Analysis of a Cluster Strategy for Near term Hydrogen Infrastructure Rollout in Southern California

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Scope of study

- Analyze "cluster" strategy for introducing H2 vehicles and refueling infrastructure in So. California over the next decade, to satisfy ZEV regulation.
  - Station placement within the Los Angeles Basin
  - Convenience of the refueling network (travel time to stations)
  - Economics – capital and operating costs of stations; cost of H2 station build-out for different station scenarios. Transition costs for H2 to reach cost competitiveness with gasoline on cents/mile basis
  - Options for meeting 33% renewable H2 requirement

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FCVs in LA Basin

2009-2011: 636 FCVs; 8-16 stations

2012-2014: 3442 FCVs; 16-30 stations

2015-2017: 25,000 FCVs 36-42 stations

(Vehicle numbers based on CAFCP survey)

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

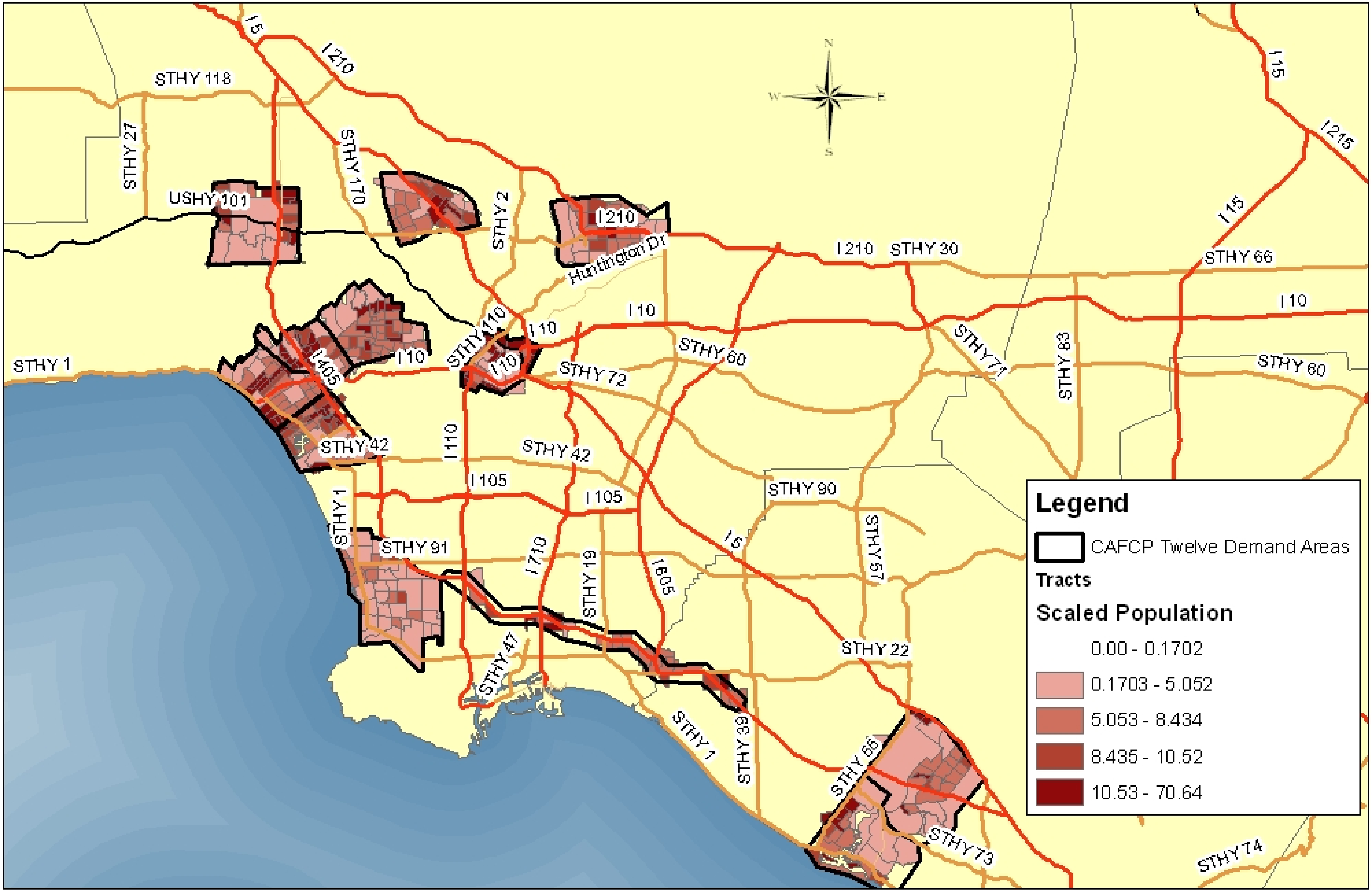
Some connector stations are added to facilitate travel throughout the LA Basin.

12 Clusters Identified by the CAFCP Survey

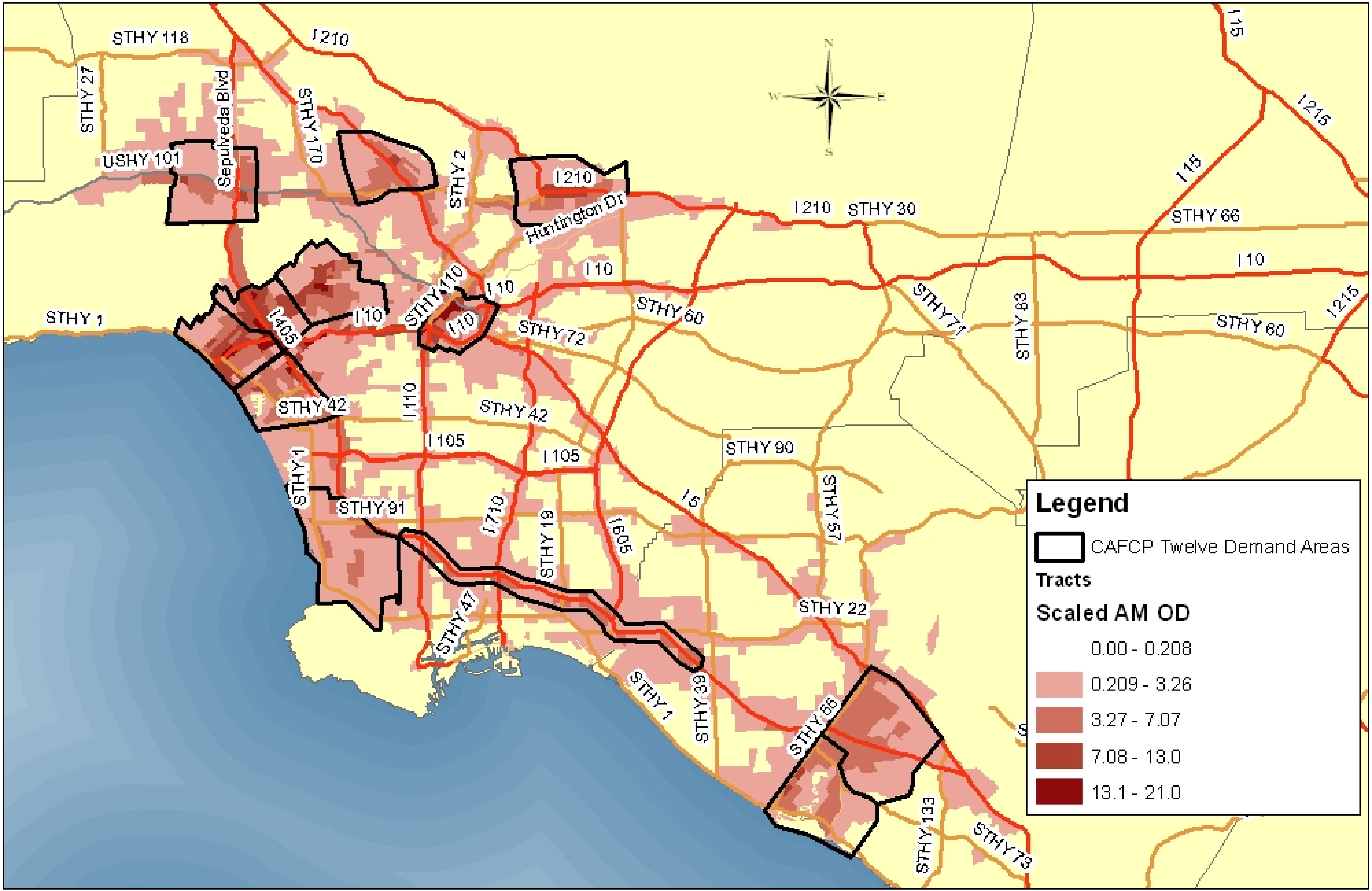
Two Ways to Measure Consumer Convenience

- Home to the nearest station
- “Diversion” time.
  - Stations are attracted to large traffic streams. This increases the chance that if you suddenly need fuel while driving around a station will be nearby.
  - Not “flow capture”, but a similar concept

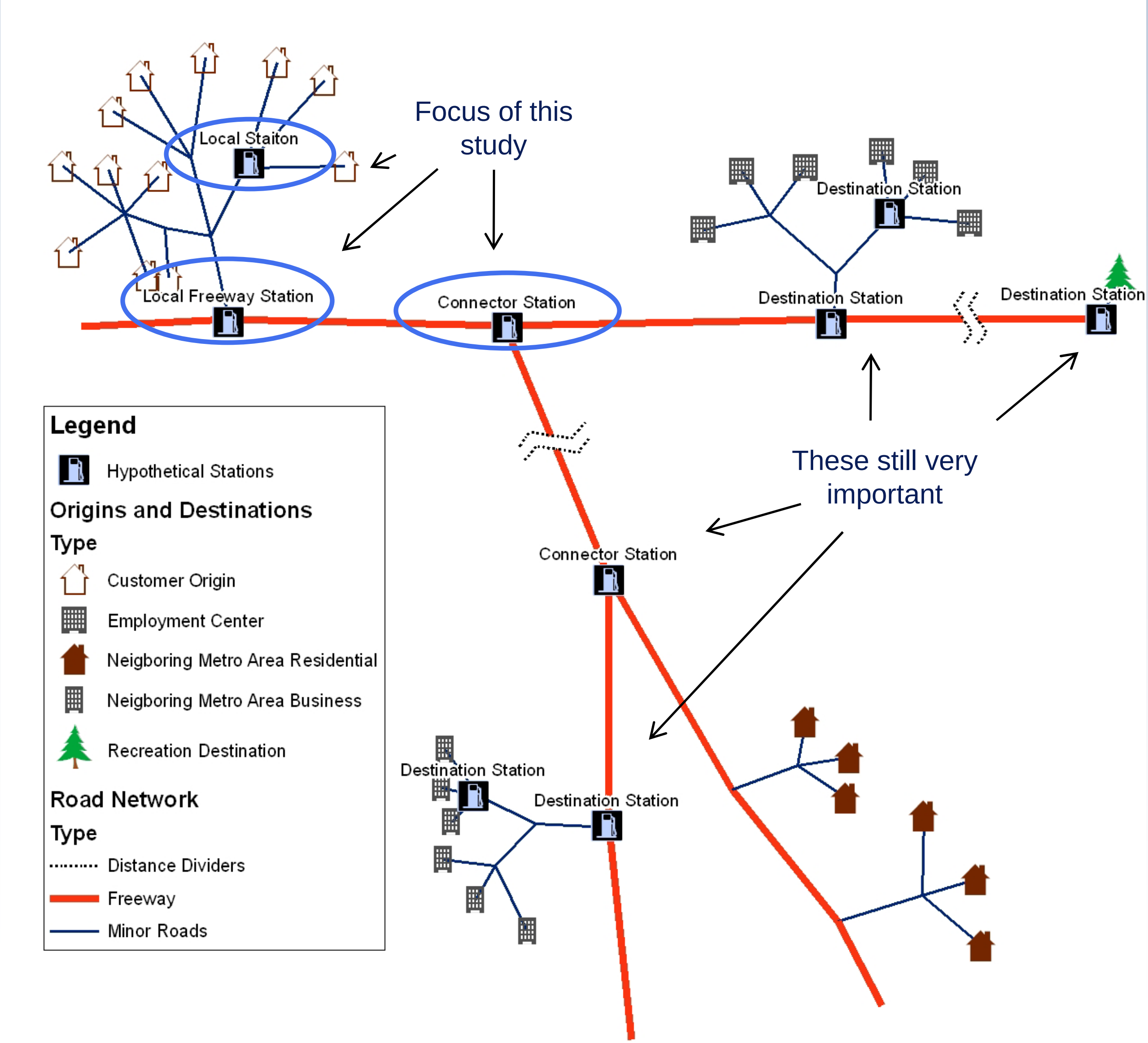
Analyzed the Population Distribution Within the 12 Clusters to Obtain Home to Station Times



