Making the Transition to Light-duty Electric-drive Vehicles in the U.S.

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National Academies' Committee on the Assessment of Technologies For Improving Fuel Economy of Light-Duty Vehicles

University of California, Davis

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Electric Drive Offers High Efficiency, Zero Emissions

LARGE SCALE SUCCESS FOR ZEVS => THREE COUPLED TRANSITIONS

- New Types of Vehicles
  - BEVs
  - PHEVs
  - H2 Fuel Cell EVs
- New Infrastructure
  - Adapt Existing Infrastructure
  - Build New Fueling Infrastructures (H2, CCS)
  - Link Transportation with Evolving Electric Grid
- Shift to zero net carbon supply pathways

NEXT 15-20 YEARS CRITICAL TO LAUNCH AND GROW MARKETS

Unprecedented Rate of Change Ahead?

Meeting 2050 goals to reduce GHG emissions requires rapid transformation of energy system beginning now.

Some analysts suggest a "Manhattan Project" to switch to a particular near-zero net carbon energy system ASAP. Others counsel resisting pressure to go big too early

> *"Energy history cautions against bold moves that might be feasible in cost insensitive sectors such as military and space, but not in a sector where new technologies need to find many customers and applications and which requires a decades-long process of experimentation, debugging and learning before scaling up should be attempted. "*

Finding a reasonable path?

Transition insights and EDV transition

- Future transportation sector likely won't be a "monoculture"
- Stakeholder coordination required to handle coupled, multiple transitions.
- Potentials for new technology hinge on corresponding institutional and organizational changes. Including financing the transition
- End use innovation is major driver of energy transitions
  - Sometimes new energy end-use technologies get adopted for reasons not emergent from traditional economic analysis.
  - Consumers can be where the transition starts
- Cost to launch ZEV LDV technologies

  << $ flows in the transportation energy system,

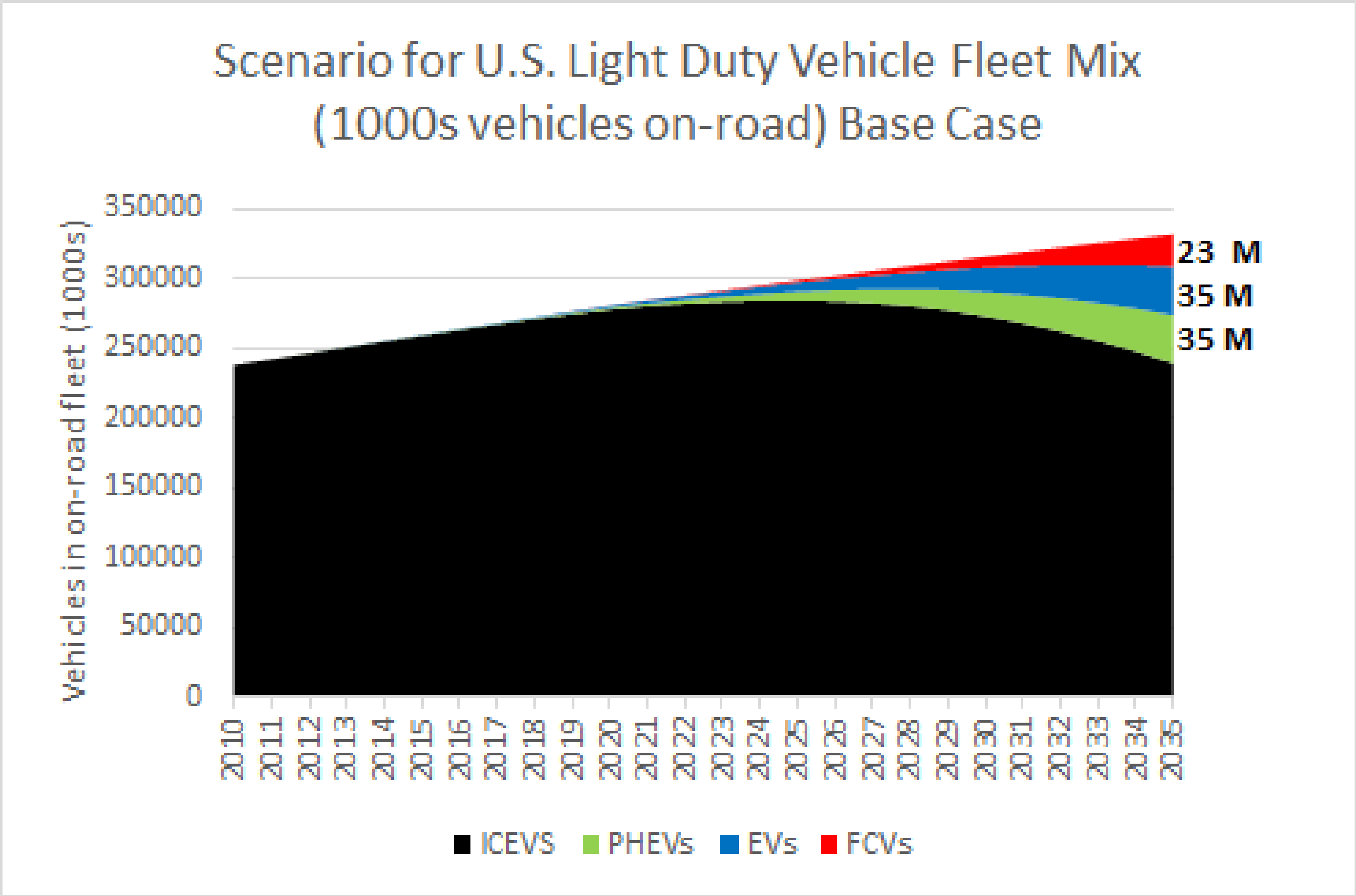
  >> than typical RD&D costs.
- Imperative of climate change => need to support multiple high value "networked demos" now, even given uncertainty and risk

TRANSITION COSTS FOR ELECTRIC DRIVE?

- Analyze a range of national US transition scenarios to find required investments in vehicles and fuels
  - to reach breakeven “competitiveness” with incumbents
  - to fully build out fuel infrastructure
- Compare these costs with expenditures that are routinely made by Americans every year for new cars and fuels.

GOAL: Provide sense of transitional costs that society (and/or stakeholders within society) might have to pay to achieve a major role for light duty electric-drive vehicles by 2035.

*Publication: Ogden, Joan M., Lewis Fulton, Daniel Sperling (2016) Making the Transition to Light-duty Electric-drive Vehicles in the U.S.: Costs in Perspective to 2035. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-16-21



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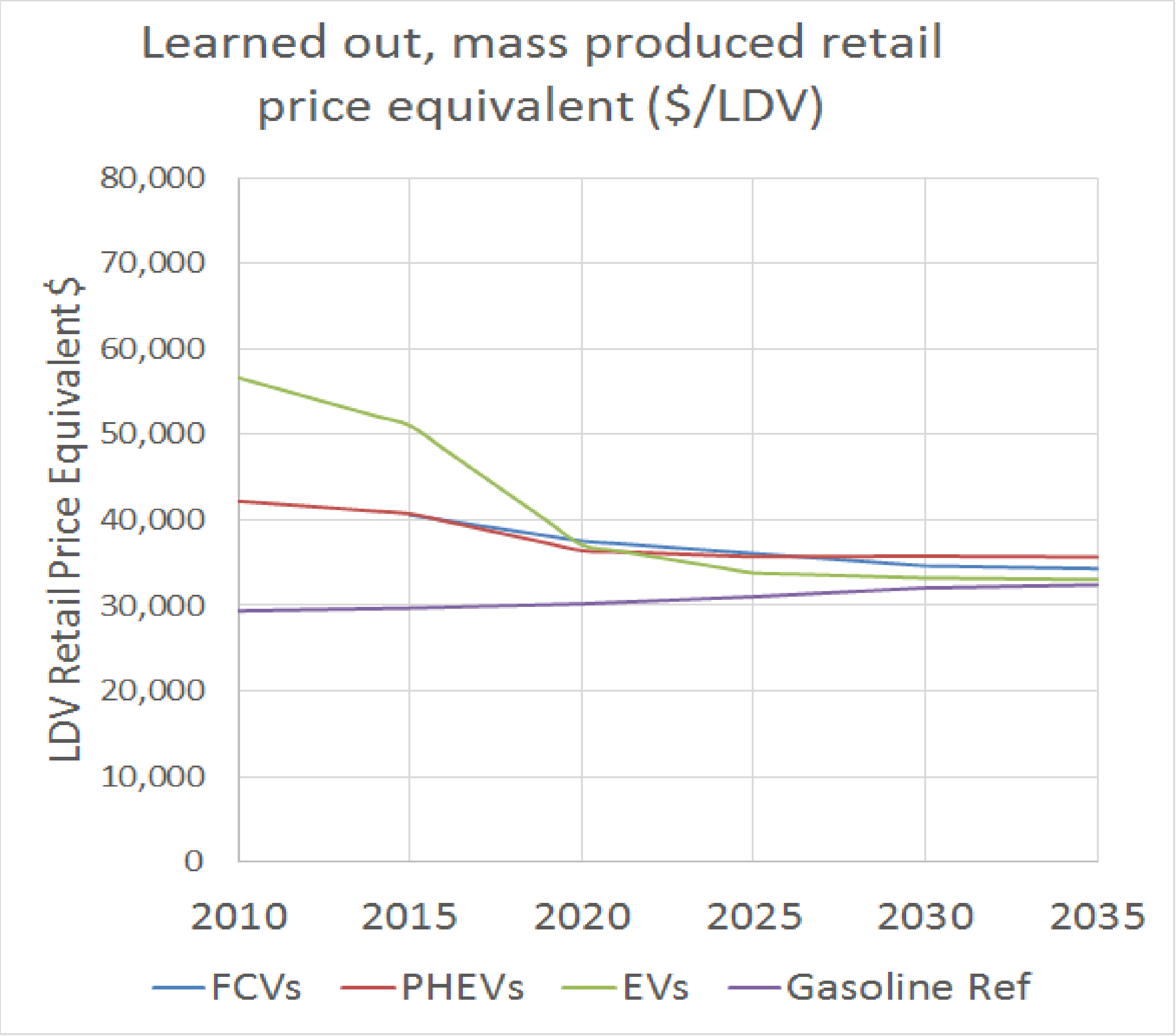
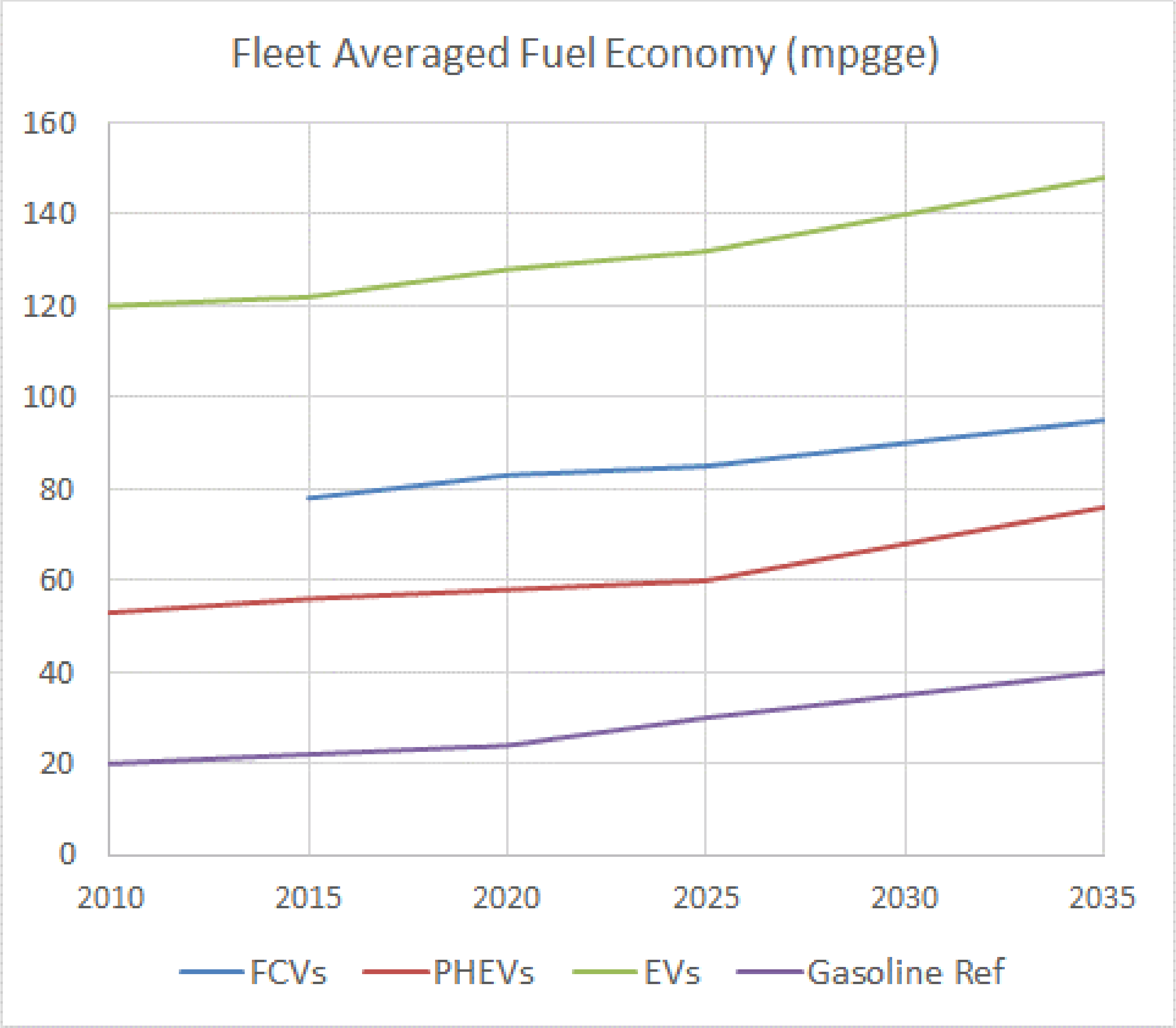


