

Sustainable Transportation Energy Pathways (STEPS)

STEPS Lookback Analysis: STEPS Hydrogen Models

Survey of retrospective modeling activities

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STEPS Hydrogen Models

- o How has the model evolved over time?
- o What sorts of retrospective analyses have been done relating to the model (or its predecessors)?
  - Updating inputs
  - Lookback analysis of outputs
  - Model changes (e.g., structural)
- o What primary insights have modelers gained from retrospective analysis? What exercises proved to be less useful?
- o What has been (or might be) the role of retrospective analysis in honing modeler or model user intuition and communication of model outputs?

There have been many assessments of H_2 and Fuel Cells dating back to 1980s and a wide range of sometimes contradictory estimates on costs, performance, infrastructure, commercialization timeline.

Can 'looking back' at the history of H2/FC modeling improve usefulness of forward-looking models?

Changing Context Set Analysis Agenda Over Time

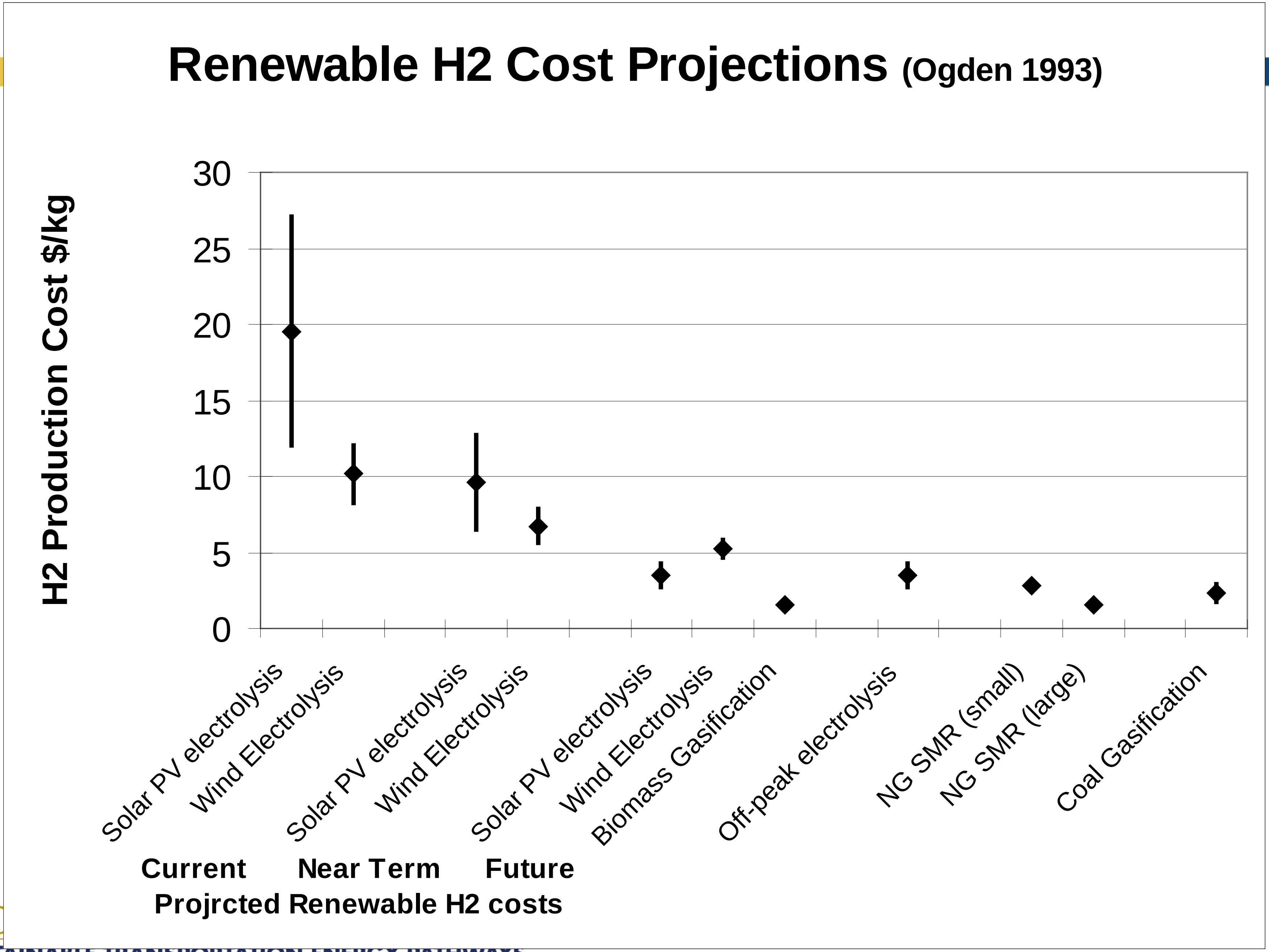
- **1980s-90s**: Early analysis focused H2 as potential long term replacement for fossil fuels. Analysis of future, full scale H2 systems, especially renewable H2 (solar, wind, biomass).
- **1990s**: Progress in PEMFC technology, initiatives like PNGV, ZEV galvanize H2/FC community and kick off major efforts in by OEMs.
- **Early 2000s**: H2 Vehicles and stations demonstrated. Industry involvement. Better models, real data, more sophisticated studies of infrastructure, societal costs and benefits (LCA). H2 FCVs seen as "car of future"
- **Mid 2000s - present**: H2 Transition issues addressed in studies by ORNL, NRC, IEA, etc. H2 and FC's highlighted as critical technologies for low carbon future.
- **Late 2000s – present**: Experience builds. Analysis in support of roadmaps and plans for H2 FCV rollout. Assessment of regional rollouts and transition costs. Seek stakeholder business cases.

This Talk: Retrospective on STEPS H2 Cost Calculations*

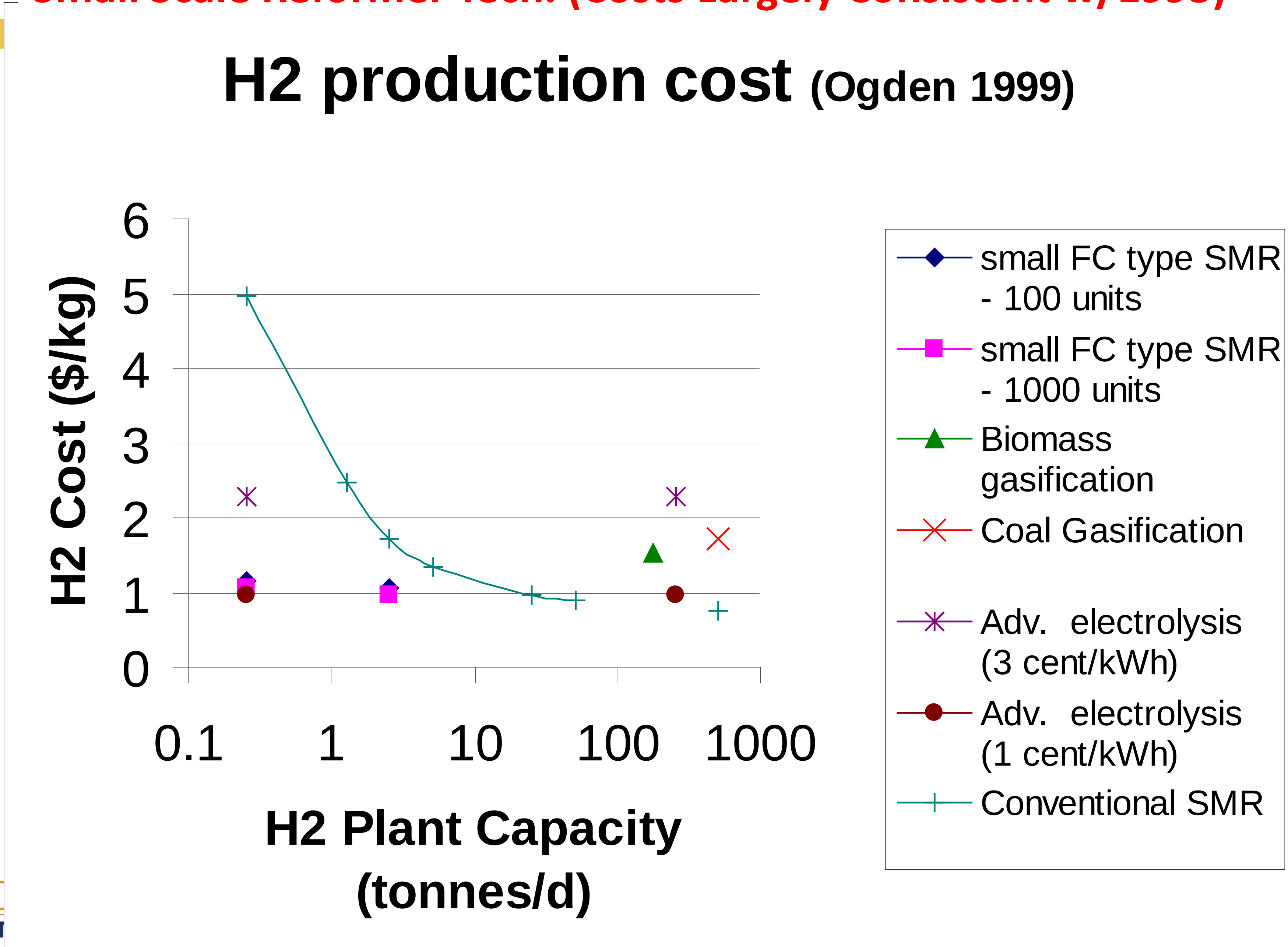
- **Hydrogen Production, Delivery & Refueling Costs**
- **Transition Costs**

- **Time frame 1990-2015.**
- **Costs shown in 2010 $.**
- **Draws on H2 research at ITS-Davis plus Ogden's earlier work at Princeton U., as well as results from other analysts.**

1993: What Does It Cost To Produce H2?