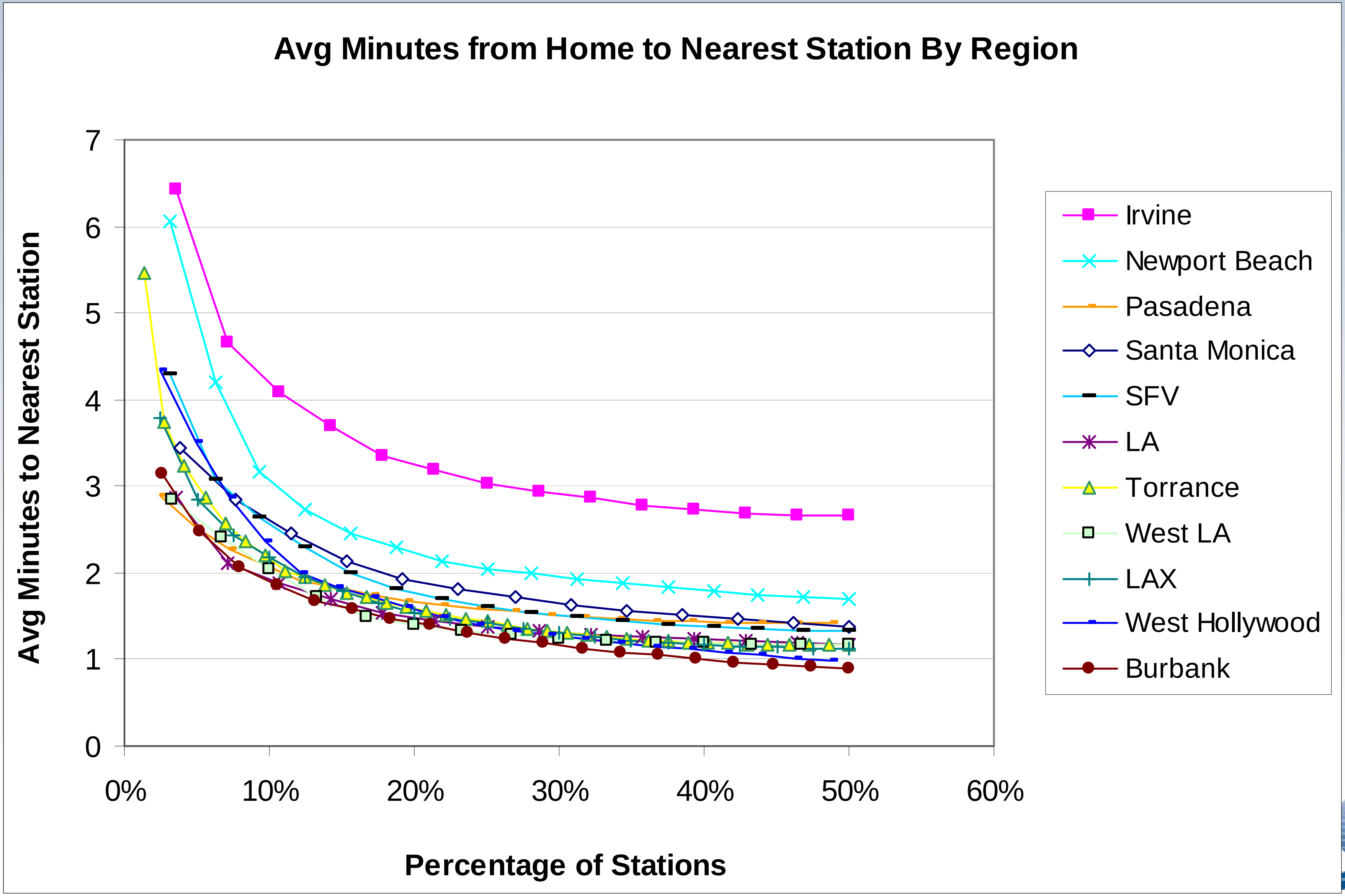
Analyzed Traffic Whose Origins are in the 12 Clusters



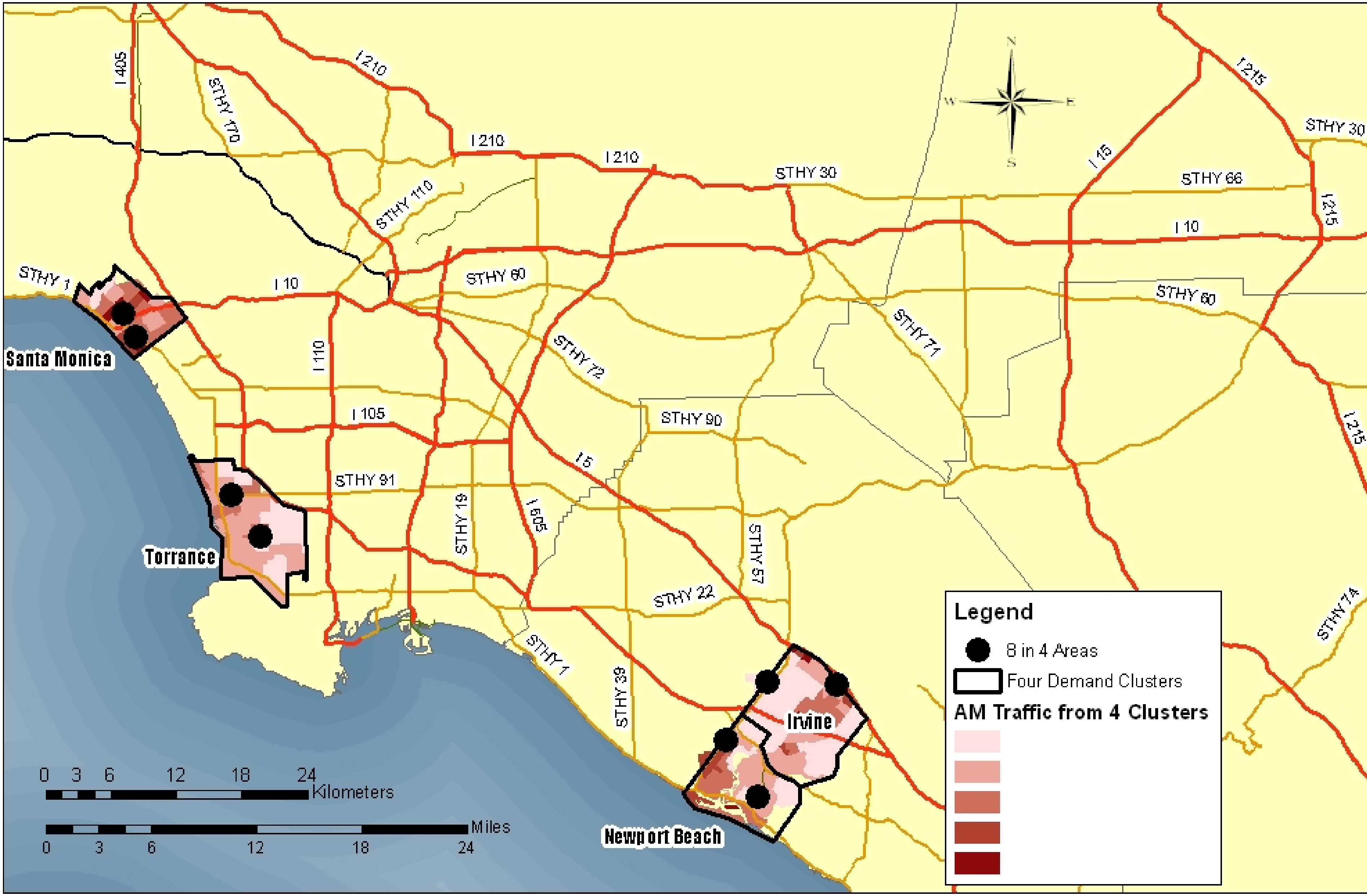
Idealized Network with Station Types



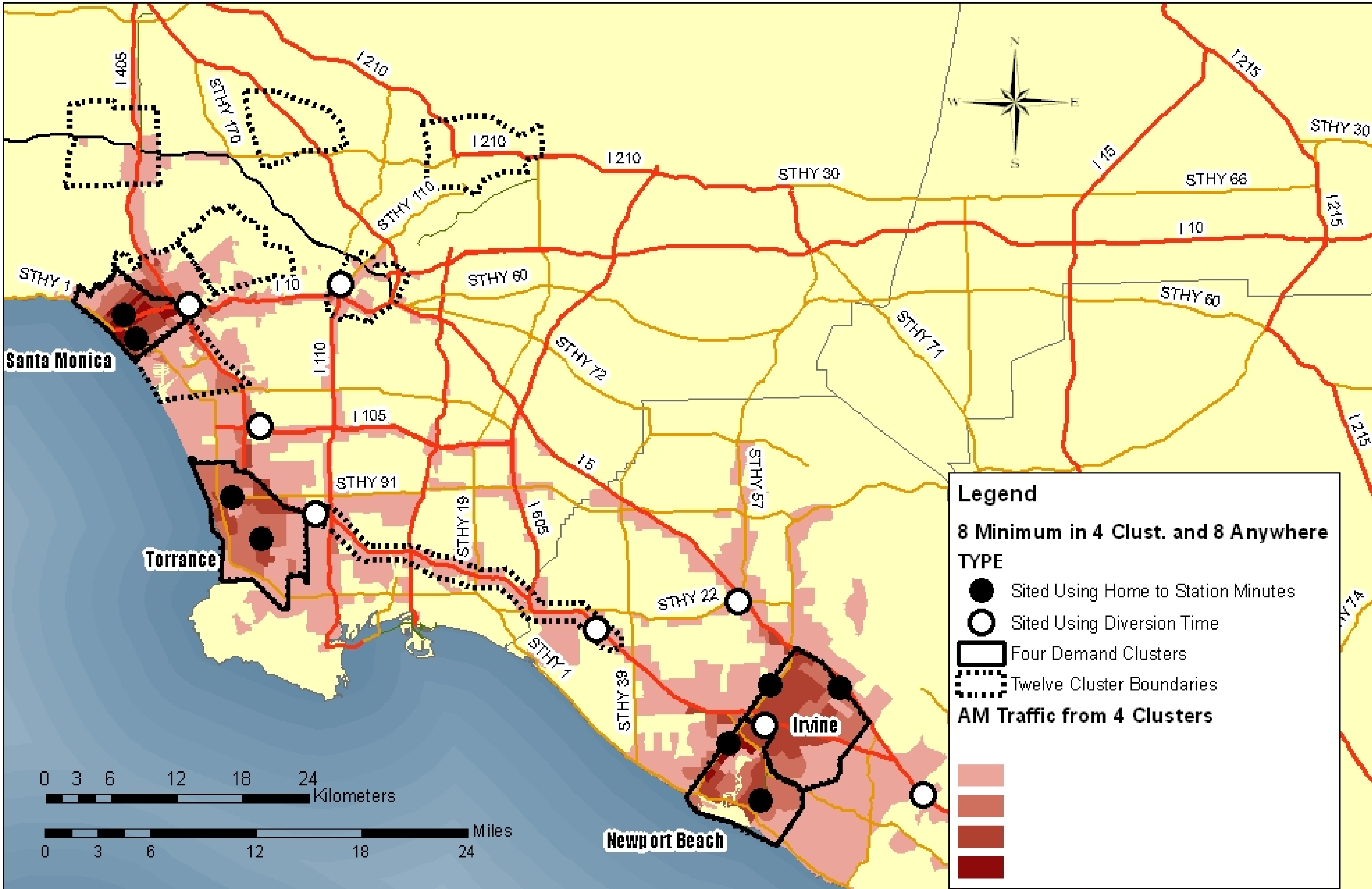
Home to Nearest Station for Each Cluster



4 Cluster Example – 2 Local Stations Per Cluster



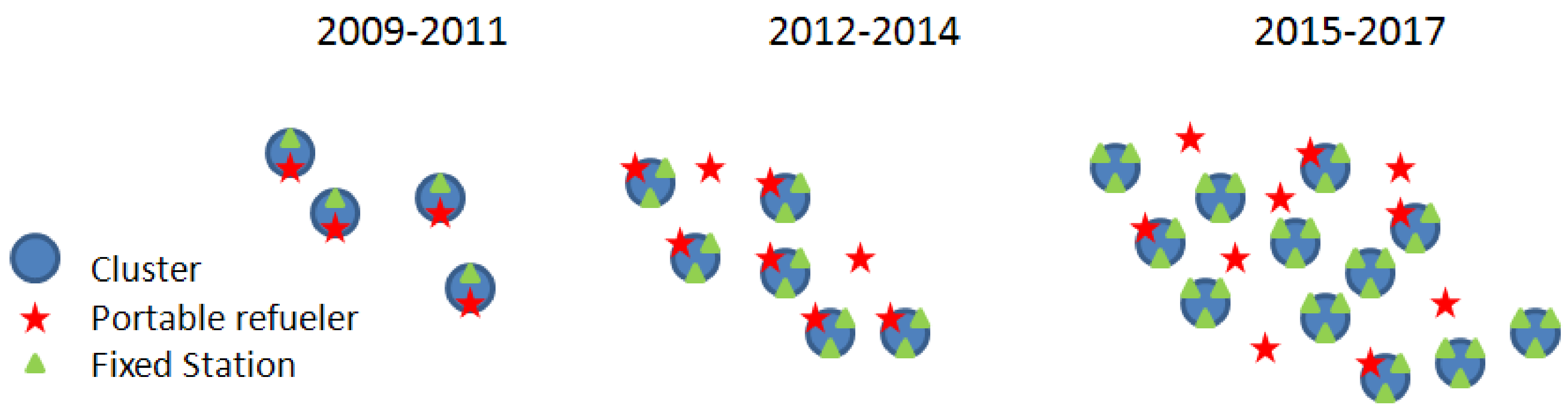
Add 8 Stations Based on Diversion Time



CONSUMER CONVENIENCE W/CLUSTER STRATEGY

METRICS: *Ave. Travel time* (home -> station)

Diversion time (time to nearest station for area-wide travel)



	636 FCVs	3442 FCVs	25,000 FCVs
# Stations	8	20	42
# clusters	4 (2 sta/cluster)	6 (3 sta/cluster)	12 (3 sta/cluster)
# connect.sta	0	2	6
Ave travel time	3.9 minutes	2.9 minutes	2.6 minutes
Diversion time	5.6 minutes	4.5 minutes	3.6 minutes

RESULTS: CLUSTERING STRATEGY

- Clustering vehicles and stations is an efficient way to design an early hydrogen refueling network, providing very good accessibility for users located within the clusters.
- Clustered networks with as few as 8-16 stations can yield average travel times of <4 minutes (home to station), and average diversion times of less than 6 minutes. (Without clustering, ave. travel time would be 10-15 minutes.)
- If a few connector stations are added between clusters, the diversion time is further reduced.
- Destination Stations in San Diego, Santa Barbara, and Las Vegas will increase the attractiveness of the vehicles.