Based on NRC 2013 vehicle costs



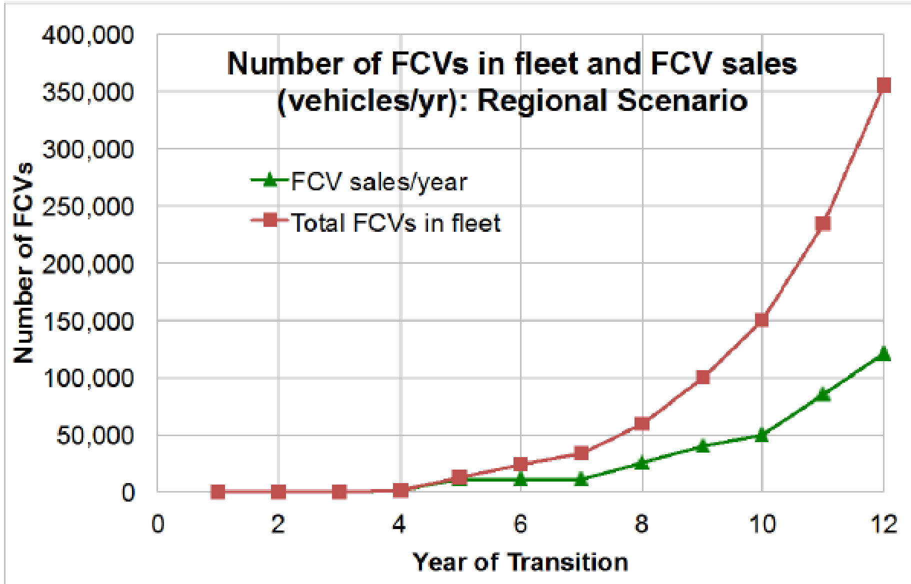
Adapted from NRC 2013 “Transition” report “Efficiency” Case, Figure 5.16

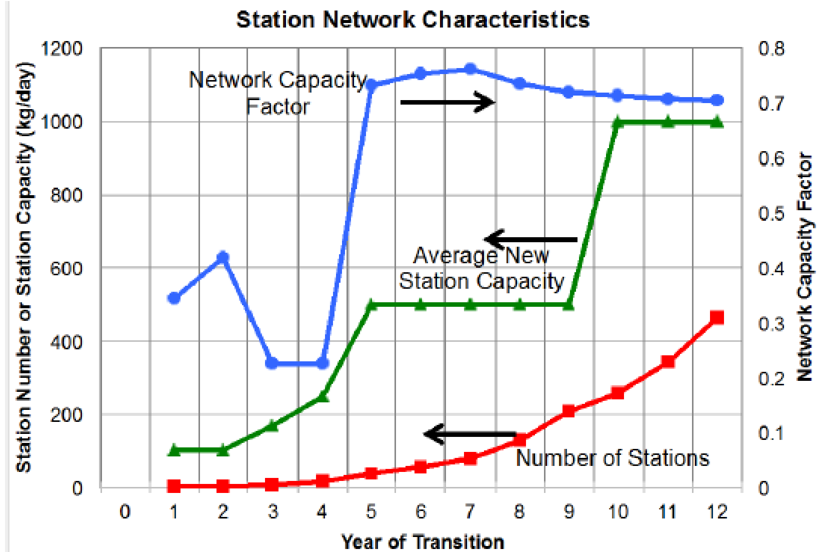
Infrastructure Assumptions
Plug-in Vehicles (PEVs) & H2 Fuel Cell Vehicles (FCVs)

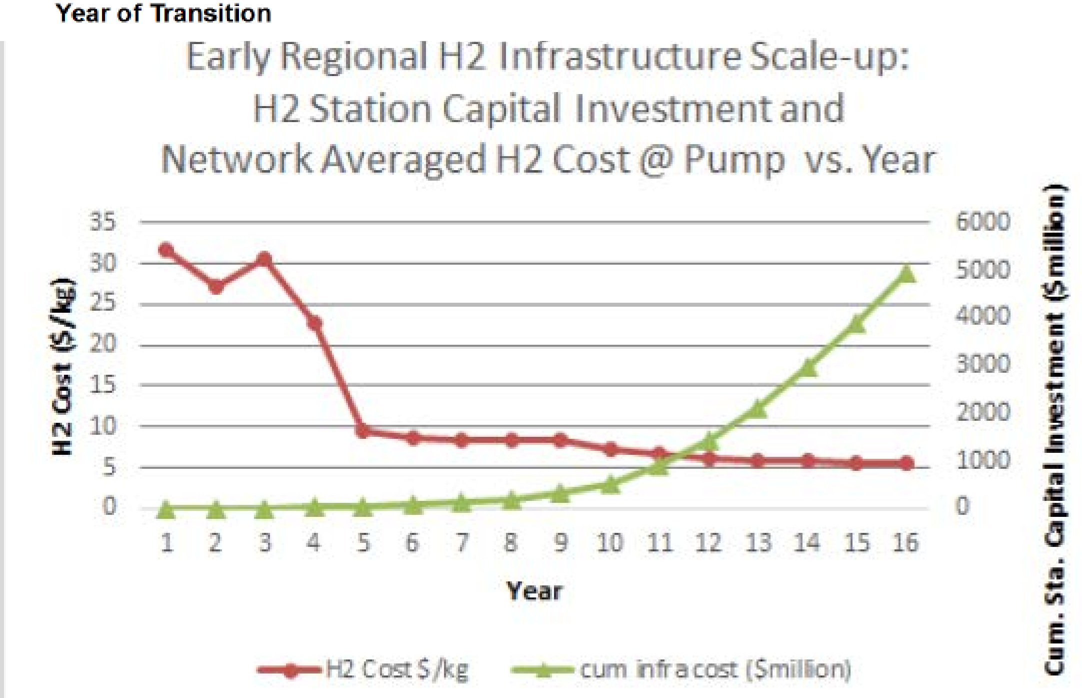
- Home chargers cost $ 2500->1600. 1 per PEV
- Public chargers cost $20,000. 1 per 100 PEVs
- H2 stations are built as FCVs are rolled out in a series of “Lighthouse cities” between 2015 and 2035, starting with California. Stations use truck delivery and onsite production, network designed using regional “cluster strategy”.
- Gasoline costs based on EIA Annual Energy Outlook ref case

REGIONAL H2 INFRASTRUCTURE ROLLOUT:

H2 COSTS BECOME COMPETITIVE W/BETTER STATION UTILIZATION, LARGER STATION SIZE







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ANALYZE US NATIONAL H2 FCV ROLLOUT SCENARIO AS A SERIES OF REGIONAL ROLLOUTS