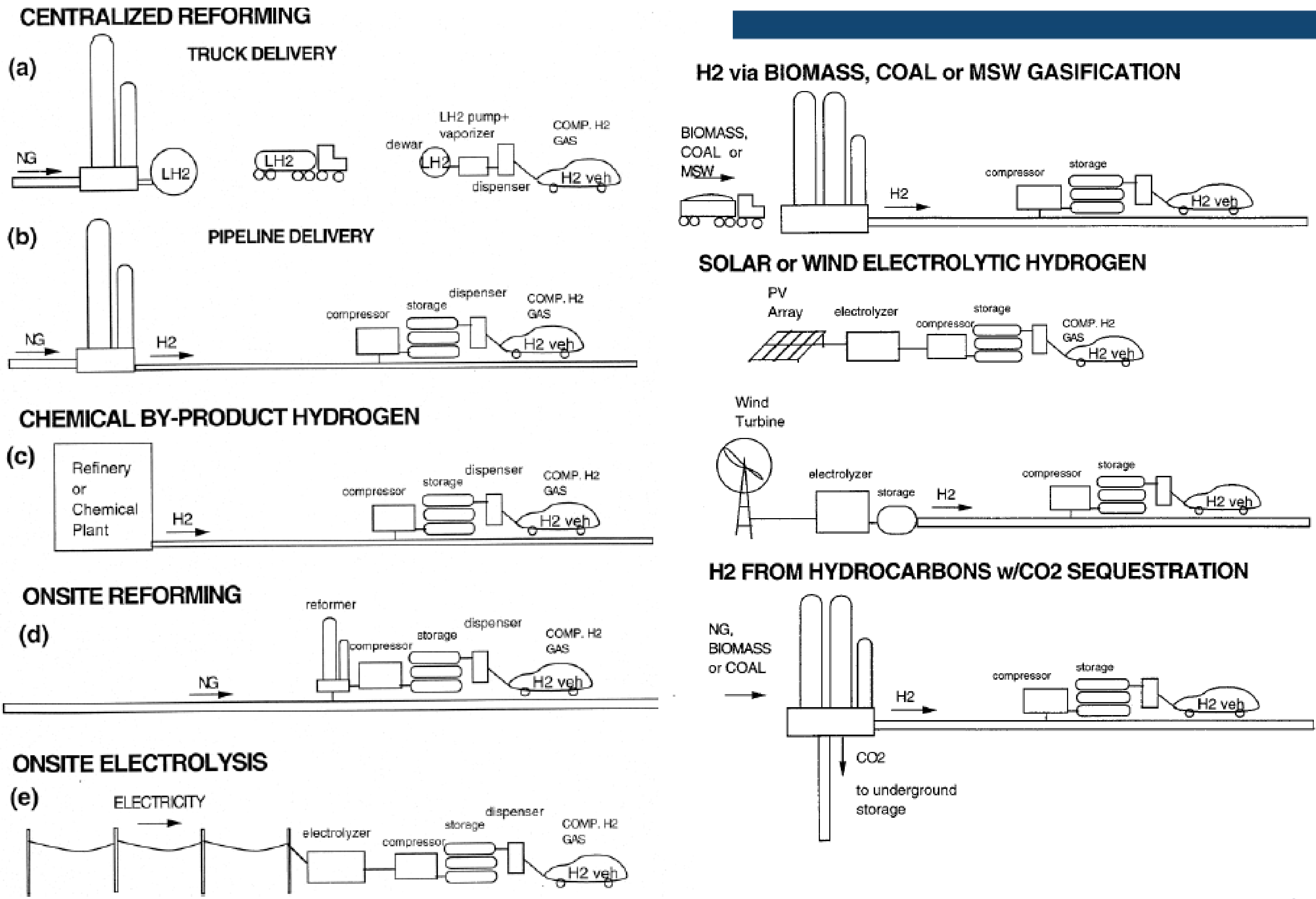


1999: What Is The Cost To Produce H2? Add Estimates For New Small Scale Reformer Tech. (Costs Largely Consistent w/1993)



1999: System Analysis of H2 Fuel Supply Chain

Near and Long Term H2 Production and Delivery Pathways (Ogden 1999)



Delivered H2 Cost
(= Production + Delivery + Refueling) (Ogden 1999)

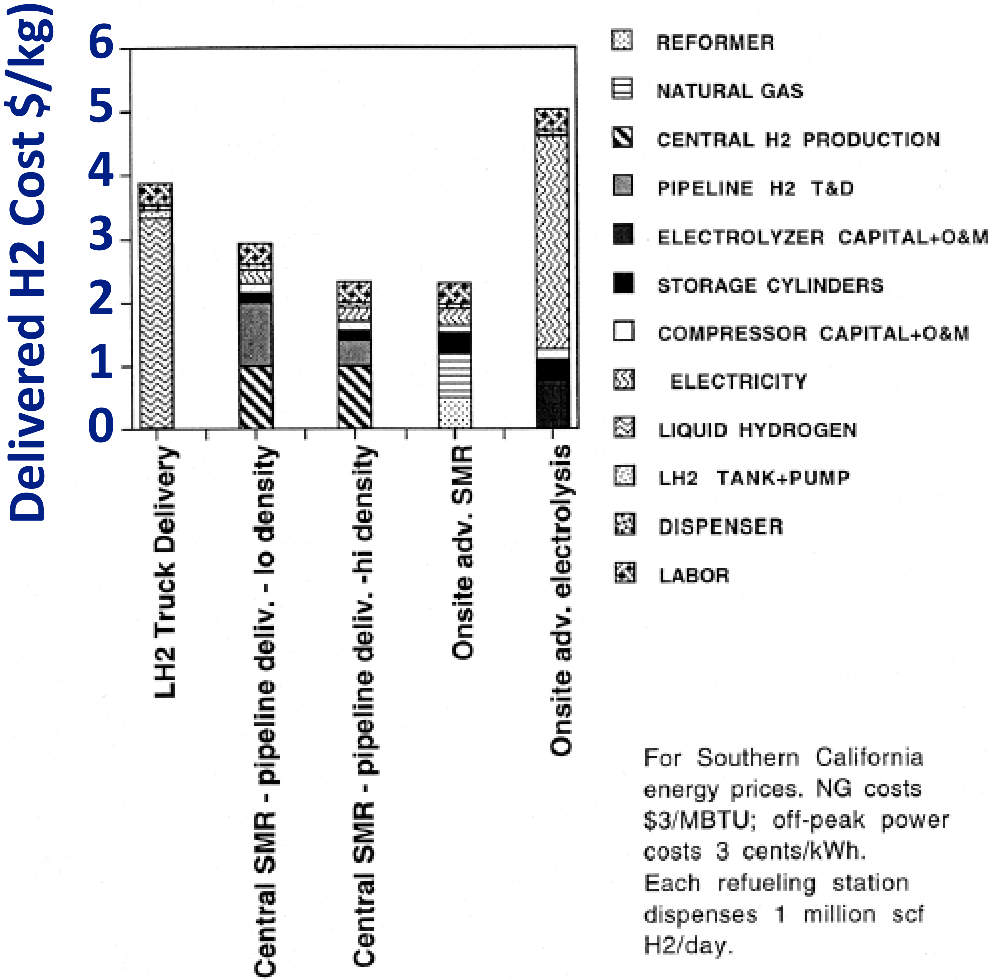
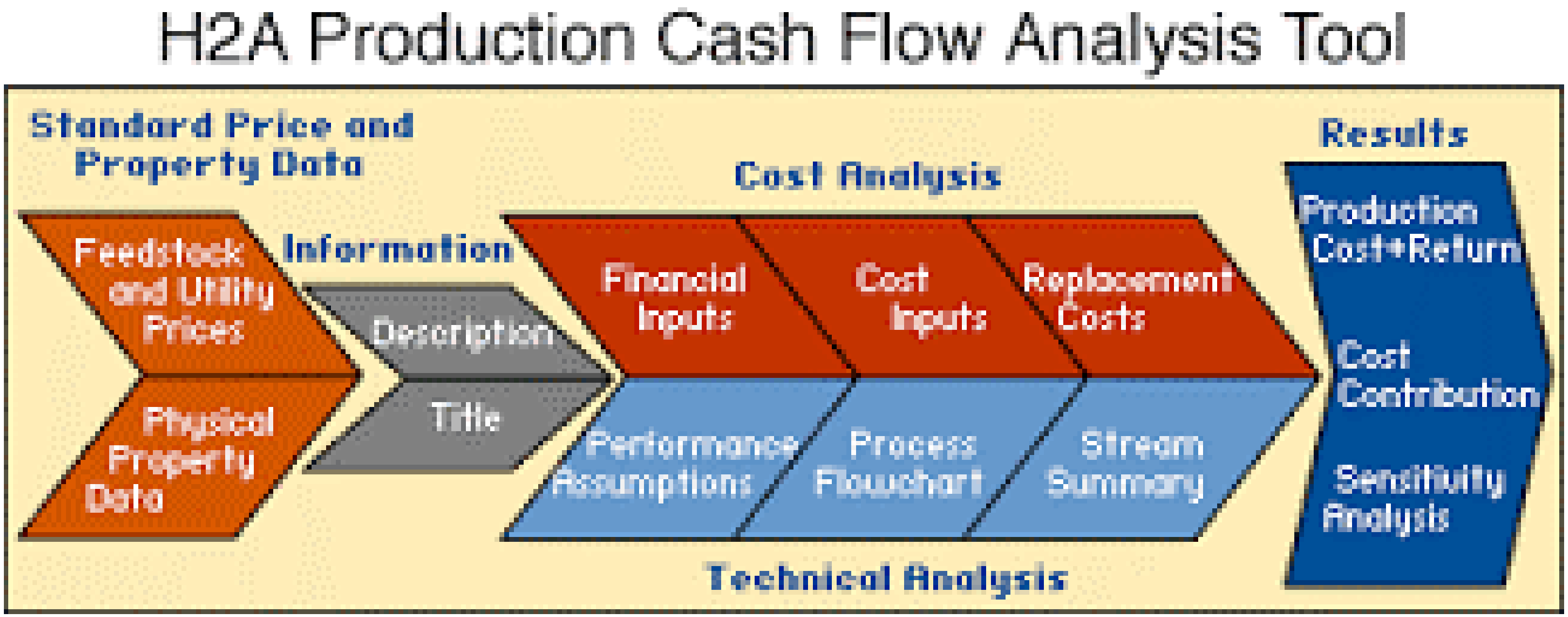


Figure 10 Delivered cost of hydrogen transportation fuel from various primary sources.