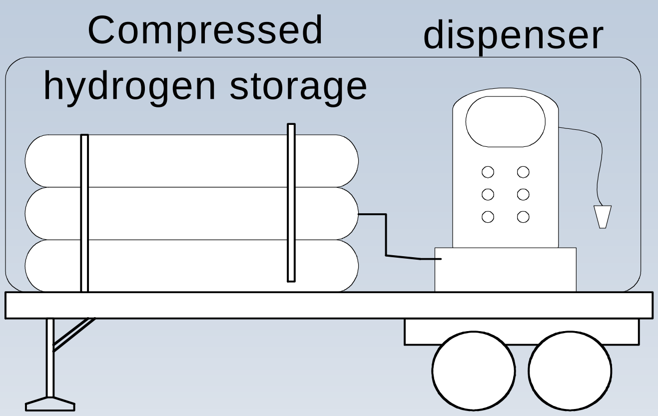
Types of H2 Stations

- ***Mobile refueler stations*** (50-100 kg/d)
- ***Portable refueler stations with compressed gas truck trailer delivery*** (100 kg/d)
- ***Liquid H_2 stations with truck delivery*** (100 kg/d, 250 kg/d, 400 kg/d, 1000 kg/d)
- ***Onsite Steam Methane Reforming (SMR)*** (100 kg/d, 250 kg/d, 400 kg/d, 1000 kg/d)
- ***Onsite Electrolyzer*** (100 kg/d, 250 kg/d, 400 kg/d, 1000 kg/d)

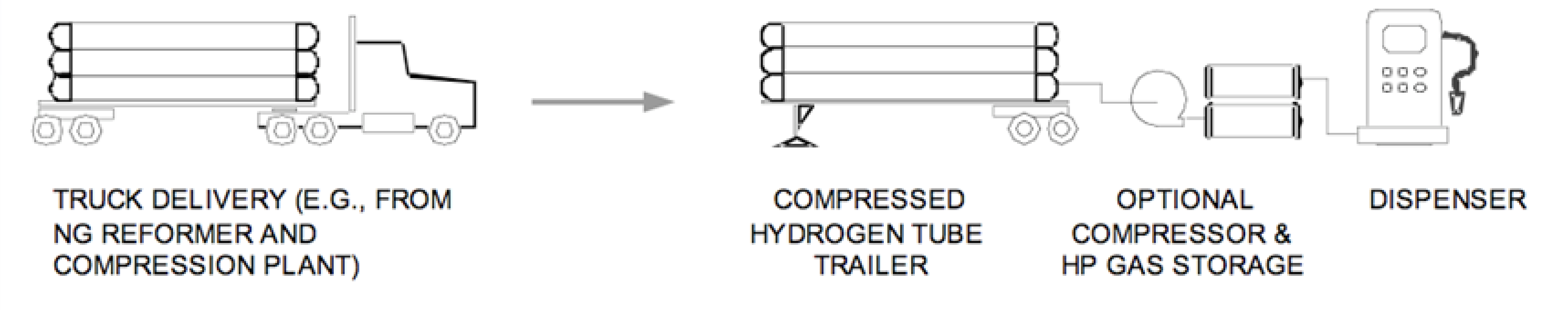
2009-2011, 50-100 kg/day stations;
2012-2014, 100, 250 or 400 kg/day stations.
2015+, 100, 250, 400 or 1000 kg/day stations.

At least 2 stations per cluster; At least 1 "fixed" station per cluster

MOBILE AND PORTABLE REFUELERS



Hydrogen Mobile Refuler



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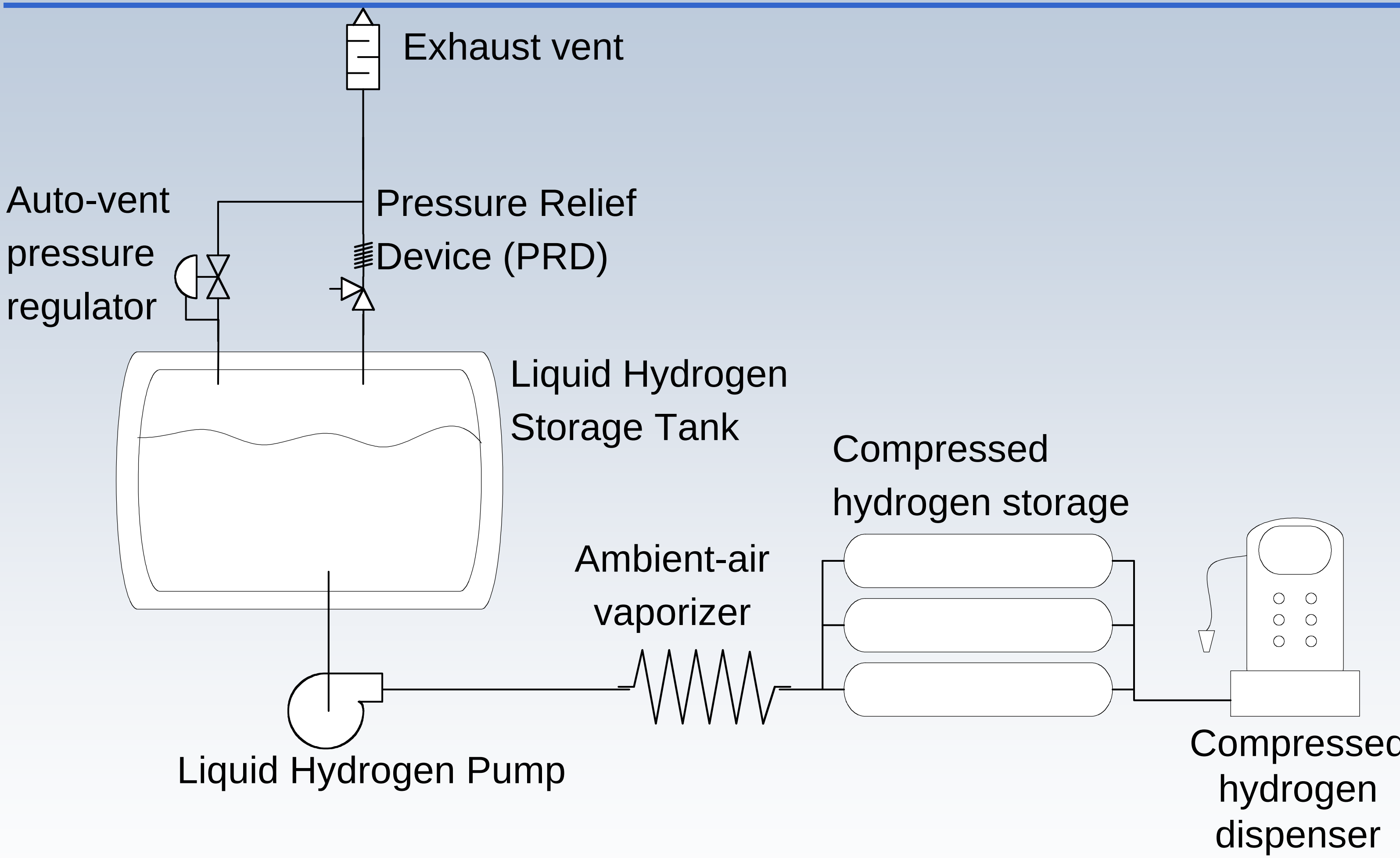
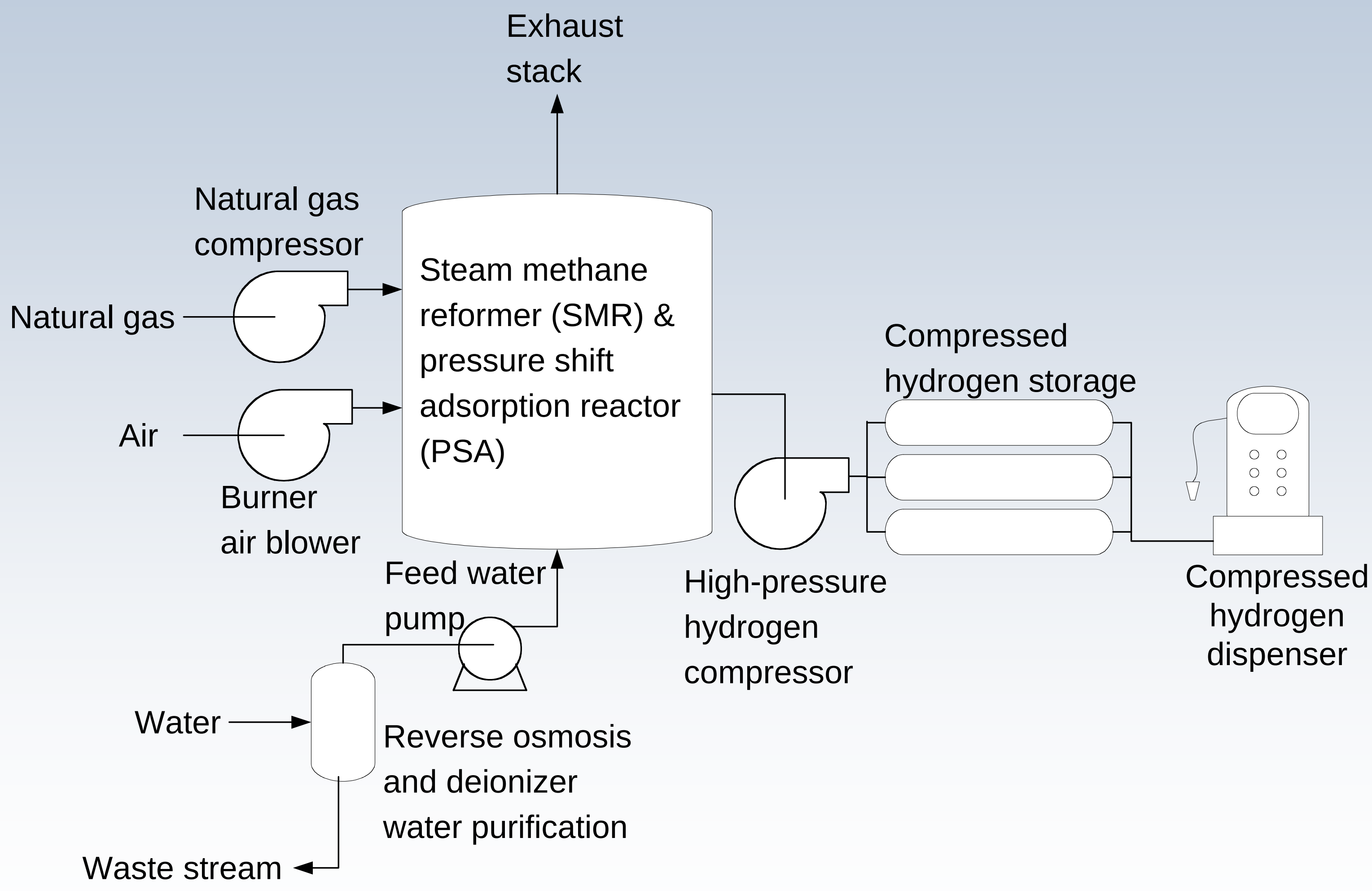
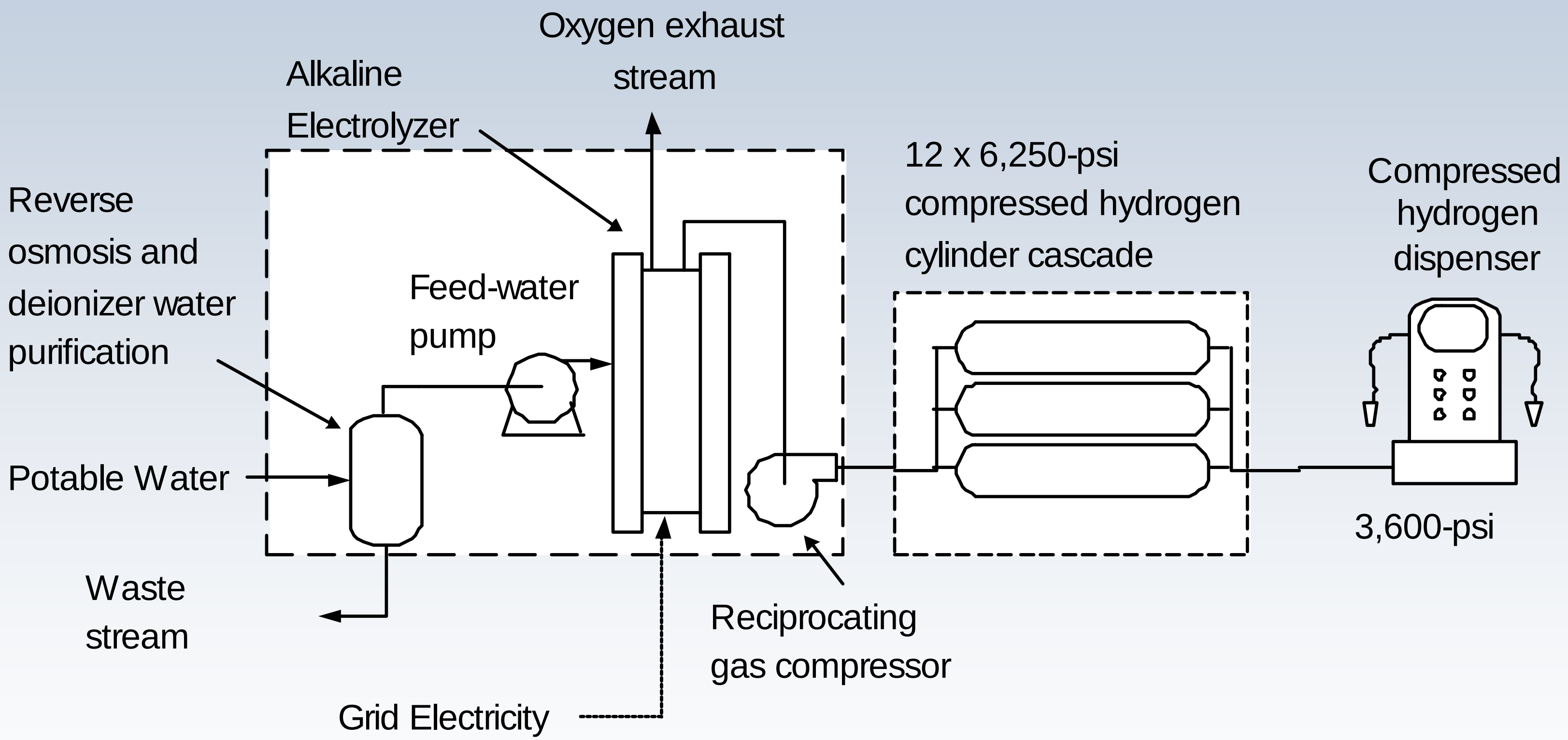
LH2 STATION