- Introduce H2 in Series of 60 Lighthouse Cities by 2035

  5 cities 2016-2020

  +5 cities 2021-2025

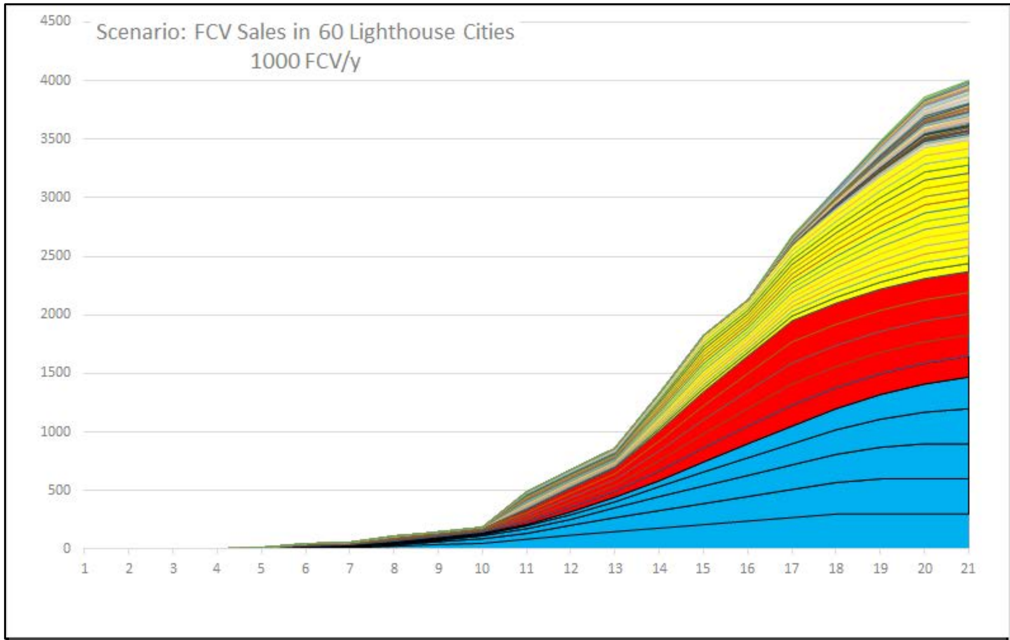
  +16 cities 2026-2030

  +34 cities 2031-2035

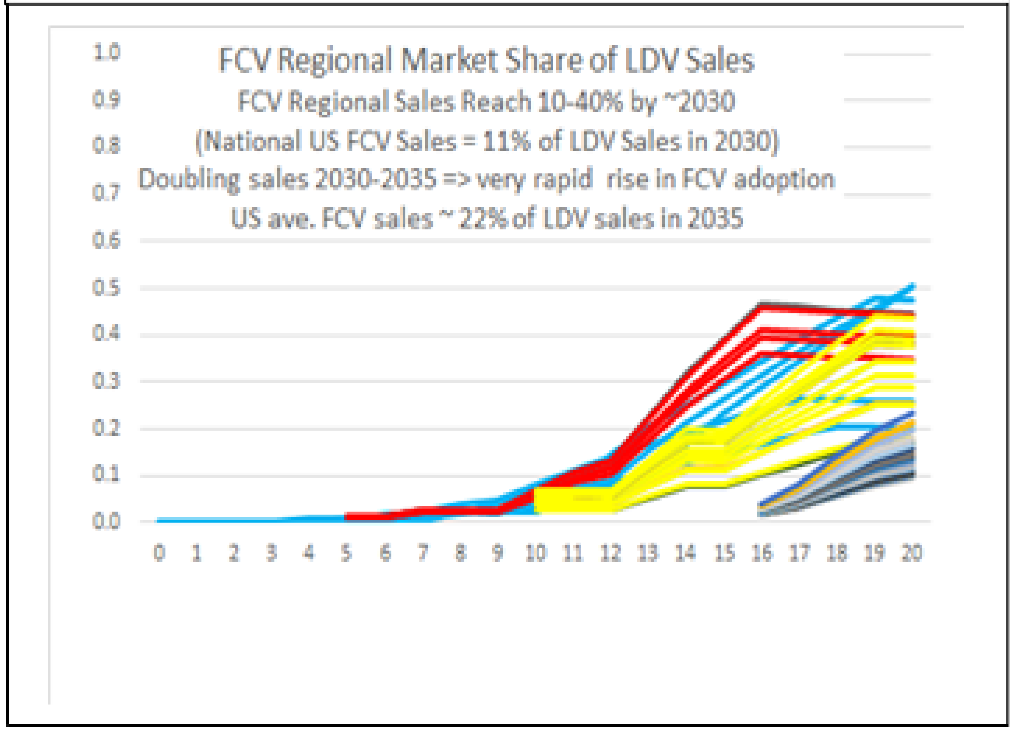
- Scenario for number of FCVs in each city => H2 Demand
- Design H2 Network in Each City Based on Cluster strategy: Stations with Truck Delivery, Onsite Production
- Find station investment ($), H2 cost ($/kg) vs. time
- Aggregate to Get National Numbers

SALES IN LIGHTHOUSE CITIES

#FCV Sales/Year

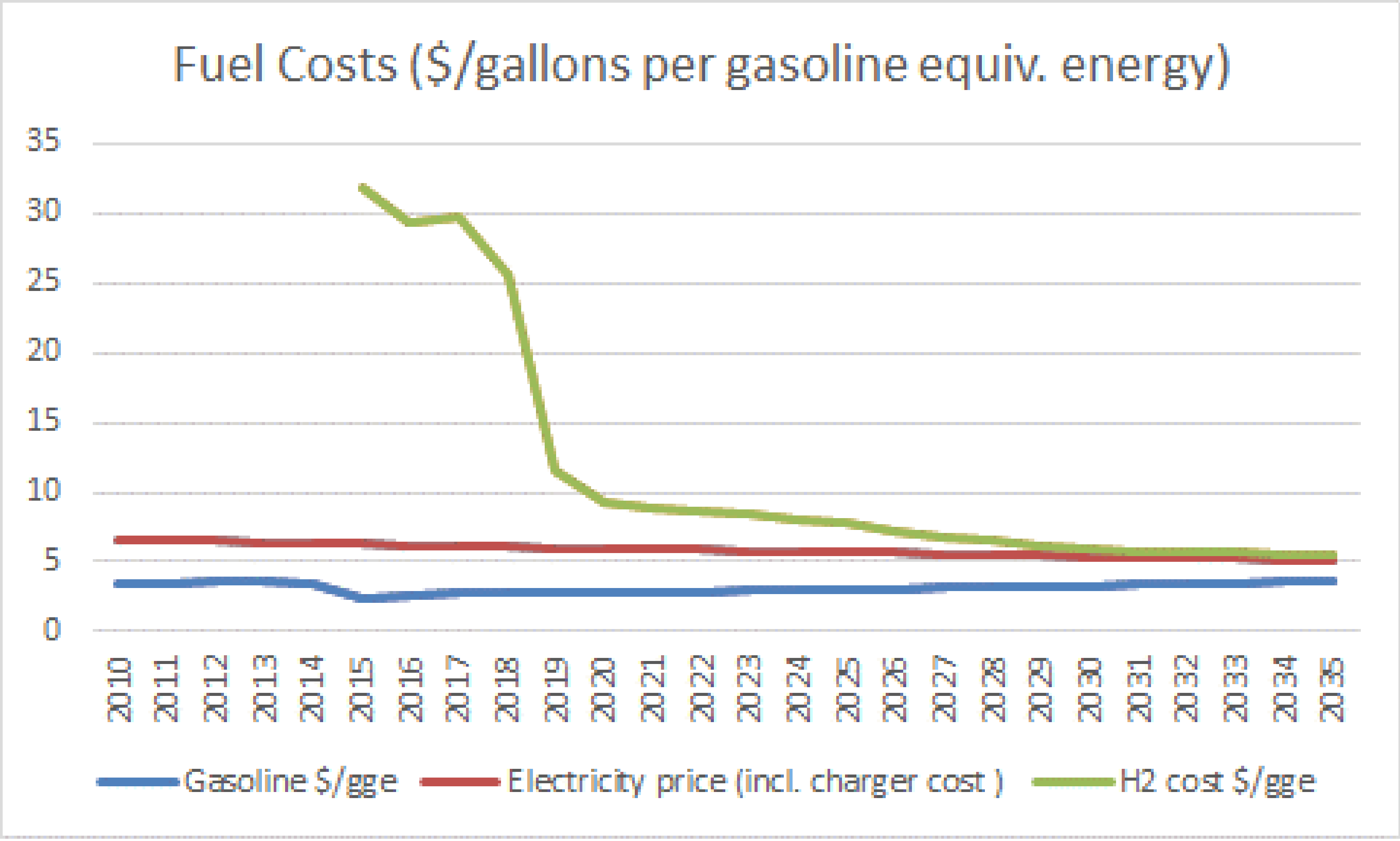


FCV Sales Fraction in Each Regional Market



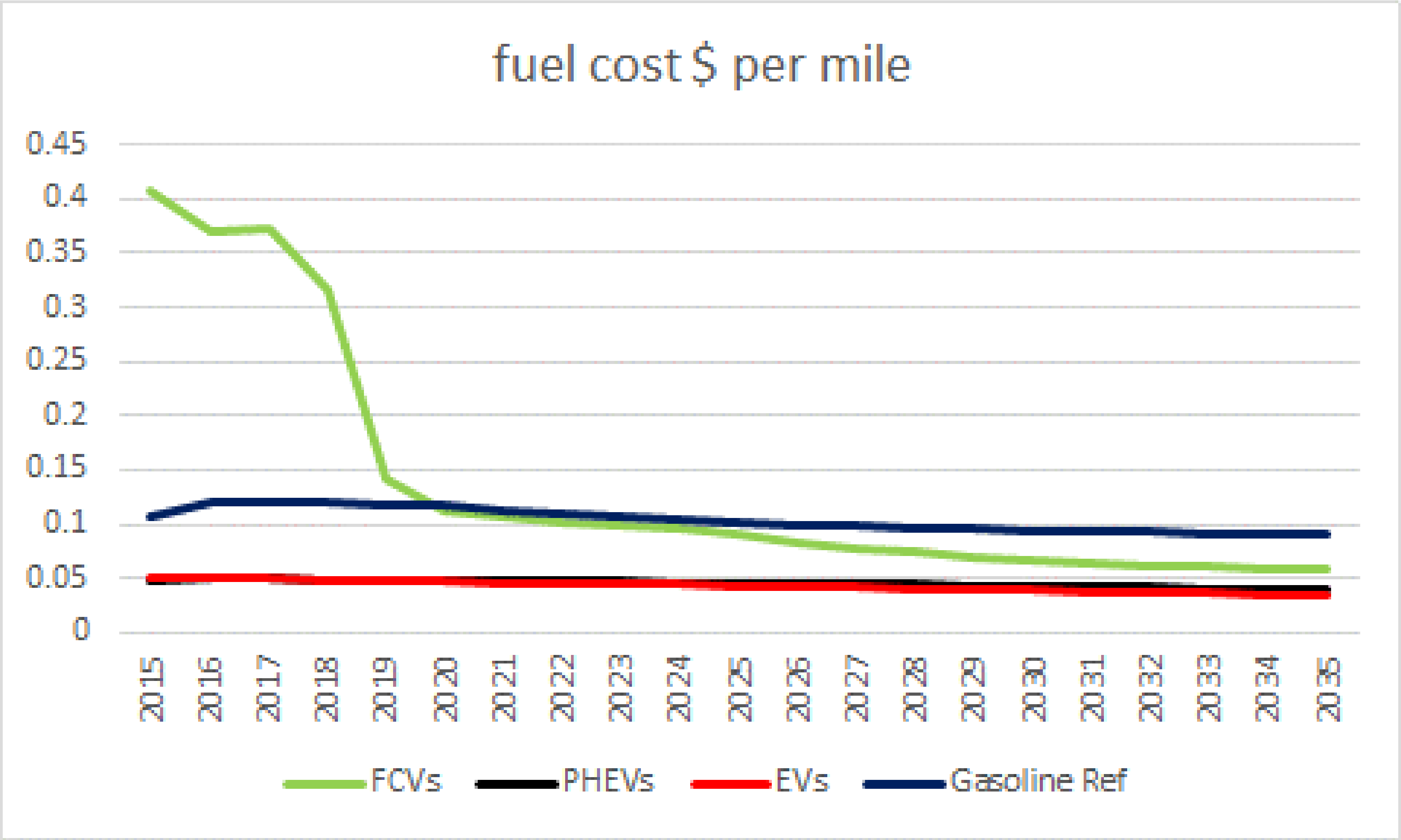
2035 FCV LDV Market Shares
US 22%; Regional 10-40%

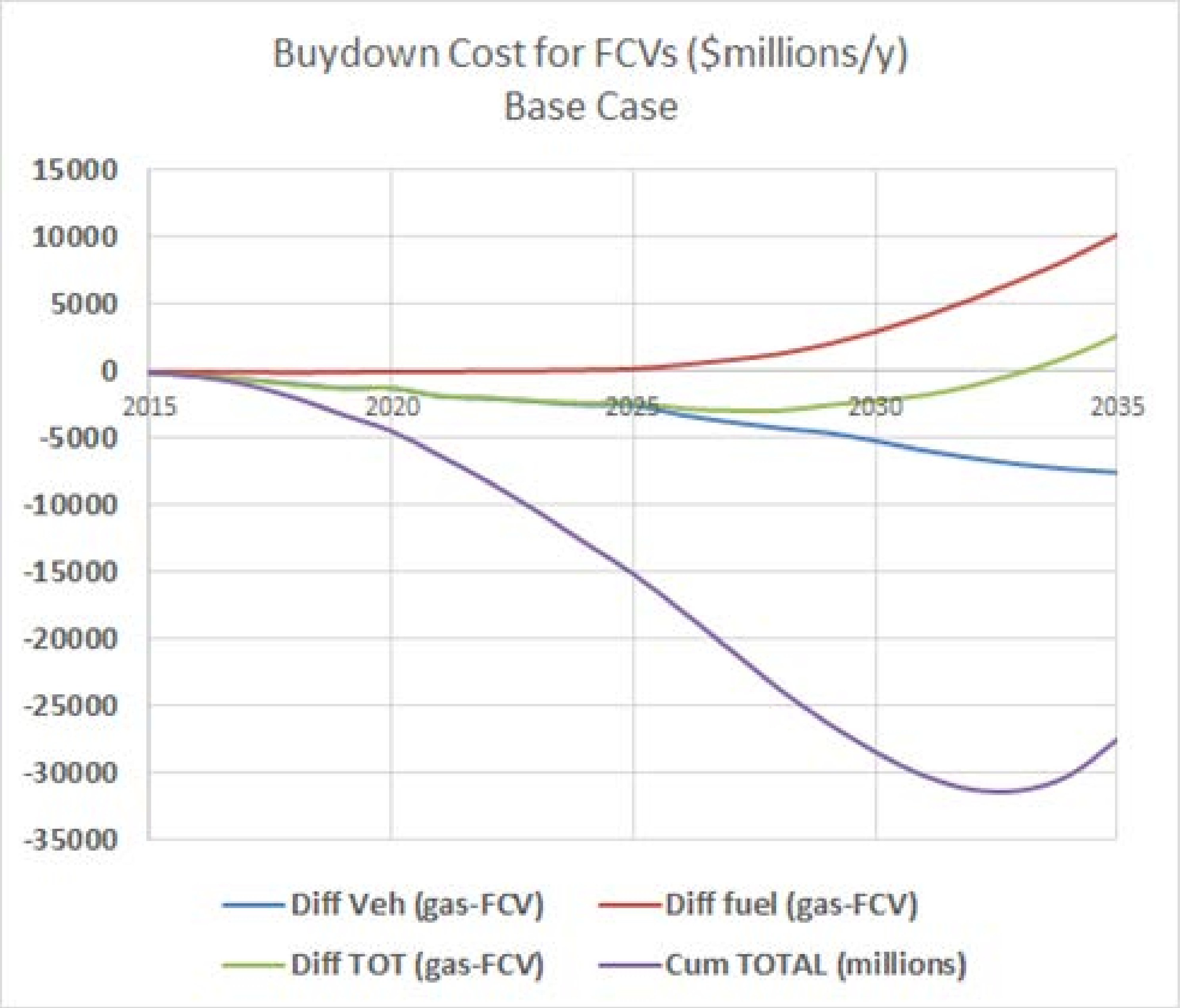
Estimated Fuel Cost ($/gallon gasoline equivalent)