LOOKBACK ALERT: this calc assumed mature, full scale H2 infrastructure with stations dispensing 2500 kg/d

Improving the Data: UCD Analysts part of USDOE-led team to Develop H2A model w/extensive industry input (2003-present)



H2A based result for Delivered H2 cost for current and future tech. ~ largely consistent w/ earlier results

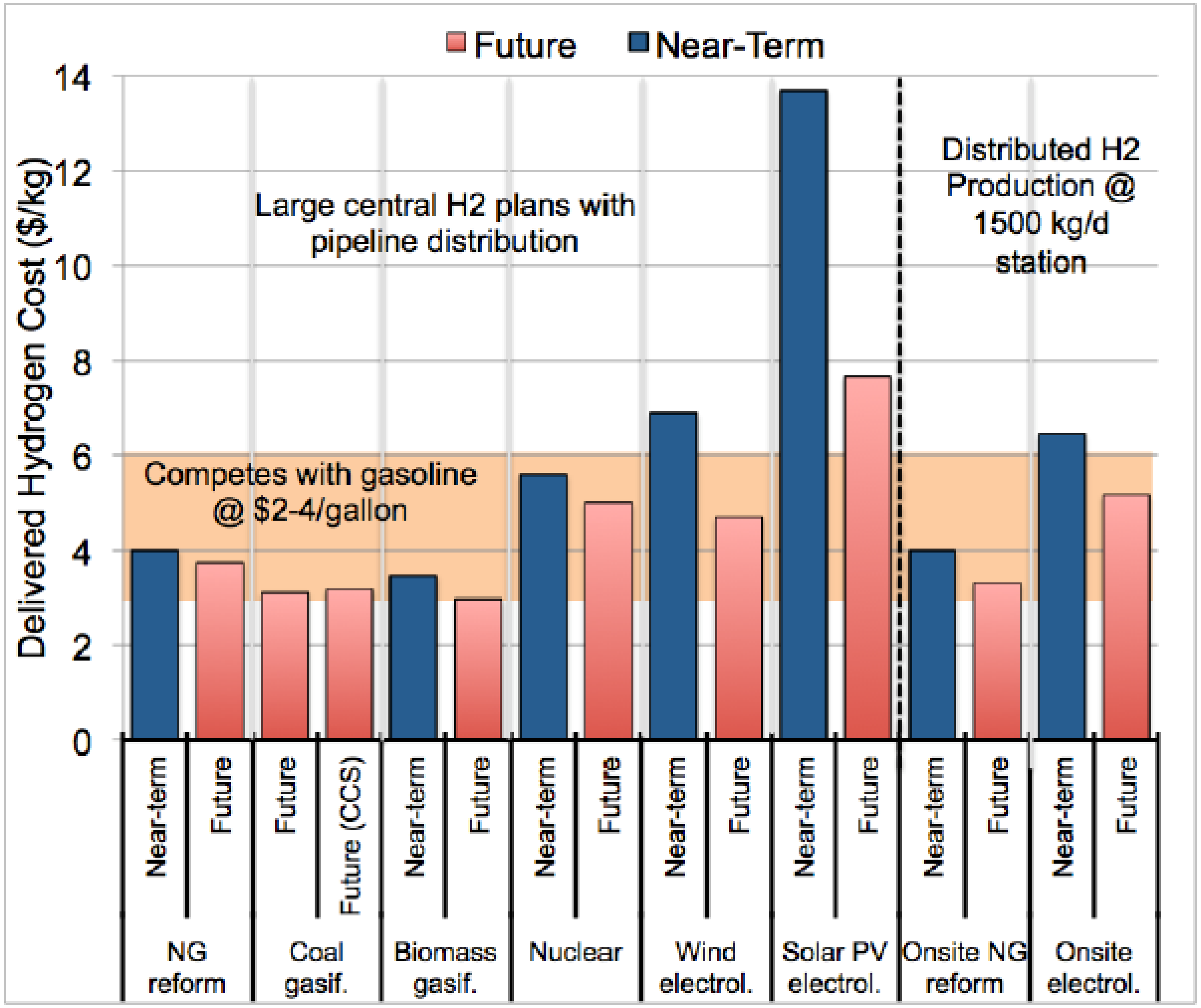
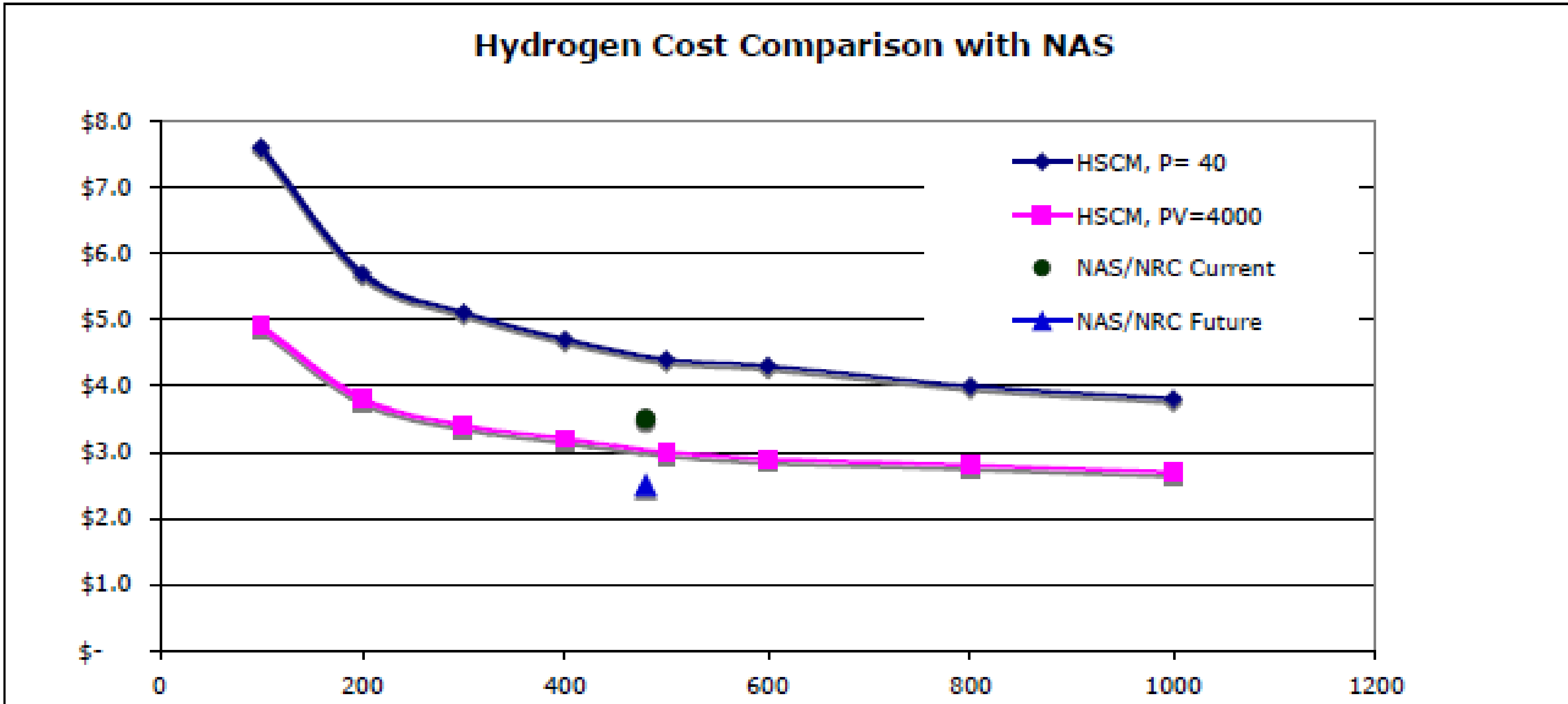


Figure 6. Delivered cost of hydrogen transportation fuel from various pathways. The grey band indicates where the fuel cost per mile for hydrogen FCVs would compete with a gasoline hybrid. (Note that fuel taxes are not included in the delivered fuel costs.) Costs assume that hydrogen supply technologies are mature and mass-produced and are based on costs from the H2A model.