Exhaust vent
Auto-vent pressure regulator
Pressure Relief Device (PRD)
Liquid Hydrogen Storage Tank
Compressed hydrogen storage
Ambient-air vaporizer
Liquid Hydrogen Pump
Compressed hydrogen dispenser

ONSITE SMR STATION



ONSITE ELECTROLYZER STATION



Economic Analysis:

Station Capital Cost Assumptions

- H2 station costs (2009-2011) based on interviews with energy company experts reflecting today's costs.
- For future fixed 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

Station Capital Cost Assumptions ($million)

	2009-2011	2012-2014	2015-2017 (high)	2015-2017 (low)
Mob. Refueler 100 kg/d	**1.0**	**1.0**	**1.0**	**0.4**
Comp.Gas Truck Delivery 100 kg/d	**3.0**	**2.2**	**2.2**	**2.1**
LH2 Truck Delivery				
100 kg/d	**4.0**	**2.6**	**2.6**	**2.3**
250 kg/d		**2.7**	**2.7**	**2.3**
400 kg/d		**2.8**	**2.8**	**2.4**
1000 kg/d		**3.2**	**3.2**	**2.6**
Onsite Reformer				
100 kg/d	**3.5-4.0**	**3.3**	**3.3**	**2.6**
250 kg/d		**4.0**	**4.0**	**3.0**
400 kg/d		**4.8**	**4.8**	**3.4**
1000 kg/d		**7.8**	**7.8**	**4.9**
Onsite Electrolyzer				
100 kg/d	-	**3.2**	**3.2**	**2.6**
250 kg/d		**4.2**	**4.2**	**3.1**
400 kg/d		**5.3**	**5.3**	**3.6**
1000 kg/d		**9.3**	**9.3**	**5.6**

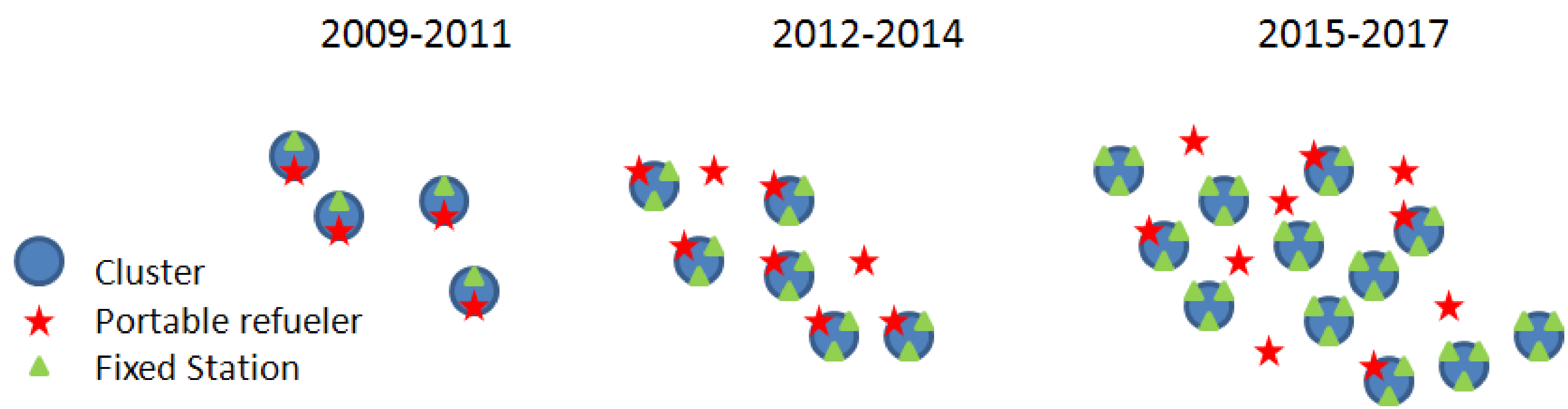
700 bar adds $500/(kg/d) or ~ $0.5 million to a 1000 kg/d station

2009-2011: Interviews; 2012-2014 =$2 million + 2 x H2A Current. tech. Costs; 2015-2017 (low) = $2 million + H2A current tech costs

Assumed Energy and Utility Prices

	CURRENT PRICE
Natural Gas (Commercial rate)	$12/MMBTU
Electricity (Commercial rate)	$0.10/kWh
Compressed H2 (for mobile refueler)	$20/kg
LH2 (truck delivered)	$10-12/kg
Land rent (Los Angeles)	$5.0/sq.ft/month
BioMethane	$20-40/MMBTU
Ethanol	$2-4/gallon gasoline equiv
Green Electricity premium	$0.01-0.05/kWh

TRANSITION SCENARIO



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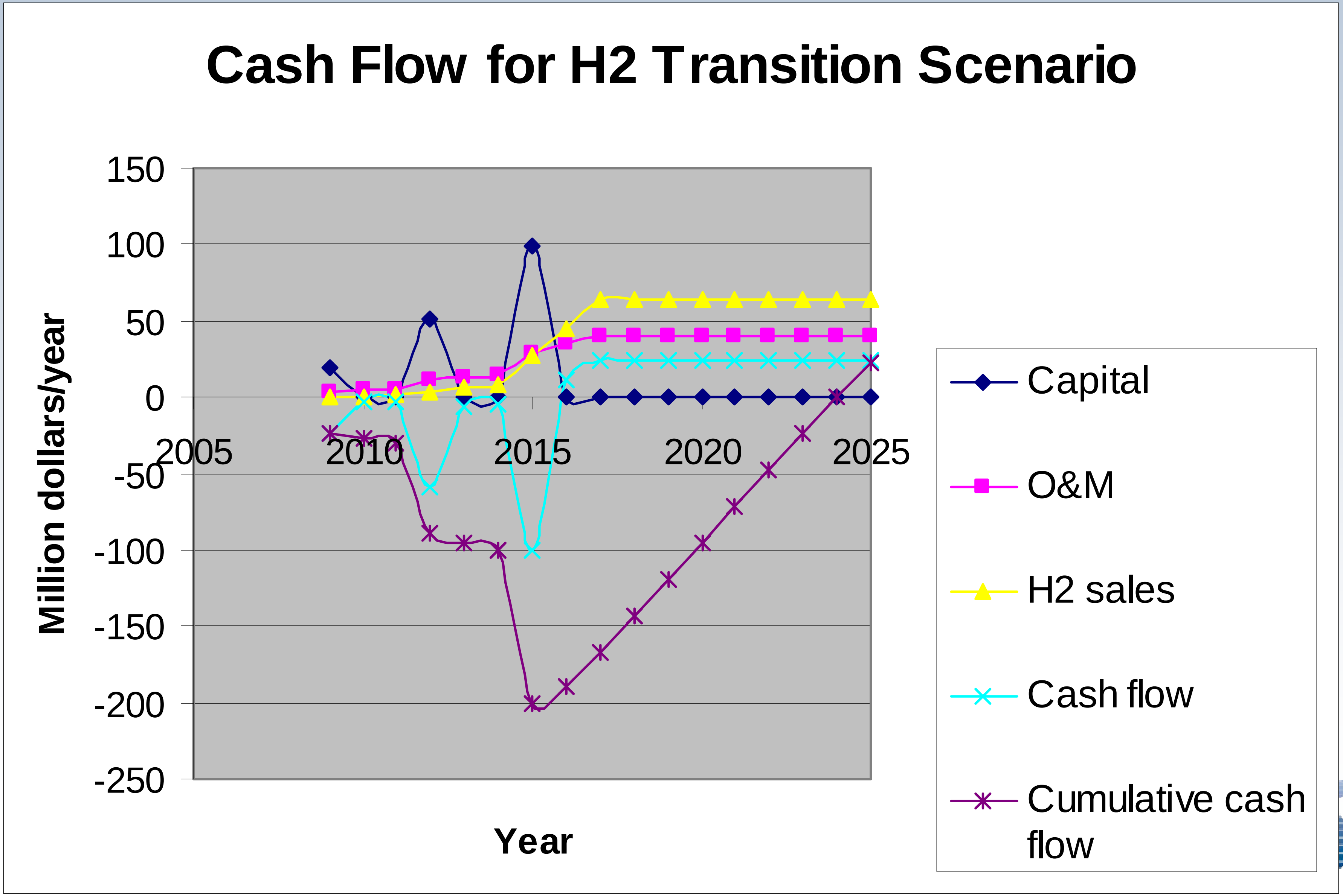
# Stations	8	20	42
# clusters	4 (2 sta/cluster)	6 (3 sta/cluster)	12 (3 sta/cluster)
# connect.sta	0	2	6
Station Mix	4 Portable refuelers 4 SMRs (100 kg/d)	8 Portable Refuelers 12 SMRS (250 kg/d)	10 Portable refuelers 12 SMRs (250 kg/d) 20 SMRs (1000 kg/d)
Capital Cost	$20Million	$52 Million	$98 Million
O&M Cost	3-5$Million/y	11-14 $Million/y	30-40 $Million/y
Ave travel time	3.9 minutes	2.9 minutes	2.6 minutes
Diversion time	5.6 minutes	4.5 minutes	3.6 minutes

Cash Flow (H2 sold @ $10/kg)

(low 2015-2017 station costs)



RESULTS: TRANSITION COST

Capital investment ~$170 million to build 40 stations through 2015. Initially, cash flow is negative (due to initial capital expenditures to build the stations). With growing demand, cash flow becomes positive after 2016.

By 2020-2025, the total investment ~$200 million (capital and operating costs) can be recouped, if H2 from these stations can be sold at $10/kg.

For our cost assumptions, the first 10 years of a H2 infrastructure could pay for itself if H2 is sold at a price competitive with gasoline at $5/gallon (cents/mile basis).