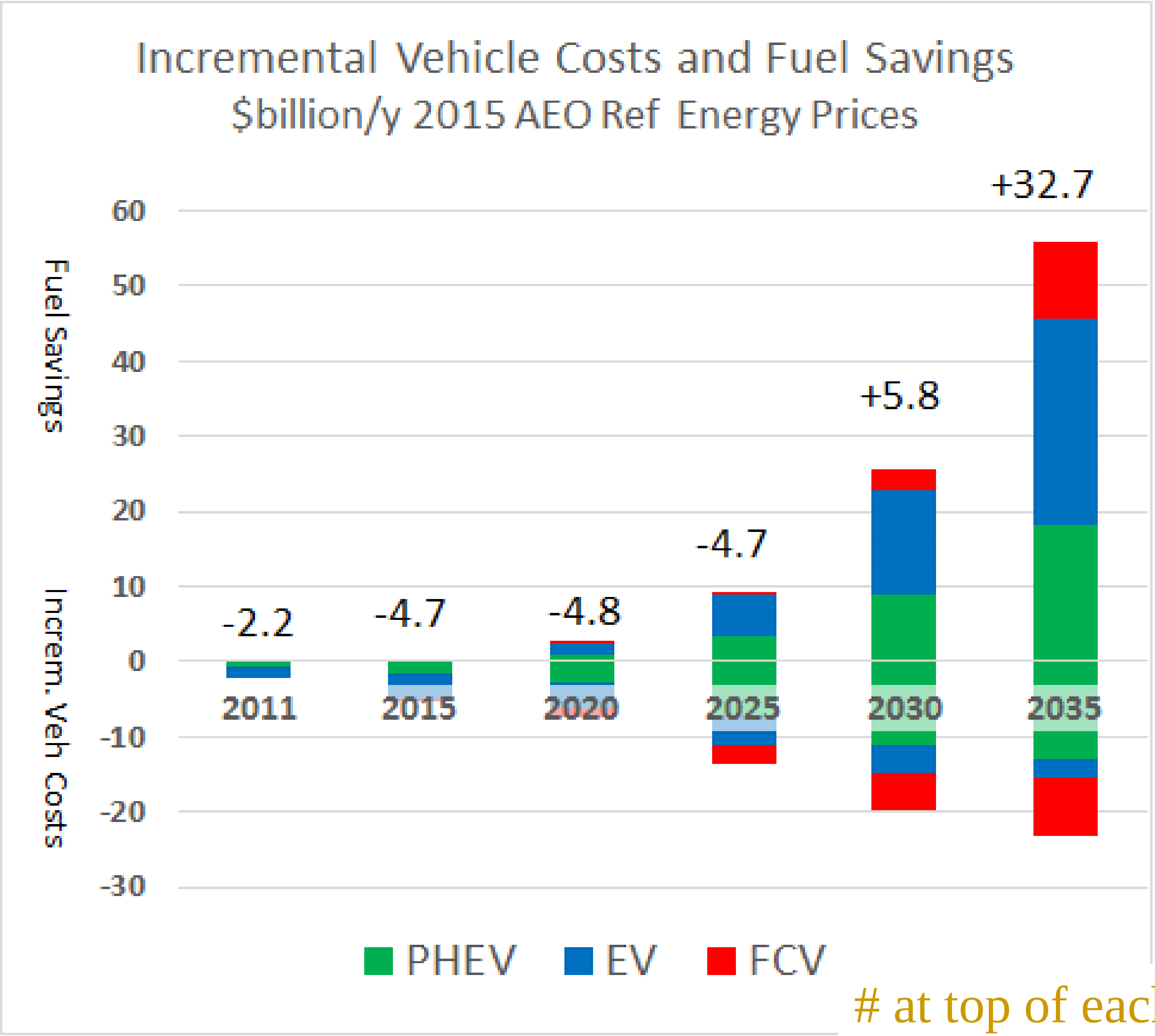


Estimated "Fuel Cost Breakeven" ($/mile)

Plug-in EVs.< gasoline ICEV throughout
FCV (H2 US ave.) < gasoline ICEV after ~2024

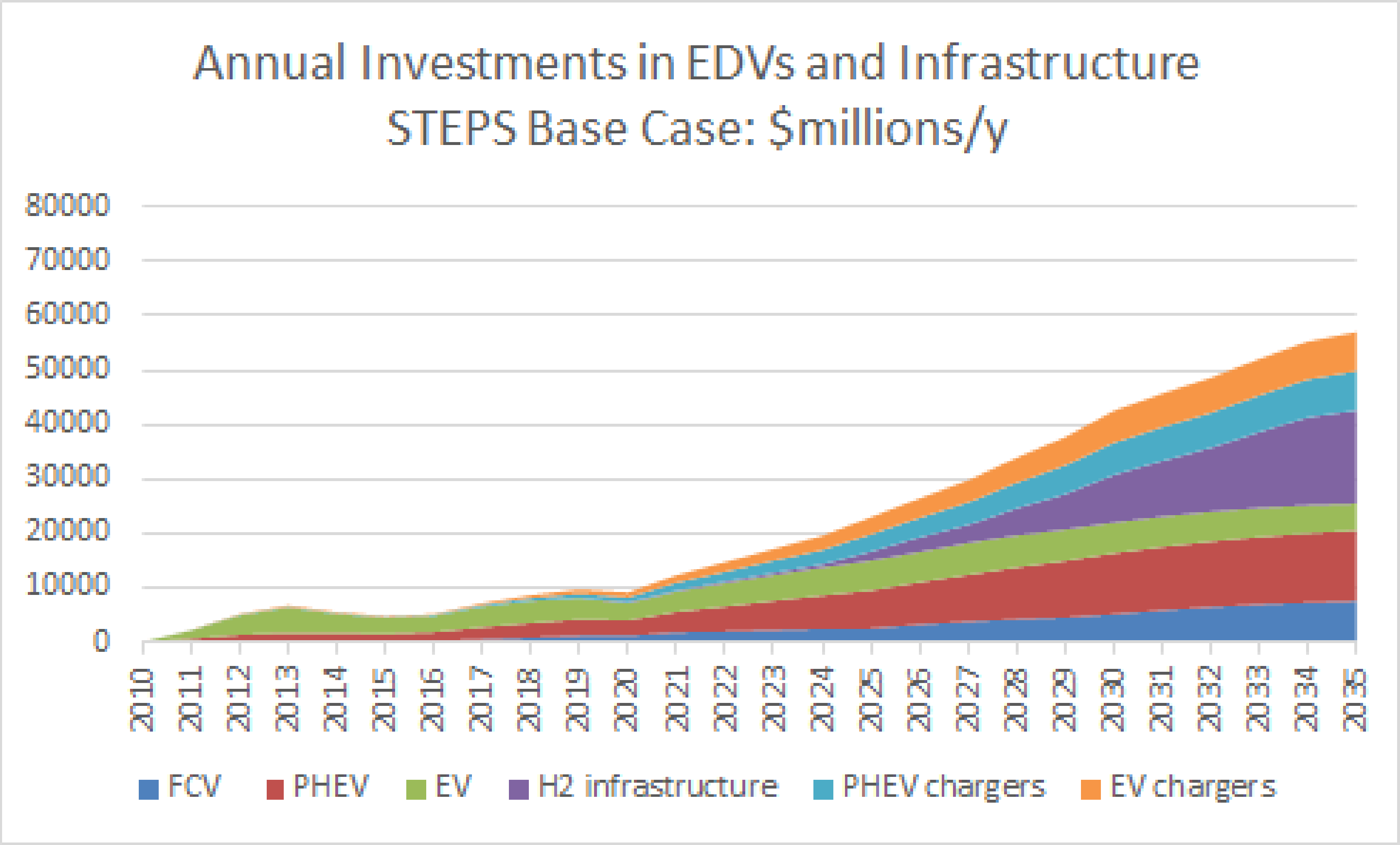



Buydown Cost for FCVs ($millions/y)
Base Case
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
2015
2020
2025
2030
2035
Diff Veh (gas-FCV)
Diff fuel (gas-FCV)
Diff TOT (gas-FCV)
Cum TOTAL (millions)

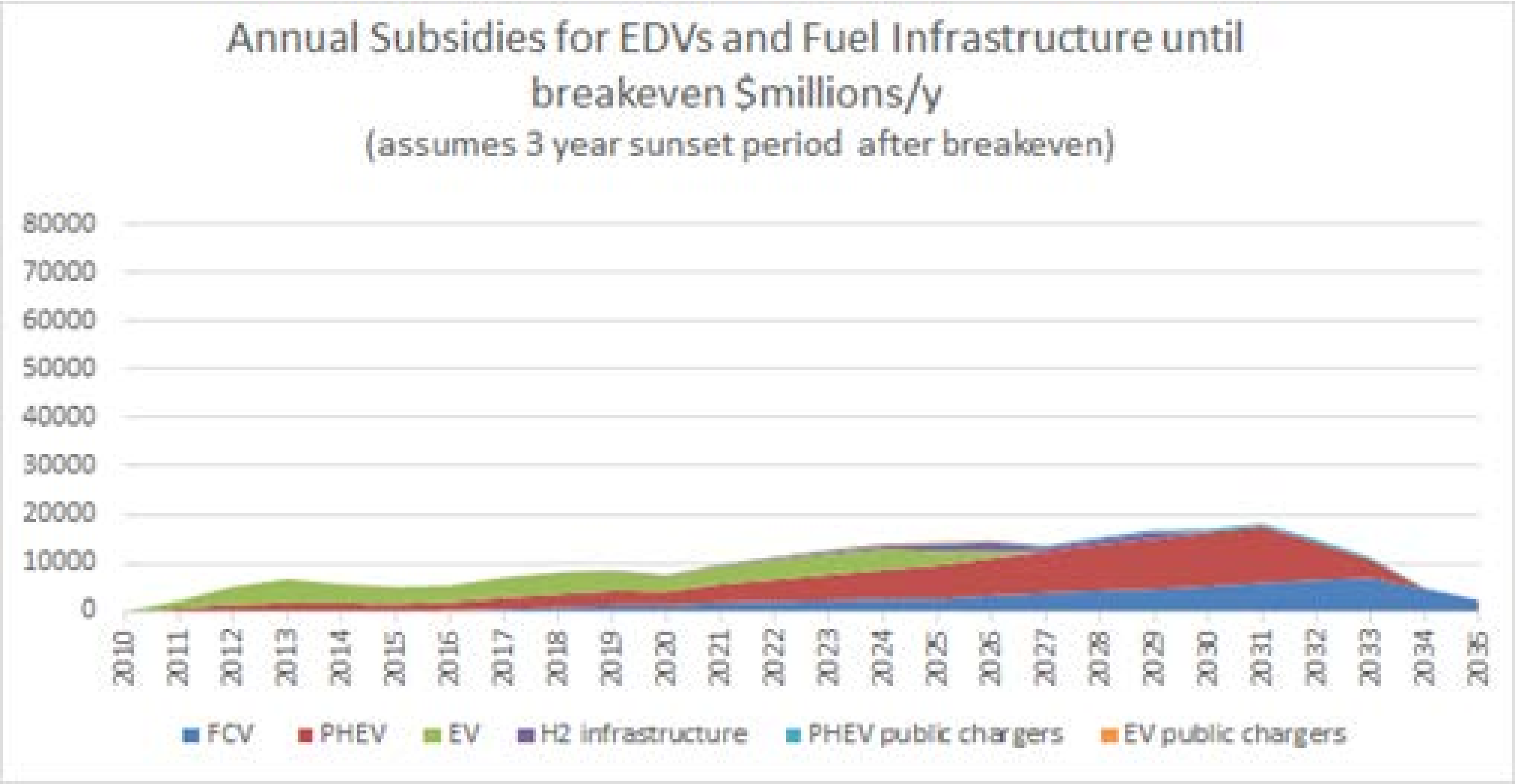


at top of each bar is net cost $billion/y

Incremental INVESTMENTS for Alt Fueled Vehicles and Infrastructure ($M/y) Ave ~$23 B/y