LOOKBACK ALERT: this calc assumed full scale H2 infrastructure w/ stations dispensing 1500 kg/d

How much would hydrogen cost in the near term? CA H2 Hwy Analysis: Near term onsite SMR estimate (Weinert and Ogden 2005)



Estimated H2 costs were higher than more idealized estimates by NAS because Weinert assumed:

1) **Technologies were not mass produced**
2) **Sta. Permitting costs, etc. were assumed to be for first of kind projects**
3) **Stations might not be fully utilized.**

How Much will hydrogen stations cost in the near term? CA H2 Roadmap Project w/ support from Toyota, Shell, Honda, Daimler, CARB. (Ogden & Nicholas 2010)

Near Term Station Capital Cost Assumptions

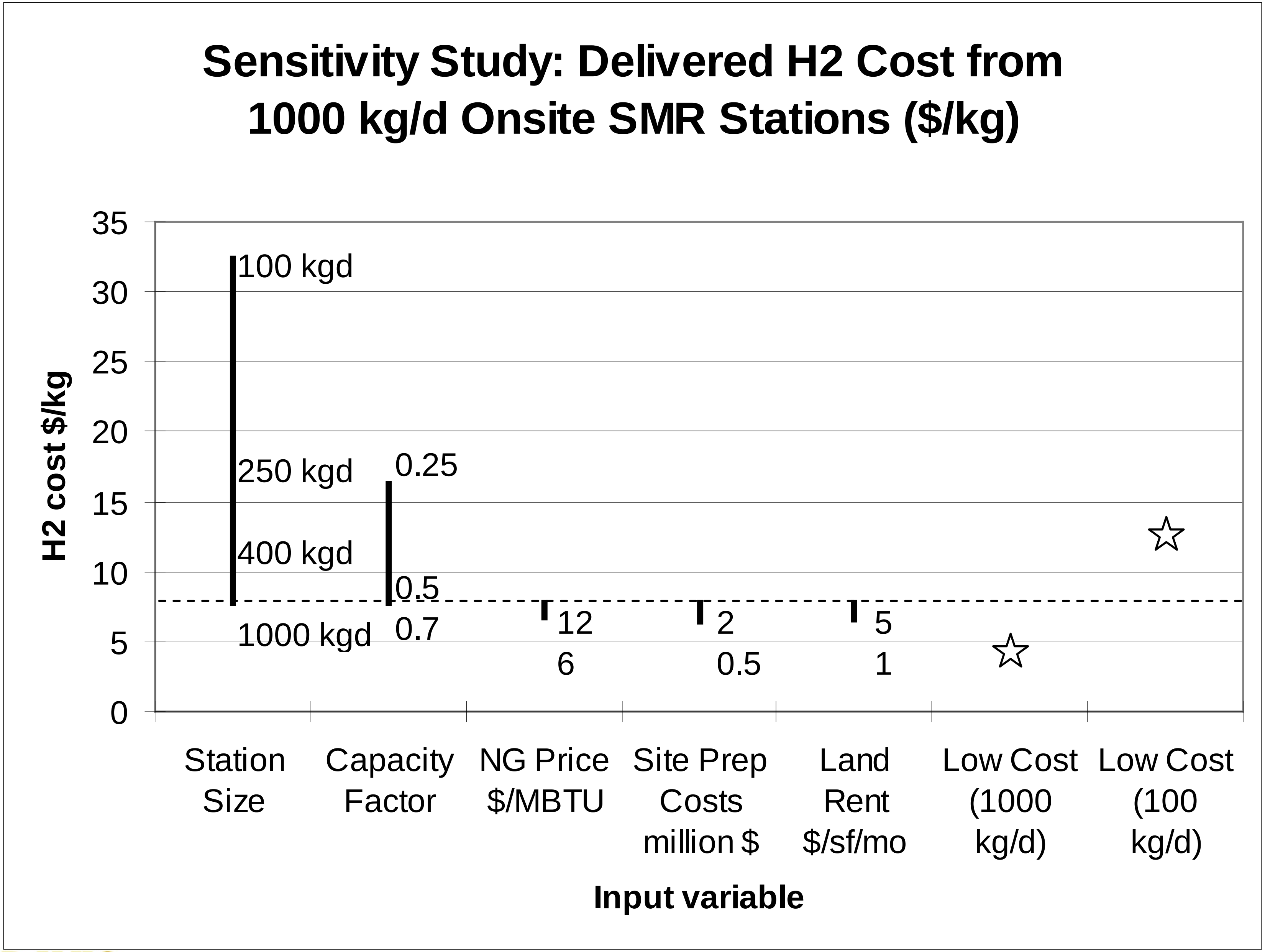
- H2 station costs (2009-2011) based on interviews with energy company experts reflecting today's costs.
- For future stations, assume $2 million for site prep, permitting, engineering, utility installation, for a green-field site before any fuel equipment goes in. H2 equipment costs are added to this.
- For 2012-2014, equipment costs = 2X H2A "current tech"
  - Rationale: H2A is based on 500 units per year. If we reduce this by a factor of ~50-100 to reflect 2012-2014 production of stations (5-10 stations per year), the equipment cost should be about 2 times the H2A estimate.
- For 2015-2017, analyze two cost cases:
  - 1) **Low Cost**: assume that the H2A current equipment costs are appropriate (we are building 100 stations/yr in LA and elsewhere, if FCVs are "taking off")
  - 2) **High Cost**: Costs are the same as in 2012-2014

Near term H2 station capital cost estimate (Ogden and Nicholas 2011, 2012)

Capital costs for hydrogen refueling stations (million $).

	Current	Phase 2 year 1-3	Phase 3 (year 4+) high	Phase 3 (year 4+) low
Mobile refueler 100 kg/d	**1.00**	**1.00**	**1.00**	**0.40**
GH2 Truck delivery				
100 kg/d	1.0	0.9	0.5	
250 kg/d	1.5	1.4	0.9	
500 kg/d			2.0	1.5
LH2 truck delivery				
100 kg/d	**4.00**	**2.58**	**2.58**	**2.29**
250 kg/d		**2.67**	**2.67**	**2.33**
400 kg/d		**2.81**	**2.81**	**2.40**
1000 kg/d		**3.21**	**3.21**	**2.61**
Onsite reformer				
100 kg/d	**3.50–4.00**	**3.18**	**3.18**	**2.59**
250 kg/d		**3.99**	**3.99**	**3.00**
400 kg/d		**4.81**	**4.81**	**3.41**
1000 kg/d		**7.76**	**7.76**	**4.88**
Onsite electrolyzer				
100 kg/d	–	**3.22**	**3.22**	**2.61**
250 kg/d		**4.21**	**4.21**	**3.11**
400 kg/d		**5.25**	**5.25**	**3.63**
1000 kg/d		**9.26**	**9.26**	**5.63**

UCD estimated Near term H2 Costs Significantly > Early Studies



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NREL HSCC model compared station costs for current and future H2 stations of different sizes (Melaina and Penev 2013)

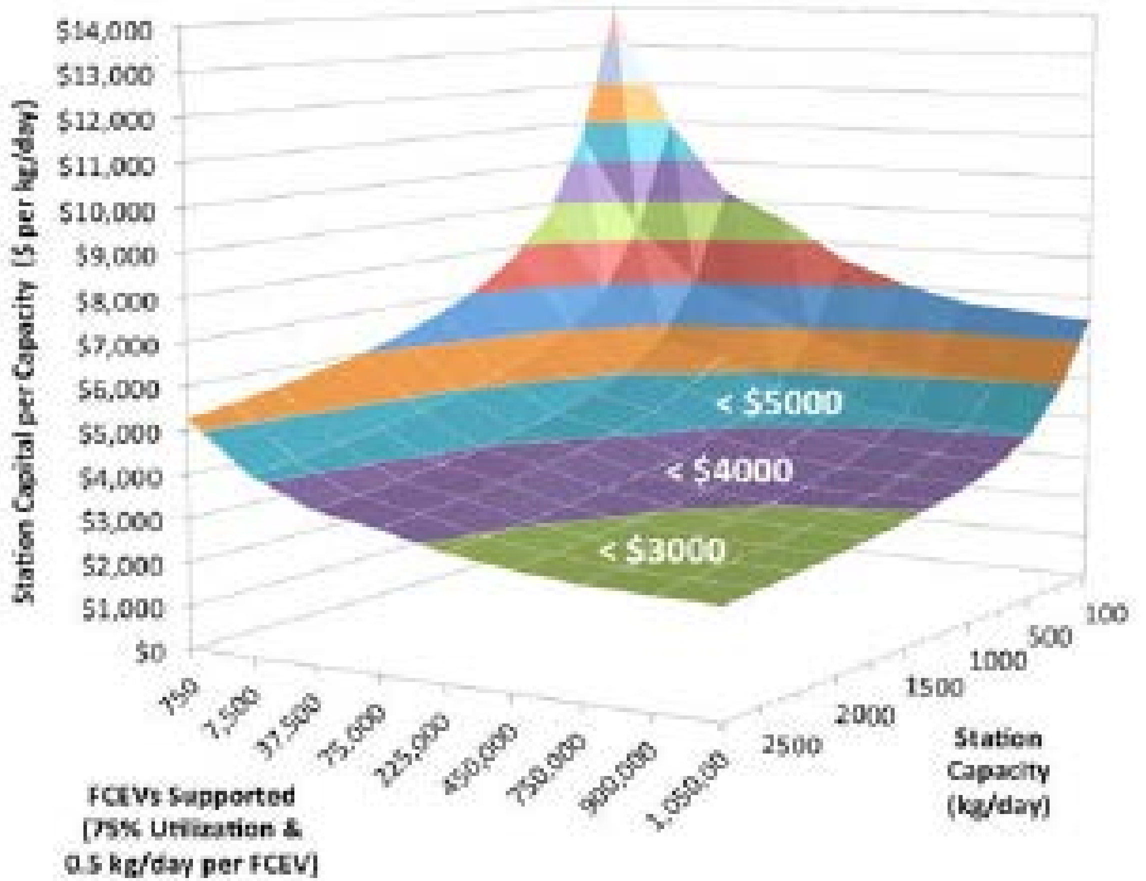
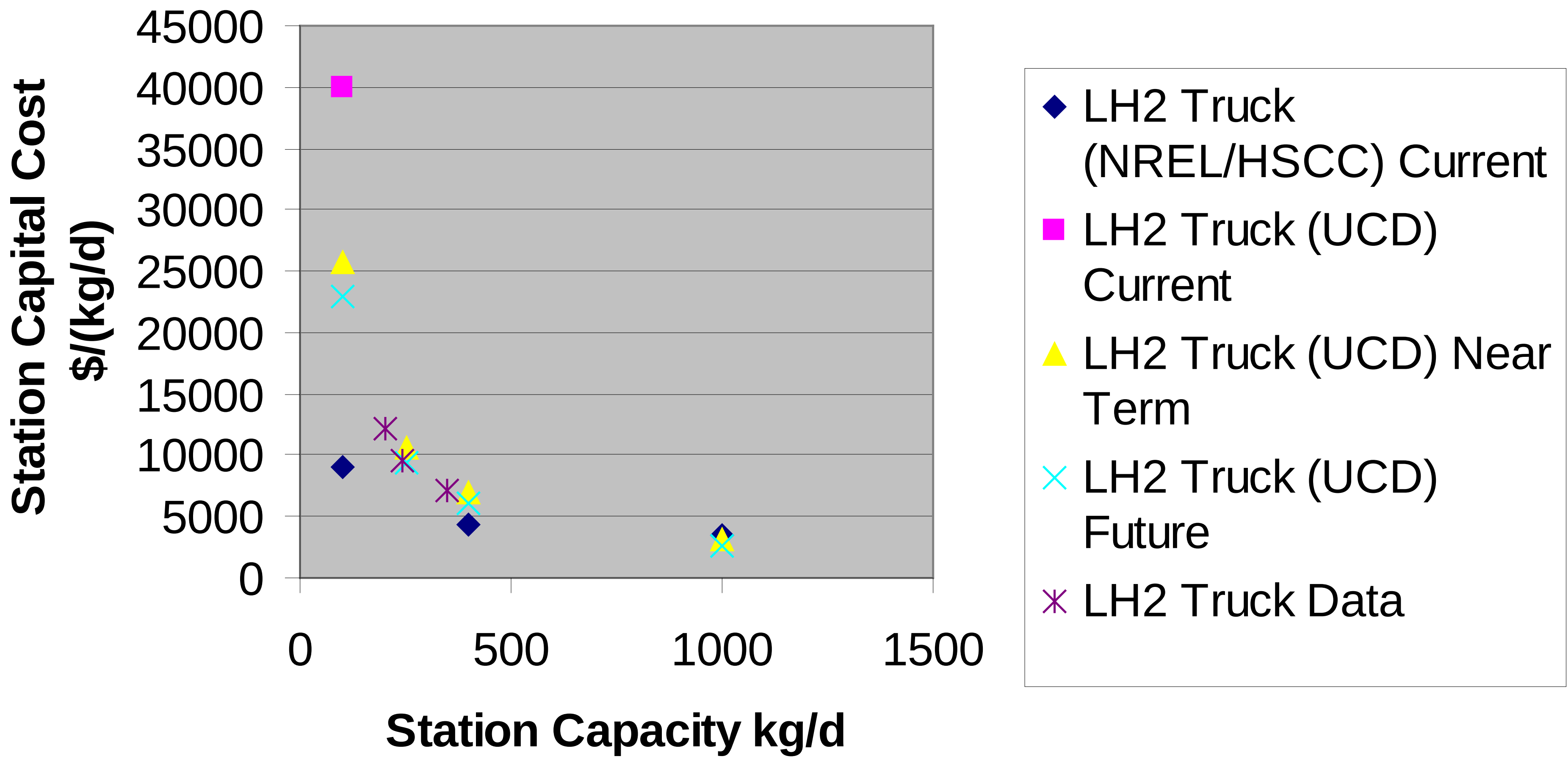