Beyond 2017, if demand continues to grow rapidly, H2 could be produced in large (1000 kg/d) onsite SMR stations at a cost of $5-7/kg, competing w/ gasoline at $2.5-3.5/gallon

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H_2 COST: SENSIVITY TO ASSUMPTIONS

Assume H2A current tech costs in 2015-2017. If H2A 2015 "learned out" station costs were used for 2015-2017 timeframe, H2 costs would be similar

Station site prep costs = $2 million. If site prep costs were $0.5 million, H2 cost would be reduced by ~$2.5/kg

Land rental (LA) = $5/sf/mo. If $1/sf/mo, H2 cost would be reduced by ~$2/kg

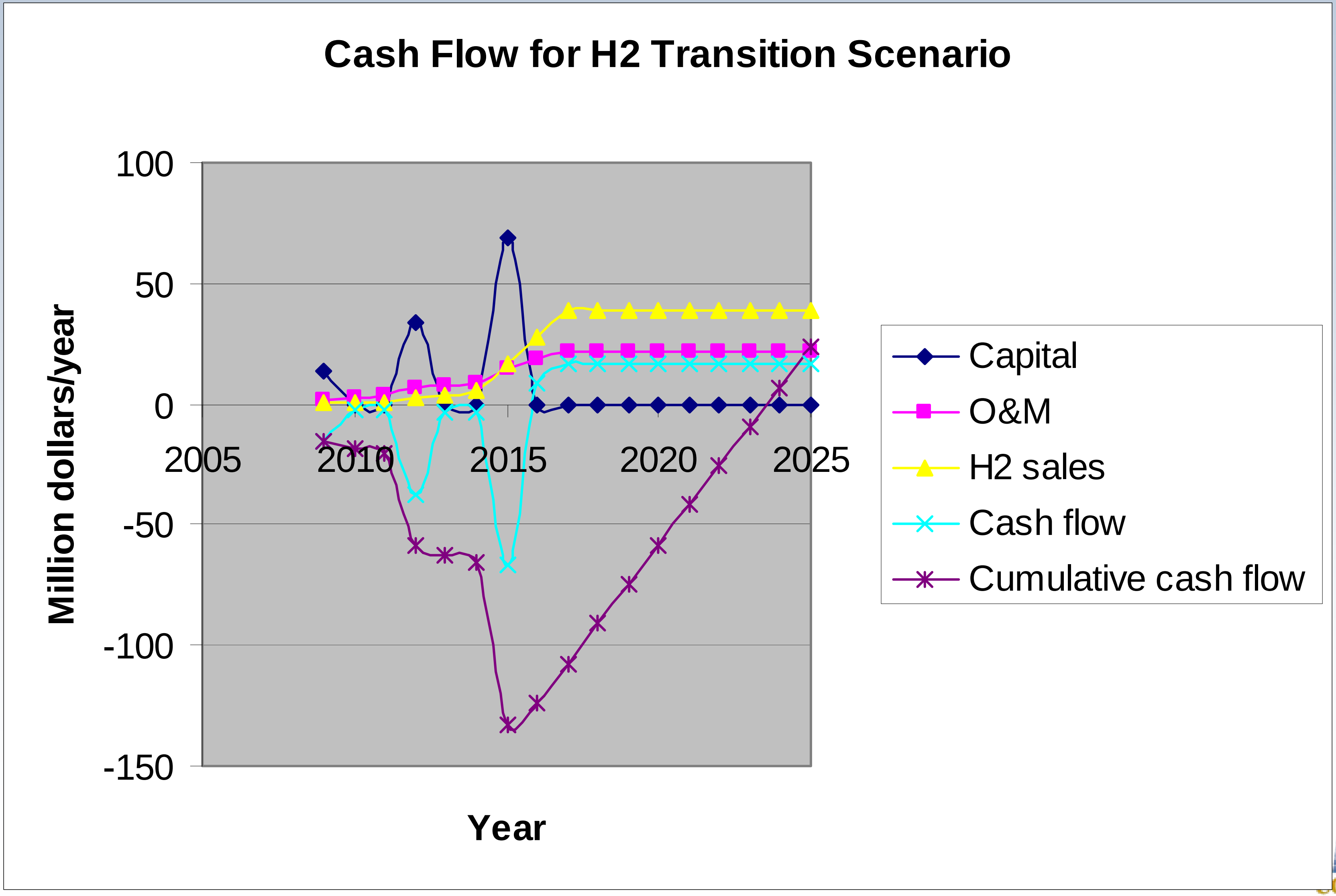
H2 fuel sales pay for entire station. If station is based on a convenience store + fuel model, H2 costs could be reduced by ~$1.5/kg.

Station dispenses 350 bar H2. If 700 bar, H2 cost incr. ~$0.5/kg

NG price $12/MBTU, if $6/MBTU, H2 cost reduced ~$1/kg

Cash Flow (H2 sold @ $6/kg)

($0.5 million site prep., $1/sf/mo land rent, NG=$6/MBTU, low 2015-2017 station costs)



Near term Renewable H2 Pathways

- Onsite Reformer using pipeline delivered biomethane
- Onsite Reformer using ethanol
- Onsite electrolysis (green electricity via grid)
- Onsite electrolysis (Solar PV at station)

Assumed Renewable Energy Prices

RENEWABLE ENERGY INPUTS	PRICE
"Green" electricity via grid for electrolysis	$0.11-0.15/kWh ($0.01-0.05/kWh premium)
"Green" electricity (onsite PV) for electrolysis	$0.39/kWh (intermittent, 22% capacity factor on electrolyzer)
Renewable pipeline quality biogas delivered to station via short pipeline (5-12 miles)	$20-40/MMBTU (CEC & USDA studies)
Renewable ethanol delivered to station	$2-4/gallon gasoline equivalent energy basis (NREL)

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RENEWABLE SCENARIO	H2 Cost Incr. vs. Base Case Transition Scenario $/kg
ONSITE SMR: 33% Renewable Biomethane + 33% Renewable Grid Electricity for compression	0.1-0.4
ONSITE SMR: 100% Biomethane + 100% Renewable Grid Electricity for compression	1.2-4.2
ONSITE SMR: 33% Bioethanol + 33% Renewable Grid Electricity for compression	0.1-0.4
ONSITE SMR: 100% Bioethanol + 100% Renewable Grid Electricity for compression	1.2-4.2
ONSITE ELECTROLYSIS: grid electricity, no renewables	4.2
ONSITE ELECTROLYSIS: 33% Renewable Grid Electricity for electrolysis and compression	4.5-5.5
ONSITE ELECTROLYSIS: 100% Solar PV Electricity for Electrolysis and Compression	20

RESULTS: RENEWABLE HYDROGEN

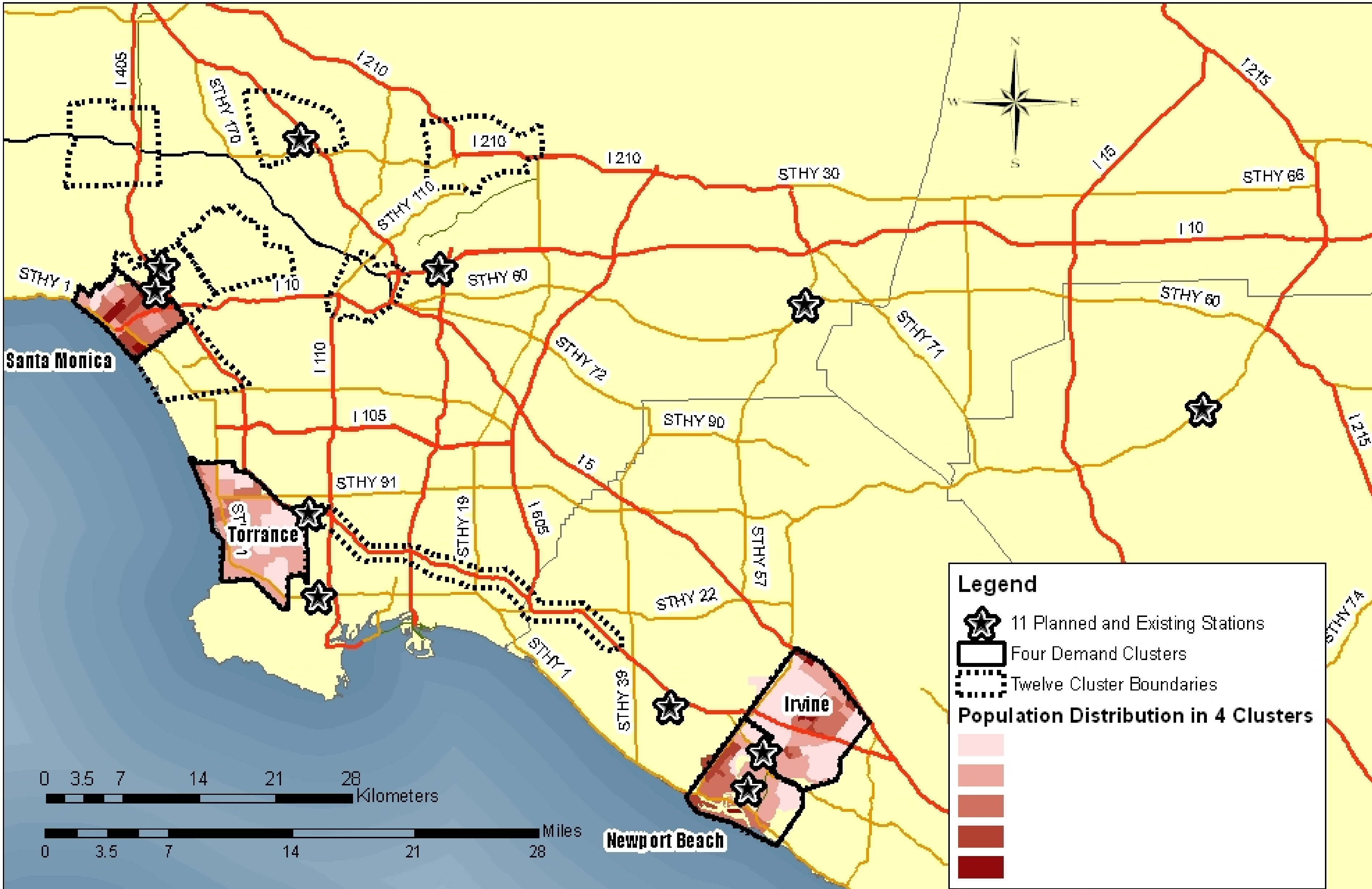
There are several options for near-term renewable hydrogen production. Onsite reformation of bio-methane could meet California's requirement for 33% renewable sources for hydrogen production at a modest cost premium of $0.1-0.4 per kg of hydrogen.

Onsite reformation is considerably lower cost than onsite electrolysis (at least $4/kg less)

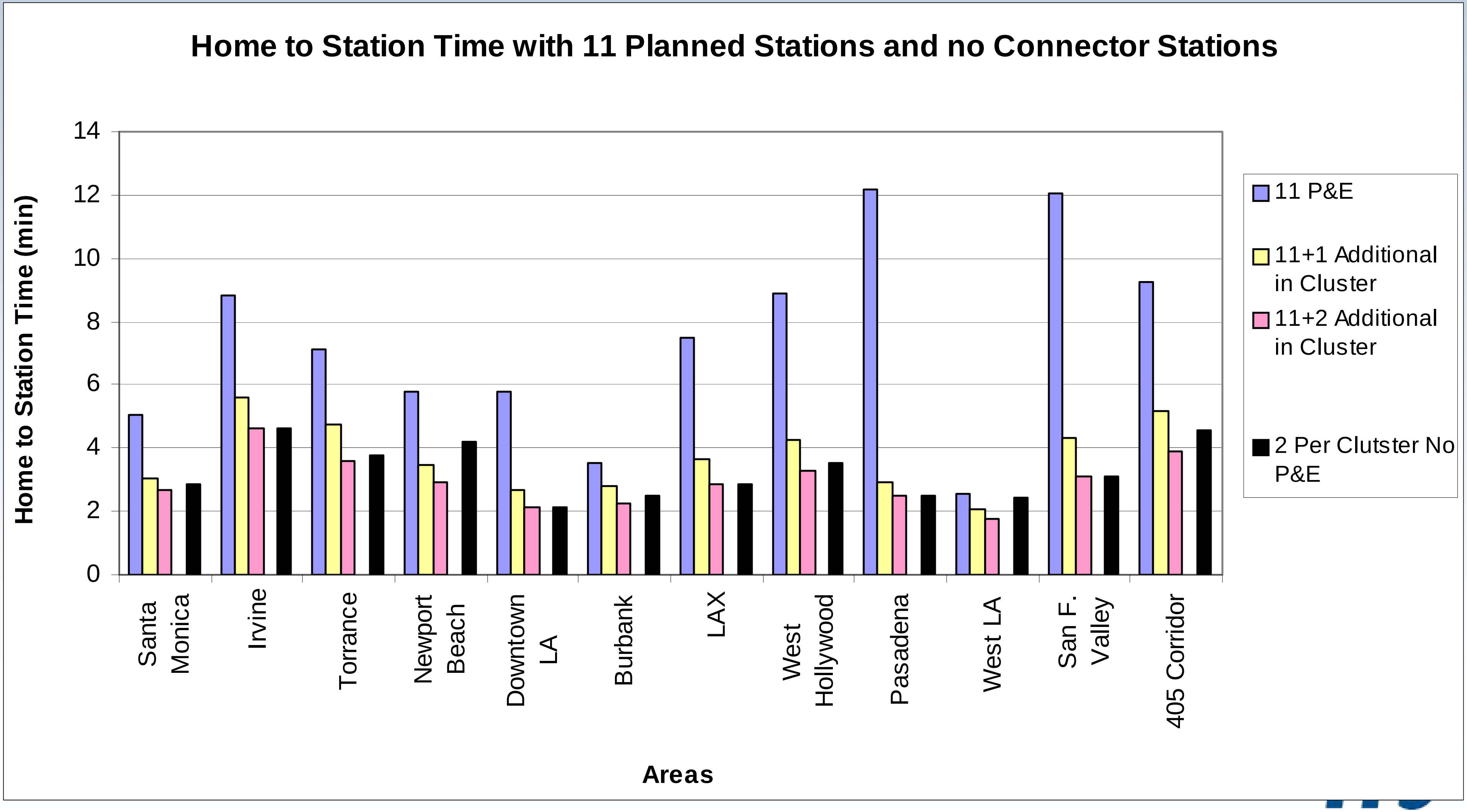
At present California's renewable hydrogen requirement SB1505 pertains to electrolytic H2 only. Expand to accommodate bio-methane.