SUBSIDIES for Electric drive Vehicles and Infrastructure w/ 5-yr phase out after Breakeven ($M/y) Ave ~$11 B/y



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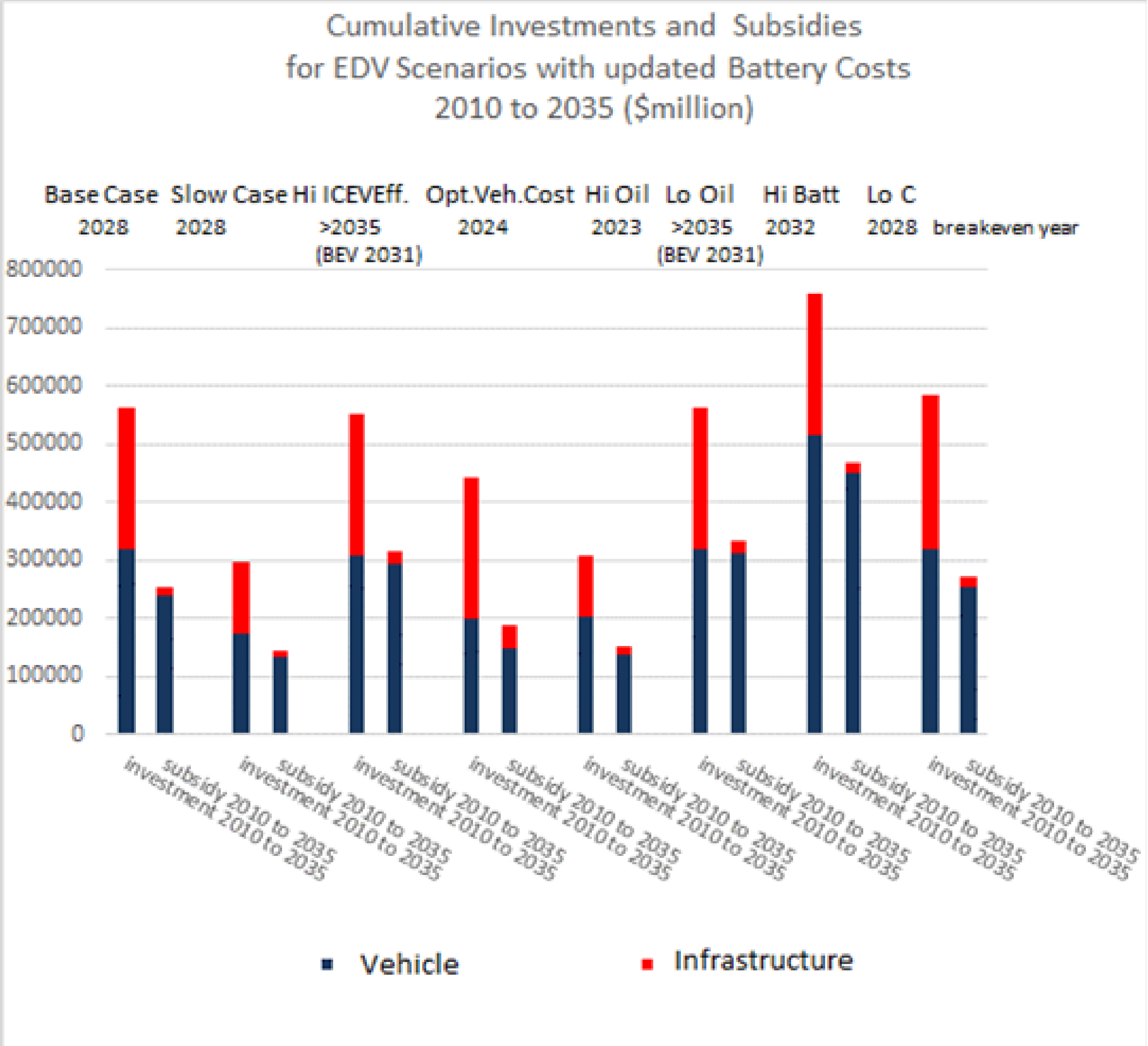

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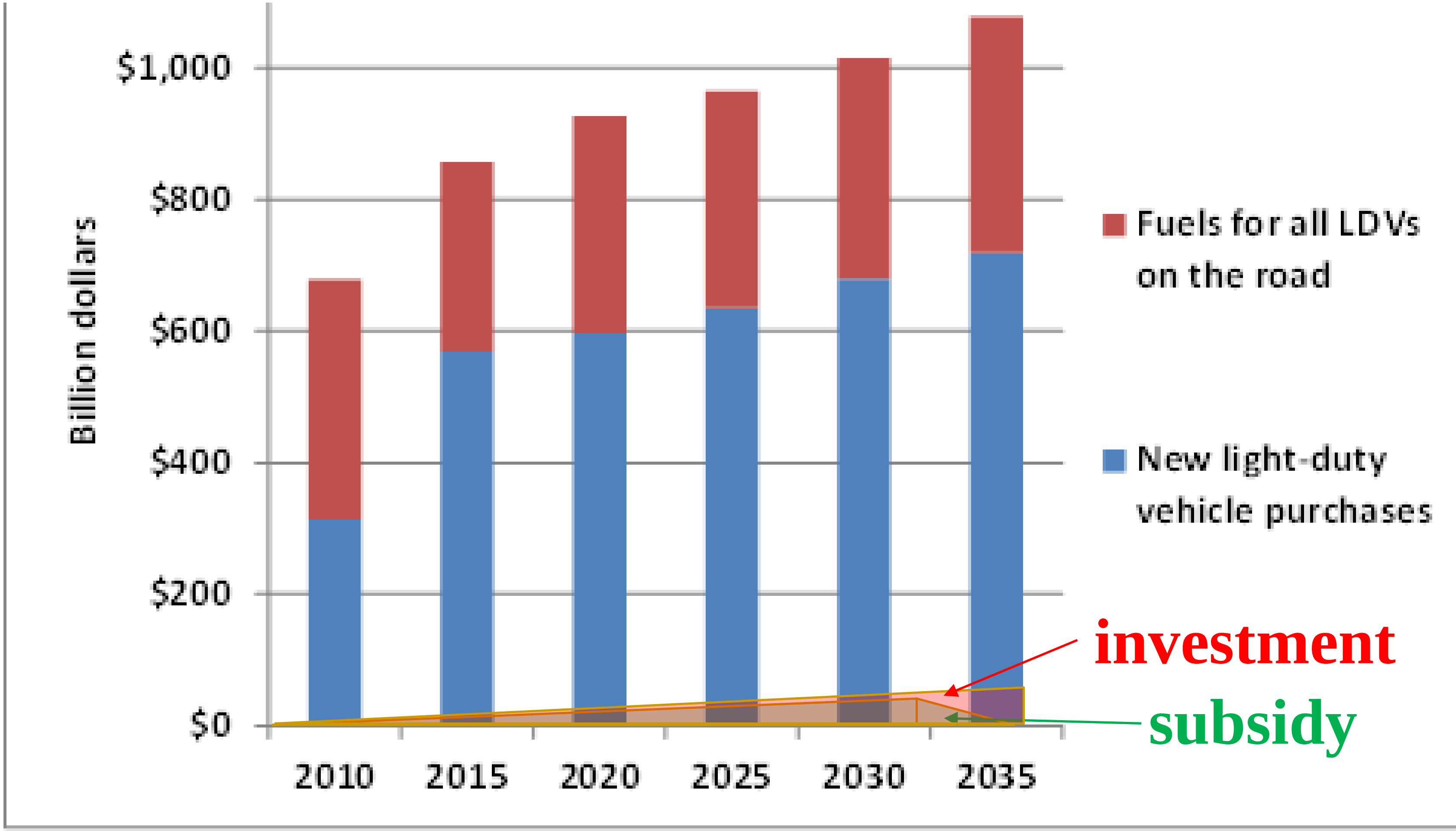
Transition costs

- Our Base case EDV scenario breaks even ~2028.
- Beyond this, fuel savings outweigh incremental costs for vehicles.
- **Cumulative INVESTMENTS** to 2035 are about $300-750 B, the majority for incremental cost of EDV vehicles.
- **Cumulative SUBSIDIES** (to breakeven w/3-yr phase out) are about $150-450 B. Required infrastructure **SUBSIDIES** are only about 5-10% of the total.
- The results are sensitive to a lot of assumptions

HOW DO TRANSITION COSTS COMPARE?
US projected to spend $19 trillion on new cars & fuels to 2035



Cum. ZEV subsides & investment costs <1-3% of total;
Subsidy phase out ~2035

Toward Transition Policies

- **Persistence and continuity of policies needed over many decades. Align policies. Signal there will be consistent policy over the long term and that it will adapt to reflect experience.**
- **Balanced, portfolio approach needed rather than relying on just one technology.**
- **Support, coordinate major stakeholders**
- **Incorporate externalities into economics.**
- **Experiment at the network scale.**
  - **City scale demonstrations of ZEV technologies as a networked system 10,000s of vehicles, 100s of stations in a region to start.**
  - **Supply early infrastructure where needed to support early vehicles**
  - **Expect a period of experimentation at the system level. Not everything may work immediately. Don't down select too soon.**
  - **The investment cost to bring the cost of ZEVs down to competitive with incumbents might be a few billion$ a year for 10-20 years.**

EXTRAS

Figure 19. Estimated greenhouse gas emissions for our base case. Most of the emissions come from gasoline usage with less than 10% of the total due to electric and hydrogen vehicles in 2035.