Figure 2. Hydrogen station cost calculator capital cost results as a function of FCEVs supported and station capacity

Model Comparison:
LH2 Truck Delivery Station Capital Costs



Modeling the Hydrogen Transition

- Market adoption
- Technology evolution
- Learning curves, manufacturing scale economies for FCVs, H2 supply
- Infrastructure initiation and scale up
- Costs and benefits over time
- What investments are needed to make H2 competitive?

How have modelers estimated FCV market adoption?

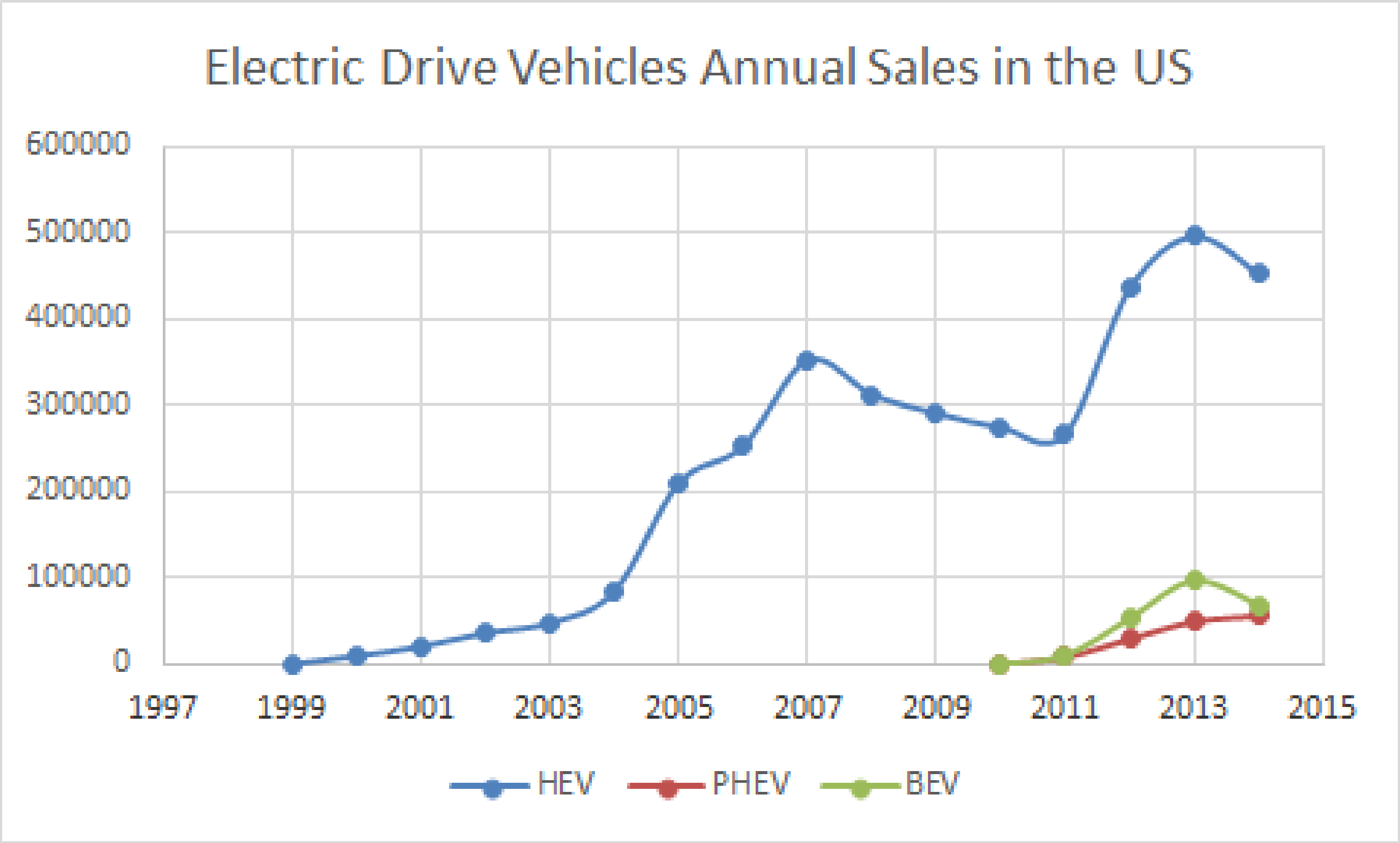
MARKET GROWTH

- Policy goals (what if we meet them?)
- Analogy with HEVS, PEVS
- Surveys of OEMs (e.g. CARB reports)
- Consumer choice models

MARKET LOCATION

- Identify early adopter areas
  - GIS analysis of correlated factors like income, etc.
  - surveys
- Lighthouse concept
- Cluster concept

Might FCVs follow similar path to HEVs & PEVs?



HEVs cum. US sales ~1 M in 2007 (8 y after market intro.), 2M in 2010 (yr. 11), 3.5 M in 2014 (yr. 15). Comparable to US goals (if FCVs ~ 50% of 3.3 million ZEV goal in 2025– 11 years after FCV intro).