EXTRA SLIDES

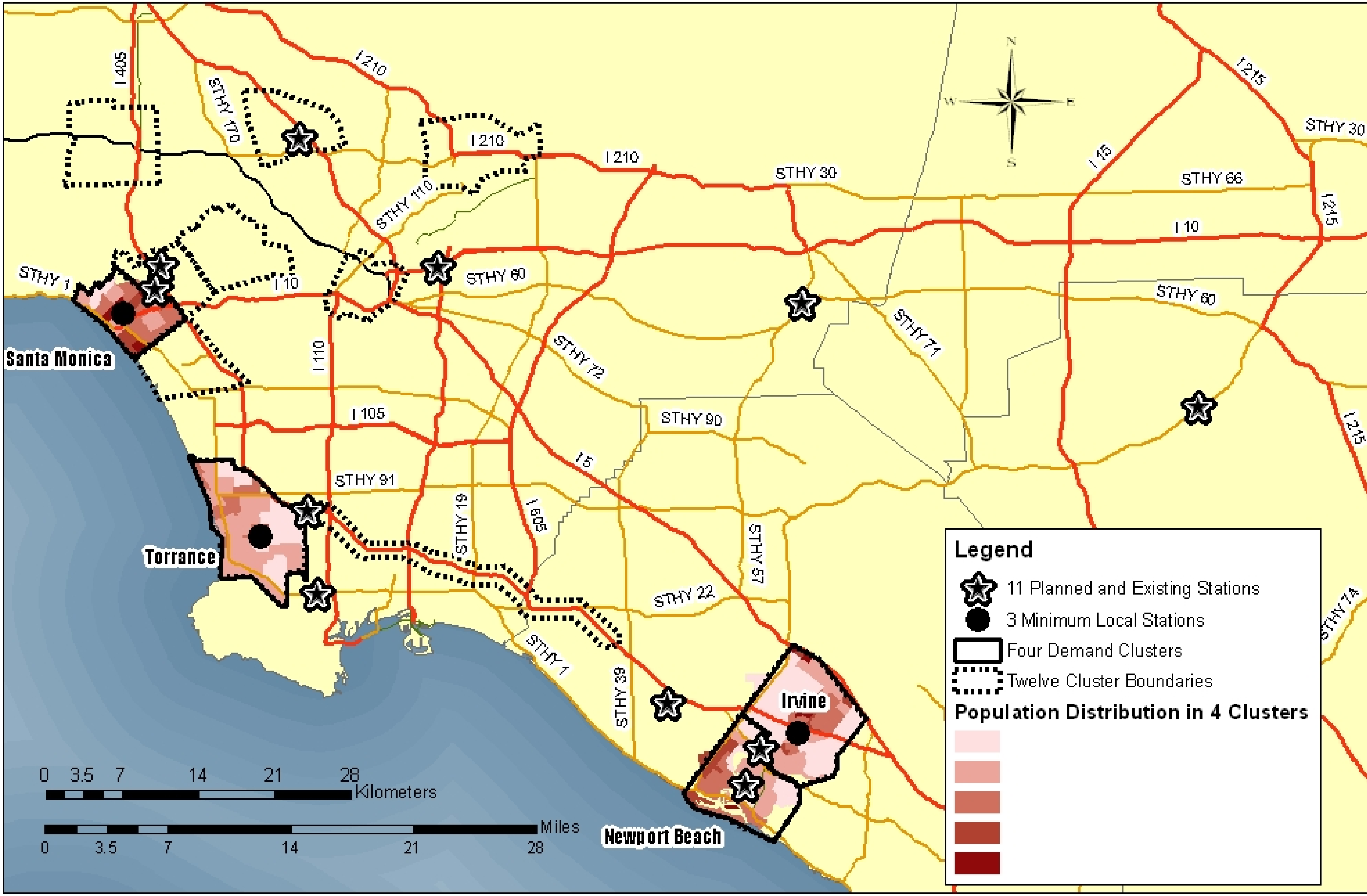
Integrating Existing Stations Into the Network



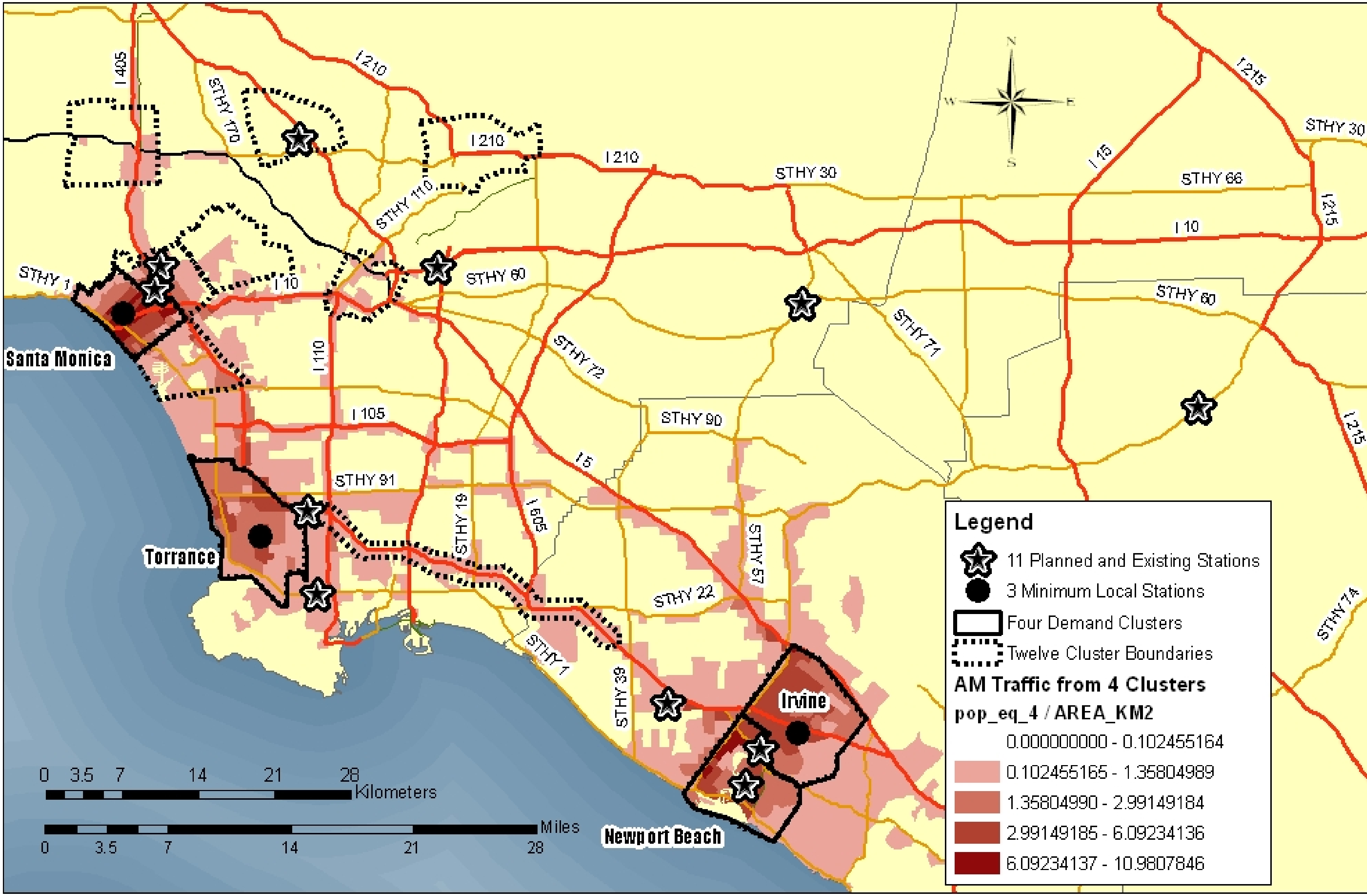
Existing Stations Home to Station Time



Add Three "Minimum" Local Stations



Existing Stations Can Serve as Connector Stations



Effect of Planned and Existing Stations in Scenarios

- Network of 11 planned and existing (P&E) stations generally well placed, but some are not in clusters
- In most cases:
  - Home-to-station travel time with P&E station network is signif. greater than w/ cluster strategy (2 sta/cluster)
  - Need to add 1 or 2 stations per cluster to planned and existing network to get comparable accessibility.
- Highlights the question: Should the customers follow the existing stations or should the stations follow the customers?
- Those stations not in clusters still reduce diversion time

Station Capital Cost Assumptions: H2A and UCD

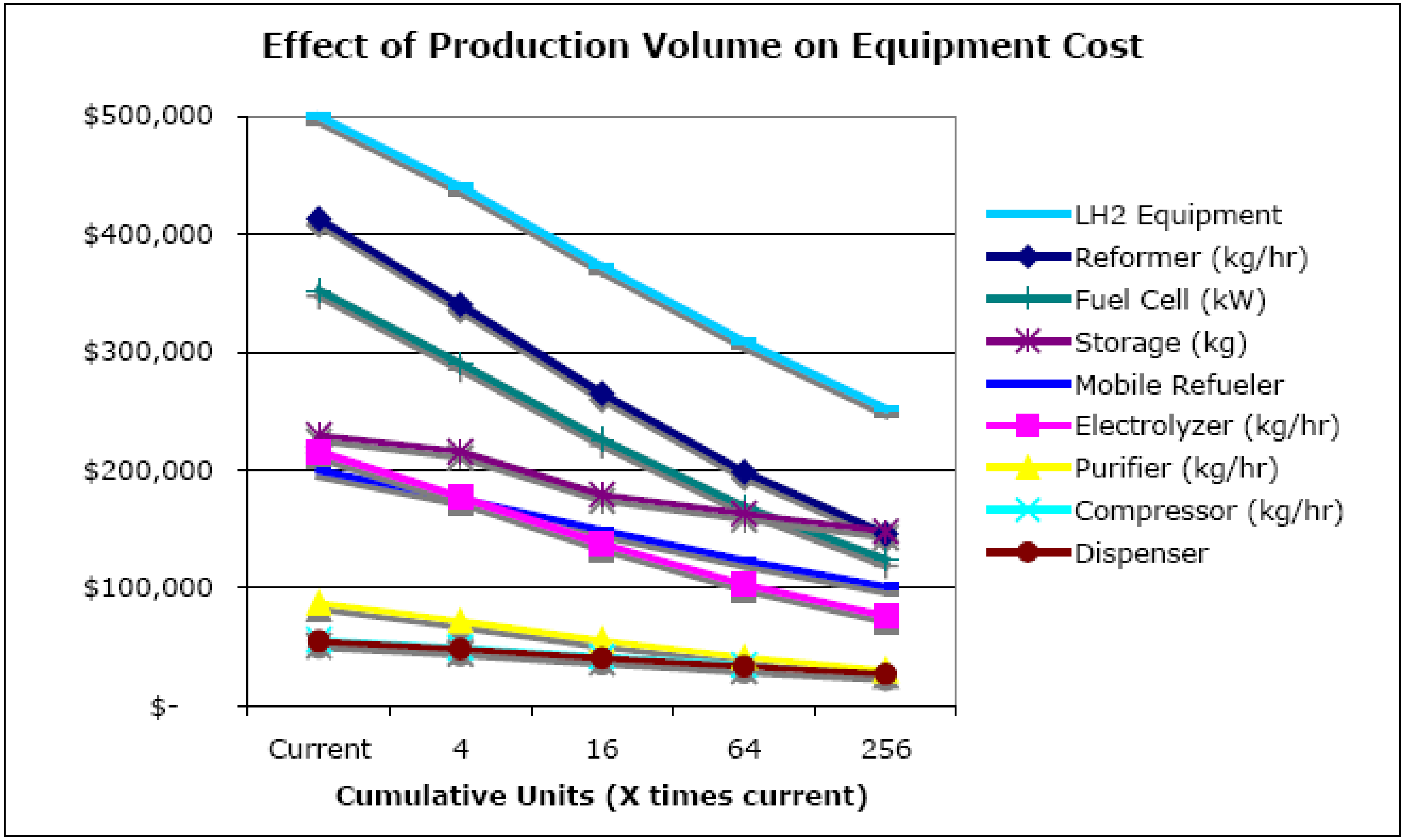
	H2A Equipment Costs (current tech)	UCD study (2009-2014) = $2 million + 2 x H2A current tech equipment costs	UCD Study 2015-2017 = $2 million + H2A current tech equipment costs
Mobile Refueler	-	$1 million	$1 million
Comp. Gas H2 Truck Deliv	100 kg/d $107,000 (equip) + $24,000 (other)	100 kg/d $214,000 (equip) + $2 million (other)	100 kg/d $107,000 (equip) + $2 million (other)
LH2 Truck Delivery	100 kg/d $289,000 (equip) + $65,000 (other) 1500 kg/d $754,000 (equip) + $170,000 (other)	100 kg/d $580,000 (equip) + $2 million (other) 1500 kg/d $1.5 million(equip) + $2 million (other)	100 kg/d $290,000 (equip) + $2 million (other) 1500 kg/d $0.75 million(equip) + $2 million (other)
Onsite Reformer	100 kg/d $143,000 (reformer) + $447,000 (station) + 284,000 (other) 1500 kg/d $957,000 (reformer)+ 3.08 million (station) + $878,000 (other)	100 kg/d $1.18 million (equip) + $2 million (other) 1500 kg/d $8 million(equip) + $2 million (other)	100 kg/d $0.59 million (equip) + $2 million (other) 1500 kg/d $4 million(equip) + $2 million (other)
Onsite Electrolyzer	100 kg/d $165330 (electrolyzer) + $446,829 (station) + 245,333 (other) 1500 kg/d $2479950 (electrolyzer) + $ 2793433 (station) + 449234 (other)	100 kg/d $1.2 million (equip) + $2 million (other) 1500 kg/d $10.6 million(equip) + $2 million (other)	100 kg/d $0.6 million (equip) + $2 million (other) 1500 kg/d $5.3 million(equip) + $2 million (other)

Station O&M Cost Assumptions

	Variable O&M	Fixed O&M
Mobile Refueler	Compressed H2 supply $20/kg H2	100 kg/d: 13 % cap.cost /y + $130,000/y (land rental)
Portable Refueler (Compressed Gas H2 Truck Delivery)	Compressed H2 supply + station H2 compression $20/kg H2 1.25 kWh/kg H2 x electricity price $/kWh	100 kg/d: 13 % cap.cost /y + $130,000/y (land rental)
LH2 Truck Delivery	LH2 supply+ station LH2 pump/compression $10/kg LH2 + 0.81 kWh/kg H2 x electricity price $/kWh	100 kg/d: 11 % cap.cost /y + $130,000/y (land rental) 250-1000 kg/d: 11% cap.cost /y + $360,000/y (land rental)
Onsite Reformer	NG feed + station H2 compression 0.156 MBTU NG/kg H2 x NG price $/MBTU + 3.08 kWh/kg H2 x elec price $/kWh	100 kg/d: 10 % cap.cost /y + $130,000/y (land rental) 250-1000 kg/d: 7% cap.cost /y + $360,000/y (land rental)
Onsite Electrolyzer	**Electrolyzer electricity + station H2 compression:** 55.2 kWh/kg H2 x elec price $/kWh	Same as onsite reformer

Variable O&M from Weinert et. al. 2006tech Performance (Reformer NG consumption 0.154 MBTU NG/kg H2 => Reformer conversion efficiency ~ 73% LHV basis);
Fixed O&M from H2A Current Tech assumptions nsurance= 1% capital cost; property tax = 1%

EFFECT OF PRODUCTION VOLUME ON EQUIPMENT COST (Weinert)



If station equipment production volume is increased from current levels by factor of 10-100, equipment capital costs are reduced by 20-50%.