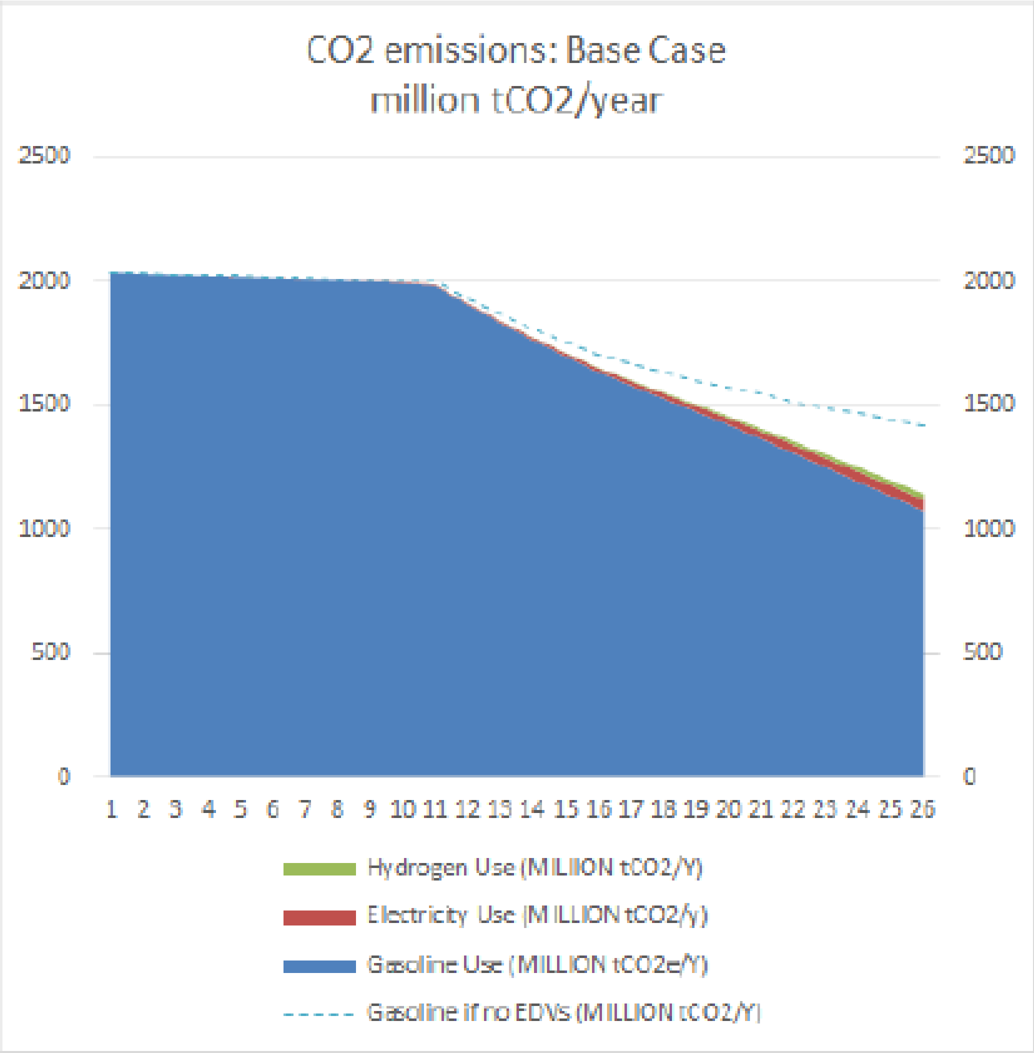


Figure 20. Cumulative net benefit (incremental EDV cost – fuel savings) and cumulative CO2 saved over time. Dividing the cumulative net benefit by the cumulative CO2 saved, gives a running time average avoided cost for CO2 $/tCO2 (Figure 21).

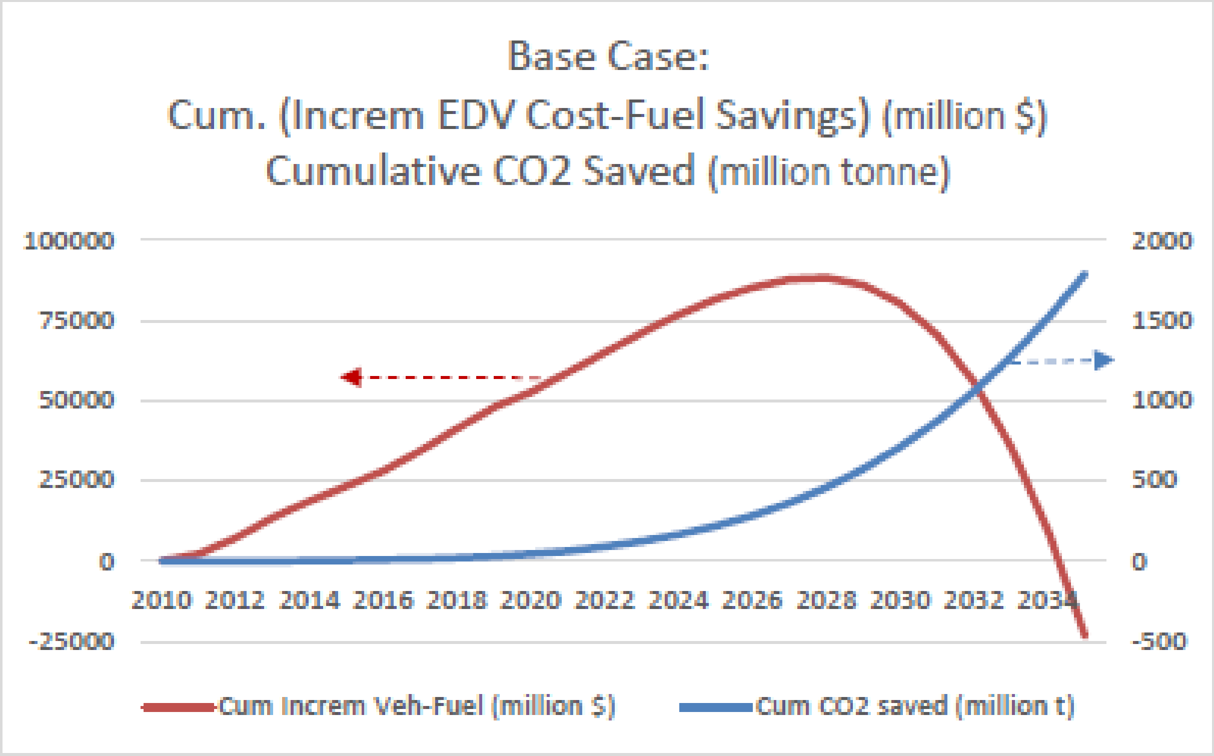
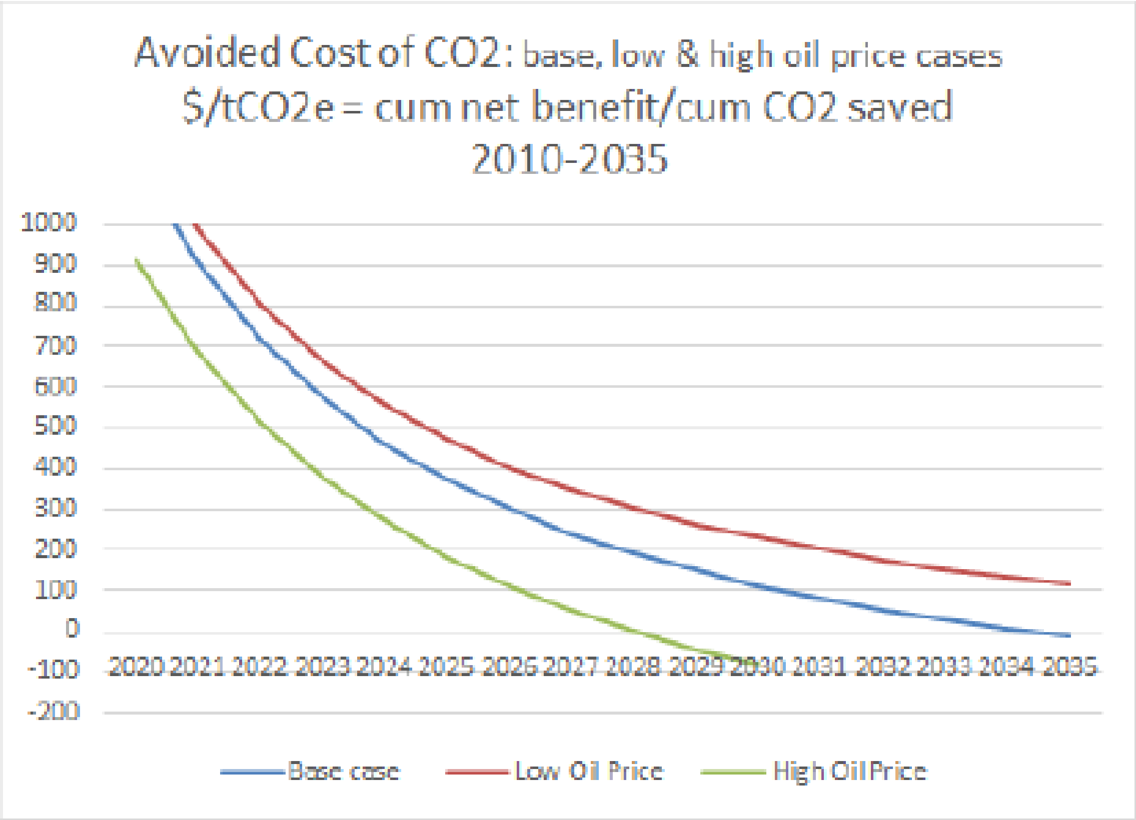
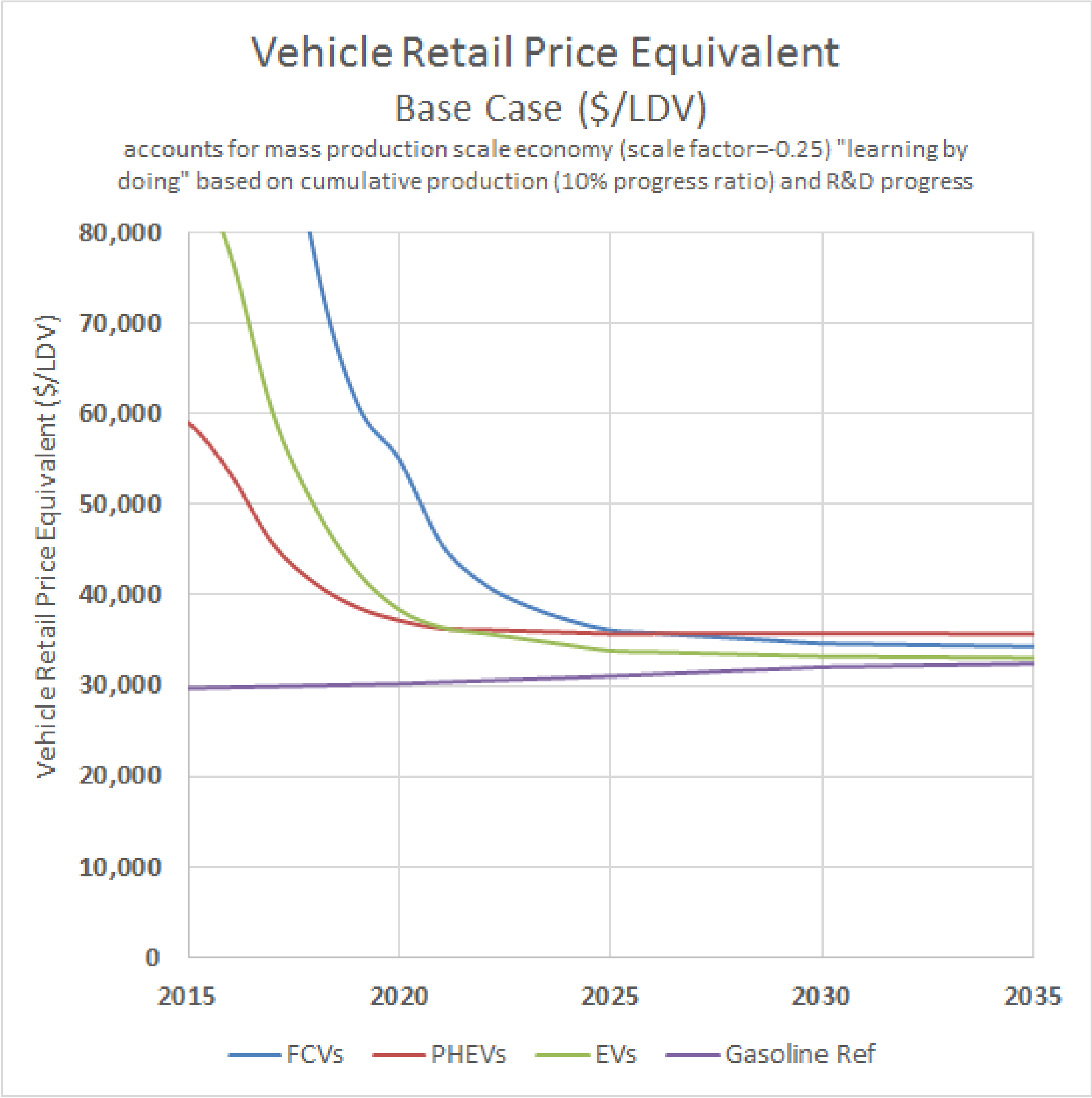


Figure 21. The average cost of CO_2 emissions is estimated our base case and high and low oil price cases. The cost of CO_2 drops over time, and becomes negative after about 2030-2035 depending on the case.