2006 DOE Scenarios for H2 FCV adoption in USA: analogy w/ HEV markets

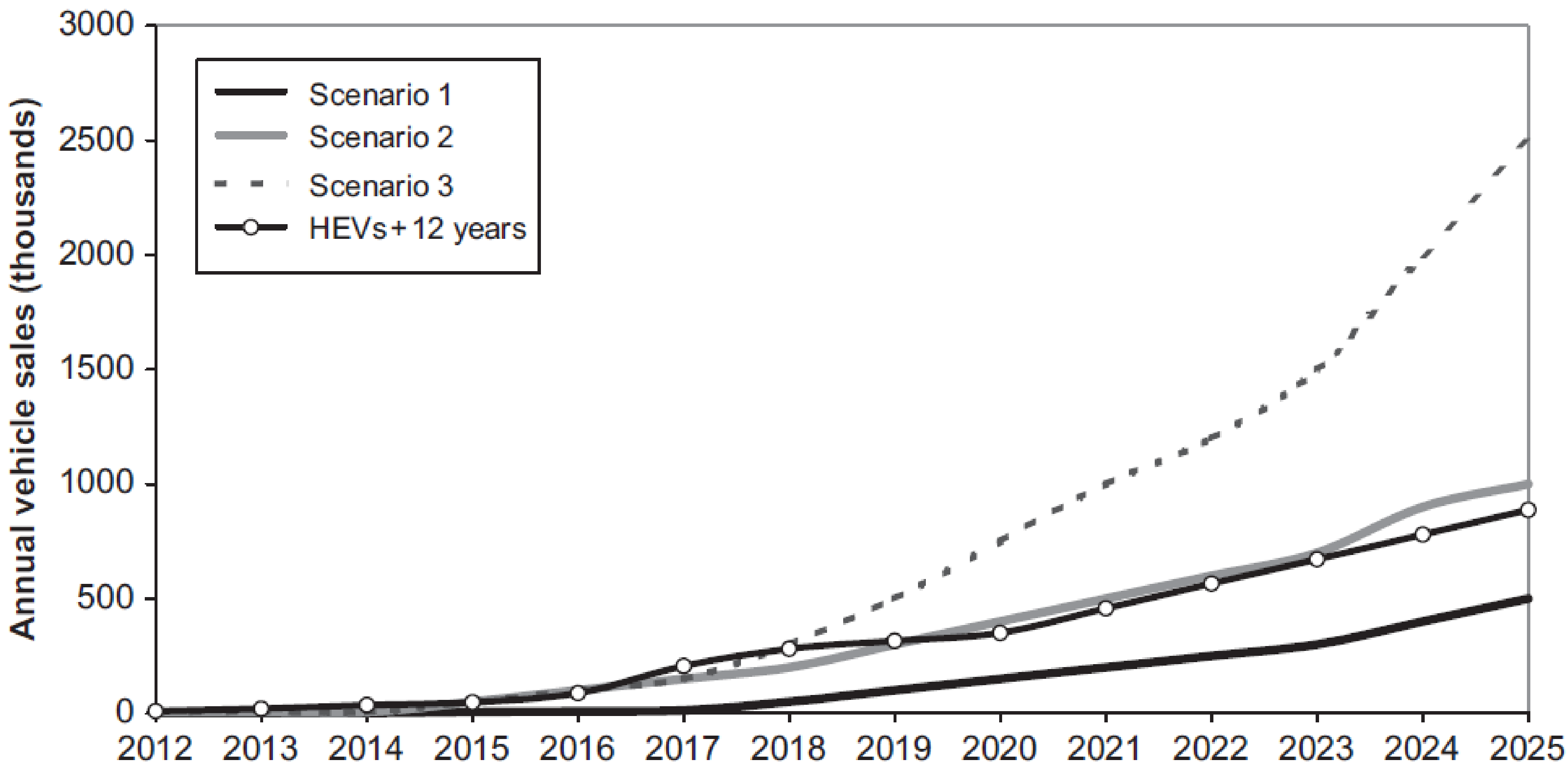


Figure 15.3. Three USDOE Scenarios for H_2 FCV market penetration (Gronich, 2006), and historical market penetration rates for gasoline hybrid vehicles displaced by 12 years.

DOE Plan for introduction of H2 FCVs in a series of lighthouse cities (used in 2008 NRC study)

Cities	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Los Angeles	1	2	2	25	40	50	85	120	160	190	210	250	270	300
New York, Chicago				25	40	50	85	120	150	175	185	225	240	270
San Francisco, Washington/Baltimore					20	30	55	85	120	140	160	190	210	230
Boston, Philadelphia, Dallas						20	50	85	120	145	165	195	210	220
Detroit, Houston							25	50	80	120	140	160	190	210
Atlanta, Minneapolis, Miami								40	75	100	115	130	160	180
Cleveland, Phoenix, Seattle									45	70	90	120	150	170
Denver, Pittsburgh, Portland, St. Louis, Cincinnati, Indianapolis, Kansas City										60	80	110	130	150
Milwaukee, Charlotte, Orlando, Columbus, Salt Lake City											55	80	110	130
Nashville, Buffalo, Raleigh												40	70	90
Nationwide													260	540

FIGURE 6.7 DOE plan for introduction of light-duty hydrogen vehicles into 27 "lighthouse" cities (thousand vehicles per year introduced between 2012 and 2025). The overall build-up rate corresponds to Case 1. The total number of vehicles in 2025 is 10 million, and 2.5 million vehicles are sold that year.

Yang and Ogden estimate of H2 cost in Lighthouse cities (NRC 2008)

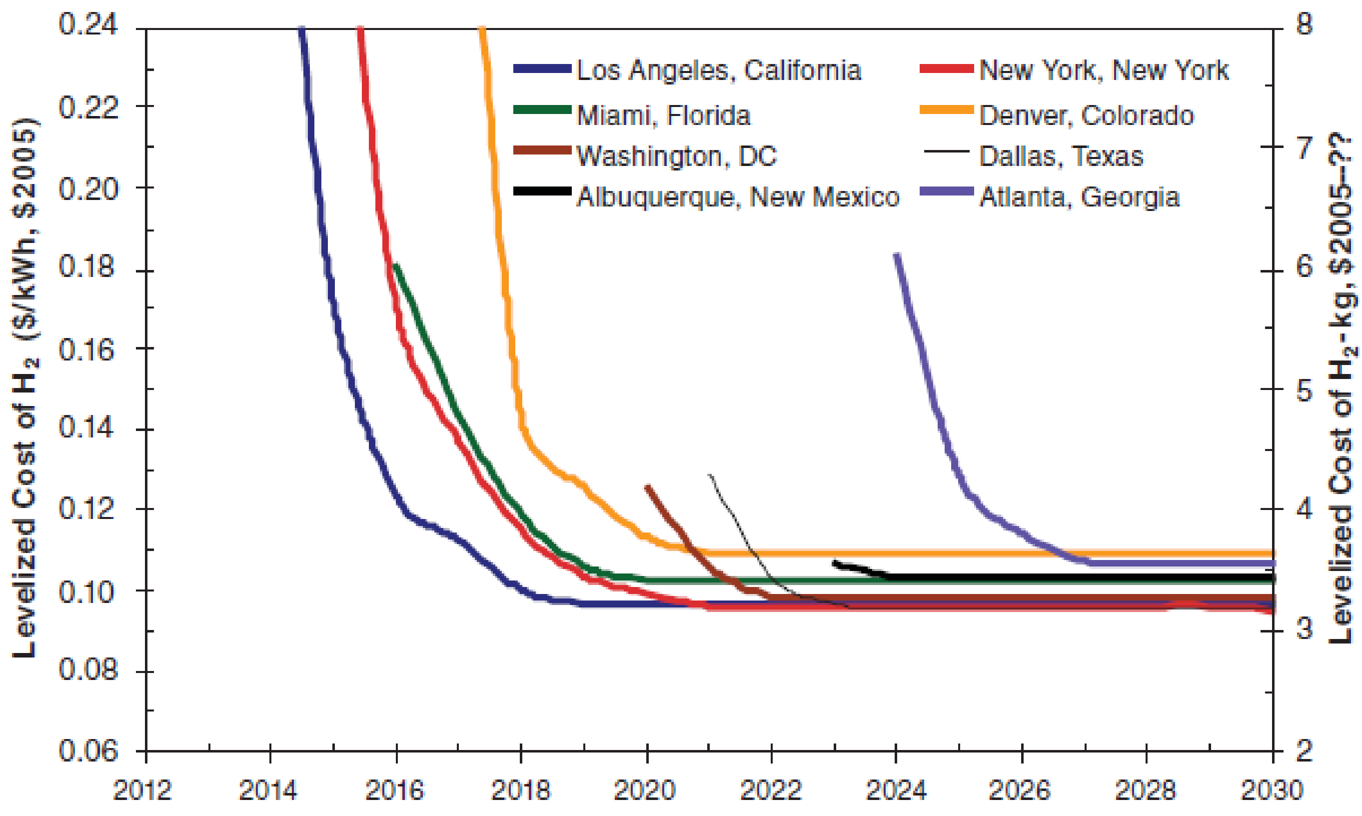


FIGURE C.2 Delivered hydrogen costs in selected cities.

Long term H2 cost consistent with earlier estimates, but H2 costs during early phase of transition are significantly higher.

Regional perspective needed: CA is good example of how thinking on H2 Infrastructure has evolved

CA H2 Highway (2004) Locate stations every 20 miles along the interstates.

Problem: This did not adequately serve H2 vehicles in cities where most people live.

Solution: Focus infrastructure mostly in cities w/ a few stations along the interstates to allow intercity travel.

CA H2 Blueprint Plan (2006) Build Optimized Urban H2 Infrastructure Based On Existing Gasoline System

Problem: For good access need H2 at 10-30% of gas stations. In LA this is ~400 stations just to get started.

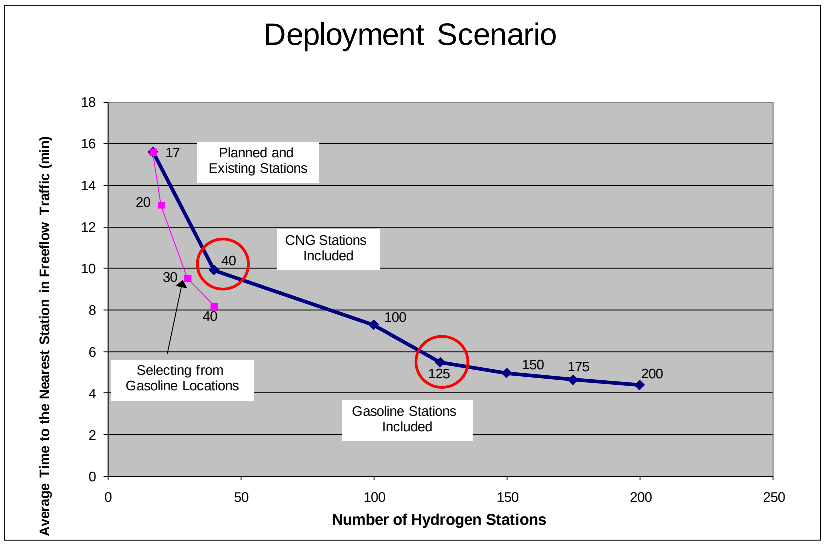
Solution: Regional "Cluster" Strategy" (current paradigm)

FCVs, H2 stations placed together in "clusters" ID'd by stakeholders as early market sites. "Connector" stations added to facilitate regional travel

How many stations needed? Where should they be located?