ASSUMED PROGRESS RATIOS IN SLIDE 19 (Weinert)

Table 3-6: Progress Ratios for Equipment

Cluster	Equipment	Progress ratio[30]
1. Nascent technology, "one-of" production volume levels	Reformers, electrolyzers, purifiers, fuel cells	0.85
2. Mature equipment, predominantly used for H2 stations	Compressor, dispenser, mobile refueler, non-capital station construction costs	0.90
3. Mature equipment, high Prod Vol levels	Storage	0.95

Station Design Technical considerations

- **Storage pressure is a key factor**
  - Station Equipment costs and op. costs will be higher at 700 bar vs. 350 bar
  - Existing mobile refueler technology works at 350 bar, but not yet developed for 700 bar.
  - Most OEMs are emphasizing 700 bar, but final pressure is still not decided.
- **H2 Station Storage capacity**
  - H2A v1.1, TIAX and Weinert's studies assumed storage = 35% of daily H2 production capacity. This may be too low for reliability reasons.
  - H2A version 2.0 increased storage to 58% of daily production capacity
  - Recommended 1-2 days storage from energy company interviews (#days of H2 production from onsite SMR)

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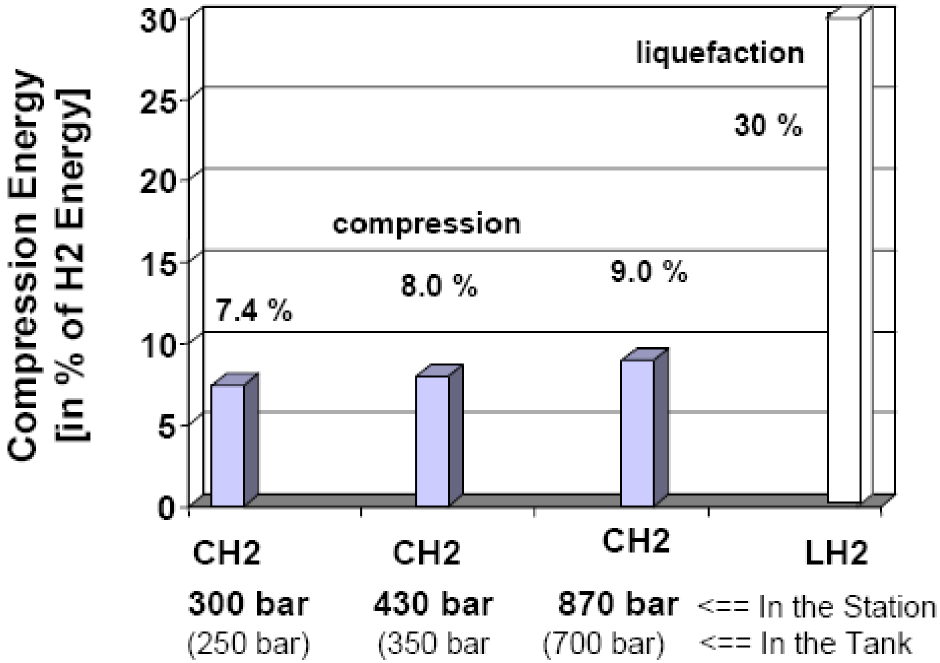
What are added costs for 700 bar station vs. 350 bar?

- These are not as well known as for 350 bar, as fewer 700 bar stations exist.
- Pre-Cooling system can add $500/kg/d of capacity
  - May cost more to pre-cool to less than -40 C.
- Higher compression needed (higher cost compressor and more electricity consumed)
- Higher cost storage vessels (H2A v.2.0 says the storage vessel capital cost in $/kg is similar)

Our base case station is 350 bar. To roughly model 700 bar we add $500/(kg/d) to the capital cost and assume compression electricity use is 22% higher

Compression Energy for H2



Basis:

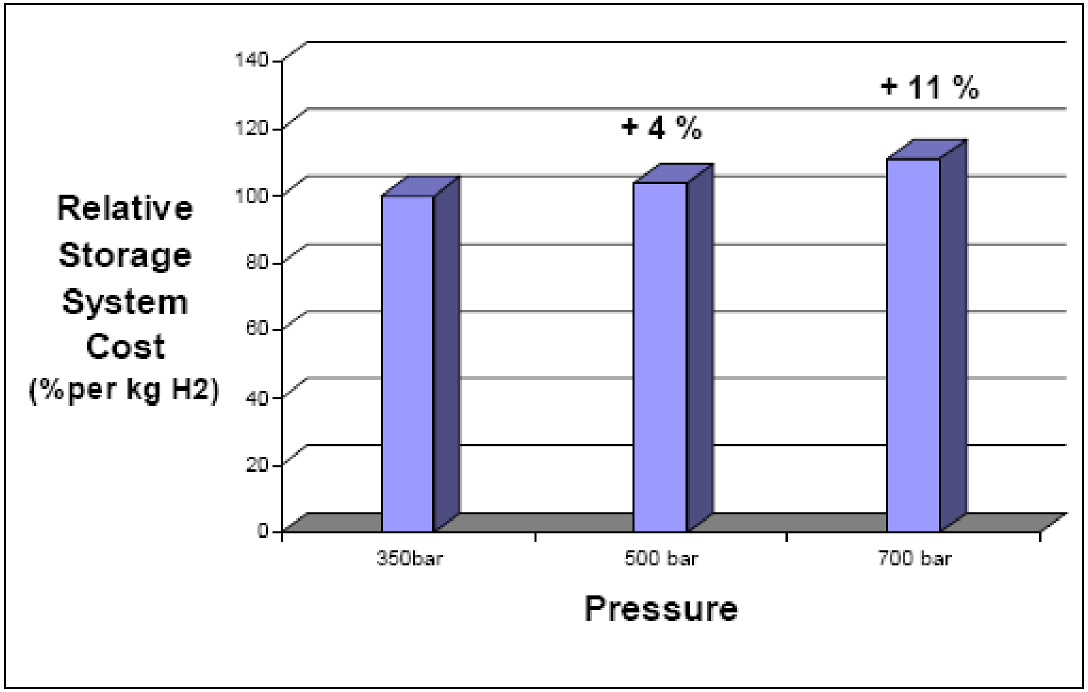
- Calculation based on „Dubbel"
- Compression energy is proportional to ln(P1/P2)
- 4-stage compressor
- Initial pressure 2 bar

Source: Friedlmeier, Daimler

Compression electricity use increased by 22% at 700 bar

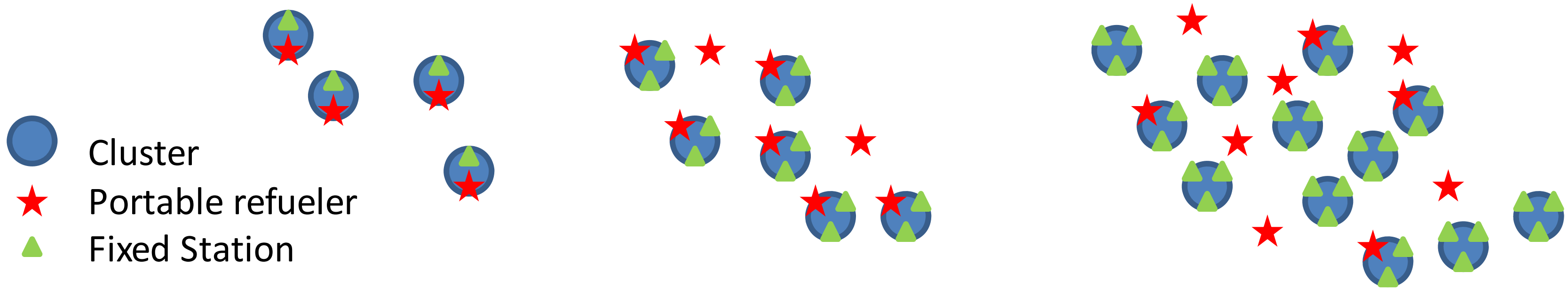
Dr. Zieger, Juno 2008 StorHy Final

Relative Vessel Cost vs Storage Pressure



Basis:	Vessel cost are 60% of system cost	
	Vessel Fibre Percentage	50%
	Vessel Outer Diameter:	325 mm
	Liner Wall Thickness:	4 mm
	Vessel Length:	1000 mm

	2009-2011	2012-2014	2015-2017



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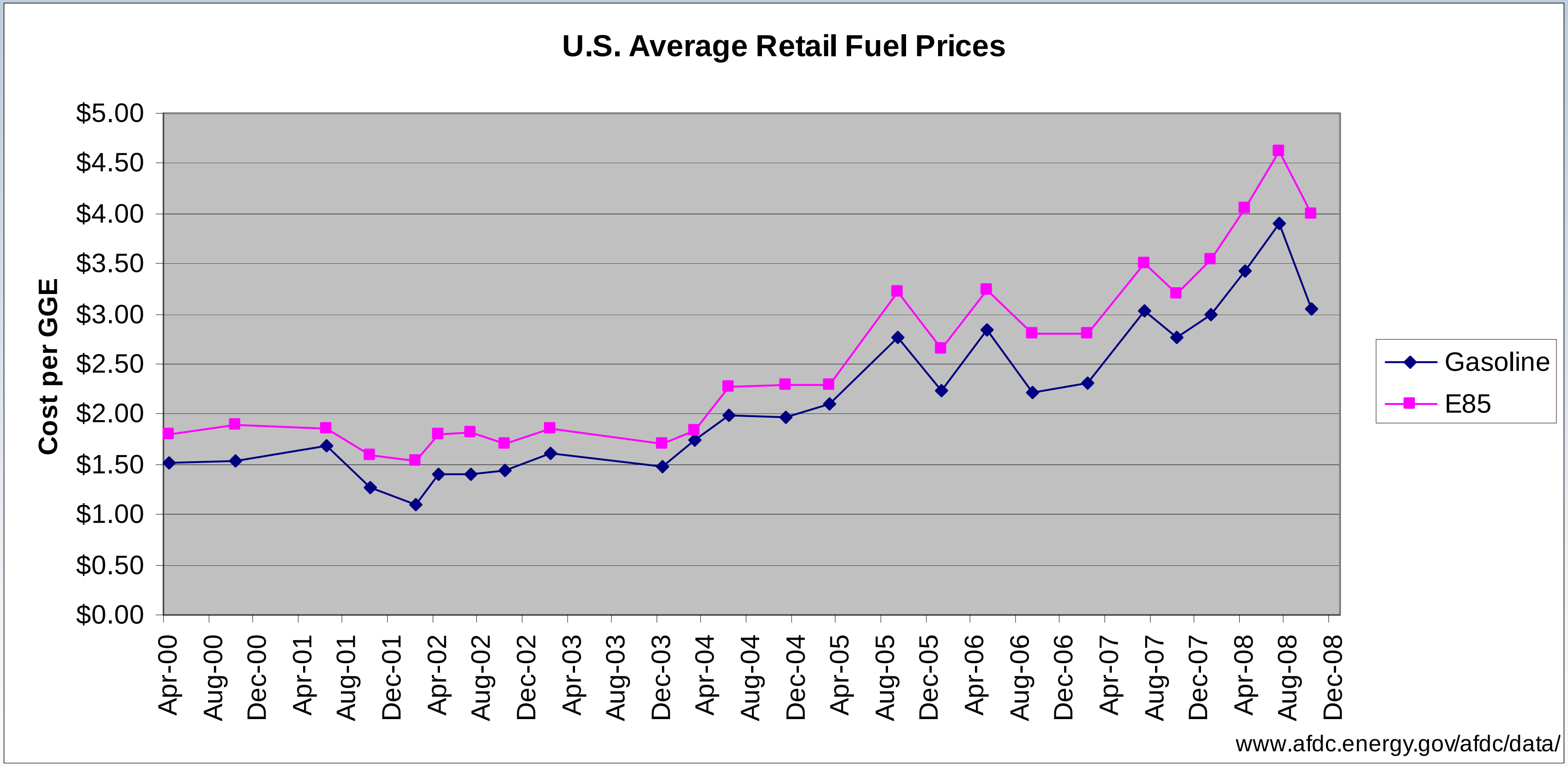
New Equip. Added	4 Portable refuelers 4 SMRs (100 kg/d)	4 Portable Refuelers 12 SMRS (250 kg/d)	2 Portable refuelers 20 SMRs (1000 kg/d)
Capital Cost	$20Million	$52 Million	$98 Million
O&M Cost	3-5$Million/y	11-14 $Million/y	30-40 $Million/y
H2 cost $/kg	77	37	13
Ave travel time	3.9 minutes	2.9 minutes	2.6 minutes
Diversion time	5.6 minutes	4.5 minutes	3.6 minutes

