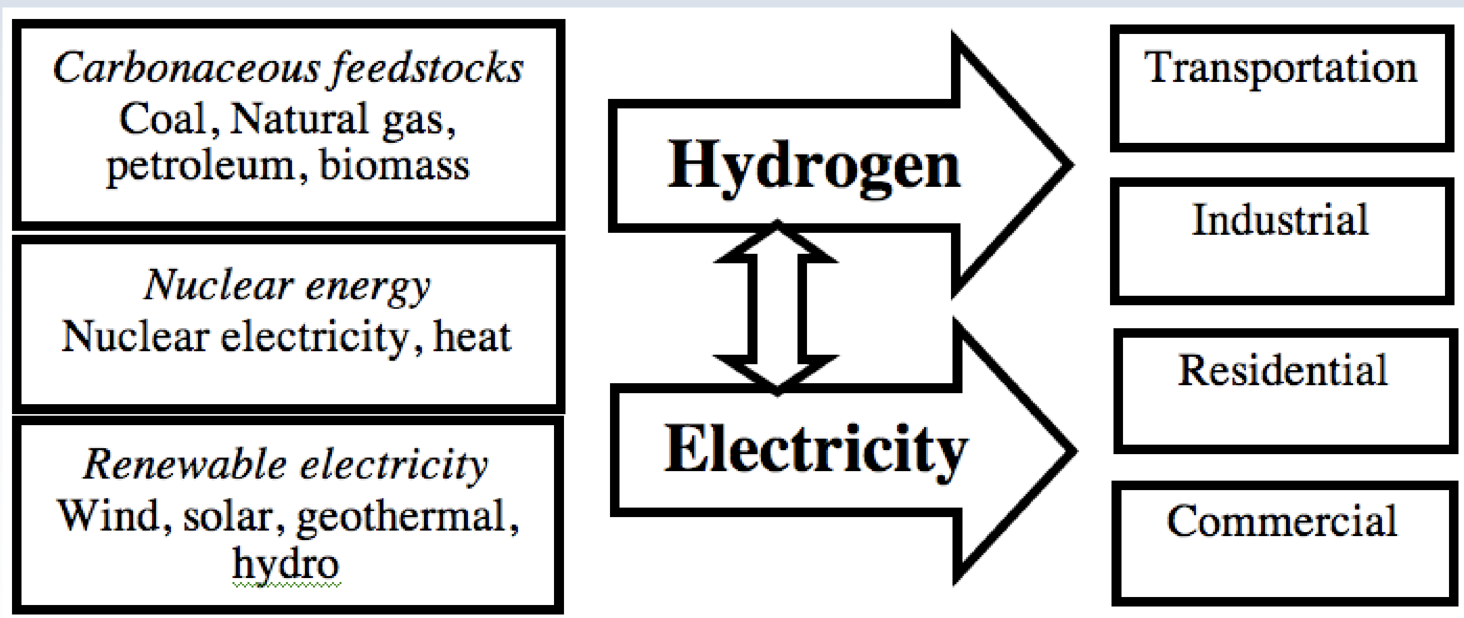
#New Sta	2011	2012	2013	2014	2015	2016	2017
Mobile Refueler	4	0	0	0	0	0	0
Compressed Gas Truck Delivery							
170 kg/d	0	0	4	0	0	0	0
250 kg/d	0	0	0	10	0	0	0
500 kg/d	0	0	0	0	20	20	20
Total sta. capacity (kg/y)	400	400	1080	3580	11580	21580	31580
# FCVs in fleet	197	240	347	1161	12106	23213	34320
H2 demand (kg/d)	137	168	250	800	8500	16000	24000

New stations added vs. year (58 total in 2017)

#New Sta	2011	2012	2013	2014	2015	2016	2017
Mobile Refueler	4	0	0	0	0	0	0
Compressed Gas Truck Delivery							
170 kg/d	0	0	4	0	0	0	0
250 kg/d	0	0	0	10	0	0	0
500 kg/d	0	0	0	0	20	0	0
SMR 1000 kg/d	0	0	0	0	0	10	10
Total sta. cap.(kg/y)	400	400	1080	3580	11580	21580	31580
# FCVs in fleet	197	240	347	1161	12106	23213	34320
H2 demand (kg/y)	137	168	250	800	8500	16000	24000

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



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