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

Vehicles placed by population



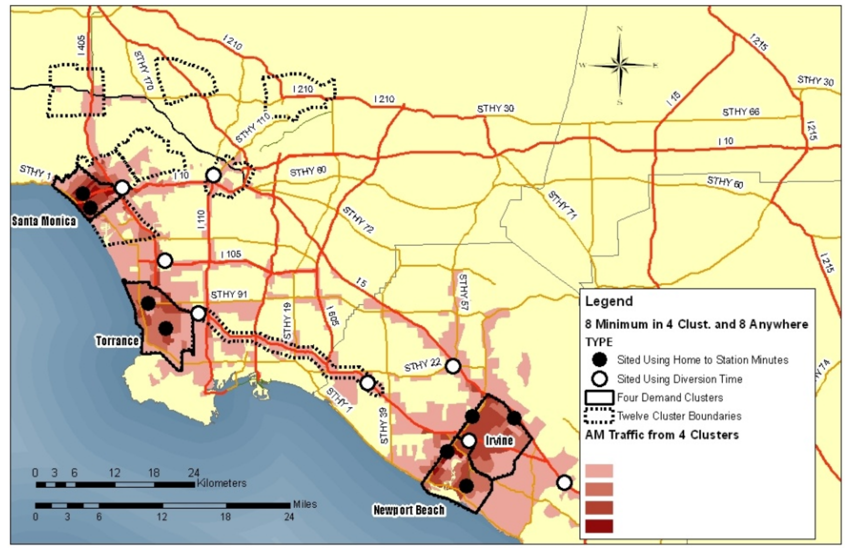
H2 Pathways CA H2 Highway Network Study 2005:

Ave. travel time to **17 optimally placed stations** in LA Basin

= 16 minutes

Cluster strategy:

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



UCD H2 Rollout Study 2010:

Ave. travel time to **16 optimally placed stations** in LA Basin

= 4 minutes

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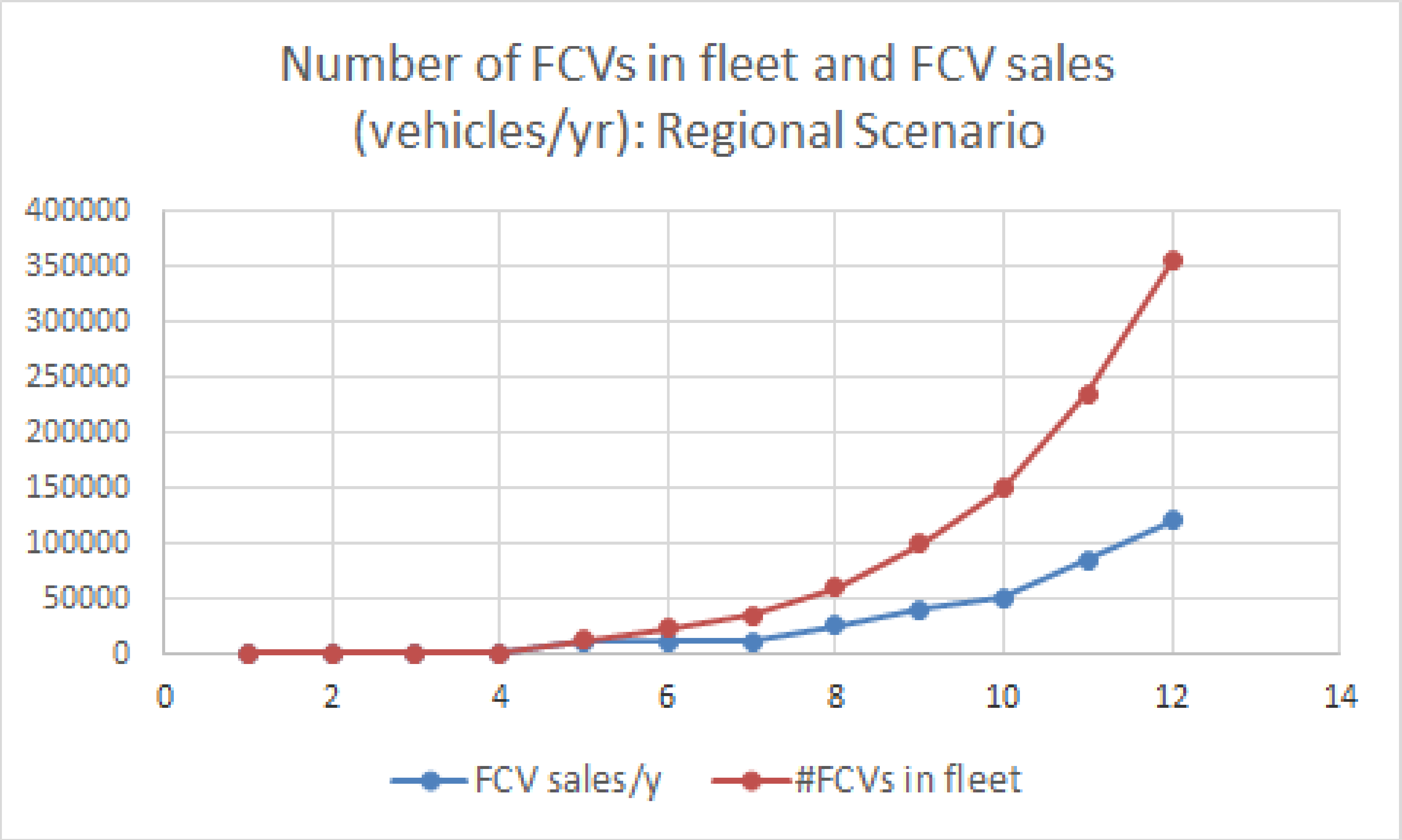
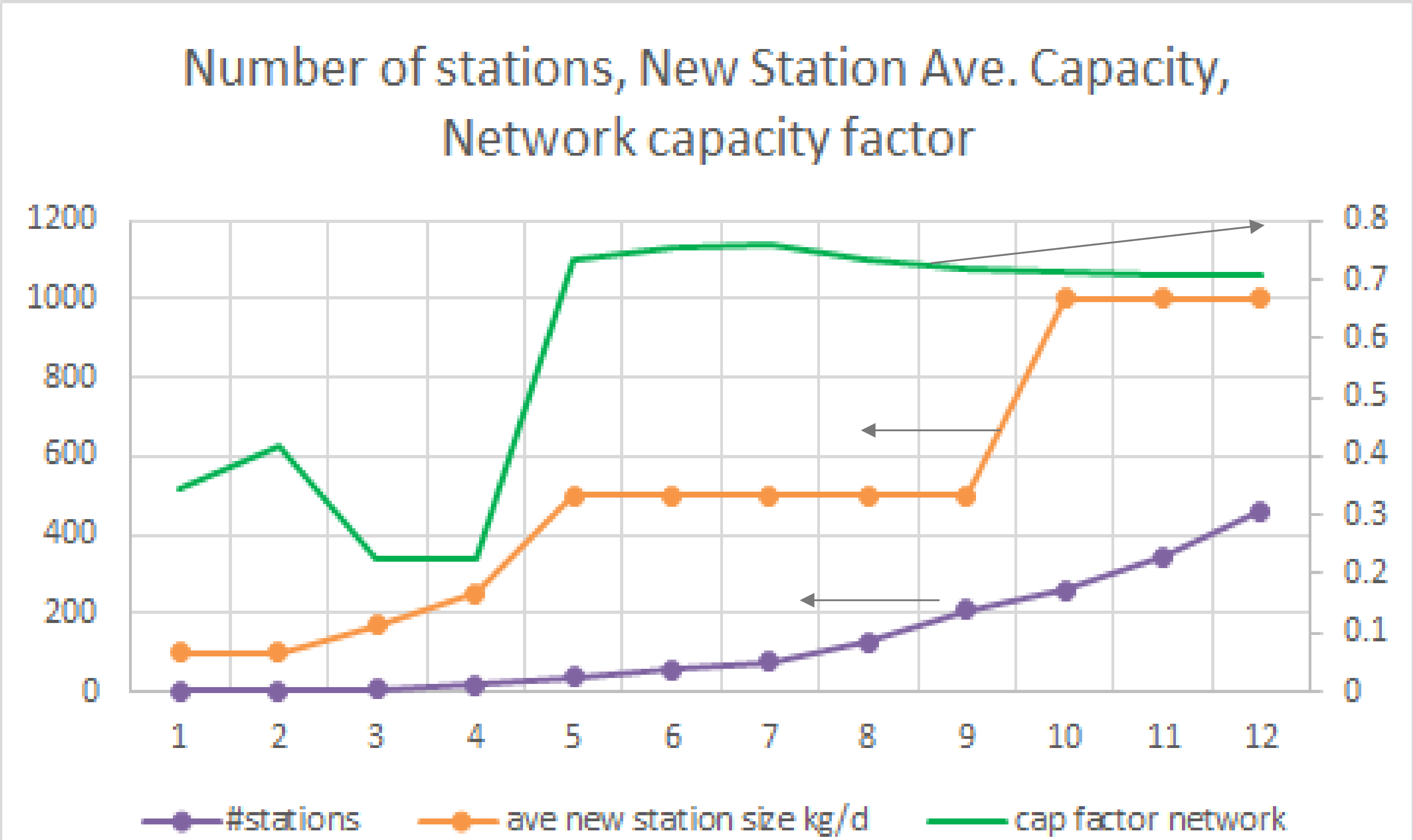
Nicholas, Michael A. and Joan M. Ogden (2010) An Analysis of Near-Term Hydrogen Vehicle Rollout Scenarios for Southern California. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-10-03.