Based on NRC 2013 vehicle costs, accounting for dis-economies of small-scale, early vehicle production (scale elasticity = -0.25)

Table 1. Summary of Base Case Scenario Assumptions for Light Duty Vehicle Fleet[8]

	2015	2020	2025	2030	2035	Notes
New Vehicle Sales (million/y)						
ICEVs	16.1	15.5	13.3	8.8	4.8	
BEVs	0.06	0.4	1.5	3	4	
PHEVs	0.06	0.4	1.5	3	4	
H2 FCVs	0.0002	0.05	0.5	2	4	
Vehicle Retail Price Equivalent ($/vehicle) (for large scale mass production)						
ICEV	29,700	30,200	31,000	32,000	32,400	NRC 2013
BEV 100 mi range	49,000 51,000	42,300 37,100	39,800 34,400	37,500 33,200	36,000 33,100	NRC 2013 Nyquist & Nilsson 2015
PHEV	40,300 40,700	38,400 36,400	37,400 35,700	36,900 35,700	36,400 35,700	NRC 2013 Nyquist & Nilsson 2015
H2 FCV		37,500	36,100	34,600	34,300	NRC 2013
Selected Vehicle Component Costs						NRC 2013
Battery pack ($/kWh)	375 410	300 200	275 150	250 150	225 150	NRC 2013 Nyquist & Nilsson 2015
Fuel Cell System ($/kW)	$45/kW	$40/kW	$37/kW	$33/kW	$31/kW	NRC 2013
H2 Storage ($/kg)		$625/kg		$565/kg		NRC 2013, 5.6 kg >300 mi range
On-road Light Duty Fleet Averaged Fuel Economy (mile per gge)						NRC 2013
ICEV	22	24	30	35	40	
BEV	122	128	132	140	148	
PHEV-30	56	58	60	68	76	60% electric VMT
H2 FCV	78	83	85	90	95	
Infrastructure Capital Cost ($ per vehicle served)						
Home Charger	2500	2300	2100	1950	1600	1 per PEV
Public Charger	200	200	200	200	200	1 per 100 PEVs; DC fast charger costs $20,000 installed
H2 Station	10,000 (truck delivery, 100 kg/d)	4,000 (truck delivery, 250 kg/d)	3,000 (truck delivery, 500 kg/d)	3,000 (truck delivery, 500 kg/d)	3,000 (onsite SMR 1,000 kg/d)	Appendix B
Fuel Cost $/gge (U.S. Average)						
Gasoline	2.36	2.80	3.02	3.28	3.62	EIA AEO 2015; ref case
Electricity	6.1	5.9	5.5	5.3	5.0	10 cent/kWh Time of Use Rates + charger cost amortized over 15 years
Hydrogen	31	9.3	7.8	6.0	5.6	Appendix B

[8] All costs are given in constant $2015 dollars.

Table 2. Investments and Subsidies to Support Electric Drive Vehicles to "Breakeven" year and to 2035 based on the scenario in Figure 2. Our approach for estimating H2 infrastructure design and cost is detailed in Appendix B. The EDV investment per vehicle is assumed to equal the incremental Retail Price Equivalent (RPE) of the EDV compared to a reference gasoline vehicle (see Figure 6).

Investment Total	H_2 FCVs	PHEVs	Battery EVs
To Fuel Cost Breakeven Equivalence w/Gasoline (Cent per Mile Basis)	By 2025-2030 $8 B H2 infrastructure capital cost to reach U.S. ave.H2 cost= $7/kg	Electricity generally competitive on cent per mile basis	Electricity generally competitive on cent per mile basis
CUMULATIVE COSTS 2010 to Breakeven	Breakeven: 2034 19.1 million FCVs	Breakeven: 2032 24 million PHEVs	Breakeven: 2025 6.5 million BEVs
INVESTMENTS			
Vehicles (Incr)	$62 B	$117 B	$58 B
Infrastructure	$82 B (all H2 sta. cap.)	$51 B (home and public chargers)	$18 B (home and public chargers)
SUBSIDIES			
Vehicles (Incr)	$60 B	$113 B	$61 B
Infrastructure	$8.3 B (H2 sta. capital until H2 cost reaches $7/kg)	$5.0 B (public chargers only)	$1.7 B (public chargers only)
CUMULATIVE COSTS 2010 to 2035	2035: 23 million FCVs	2035: 35 million PHEVs	2035: 35 million BEVs
INVESTMENTS			
Vehicles (Incr.)	$71 B	$155 B	$113 B
Infrastructure	$99 B (all H2 sta. cap.)	$72 B (home and public chargers)	$71 B (home and public chargers)
SUBSIDIES			
Vehicles (Incr.)	$63 B	$117 B	$63 B
Infrastructure	$8.3 B (H2 sta. capital until H2 cost reaches $7/kg)	$6 B (public chargers only)	$2 B (public chargers only)

Table A.2 Assumed Automotive Battery Manufacturing Costs ($/kWh) for Two Studies: NRC (2013) and Nyquist and Nilsson (2015). We replaced the battery costs in Table F.28 (NRC 2013) with those from Nyquist and Nilsson (2015).

year	NRC 2013		Nyquist and Nilsson 2015	
	Base Case Battery Cost $/kWh	Optimistic Case Battery Cost $/kWh	Base Case Battery Cost $/kWh	Optimistic Case Battery Cost $/kWh
2010	450	450	450	450
2015	375	350	410	300
2020	300	275	200	200
2025	275	250	150	150
2030	250	200	150	150
2035	225	180	150	150
2040	200	160	150	150
2045	180	155	150	150
2050	160	150	150	150

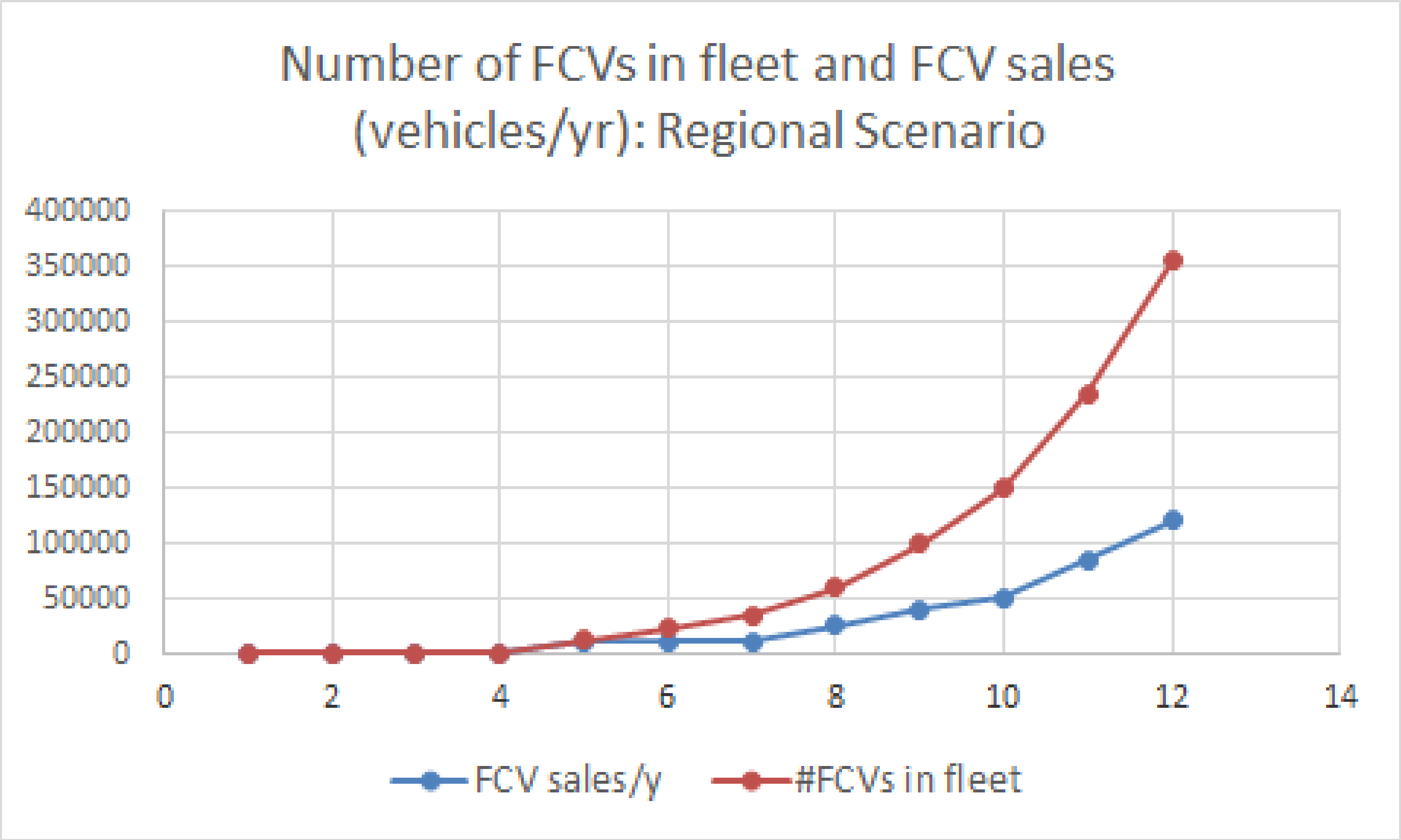
Table B.2. Hydrogen Station Cost Assumptions: 700 bar dispensing. (Compressed Gas Truck costs based on industry input; Onsite SMR and electrolyzer costs from (Ogden and Nicholas 2011).