US average E85 prices from 2000 to 2008



Source: http://www.afdc.energy.gov/afdc/data/fuels.html

Biomethane Prices in California (1)

Costs of Digestion and Upgrade to Biomethane			Current Natural Gas Prices	
	Cost ($ per 1,000 ft[3]) biomethane			Price
Cost Category	Low Est.	High Est.	Price Category	($ per 1,000 ft[3])
Production cost	$8.44	$11.54	Wellhead	$6.05
Storage	$0.00	$2.80	City gate	$7.44
Transportation	$0.00	$0.90	Distribution	$9.84

Biomethane Delivered Cost to Station:

$ 8.4-15.2/1000 scf

~ $8.4-15.2/MMBTU

Biomethane from Dairy Waste

A Sourcebook for the Production and Use of Renewable Natural Gas in California

Prepared for Western United Dairymen
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Biomethane Prices in California (2)

Enhanced Environmental Quality Pipeline-Quality Gas without Grant

Enhanced Environmental Quality Pipeline-Quality Gas COE and Components (nominal levelized 2007$)

Dairy Name	EEQ Gas COE, with 17% IRR ($/therm)	After-tax O&M Component[1] ($/therm)	Capital Component ($/therm)
Hilarides covered lagoon	2.096	0.083	2.013
Eden-Vale plug-flow	2.927	0.207	2.720
Koetsier plug-flow	3.011	0.178	2.834
Meadowbrook plug-flow	3.354	0.134	3.220
IEUA modified mix plug-flow	4.025	1.164	2.861
Van Ommering plug-flow	4.172	0.287	3.885
Castelanelli Bros. (~5 mile pipeline) covered lagoon	4.683	0.137	4.546
Cottonwood covered lagoon	5.819	0.537	5.282
Blakes Landing (~12 mile pipeline) covered lagoon	35.128	0.584	34.544

Biomethane Cost at Pipeline inlet:
$ 2.1-4.2/therm ~ $20-42/MMBTU

pier

Cost of Electricity & Pipeline Quality Natural Gas from Biogas

Zhiqin Zhang and Gerry Braun
California Energy Commission
Public Interest Energy Research (PIER) Program

Prepared for 24th Annual BioCycle West Coast Conference 2008
April 14 - 16, 2008 • San Diego, CA

Green Electricity Price Premiums in CA 1-5 cents/kWh

State-Specific Utility Green Pricing Programs (last updated May 2008)					
State	**Utility Name**	**Program Name**	**Type**	**Start Date**	**Premium**
CA	Anaheim Public Utilities	Sun Power for the Schools	PV	2002	Contribution
CA	Anaheim Public Utilities	Green Power for the Grid	wind, landfill gas	2002	1.5¢/kWh
CA	Burbank Water and Power	Green Energy Champion	various	2007	2.0¢/kWh
CA	Los Angeles Department of Water and Power	Green Power for a Green LA	wind, landfill gas	1999	3.0¢/kWh
CA	PacifiCorp: Pacific Power	Blue Sky Block	wind	2000	1.95¢/kWh
CA	Palo Alto Utilities / 3Degrees	Palo Alto Green	wind, PV	2003 / 2000	1.5¢/kWh
CA	Pasadena Water & Power	Green Power	wind	2003	2.5¢/kWh
CA	Roseville Electric / 3Degrees	Green Roseville	wind, PV	2005	1.5¢/kWh
CA	Sacramento Municipal Utility District	SolarShares	PV	2007	5.0¢kWh or $30/month
CA	Sacramento Municipal Utility District	Greenergy	wind, landfill gas, hydro, PV	1997	1.0¢/kWh or $6/month
CA	Silicon Valley Power / 3Degrees	Santa Clara Green Power	wind, PV	2004	1.5¢/kWh
CA	Truckee Donner PUD	Voluntary Renewable Energy Certificates Program	wind	2008	2.0¢/kWh

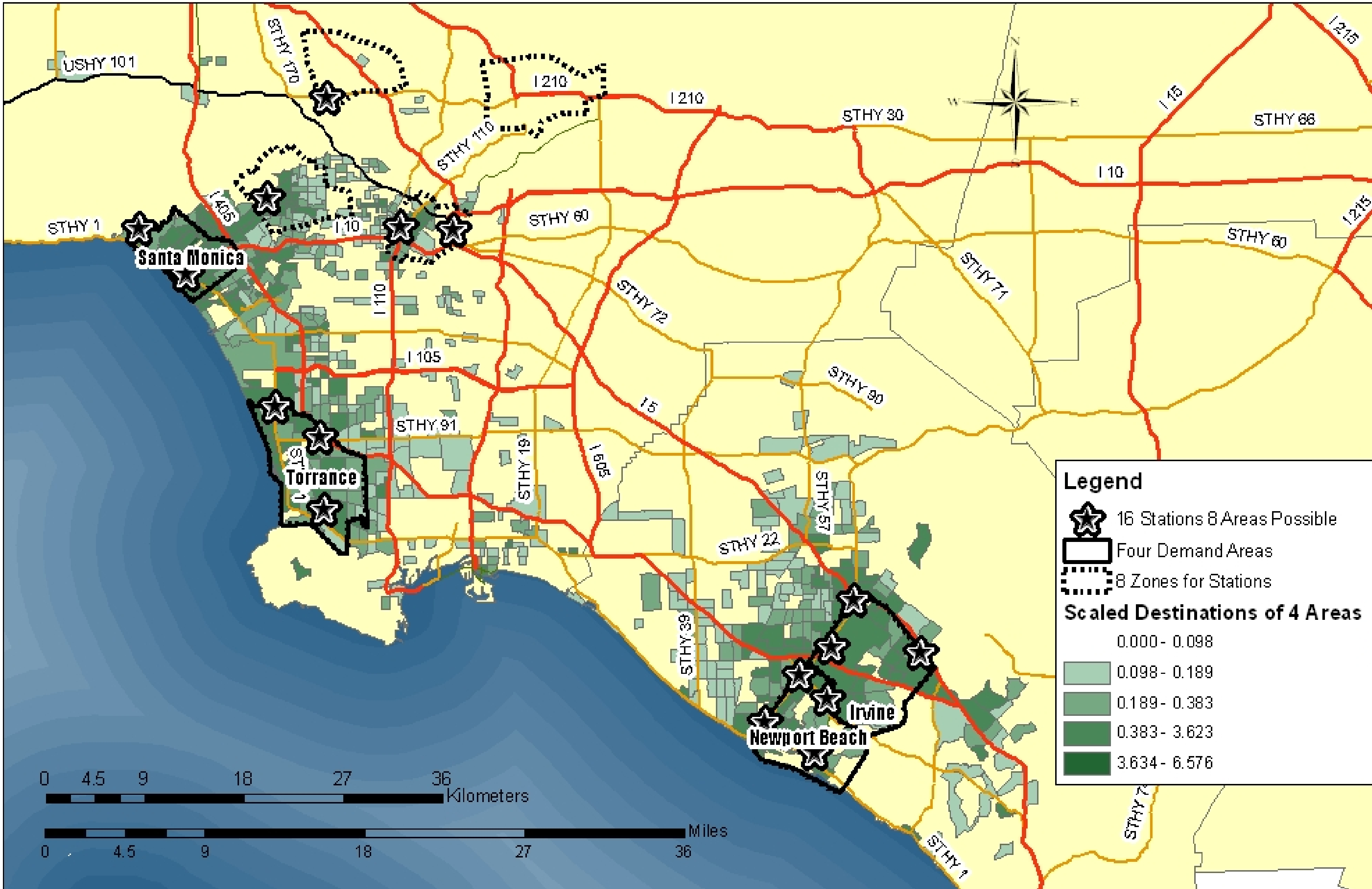
Source: National Renewable Energy Laboratory, Golden, Colorado.
Notes: Utility green pricing programs may only be available to customers located in the utility's service territory. For additional details, please see the full green pricing
products

Green Electricity Prices

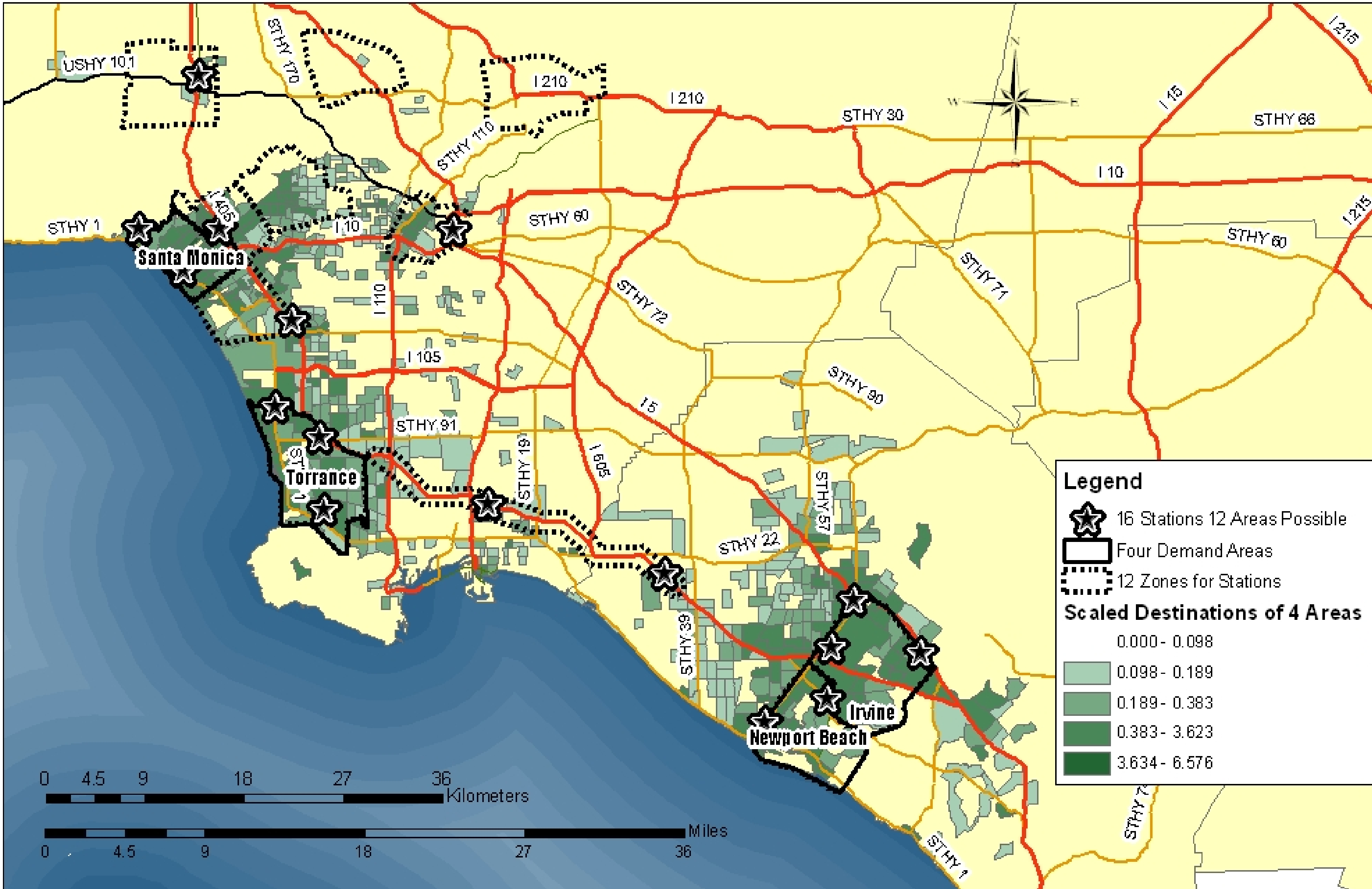
Via Solar PV for electrolysis

- $5/peak Watt (PV array plus power conditioning)
- 220 Watts/m2 annual ave. insolation (~22% capacity factor assuming peak insolation of 1000 W/m2)
- Cost of electricity $/kWh (15% capital recovery factor)
- = 15% x $5,000/kWp/(0.22 kW/kWp x 8760 h/y) ~ $0.39/kWh

Destinations of 4 Clusters: 16 Stations in 8 Areas



Destinations of 4 Clusters: 16 Stations in 12 Areas



Destinations of 4 Clusters: 16 Stations Regionwide