Scenario for Regional H2 FCV Rollout Years 1-12 How Much Investment is Needed to Launch Infrastructure?

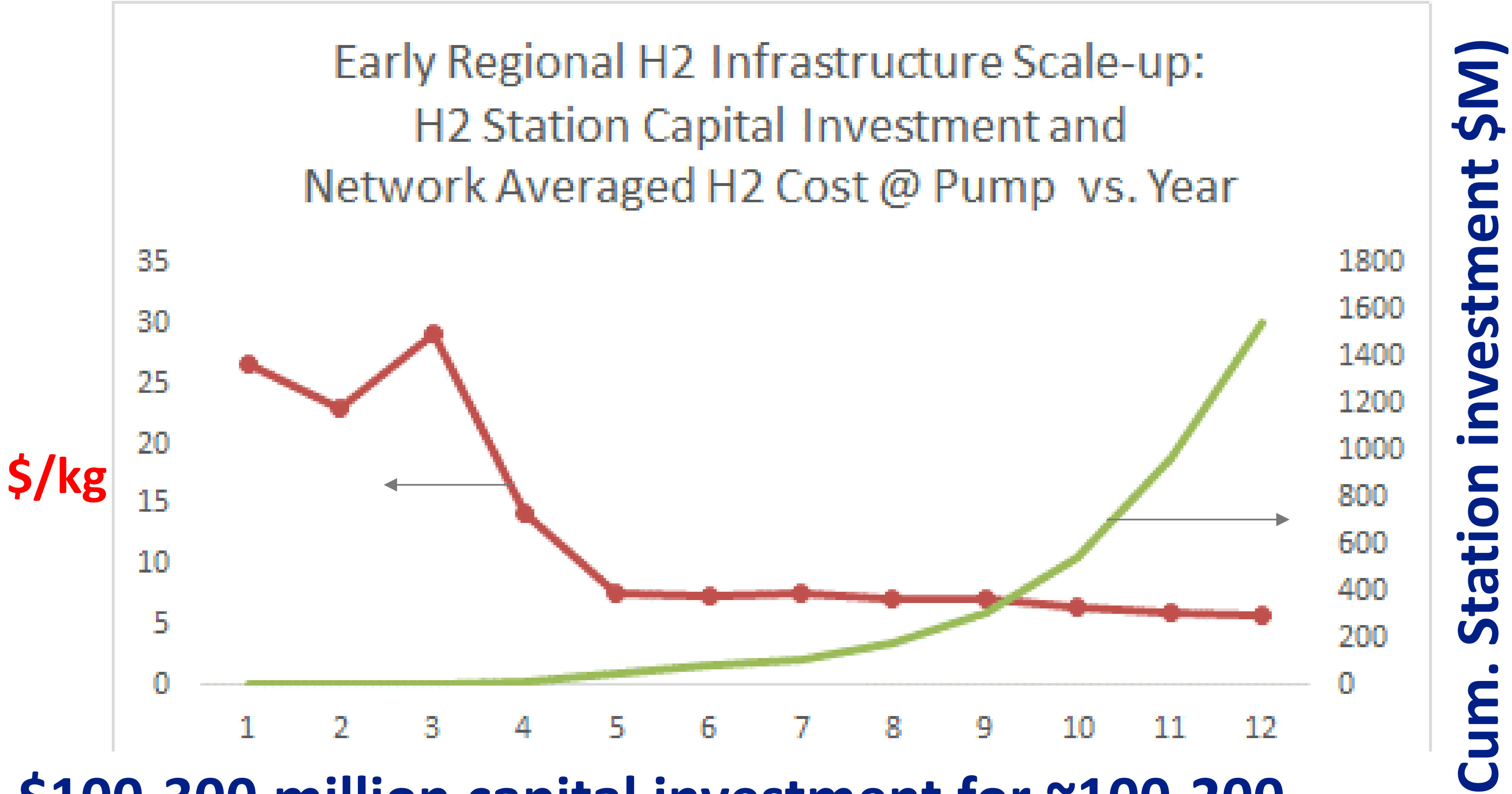


Scenario for regional station rollout to year 12



At first, network capacity factor low, as stations are built ahead of vehicle deployment. In first few years stations small, located to provide coverage for early adopters

Investment to launch regional H2 fuel supply

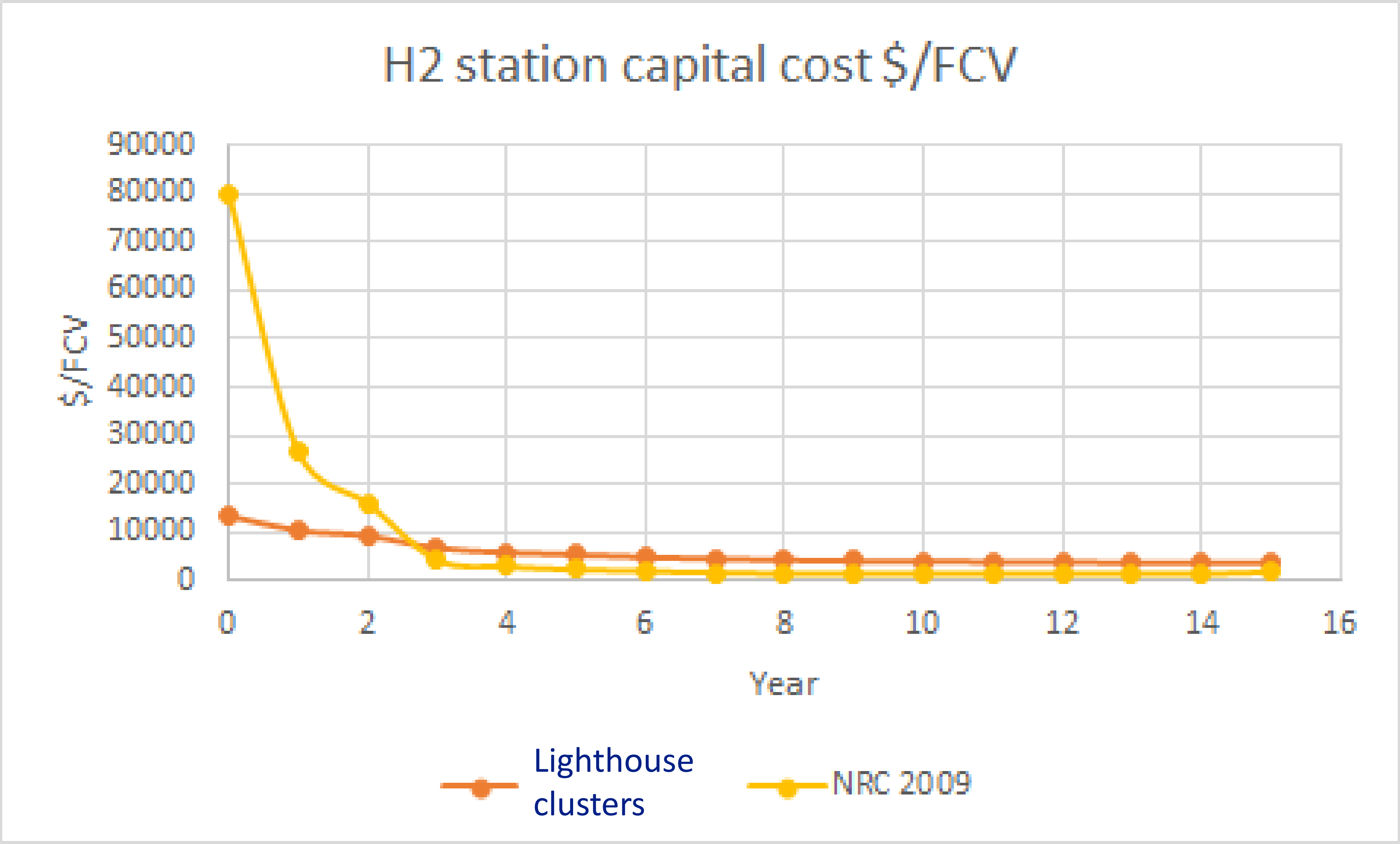


$100-300 million capital investment for ~100-200 stations (serving 50,000-100,000 FCVs) to reach H2 <$7/kg, Assumes FCV market grows rapidly.

National H2 Infrastructure Rollout ("Lighthouse + Clusters")

- Analyze H2 FCV rollout in a series of "lighthouse cities" (LA, NYC, etc.) between 2015 and 2030
- Adopt "cluster strategy" to build H2 infrastructure in each city (2008 NRC report did not use "clustering", but assumed initial rollout where 5-10% of gasoline stations had H2,(e.g. ~200-400 large stations in LA)
- Estimate investment costs, station numbers, hydrogen cost in each city
- Aggregate to find national H2 and infra. cost over time

Compare "lighthouse + clusters" to NRC 2009 study: Better information on early station costs and infra design -> lower early infra capital cost than those estimated by NRC in 2008. But later infra costs are higher.



What has "looking back" taught us about modeling H2 costs?

- Estimating H2 production costs, and delivery and station component costs is relatively straightforward. Estimates are fairly consistent over time – **GIVEN THE SAME CONDITIONS**!
- When calculating H2 costs, assumptions about near term vs. long term, scale, tech. maturity, performance, level of mass production, matter a lot.
- The near term, transitional H2 cost tends to be higher than the long term, learned out, scaled up mature H2 economy cost.
- Transition costs depend on rate of market adoption, technology learning, rollout strategy, location and policy constraints. Societal costs important.
- Viable transitions require business case for all stakeholders and consistent support business case analysis; consumer choice models.

The range of H2 costs in the literature is not such a muddle as one might think. You have to be precise in what you're asking to understand the answers. Over 25 years , the questions asked have gone from the rather theoretical to the very real!

H2 Research Team/Acknowledgments

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r	
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