Time frame	Capital Cost	Annual O&M cost $/yr
COMPRESSED GAS TRUCK DELIVERY		
Phase 1 (years 1-2) 100 kg/d 250 kg/d	 $1 million $1.5 million	$100 K (fixed O&M) + 1 kWh/kgH_2 x kg H_2/yr x $/kWh (compression electricity cost) + H_2 price $/kg x kg H_2/y (H_2 cost delivered by truck)
Phase 2 (years 3-4) 170 kg/d 250 kg/d	 $0.9 million $1.4 million	Same as above
Phase 3 (year 5+) 170 kg/d 250 kg/d 500 kg/d	 $0.5 million $0.9 million $1.5-2 million	Same as above
ONSITE STEAM METHANE REFORMER		
Phase 3 (year 5+) 1000 kg/d	$4.38 million	7% capital costs + $216,000 rent (fixed O&M) 0.154 MBTU/kg x NG price($/MBTU) x kg H_2/yr (natural gas feedstock cost) + 3.08 kWh/kg x kg H_2/yr x $/kWh (compression electricity cost)
ONSITE ELECTROLYZER		
Phase 2 (years 3-4) 170 kg/d 250 kg/d 500 kg/d	 $2.7 million $3.7 $4.7	 10% capital costs + $80,000 rent (fixed O&M) 9% capital costs + $120,000 rent (fixed O&M) 8% capital costs + $144,000 rent (fixed O&M) (53.4 kwh/kg + 1.74 kWh/kg) x $/kWh (variable O&M) (electrolysis + compression) x (elec. price)
Phase 3 (year 5+) 500 kg/d 1000 kg/d	 $3.1 million $5.1 million	 8% capital costs + $144,000 rent (fixed O&M) 7% capital costs + $216,000 rent (fixed O&M) (53.4 kwh/kg + 1.74 kWh/kg) x $/kWh (variable O&M) (electrolysis + compression) x (elec. price)

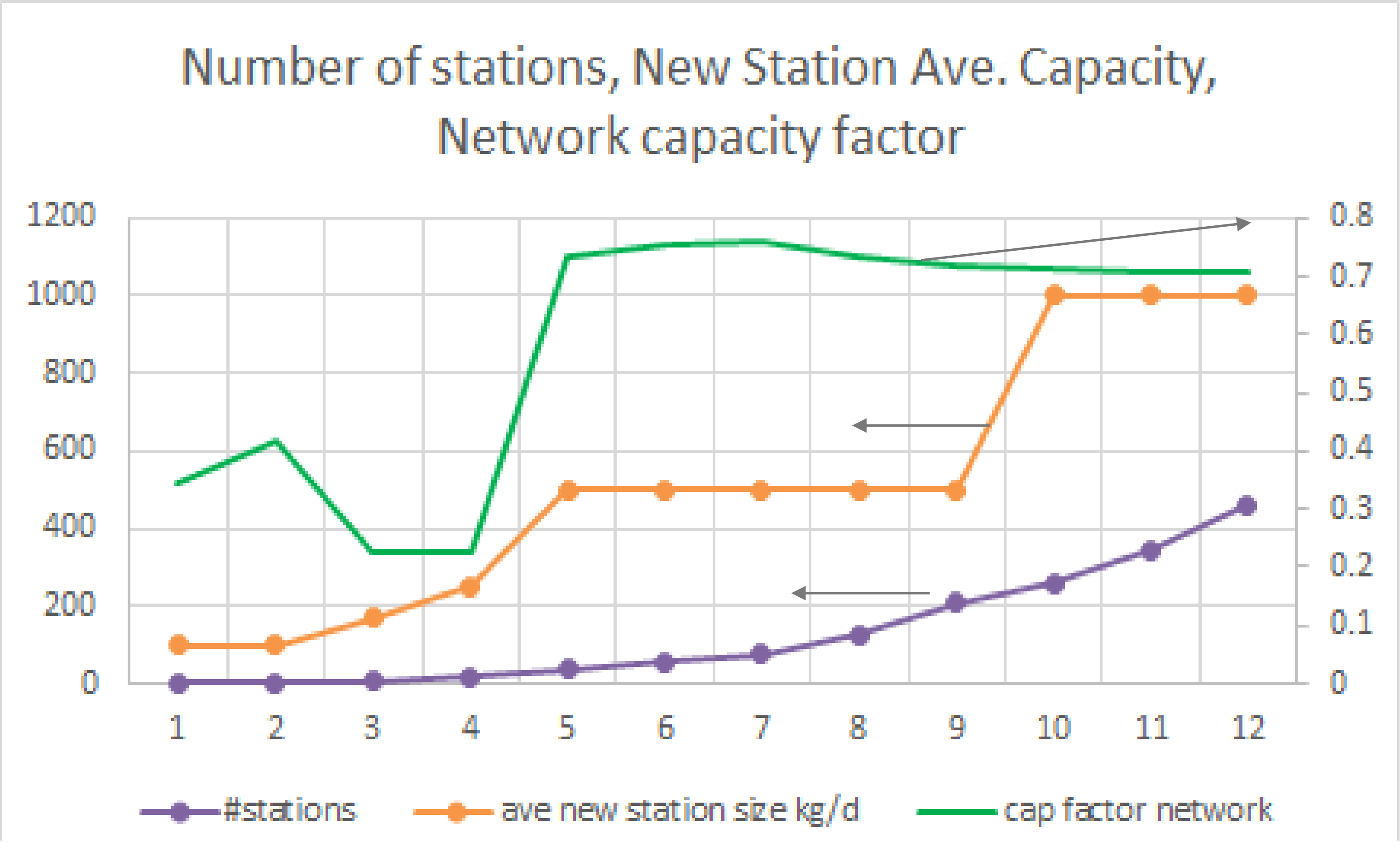
Table B.1. Scenario for rollout of FCVs and hydrogen stations in an “early lighthouse city”.

Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
# FCVs in fleet	197	240	347	1161	12106	23213	34320	59320	99320	149320	234320	354320
H2demand kg/d	138	168	243	813	8474	16249	24024	41524	69524	104524	164024	248024
#NEW STATIONS INSTALLED PER YEAR BY STATION SIZE (kg/d) AND TYPE												
Station Size												
Compressed Gas Truck Delivery												
100 kg/d	4											
170 kg/d			4									
250 kg/d				10								
500 kg/d					20	20	20	50	80			
Onsite Steam Reformer												
1000 kg/d										50	85	120
TOTAL STATION CAPACITY (kg/d)												
	400	400	1080	3580	13580	23580	33580	58580	98580	148580	233580	353580
NETWORK CAPACITY FACTOR												
	0.34	0.42	0.22	0.23	0.62	0.69	0.72	0.71	0.71	0.70	0.70	0.70
TOTAL NUMBER OF STATIONS												
	4	4	8	18	38	58	78	128	208	258	343	465
CUMULATIVE CAPITAL INVESTMENT IN STATIONS ($ millions)												
	4	4	8	23	53	83	113	188	308	526	899	1424
LEVELIZED COST OF HYDROGEN ($/kg)												
Network Average for entire rollout												
	31.8	27.2	30.5	22.7	9.4	8.7	8.5	8.4	8.3	7.3	6.58	6.14
Next Station Built (at 70% capacity factor)												
						8.0	8.0	8.0	6.1	6.1	6.1	6.1

Scenario for Regional H2 FCV Rollout Years 1-12

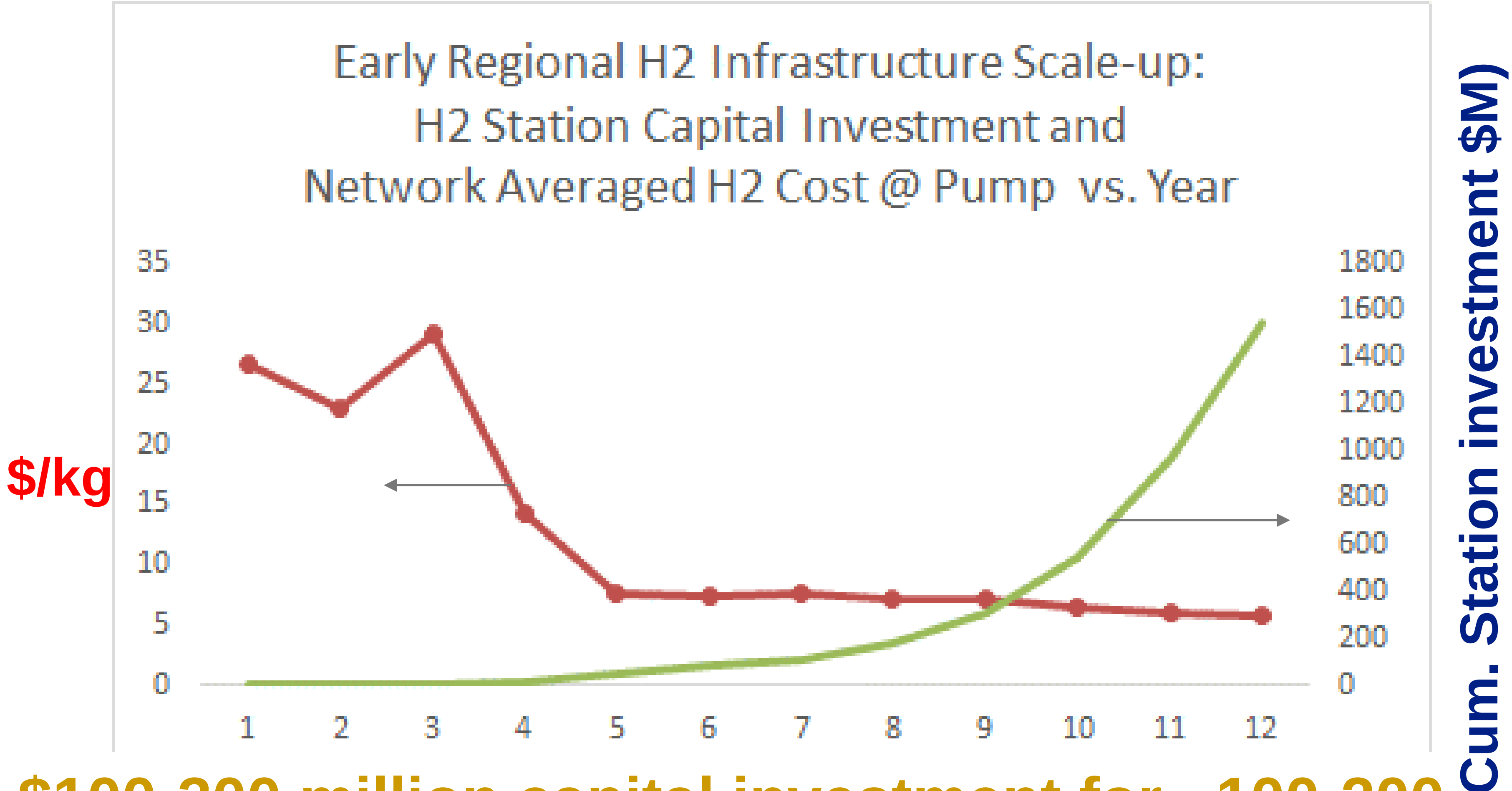


Scenario for regional station rollout to year 12



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.

Key Consumer Attributes of Fuel Cell & Plug-in Vehicles

Table 2. Comparison of Key Consumer Attributes of Fuel Cells and Plug-in Vehicles

	Hydrogen Fuel Cell Vehicles	**Plug-in Hybrid and Battery Electric Vehicles**	**Gasoline and Hybrid Vehicles**
Refueling time	Shorter (3-5 minutes)	Longer (20 min to many hours), PHEV can refuel gasoline quickly	Short (3-5 minutes)
Vehicle sizes	Small to large vehicles	Small to midsize vehicles	Small to large vehicles
Vehicle range	300+ miles per refill	10-265 miles of all electric range	400+ miles per refill
Refueling paradigm	H_2 stations similar to gas stations	Chargers (home and public)	Ubiquitous gas stations

Conclusions Transition Cost Results

- EDVs "break even" economically with incumbent gasoline vehicles in the 2023-2032 time frame for a range of scenarios with varying assumptions about technology, vehicle adoption rate and fuel costs.
- Cumulative Transition **investment costs** for light-duty EDVs and fuels (summed between 2010 and 2035) are estimated to be in the range of **$300 to $600 Billion**.
- Cumulative Transition **subsidy costs** (e.g. investments needed to breakeven) for light-duty EDVs and fuels are estimated to be in the range of **$175-350 Billion**.
- The majority of transition costs are for vehicle incremental costs. Required subsidies are 10-20% lower than investments for vehicles, and required subsidies are 80-90% lower than investments for fuel infrastructure. Thus the differences are large and are worthy of additional investigation.
- **Transition costs over the next 20 years of several hundred billion dollars would be quite small in comparison to the $19 trillion expected to be paid overall for new light-duty vehicles and for fuels for all LDVs in this time frame.**
  - Investment costs for EDVs and their fuels to 2035 are about 1.5 to 3% of this $19 trillion total, with the estimated subsidy costs about 1-2%.
  - On an annual basis, the Base Case investment costs range from about $5 billion to $55 billion with subsidies ranging from $5 billion to $20 billion, in a vehicles/fuels market with nearly $1 trillion spent annually.

Wild cards

- Shared mobility, electrification, autonomous vehicles (will this decrease VMT, GHGs, air pollution?)
- How much might virtual reality replace physical travel?
- Urban design may give us very different transport paradigms (China is planning for battery cars in cities and intercity transit via FC buses, elec train).
- What will future consumers want?